



## Optimizing Mist Irrigation Scheduling for Sustainable Oyster Mushroom (*Pleurotus* spp.) Production in Controlled Environment Agriculture

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### ABSTRACT

Mushroom cultivation requires precise control of temperature and relative humidity to optimize yield. Mist irrigation is a cost-effective technique for creating favorable growing conditions, but its optimal duration remains uncertain. This study aimed to determine the effects of different mist irrigation durations on the yield of three *Pleurotus* mushroom species—*P. ostreatus* Hungarian, *P. ostreatus*, and *P. eous*—under controlled nursery conditions. Mushroom bags were incubated for 30 days and then placed in a nursery equipped with an automated mist irrigation system set to operate for 3, 4, or 5 minutes per hour between 08:00 and 17:00 over a 60-day production cycle. Yield per bag, temperature, and relative humidity were recorded daily. Results showed that the 4-minute irrigation treatment produced the highest average yields—229.33g for *P. ostreatus* Hungarian, 294.79g for *P. ostreatus*, and 237.44g for *P. eous*—representing a 12.50% increase compared to the 3-minute control. Relative humidity was inversely related to temperature; the highest humidity (91.70%) and lowest temperature (26.85°C) occurred under the 5-minute treatment, whereas the lowest humidity (71.09%) and highest temperature (28.42°C) occurred under the 3-minute treatment. The findings suggest that maintaining moderate humidity and temperature through optimized mist irrigation enhances *Pleurotus* mushroom yields, with a 4-minute duration per hour being the most effective under the tested conditions. These findings provide essential parameters for programming automated irrigation systems in smart agriculture applications.

**Keywords:** Automated environmental control, Evaporative cooling, Microclimate control, Smart agriculture, Water-use efficiency.

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### INTRODUCTION

Mushrooms in the *Pleurotaceae* family, scientifically referred to as *Pleurotus* spp. and commonly known as oyster mushrooms, have a smooth, oyster-shaped cap varying in color and size depending on species and a medium-length stalk. Oyster mushroom mycelium growth is possible in temperatures ranging from as low as 5°C to as high as 40°C but is particularly noticeable in

the temperature range of 20°C to 30°C depending on species (Setiawan, 2001; Sarker et al., 2008). These mushrooms represent one of the most commercially important edible fungi worldwide, valued not only for their culinary applications but also for their nutritional profile, containing high-quality proteins, dietary fiber, vitamins, and bioactive compounds with potential medicinal properties (Devi et al., 2024; Sreedharan et al., 2025).

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The global significance of optimizing mushroom cultivation practices has become increasingly evident in recent years. The mushroom cultivation market was valued at USD 4.55 billion in 2025 and is projected to reach USD 9.35 billion by 2033, reflecting a compound annual growth rate of approximately 9.7% (Sunil et al., 2025). Indoor growing systems dominate this market, accounting for over 60% of mushroom cultivation revenue in 2023, attributed to their ability to provide controlled environment advantages and achieve higher yields compared to traditional outdoor cultivation methods (More, 2025). This economic growth underscores the critical importance of developing precise environmental control methods, particularly optimized irrigation systems that can enhance productivity while maintaining sustainability (Charoenrak et al., 2024; Guragain et al., 2024).

Controlled environment agriculture (CEA) has emerged as a transformative approach to mushroom production, enabling year-round cultivation with consistent quality and reduced dependency on seasonal variations (Beacham et al., 2019; Kozai et al., 2020). Within CEA systems, environmental parameters such as temperature, humidity, light, and air circulation can be precisely regulated to match the optimal requirements of different mushroom species. Among these parameters, temperature and relative humidity are particularly critical for *Pleurotus* cultivation, as they directly influence mycelial growth rate, primordia formation, fruiting body development, and overall yield quality (Stamets, 2000; Miles and Chang, 2004).

One commonly applied cultivation method for environmental control is mist irrigation, also known as evaporative cooling or fogging systems. Mist irrigation is a form of evaporative cooling that relies predominantly on phase transition—a physical process of transition between basic matter states involving heat transfer through the convection of fluid in motion—in lowering the temperature and increasing the relative humidity in a growing chamber (Kachhwaha et al., 1998; Sureshkumar et al., 2008). When water droplets are dispersed as fine mist, they evaporate rapidly, absorbing heat from the surrounding air and thereby reducing temperature while simultaneously increasing moisture content. This dual effect makes mist irrigation particularly suitable for mushroom cultivation, where maintaining high humidity levels (typically 80–95%) and moderate temperatures (16–28°C) is essential for optimal fruiting (Kolaly et al., 2020; Setiawan et al., 2021).

Recent advances in smart agriculture have demonstrated the potential for integrating Internet of Things (IoT) technology with traditional mist irrigation systems, enabling automated environmental monitoring and control with real-time adjustments (Choosumrong et al., 2023; Rukhiran et al., 2023). IoT-based systems can utilize sensors to continuously monitor temperature, humidity, CO<sub>2</sub> levels, and other parameters, automatically adjusting misting duration and frequency to maintain optimal growing conditions (Thakur et al., 2021; Guragain et al., 2024; Phasinam et al., 2024). Machine learning algorithms can further enhance these systems by predicting environmental fluctuations and optimizing

irrigation schedules based on historical data and real-time conditions (Charoenrak et al., 2025). However, despite these technological advances, the fundamental understanding of optimal irrigation durations—the core parameter that must be programmed into these advanced systems—remains essential and requires experimental validation under controlled conditions (Arif et al., 2025). Previous research has established baseline environmental requirements for *Pleurotus* cultivation. Najmurokhan et al. (2020) demonstrated that mushroom cultivation during the dry season required temperature and relative humidity control to create an environment conducive to mushroom growth, specifically temperatures ranging from 22 to 28°C and relative humidity ranging from 60 to 80%. Their findings indicated that such optimal environments could be achieved using simple misting systems with chemical diffusers (Kitipanasil et al., 2019). Similarly, Suksawang et al. (2022) reported that during the rainy season, *P. sajor-caju*—a term referring to some warm weather varieties of *Pleurotus* mushrooms—produced higher yields in the temperature range of 25 to 35°C and relative humidity of 75% to 90% (Wibowo et al., 2023). A comparative study by Krupodorova and Barshteyn (2020) found that *P. fossulatus*, a mushroom species closely related to *P. eryngii*, grew well in the temperature range of 20±1°C, whereas the growth of *P. eous* was most pronounced in the temperature range of 21°C to 35°C and the relative humidity range of 65% to 95% (Huang et al., 2024; Negi et al., 2025).

While these early studies focused primarily on optimal environmental conditions, more recent research has examined the specific technologies and control strategies for achieving these conditions. Montero et al. (1990) employed cold mist irrigation in conjunction with shade structures in greenhouse environments, finding that the innovation could drop daytime temperature by 5°C and sustain relative humidity at levels close to 85%. Abdel-Ghany and Kozai (2006) developed an evaporative cooling system based on energy and mass balance calculations that diffused mist at a flow rate of 10 g/s, demonstrating that misting for 60 seconds could reduce temperature by up to 30%. Similarly, Pongpanich et al. (2015) reported that an evaporative cooling system could lower the temperature in a closed nursery by 4 to 6°C. More recently, Isaranontakul and Rukphong (2019) utilized an Android operating system integrated with a control application for mushroom cultivation, discovering that automated on-off switching could effectively regulate temperature and relative humidity within ranges that promoted optimal growth.

Despite this growing body of literature on environmental control technologies, a critical research gap remains: while numerous studies have identified optimal temperature and humidity ranges for mushroom cultivation and demonstrated various technologies capable of achieving these conditions, there is limited systematic investigation into the specific irrigation durations required to optimize yields across different *Pleurotus* species under standardized controlled environment conditions. Most existing research has focused on continuous monitoring and adjustment systems or has examined broad environmental ranges, but few studies have systematically

compared discrete irrigation durations (e.g., 3, 4, or 5 minutes per hour) to identify optimal scheduling parameters. This information is essential for programming both simple timer-based systems used by small-scale growers and sophisticated IoT-based automated systems deployed in commercial operations.

Furthermore, water-use efficiency has become an increasingly important consideration in sustainable agriculture, including mushroom cultivation (Rukhiran et al., 2023). Excessive irrigation not only wastes water resources but can also create overly humid conditions that promote contamination by competing fungi and bacteria, while insufficient irrigation leads to suboptimal growing conditions and reduced yields. Identifying the precise irrigation duration that maximizes yields while minimizing water use is therefore essential for both environmental sustainability and economic viability of mushroom production systems.

Therefore, this research aimed to address these gaps by systematically examining the effects of mist irrigation controlled with an automatic water valve on the yields of three commercially important species of *Pleurotus* mushrooms: *P. ostreatus* Hungarian (commonly referred to as Hungarian mushrooms), *P. ostreatus* (commonly referred to as grey mushrooms), and *P. eous* (commonly referred to as Bhutan mushrooms). Specifically, this study compared mushroom yields between three discrete irrigation treatments—3 minutes, 4 minutes, and 5 minutes per hour—to identify the optimal irrigation scheduling parameter. The findings from this research provide practical, evidence-based irrigation duration parameters that can be directly programmed into automated irrigation systems, whether simple timer-based controllers or sophisticated IoT-enabled smart agriculture platforms, thereby contributing to more efficient, sustainable, and productive *Pleurotus* mushroom cultivation systems.

## MATERIALS & METHODS

### Experimental Location and Climate

The experiment was conducted at the Department of Crop Production, Faculty of Agricultural Technology, Rajamangala University of Technology Thanyaburi, Pathum Thani Province, Thailand (13.9787° N, 100.6132° E). The study area is characterized by a tropical savanna climate (Aw) according to the Köppen–Geiger climate classification system, with high temperatures and distinct wet and dry seasons (Fig. 1). The average annual temperature ranges between 26 and 32 °C, and 50–70% relative humidity, necessitating artificial climate control for optimal mushroom production.

### Mushroom Bag Preparation

Mushroom bags were prepared by mixing 50kg of rubber wood sawdust, 1kg of gypsum (calcium sulfate dihydrate,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), 100g of magnesium sulfate ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ), and 30L of water. The substrate components were thoroughly mixed to ensure uniform distribution, and the mixture was filled into heat-resistant polypropylene bags measuring 165mm × 318mm. The bags were then sterilized using steam at 121°C and 15psi

pressure for 4 hours in an autoclave to eliminate competing microorganisms. After sterilization, bags were allowed to cool to room temperature (approximately 25°C) in a clean environment for 12–16 hours.

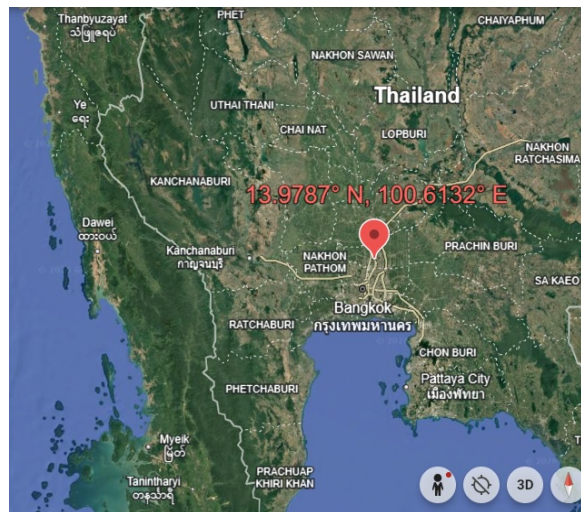


Fig. 1: Geographic location of the experimental site.

Once cooled, each sterilized substrate bag was inoculated with 50g of spawn (mycelium-colonized grain substrate) of either *P. ostreatus* Hungarian, *P. ostreatus*, or *P. eous* species. Inoculation was performed in a laminar flow cabinet to maintain sterile conditions. The inoculated bags were sealed and transferred to a dark incubation room maintained at 25–28°C and 60–70% relative humidity for mycelial colonization. The bags were incubated for 30 days until completely covered with white mycelium, indicating full substrate colonization and readiness for fruiting initiation.

### Experimental Design and Irrigation Treatments

After the incubation period, fully colonized mushroom bags were transferred to a climate-controlled growing chamber (nursery) equipped with an automated mist irrigation system. The irrigation system consisted of high-pressure misting nozzles (50micron droplet size) installed at 2-meter intervals throughout the chamber, connected to a programmable solenoid valve controller and water filtration system. The irrigation schedule was programmed to operate between 08:00 and 17:00 daily (9 hours total), with misting occurring at the beginning of each hour (Fig. 2).

The experiment followed a randomized complete block design (RCBD) with three irrigation treatments and three mushroom species, replicated 10 times each. The three irrigation duration treatments were selected based on preliminary trials and manufacturer recommendations for misting systems: 3 minutes per hour (control, representing conservative water use), 4 minutes per hour (moderate irrigation), and 5 minutes per hour (intensive irrigation). Each treatment consisted of 10 mushroom bags per species, totaling 30 bags per treatment and 90 bags in the entire experiment. Bags were arranged in a randomized pattern within the growing chamber to minimize position effects.



**Fig. 2:** Mushroom growing chamber with automated mist irrigation system.

Treatment specifications were as follows:

Treatment 1 (Control): 3 minutes of mist irrigation per hour, applied to *P. ostreatus* Hungarian, *P. ostreatus*, and *P. eous* (9 irrigation cycles daily, 27 minutes total misting time per day)  
 Treatment 2: 4 minutes of mist irrigation per hour, applied to *P. ostreatus* Hungarian, *P. ostreatus*, and *P. eous* (9 irrigation cycles daily, 36 minutes total misting time per day)  
 Treatment 3: 5 minutes of mist irrigation per hour, applied to *P. ostreatus* Hungarian, *P. ostreatus*, and *P. eous* (9 irrigation cycles daily, 45 minutes total misting time per day)

### Growing Chamber Management and Monitoring

The growing chamber was equipped with automated ventilation fans programmed to operate for 15 minutes every 2 hours to maintain adequate air circulation and prevent CO<sub>2</sub> accumulation. Natural light was allowed to enter through translucent panels in the chamber roof, providing approximately 500–800lux of diffuse light during daylight hours, sufficient for *Pleurotus* fruiting body development without requiring supplemental artificial lighting.

Temperature and relative humidity were continuously monitored using calibrated digital sensors (accuracy  $\pm 0.5^{\circ}\text{C}$  for temperature,  $\pm 3\%$  for relative humidity) positioned at the center of each treatment block. Data were recorded automatically at 30-minute intervals using a data logger, and daily average values were calculated for analysis. The surfaces of mushroom bags were inspected daily and gently washed with clean water after each harvest to remove residual spores and debris. Mist irrigation nozzles were cleaned and descaled twice monthly to ensure consistent droplet size and distribution. The growing chamber floor was swept and disinfected weekly. Integrated pest management protocols were implemented to prevent fruit fly and snail infestations, including installation of insect screening on ventilation openings and placement of beer traps for monitoring.

### Data Collection and Statistical Analysis

The production cycle lasted 60 days from the day bags were placed in the growing chamber. Mushroom fruiting

bodies were harvested when caps reached full expansion but before spore release (typically when cap margins just began to flatten). Each harvest was weighed immediately using a calibrated digital balance (precision 0.01 g), and cumulative yield per bag was calculated by summing all harvests over the 60-day period. Multiple flushes (fruiting cycles) occurred during this period, typically 2–4 flushes per bag depending on species and treatment.

Data were analyzed using analysis of variance (ANOVA) for a randomized complete block design with three factors: irrigation duration (3 levels), mushroom species (3 levels), and block (10 replicates). Treatment means were separated using Duncan's Multiple Range Test (DMRT) at a 95% confidence level. Coefficient of variation (CV) was calculated to assess experimental precision.

## RESULTS

### Yield of *Pleurotus* Mushroom Species

Mist irrigation duration significantly affected mushroom yields across all three *Pleurotus* species tested (Table 1 and Fig. 3). The 4-minute irrigation treatment produced the highest average yields for *P. ostreatus* Hungarian (229.33g per bag), *P. ostreatus* (294.79g per bag), and *P. eous* (237.44g per bag). These yields were significantly higher than both the 3-minute control treatment and the 5-minute treatment at the 95% confidence level ( $p < 0.05$ ).

**Table 1:** Average yield weight per bag of three *Pleurotus* mushroom species under different mist irrigation durations

Irrigation Treatment	<i>P. ostreatus</i> Hungarian (g)	<i>P. ostreatus</i> (g)	<i>P. eous</i> (g)
3 minutes/hour (control)	203.84b	262.03b	211.06b
4 minutes/hour	229.33a	294.79a	237.44a
5 minutes/hour	183.46c	235.83c	189.95c
F-test	*	*	*
CV (%)	0.49	0.30	0.28

Notes: \*indicates significant differences at the 95% confidence level; For the DMRT, means with different vertical letters, i.e., a, b, and c, demonstrate significant differences in the groupings at the 95% confidence level.



**Fig. 3:** Fruiting body characteristics of three *Pleurotus* species cultivated under controlled environmental conditions: (A) *Pleurotus ostreatus*

Hungarian, (B) *Pleurotus ostreatus*, and (C) *Pleurotus eous* grown in a mushroom growing chamber with an automated mist irrigation system.

Compared to the 3-minute control treatment, the 4-minute irrigation increased yields by 12.50% for *P. ostreatus* Hungarian (from 203.84g to 229.33g), 12.49% for *P. ostreatus* (from 262.03g to 294.79g), and 12.50% for *P. eous* (from 211.06g to 237.44g). Conversely, the 5-minute irrigation treatment produced significantly lower yields than both other treatments, with *P. ostreatus* Hungarian yielding 183.46g per bag, *P. ostreatus* yielding 235.83g per bag, and *P. eous* yielding 189.95g per bag. Interestingly, the 3-minute control treatment produced 11.27% higher yields on average compared to the 5-minute treatment, suggesting that excessive irrigation was more detrimental to productivity than conservative irrigation.

Among the three species, *P. ostreatus* consistently produced the highest absolute yields under all irrigation treatments, followed by *P. eous* and *P. ostreatus* Hungarian. The coefficient of variation (CV) values were low across all species (0.28–0.49%), indicating high experimental precision and consistency in measurements.

### Temperature and Relative Humidity Relationships

Environmental monitoring revealed a strong inverse relationship between relative humidity and temperature in the growing chamber (Table 2). As mist irrigation duration increased, relative humidity rose while temperature decreased, demonstrating the evaporative cooling effect of the misting system.

**Table 2:** Temperatures and relative humidity in the nursery

Irrigation Treatment	Relative humidity (%)	Temperatures (°C)
3 minutes/hour (control)	71.09c	28.42a
4 minutes/hour	79.99b	27.33ab
5 minutes/hour	91.70a	26.85b
F-test	*	*
CV (%)	2.61	1.87

Notes: \* indicates significant differences at the 95% confidence level; For the DMRT, means with different vertical letters, i.e., a, b, and c, demonstrate significant differences in the groupings at the 95% confidence level.

The 5-minute irrigation treatment produced the highest average relative humidity at 91.70% and the lowest average temperature at 26.85°C. The 4-minute treatment maintained intermediate conditions with 79.99% relative humidity and 27.33°C temperature. The 3-minute control treatment resulted in the lowest relative humidity at 71.09% and the highest temperature at 28.42°C. All differences between treatments were statistically significant ( $p < 0.05$ ).

The coefficient of variation for humidity measurements was 2.61%, while temperature measurements showed a CV of 1.87%, indicating consistent environmental control within each treatment. These data demonstrate that the mist irrigation system effectively modulated the growing environment, with each minute of additional misting per hour contributing to measurable changes in both humidity and temperature parameters.

## DISCUSSION

The present study demonstrates that mist irrigation

duration significantly influences both environmental conditions and mushroom yields in controlled environment agriculture systems. The 4-minute per hour irrigation treatment emerged as optimal across all three *Pleurotus* species tested, achieving average yields of 229.33g for *P. ostreatus* Hungarian, 294.79g for *P. ostreatus*, and 237.44g for *P. eous*. This treatment maintained environmental conditions of 27.33°C temperature and 79.99% relative humidity, which align closely with the optimal ranges reported in previous research and can be explained through fundamental physiological principles of fungal growth and development.

### Physiological Basis for Optimal Environmental Conditions

The superior performance of the 4-minute irrigation treatment can be understood through the relationship between environmental parameters and fungal metabolism. Temperature directly affects enzymatic activity within mycelial cells, with most fungal enzymes exhibiting optimal activity in the 25–30°C range (Miles and Chang, 2004). The 27.33°C temperature achieved by 4-minute irrigation falls within this optimal range, supporting efficient nutrient metabolism, protein synthesis, and energy production. At higher temperatures (such as the 28.42°C observed under 3-minute irrigation), increased respiration rates can lead to excessive carbon loss, reducing the efficiency of substrate conversion to fruiting body biomass (Stamets, 2000). Conversely, slightly lower temperatures (26.85°C under 5-minute irrigation) may reduce enzymatic activity sufficiently to slow growth rates, though this temperature effect alone does not fully explain the yield reduction observed in the 5-minute treatment.

Relative humidity plays a critical role in maintaining turgor pressure within fungal cells and facilitating water transport from substrate to developing fruiting bodies (Royse et al., 2017). The 79.99% humidity achieved by 4-minute irrigation appears optimal for *Pleurotus* cultivation, providing sufficient atmospheric moisture to prevent desiccation stress while avoiding the problems associated with excessive humidity. Mushroom development requires continuous water uptake from the substrate through the mycelial network, with water constituting 85–95% of fresh fruiting body weight (Sánchez, 2010). Adequate atmospheric humidity reduces transpirational water loss from developing mushroom caps, allowing more efficient water transport and expansion of fruiting bodies. However, when humidity becomes excessive, as in the 5-minute treatment (91.70%), several detrimental effects may occur.

### Explaining Yield Reduction under Excessive Irrigation

The yield reduction observed in the 5-minute irrigation treatment, despite maintaining humidity and temperature within ranges generally considered favorable for mushroom growth, represents one of the most intriguing findings of this study. Several interconnected mechanisms likely contribute to this phenomenon. First, extremely high humidity (>90%) can impair gas exchange processes essential for aerobic fungal metabolism (Eastwood et al., 2011). Mushroom cultivation requires

adequate oxygen availability for cellular respiration, and excessively humid conditions can create a boundary layer of water vapor around fruiting bodies that reduces oxygen diffusion rates. This oxygen limitation may constrain growth even when other environmental parameters appear optimal.

Second, very high humidity combined with frequent wetting creates ideal conditions for bacterial and competing fungal contaminants (Wiesnerová et al., 2023). While visible contamination was not quantified in this study, subclinical microbial competition could have reduced yields by diverting nutrients away from *Pleurotus* mycelium or producing inhibitory metabolites. This interpretation is consistent with findings by Rukhiran et al. (2023), who reported that IoT-controlled systems maintaining humidity at 75–85% produced higher quality mushrooms with fewer contamination issues compared to systems maintaining humidity above 90%.

Third, excessive moisture on substrate surfaces may create anaerobic microsites that inhibit mycelial growth and nutrient transport. *Pleurotus* mushrooms are obligate aerobes requiring oxygen for all growth stages (Stamets, 2000). Water-saturated substrate surfaces can limit oxygen penetration, forcing mycelium to concentrate in surface layers where conditions remain aerobic. This restricted mycelial distribution may limit the total volume of substrate that can be effectively colonized and utilized, ultimately constraining yield potential. Recent studies using computed tomography imaging have demonstrated that substrate moisture distribution significantly affects mycelial architecture and resource utilization efficiency (Pajor et al., 2013).

### Comparison with Recent Literature

Our findings align well with several recent studies examining environmental optimization for mushroom cultivation. Uddin et al. (2011) reported optimal *Pleurotus* yields in the temperature range of 14°C to 27°C and relative humidity of 70–80%, closely matching the conditions achieved by our 4-minute irrigation treatment. More recently, Washa (2025) demonstrated that *P. ostreatus* maintained at 21°C and 80% relative humidity produced significantly higher yields than cultures maintained at either higher or lower humidity levels, supporting our finding that moderate humidity outperforms both conservative and excessive irrigation strategies.

Singjaroen and Sakaew (2016) designed a microcontroller-based mist irrigation system for mushroom cultivation, targeting temperature of 25–35°C and humidity of 80–90%. Their automated system increased average yield to 1.865kg compared to 1.455kg from unregulated conditions, representing a 28.2% increase. While this improvement exceeds our observed 12.50% increase, their study compared automated versus uncontrolled conditions rather than optimizing irrigation duration within a controlled system. The complementary nature of these findings suggests that combining optimized irrigation scheduling (as demonstrated in our study) with automated environmental monitoring (as in

their system) could yield additive benefits.

Amen and Villaverde (2019) applied an Arduino Uno microcontroller integrated with a fuzzy logic-based sensor system to regulate temperature and humidity in *Pleurotus* cultivation, achieving optimal yields at 22–29°C and relative humidity above 70%. Their use of fuzzy logic control represents an advance over simple threshold-based systems, allowing for more nuanced responses to environmental fluctuations. However, their system lacked specific irrigation duration parameters, instead adjusting continuously based on sensor feedback. Our study provides the discrete duration parameters (4 minutes per hour) that could be used to program such systems when continuous monitoring is not available or to establish baseline settings for adaptive control algorithms.

Similarly, Chitra et al. (2018) showed that oyster mushroom growth was more pronounced at 74–79% relative humidity compared to 55–68%, with temperature ranges of 22–28°C proving optimal. Their findings reinforce our observation that moderate humidity (around 75–80%) outperforms both lower and higher humidity levels.

Our results contrast somewhat with Kong (2004), who described 15–25°C as optimal for *P. florida* and *P. sajor-caju* cultivation. However, this apparent discrepancy can be explained by species differences and cultivation stage. Kong's temperature recommendations were primarily for spawn running (mycelial colonization), which typically occurs at lower temperatures than fruiting. Our study focused specifically on the fruiting stage, during which most *Pleurotus* species prefer slightly warmer conditions to support rapid fruiting body development (Miles and Chang, 2004). Additionally, *P. florida* and *P. sajor-caju* are considered cooler-temperature species compared to the warm-adapted *P. eous* tested in our study, explaining the temperature range difference.

### Integration with IoT and Smart Agriculture Systems

The practical significance of our findings extends to the rapidly developing field of IoT-based mushroom cultivation systems. Guragain et al. (2024) recently developed a low-cost centralized IoT ecosystem for oyster mushroom cultivation, incorporating automated sensors and actuators for environmental control. Their system required specific programming parameters for irrigation scheduling, and our findings directly address this need by providing evidence-based duration settings. The 4-minute per hour irrigation schedule identified in our study could serve as a baseline program for such systems, with IoT sensors providing real-time feedback to fine-tune duration based on ambient conditions.

Rukhiran et al. (2023) investigated IoT-based mushroom cultivation with solar renewable energy integration, assessing sustainability impacts on yield and quality. Their system achieved notable success but required manual calibration of irrigation parameters. Our experimental determination of optimal irrigation duration provides a scientific basis for such calibration, potentially reducing the trial-and-error period when establishing new IoT-controlled cultivation facilities. Furthermore, the inverse relationship between humidity and temperature we

documented could inform predictive algorithms in smart agriculture systems, allowing anticipatory adjustments to irrigation schedules based on temperature forecasts.

### Water-Use Efficiency and Sustainability Implications

From a sustainability perspective, the finding that 4-minute irrigation outperformed 5-minute irrigation has important implications for water-use efficiency. The 4-minute treatment used 20% less water than the 5-minute treatment (36 vs. 45 minutes total daily misting time) while producing 25–31% higher yields, depending on species. This represents a substantial improvement in water productivity—the ratio of economic output to water input. In a global context where agriculture accounts for approximately 70% of freshwater withdrawals (FAO, 2020), even small improvements in water-use efficiency can have significant cumulative impacts.

De Silva et al. (2023) recently analyzed water footprints of oyster mushroom cultivation under small-scale polybag farming conditions in Sri Lanka, finding a water footprint of 1,181 m<sup>3</sup>/ton of mushrooms produced, with on-farm water requirement as low as 4.4L/kg. Their study identified mushrooms as a water-efficient food item compared to animal protein sources, and emphasized that improvement in yield and shortening of the growing cycle are key means of reducing water footprint. Our findings align with and contribute to this sustainability goal by identifying irrigation parameters that maximize productivity per unit water consumed, thereby improving water-use efficiency through optimized irrigation scheduling rather than simply reducing water application.

Additionally, the energy implications of irrigation duration deserve consideration. While not directly measured in our study, pumping and pressurizing water for mist generation requires electrical energy. The 4-minute treatment's superior efficiency thus likely translates to improved energy productivity as well as water productivity. As mushroom cultivation scales to meet growing global demand, such efficiency improvements become increasingly important for maintaining environmental sustainability while expanding production (Grimm & Wösten, 2018).

### Species-Specific Responses and Broader Applicability

While the 4-minute irrigation treatment proved optimal for all three *Pleurotus* species tested, the absolute yield differences among species warrant discussion. *P. ostreatus* consistently produced the highest yields (262–295 g per bag across treatments), followed by *P. eous* (190–237 g) and *P. ostreatus* Hungarian (183–229 g). These differences likely reflect inherent genetic differences in growth rate, substrate utilization efficiency, and fruiting body morphology rather than differential responses to irrigation (Philippoussis, 2009). The fact that all three species responded similarly to irrigation treatments—with 4 minutes proving optimal—suggests that the environmental optima we identified may have broad applicability across the *Pleurotus* genus.

However, extrapolation to other fungal genera should be undertaken cautiously. Different mushroom families have evolved distinct environmental preferences reflecting

their natural ecological niches (Kües & Liu, 2000). For example, *Agaricus bisporus* (button mushrooms) typically require cooler temperatures (16–18°C) and slightly lower humidity (70–75%) than *Pleurotus* species, while *Lentinula edodes* (shiitake) may tolerate wider environmental fluctuations. Future research should investigate whether the 4-minute per hour irrigation schedule identified here remains optimal for other commercially important species, or whether species-specific optimization is necessary.

### Practical Implications for Mushroom Cultivators

Our findings offer immediate practical value for mushroom growers operating across a range of scales and technological sophistication levels. Small-scale cultivators using simple timer-based misting systems can directly implement the 4-minute per hour schedule identified here, expecting yield improvements of approximately 12.5% compared to more conservative irrigation strategies. Medium-scale operations employing programmable logic controllers can incorporate these parameters into their automated systems as baseline settings. Large commercial facilities with IoT-enabled smart agriculture platforms can use our findings as calibration points for their adaptive control algorithms, potentially combining fixed-duration schedules during stable conditions with dynamic adjustments during environmental fluctuations. In all cases, the key insight remains: moderate, optimized irrigation outperforms both conservative and excessive approaches, with benefits for both productivity and resource-use efficiency.

### Conclusion

The objective of the present study was to examine the effects of mist irrigation on the yields of *Pleurotus* mushrooms by varying the irrigation period from 3 minutes to 4 minutes and then to 5 minutes per hour. According to the findings, the 4 minutes irrigation method achieved the highest average yield weight for all the three species under investigation, namely *P. ostreatus* Hungarian, *P. ostreatus*, and *P. eous*, with the figures standing at 229.33 g, 294.79 g, and 237.44 g, respectively. Also, it was found that 4 minutes of irrigation contributed to a 12.50% increase in average yield weight compared to that obtained from the control method of 3 minutes irrigation. In addition, the relative humidity in the nursery had an inverse relationship with the temperature with a decline in the former leading to a rise in the latter. That is, with the 5 minutes irrigation method, the relative humidity was the highest at 91.70%, while the temperature was the lowest at 26.85°C. Conversely, the 3-minute irrigation method resulted in the lowest relative humidity of 71.09% but the highest temperature of 28.42 °C. Based on the findings, it can be concluded that temperature and relative humidity regulation is likely to provide optimal conditions for the growth of mushrooms, especially those in the family of *Pleurotaceae*.

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## REFERENCES

- Abdel-Ghany, A.M., & Kozai, T. (2006). Cooling efficiency of fogging systems for greenhouses. *Biosystems Engineering*, 94(1), 97–109. <https://doi.org/10.1016/j.biosystemseng.2006.02.008>
- Amen, J.C., & Villaverde, J.F. (2019). Fuzzy logic-based controlled environment for the production of oyster mushroom. *2019 IEEE 11th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management* (pp. 1–5). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/HNICEM48295.2019.9072902>
- Arif, A.H., Riaz, A., & Akhlaq, A. (2025). Global sustainable agriculture: Challenges, strategies, and future pathways. *Science & Society Insights*, 4, 1–13. <https://doi.org/10.65822/j.sasi/2025.29>
- Beacham, A.M., Vickers, L.H., & Monaghan, J.M. (2019). Vertical farming: a summary of approaches to growing skywards. *The Journal of Horticultural Science and Biotechnology*, 94(3), 277–283. <https://doi.org/10.1080/14620316.2019.1574214>
- Charoenrak, P., Watcharinrat, D., Supamattra, S., Akkarakultron, P., Phasinam, T., & Phasinam, K. (2025). Efficiency of drip irrigation combined with *Bacillus* bacteria application in enhancing growth and yield of Jinda chilis. *Multidisciplinary Science Journal*, 7(4), e2025166. <https://doi.org/10.31893/multiscience.2025166>
- Charoenrak, P., Watcharinrat, D., Suvanapa, K., Saengngam, N., Supamattra, S., Phasinam, T., & Phasinam, K. (2024). Optimizing growth of crystal lettuce using controlled environments in a Thai plant factory. *International Journal of Agriculture and Biosciences*, 13(3), 494–499. <https://doi.org/10.47278/journal.ijab/2024.150>
- Chitra, K., Sathyaparvathavarthini, B., Mahalakshmi, S., Kamali, R., Sharavanan, P.T., Balisaskumar, C., & Dhanalakshmi, K. (2018). Effect of abiotic factors on oyster mushroom production (*Pleurotus species*). *International Journal of Current Microbiology and Applied Sciences*, 7(7), 1032–1036. <https://doi.org/10.20546/ijcmas.2018.707.125>
- Choosumrong, S., Hataitara, R., Panumonwatee, G., Raghavan, V., Nualsri, C., Phasinam, T., & Phasinam, K. (2023). Development of IoT based smart monitor and control system using MQTT protocol and Node-RED for parabolic greenhouse solar drying. *International Journal of Information Technology*, 15(4), 2089–2098. <https://doi.org/10.1007/s41870-023-01237-3>
- Devi, P.V., Islam, J., Narzary, P., Sharma, D., & Sultana, F. (2024). Bioactive compounds, nutraceutical values and its application in food product development of oyster mushroom. *Journal of Future Foods*, 4(4), 335–342. <https://doi.org/10.1016/j.jfutfo.2023.11.005>
- De Silva, S.T.D., Atapattu, N.S.B.M., & Kumara, K.L.W. (2023). The Water Footprint of Oyster mushroom (*Pleurotus ostreatus*) Cultivation under Small-scale Polybag Farming Conditions in Sri Lanka. *Journal of Agricultural Sciences—Sri Lanka*, 18(2), 172–182. <https://doi.org/10.4038/jas.v18i2.10251>
- Eastwood, D.C., Floudas, D., Binder, M., Majcherzyk, A., Schneider, P., Aerts, A., Asiegbu, F.O., Baker, S.E., Barry, K., Bendiksby, M., Blumentritt, M., Coutinho, P.M., Cullen, D., De Vries, R.P., Gathman, A., Goodell, B., Henrissat, B., Ihrmark, K., Kausarud, H., Kohler, A., LaButti, K., Lapidus, A., Lavin, J.L., Lee, Y.H., Lindquist, E., Lilly, W., Lucas, S., Morin, E., Murat, C., Oguiza, J.A., Park, J., Pisabarro, A.G., Riley, R., Rosling, A., Salamov, A., Schmidt, O., Schmutz, J., Skrede, I., Stenlid, J., Wiebenga, A., Xie, X., Kües, U., Hibbett, D.S., Högborg, N., Martin, F., Grigoriev, I.V., & Watkinson, S.C. (2011). The plant cell Wall—Decomposing machinery underlies the functional diversity of forest fungi. *Science*, 333(6043), 762–765. <https://doi.org/10.1126/science.1205411>
- FAO (2020). *The State of Food and Agriculture 2020: Overcoming Water Challenges in Agriculture*. Food and Agriculture Organization of the United Nations. <https://doi.org/10.4060/cb1447en>
- Grimm, D., & Wösten, H.A.B. (2018). Mushroom cultivation in the circular economy. *Applied Microbiology and Biotechnology*, 102(18), 7795–7803. <https://doi.org/10.1007/s00253-018-9226-8>
- Guragain, D.P., Shrestha, B., & Bajracharya, I. (2024). A low-cost centralized IoT ecosystem for enhancing oyster mushroom cultivation. *Journal of Agriculture and Food Research*, 15, 100952. <https://doi.org/10.1016/j.jafr.2023.100952>
- Huang, Z., Wei, Y., & Hadigheh, S.A. (2024). Variations in the Properties of Engineered Mycelium-Bound Composites (MBCs) under Different Manufacturing Conditions. *Buildings*, 14(1), 155. <https://doi.org/10.3390/buildings14010155>
- Isaranontakul, P., & Rukphong, C. (2019). The Android Application of control fog watering Indian Oyster Mushroom. *Journal of Information Science and Technology*, 9(1), 1–8. <https://doi.org/10.14456/jist.2019.1>
- Kachhwaha, S.S., Dhar, P.L., & Kales, S.R. (1998). Experimental studies and numerical simulation of evaporative cooling of air with a water spray: I. Horizontal parallel flow. *International Journal of Heat and Mass Transfer*, 41(2), 447–464. [https://doi.org/10.1016/S0017-9310\(97\)00133-6](https://doi.org/10.1016/S0017-9310(97)00133-6)
- Kitipanasil, P., Damrongwattana, J., Dechochai, U., & Khaenamkaew, D. (2019). Tha Chang Hedhangfa: Straw Oyster Mushroom Housing to Promote of Career Occupations in the Community: A Case Study Baan Tha Chang Oyster Mushroom Group Moo.5 Chang Sai Sub - District Chang Klang District Nakhon Si Thammarat Province Thailand. *Journal of Social Science Development*, 2(2), 62–78.
- Kolaly, W.E., Ma, W., Li, M., & Darwesh, M. (2020). The investigation of energy production and mushroom yield in greenhouse production based on mono photovoltaic cells effect. *Renewable Energy*, 159, 506–518. <https://doi.org/10.1016/j.renene.2020.05.144>
- Kong, W.S. (2004). Spawn: Descriptions of commercially important *Pleurotus* species. In *Mushroom growers' handbook 1: Oyster mushroom cultivation* (pp. 54–57). MushWorld.
- Kozai, T., Niu, G., & Takagaki, M. (2020). Plant factory: An indoor vertical farming system for efficient quality food production. (2nd ed.). London: Academic Press. <https://doi.org/10.1016/c2018-0-00969-x>
- Krupodorova, T.A., & Barshteyn V.Y. (2020). The effect of cultivation conditions on growth and therapeutic activity of pleurotus eryngii. *Actual problems of natural sciences: modern scientific discussions: Collective monograph* (pp. 331–350). Baltija Publishing. <https://doi.org/10.30525/978-9934-588-45-7.19>
- Kües, U., & Liu, Y. (2000). Fruiting body production in basidiomycetes. *Applied Microbiology and Biotechnology*, 54(2), 141–152. <https://doi.org/10.1007/s002530000396>
- Miles, P.G., & Chang, S. (2004). *Mushrooms: Cultivation, Nutritional Value, Medicinal Effect, and Environmental Impact*. (2nd ed.). Boca Raton:

- CRC Press. <https://doi.org/10.1201/9780203492086>
- Montero, J.I., Antón, A., Beil, C., & Franquet, A. (1990). Cooling of greenhouses with compressed air fogging nozzles. *Acta Horticulturae*, 281, 199–209. <https://doi.org/10.17660/ActaHortic.1990.281.22>
- More, V. (2025). Mushroom cultivation market. <https://www.marketresearchfuture.com/reports/mushroom-cultivation-market-26714>
- Najmurokhan, A., Kusnandar, Daelami, A., Nurlina, E., Komarudin, U., & Ridhatama, H. (2020). Development of Temperature and Humidity Control System in Internet-of-Things based Oyster Mushroom Cultivation. *2020 3rd International Seminar on Research of Information Technology and Intelligent Systems* (pp. 551–555). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/isriti51436.2020.9315426>
- Negi, V., Jarial, R.S., & Jarial, K. (2025). Evaluation of Physiological Parameters and Antimicrobial Properties of *Pleurotus eous*. *International Journal of Bio-resource and Stress Management*, 16(5), 1–7. <https://doi.org/10.23910/1.2025.5975>
- Pajor, R., Fleming, A., Osborne, C.P., Rolfe, S.A., Sturrock, C.J., & Mooney, S.J. (2013). Seeing space: visualization and quantification of plant leaf structure using X-ray micro-computed tomography. *Journal of Experimental Botany*, 64(2), 385–390. <https://doi.org/10.1093/jxb/ers392>
- Phasinam, T., Nualsri, C., Choosumrong, S., Watcharinrat, D., & Phasinam, K. (2024). Enhancing banana drying efficiency: A phase change heat storage system utilizing charcoal briquettes. *International Journal of Agriculture and Biosciences*, 13(2), 144–151. <https://doi.org/10.47278/journal.ijab/2024.098>
- Philippoussis, A.N. (2009). Production of Mushrooms Using Agro-Industrial Residues as Substrates. In Nigam, P., & Pandey, A. (eds.), *Biotechnology for Agro-Industrial Residues Utilisation* (pp. 163–196). Springer. [https://doi.org/10.1007/978-1-4020-9942-7\\_9](https://doi.org/10.1007/978-1-4020-9942-7_9)
- Pongpanich, N., Chayaprasert, W., Sanchatjate, P., Moonmangmee, I., & Sangpetchsong, K. (2015). The development and testing of an evaporative cooling system to control the temperature and relative humidity in a nursery. In *Proceedings of the 16th TSAE National Conference and 8th TSAE International Conference* (pp. 361–365). Thai Society of Agricultural Engineering.
- Royse, D.J., Baars, J., & Tan, Q. (2017). Current overview of mushroom production in the world. In Diego, C.Z., & Pardo-Giménez, A. (Eds.), *Edible and Medicinal Mushrooms: Technology and Applications* (pp. 5–13). Wiley-Blackwell. <https://doi.org/10.1002/9781119149446.ch2>
- Rukhiran, M., Sutanthavibul, C., Boonsong, S., & Netinant, P. (2023). IoT-based mushroom cultivation system with solar renewable energy integration: Assessing the sustainable impact of the yield and quality. *Sustainability*, 15(18), 13968. <https://doi.org/10.3390/su151813968>
- Sánchez, C. (2010). Cultivation of *Pleurotus ostreatus* and other edible mushrooms. *Applied Microbiology and Biotechnology*, 85(5), 1321–1337. <https://doi.org/10.1007/s00253-009-2343-7>
- Sarker, N.C., Hossain, M.M., Sultana, N., Mian, I.H., Karim, A.J.M.S., & Amin, S.M.R. (2008). Effect of wheat bran and rice bran supplements to waste paper and wheat straw substrates on growth and yield of oyster mushroom (*Pleurotus ostreatus* (Jacquin ex Fr.) Kummer). *Bangladesh Journal of Mushroom*, 2(2), 1–15.
- Setiawan, B.I. (2001). Designing temperature control system for mushroom cultivation. *IFAC Proceedings Volumes*, 34(11), 158–161. [https://doi.org/10.1016/S1474-6670\(17\)34124-1](https://doi.org/10.1016/S1474-6670(17)34124-1)
- Setiawan, R.J., Tarnadi, A., & Surfani, I. (2021). Design and Manufacture an Automatic Mushroom Sprinkler based Internet of Things to Increase Oyster Mushroom Productivity. *JMPM (Jurnal Material Dan Proses Manufaktur)*, 5(1), 1–9. <https://doi.org/10.18196/jmpm.v5i1.12043>
- Singjaroen, B., & Sakaew, S. (2016). Temperature and humidity control systems for mushroom greenhouses. In *Proceedings of the 1st Rajamangala University of Technology Suvarnabhumi National Academic Conference* (pp. 176–183). Rajamangala University of Technology Suvarnabhumi.
- Sreedharan, P.L., Kishorkumar, M., Neumann, E.G., & Kurup, S. S. (2025). The emerging role of oyster mushrooms as a functional food for complementary cancer therapy. *Foods*, 14(1), 128. <https://doi.org/10.3390/foods14010128>
- Stamets, P. (2000). *Growing Gourmet and Medicinal Mushrooms*. (3rd ed.). Berkeley: Ten Speed Press.
- Suksawang, W., Dumnil, S., Wannakayont, A., & Lonkunthosh, N. (2022). Development of a mushroom house with a combination of technology. *Journal of MCU Nakhondhat*, 9(11), 181–195.
- Sunil, A., Sagala, S.L., Shibu, R.P., & Shamshina, J. (2025). Valorization of spent mushroom substrate (SMS). <https://acs.digitellinc.com/p/s/valorization-of-spent-mushroom-substrate-sms-641770>
- Sureshkumar, R., Kale, S.R., & Dhar, P.L. (2008). Heat and mass transfer processes between a water spray and ambient air: I. Experimental data. *Applied Thermal Engineering*, 28(5–6), 349–360. <https://doi.org/10.1016/j.applthermaleng.2007.09.010>
- Thakur, A., Daniel, C., & Shukla, A.K. (2021). A Fuzzy-Based Decision System to Control and Monitor Mushroom Growth. In Kumar, N., Tibor, S., Sindhvani, R., Lee, J., & Srivastava, P. (Eds.), *Advances in Interdisciplinary Engineering. Lecture Notes in Mechanical Engineering* (pp. 121–128). Springer. [https://doi.org/10.1007/978-981-15-9956-9\\_12](https://doi.org/10.1007/978-981-15-9956-9_12)
- Uddin, M.N., Yesmin, S., Khan, M.A., Tania, M., Moonmoon, M., & Ahmed, S. (2011). Production of oyster mushrooms in different seasonal conditions of Bangladesh. *Journal of Scientific Research*, 3(1), 161–167. <https://doi.org/10.3329/jsr.v3i1.6130>
- Washa, W.B. (2025). Maximizing production of *Pleurotus ostreatus* (Oyster) in Tanzania. *Australian Journal of Crop Science*, 19(4), 442–448. <https://doi.org/10.21475/ajcs.25.19.04.p331>
- Wibowo, B.C., Rozaq, I.A., & Pratama, T.P. (2023). Implementation of monitoring and control temperature and humidity based on IoT in the oyster mushroom cultivation room. *PROtek Jurnal Ilmiah Teknik Elektro*, 10(2), 85–92. <https://doi.org/10.33387/protk.v10i2.4863>
- Wiesnerová, L., Hřebečková, T., Jablonský, I., & Koudela, M. (2023). Effect of different water contents in the substrate on cultivation of *Pleurotus ostreatus* Jacq. P. Kumm. *Folia Horticulturae*, 35(1), 25–31. <https://doi.org/10.2478/fhort-2023-0002>