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Development of Fogponics Technology for Mushroom Production

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Engr. RS L. Lagrimas[1]
Wilfredo D. Timajo[2], PhD

[1]Instructor II, Rizal Technological University, 704 Boni Avenue, Mandaluyong City, Philippines
[2]Associate Professor V, Rizal Technological University, 704 Boni Avenue, Mandaluyong City, Philippines

Abstract

Fogponics is a controlled-environment cultivation technique that uses fine mist to maintain moisture conditions within the growing environment. This study investigated the effect of fan speed on the production performance of oyster mushrooms (Pleurotus ostreatus) cultivated using an automated fogponics system. Two fan-speed conditions, 1,500 rpm and 3,000 rpm, were evaluated using 120 fruiting bags distributed equally between the treatments over a 60-day cultivation period. Harvest weight, fruiting-body count, and biological efficiency were measured. The 3,000-rpm treatment produced a cumulative harvest weight of 11,303 g, 2,236 fruiting bodies, and a mean biological efficiency of 59.80 ± 12.27%, compared with 9,461 g, 1,891 fruiting bodies, and 50.06 ± 14.07% under the 1,500-rpm treatment. Significant differences were observed in harvest weight ($p < .001$), fruiting-body count ($p = .003$), and biological efficiency ($p < .001$). The results demonstrate that the 3,000-rpm condition provided better production performance than the 1,500-rpm condition under the experimental configuration evaluated. These findings provide empirical evidence that controlled airflow is an important operational consideration in fogponic oyster mushroom cultivation. Further studies incorporating multiple airflow levels, direct airflow and energy measurements, and larger-scale cultivation systems are recommended to determine optimal and commercially applicable operating conditions.

Keywords: fogponics, oyster mushroom, airflow regulation, biological efficiency, controlled environment agriculture

INTRODUCTION

Rapid urbanization and environmental challenges have increased the demand for sustainable and resource-efficient agricultural systems. Conventional farming methods continue to face limitations due to decreasing arable land, water scarcity, and climate variability, leading to the development of controlled environment agriculture (CEA) technologies such as hydroponics, aeroponics, and fogponics. Among high value crops suitable for indoor cultivation, oyster mushroom (*Pleurotus ostreatus*) is widely recognized for its nutritional value, rapid growth cycle, and adaptability to controlled environments. However, successful mushroom cultivation depends heavily on stable environmental conditions, particularly temperature, humidity, and ventilation.

Fogponics has emerged as a promising cultivation method because it utilizes fine nutrient-rich mist to maintain moisture and environmental stability while reducing water consumption. Nevertheless, maintaining proper fog distribution and airflow remains a challenge, as excessive or insufficient moisture may negatively affect mushroom productivity and biological efficiency. Recent developments in automation and IoT technologies have enabled real-time environmental monitoring and automated climate regulation, improving cultivation consistency and efficiency.

Despite these advancements, limited studies have specifically examined how controlled airflow and fan speed influence the production performance of oyster mushrooms within fogponic cultivation systems. Therefore, this study aims to investigate the effects of controlled fan speeds (1,500 rpm and 3,000 rpm) on harvest performance and biological efficiency in oyster mushroom cultivation using an automated microcontroller-based fogponics system.

LITERATURE REVIEW

Oyster mushroom (Pleurotus ostreatus) cultivation is recognized as a promising agribusiness activity because of its relatively low production cost, high nutritional value, and adaptability to controlled cultivation environments. However, achieving optimal yield and biological efficiency depends on maintaining suitable environmental conditions, particularly temperature, relative humidity, airflow, and carbon dioxide concentration. Recent advances in controlled-environment agriculture have enabled more precise regulation of these conditions through sensors, microcontrollers, automated ventilation, and mist-based cultivation technologies.

Among these technologies, fogponics provides a potential approach for maintaining moisture and microclimatic conditions through the generation and distribution of fine mist. However, the effectiveness of a fogponic system depends not only on mist generation but also on how the mist is distributed throughout the cultivation environment. This makes airflow an important system parameter because it may influence moisture distribution, ventilation, gas exchange, and microclimate uniformity. Accordingly, this review examines controlled-environment cultivation, oyster mushroom environmental requirements, fogponic systems, airflow regulation, and automated monitoring to establish the basis for investigating fan speed in fogponic oyster mushroom production.

Controlled Environment Agriculture and Soilless Cultivation Systems. Rapid urbanization, declining availability of agricultural land, and increasing pressure on water resources have accelerated the adoption of controlled-environment agriculture (CEA). Rukhiran et al. (2023) demonstrated the potential of automated cultivation systems to improve environmental control, resource efficiency, and agricultural productivity. Soilless cultivation approaches, including hydroponics, aeroponics, and fog-based systems, are particularly suitable for controlled environments because water and environmental conditions can be regulated more precisely than in conventional open-field cultivation.

Hultberg et al. (2022) further demonstrated the potential of integrated controlled cultivation for improving resource utilization in combined plant and mushroom production. Collectively, these studies indicate that the effectiveness of CEA depends not merely on creating an enclosed cultivation environment but on maintaining favorable microclimatic conditions within that environment. For fog-based cultivation, this requirement places particular importance on the interaction between moisture generation and air circulation, since the generated mist must be distributed throughout the cultivation space to maintain suitable growing conditions.

Environmental Requirements for Oyster Mushroom Cultivation. Environmental regulation is particularly important in oyster mushroom cultivation because fruiting and development are highly sensitive to temperature, relative humidity, ventilation, and carbon dioxide concentration. Rahman et al. (2023) reported that favorable fruiting conditions for oyster mushrooms require controlled temperature and high relative humidity. Maintaining these conditions is necessary to support fruiting-body development and biological efficiency.

Similarly, Chitra et al. (2018) emphasized that variations in abiotic environmental factors can influence oyster mushroom production. Proper ventilation and humidity regulation are therefore essential components of a controlled mushroom cultivation environment. Unlike conventional crops, where airflow may primarily support temperature regulation and gas exchange, mushroom cultivation requires airflow to be balanced with high humidity requirements. Excessive air movement may promote moisture loss, whereas inadequate ventilation may result in unfavorable microclimatic conditions. This relationship makes controlled airflow particularly relevant when mist or fog is used to maintain the cultivation environment.

Fog Distribution, Airflow, and Environmental Stability. Fog distribution and airflow management are critical factors in maintaining favorable microclimatic conditions in mist-based cultivation systems. Islam et al. (2017) demonstrated the importance of humidification management in reducing contamination risks during indoor oyster mushroom cultivation. Their findings indicate that moisture conditions must be carefully controlled because inappropriate humidification may adversely affect mushroom cultivation. Thus, effective environmental regulation requires not only the generation of moisture but also appropriate ventilation and distribution throughout the cultivation environment.

Airflow is also directly relevant to oyster mushroom growth. Oh et al. (2019) investigated the effects of air velocity on the growth and yield of Pleurotus ostreatus and found that differences in air velocity affected fruiting-body characteristics and commercial yield. Their findings demonstrate that airflow should not be considered solely as a ventilation mechanism; rather, air movement itself represents an environmental variable capable of influencing mushroom growth and productivity.

The importance of air circulation extends beyond mushroom cultivation. In a fogponic system for spinach, Heltha et al. (2025) incorporated fan-driven air circulation as part of the environmental-control system for regulating conditions within the cultivation chamber. This demonstrates that airflow has an operational role in mist-based cultivation systems, where environmental regulation depends on the interaction among mist generation, temperature, humidity, and air circulation.

Taken together, these studies establish two complementary findings: airflow influences oyster mushroom growth and productivity, while air circulation contributes to environmental regulation in fogponic cultivation. However, these relationships have largely been investigated separately. Limited evidence is available on how controlled fan-speed variation within a fogponic oyster mushroom system affects harvest performance and biological efficiency. This intersection provides the specific research gap addressed by the present study.

IoT and Automated Environmental Monitoring Systems. Automation and IoT technologies provide mechanisms for maintaining environmental conditions required for controlled mushroom production. Ariffin et al. (2021) demonstrated the use of microcontroller-based monitoring and fuzzy-logic control for oyster mushroom cultivation. Similarly, Kaewwiset and Yodkhad (2017) applied fuzzy-logic control to regulate temperature and humidity in a mushroom nursery, while Abd Wahab et al. (2019) investigated automated temperature and humidity control for mushroom-house applications.

Collectively, these studies demonstrate the progression of mushroom cultivation from passive environmental management toward sensor-based automated regulation. However, their primary emphasis is temperature and humidity control rather than the systematic manipulation of airflow intensity. Consequently, an opportunity remains to integrate automated environmental monitoring with controlled fan-speed operation to determine whether airflow regulation contributes measurably to mushroom productivity.

Environmental Control and Mushroom Productivity. Previous studies consistently demonstrate that environmental management influences mushroom productivity. Islam et al. (2017) and Chitra et al. (2018) emphasized the importance of appropriate humidity and other environmental conditions for mushroom development, while Yang et al. (2013) and Miah et al. (2016) demonstrated that cultivation conditions and substrate characteristics influence yield and biological efficiency. More recent automated cultivation studies have further shown the potential of sensor-based environmental regulation to improve cultivation consistency and sustainability (Rahman et al., 2023; Rukhiran et al., 2023).

These findings collectively indicate that mushroom productivity results from the interaction of biological, substrate, and environmental factors. Nevertheless, compared with temperature and humidity, airflow intensity has received less attention as an experimentally manipulated parameter, particularly when airflow is used to distribute fog within an automated cultivation chamber.

Sustainable Urban Agriculture Systems. Urbanization and decreasing agricultural land availability have intensified the demand for sustainable food production technologies. Controlled-environment agriculture systems such as hydroponics, aeroponics, and fogponics provide viable alternatives for urban food production by reducing dependency on soil and minimizing water usage (Hultberg et al., 2022).

Fogponics systems offer improved nutrient delivery efficiency and environmental control, making them suitable for compact and indoor farming environments. Furthermore, sustainable cultivation technologies contribute to food security by enabling year-round production under controlled conditions. Recent studies have shown that integrating renewable energy systems and automated environmental control improves the sustainability and operational efficiency of mushroom cultivation systems (Rukhiran et al., 2023).

For urban and small-scale mushroom production, however, the sustainability of automated fogponic systems depends on achieving adequate environmental control without unnecessary resource and energy consumption. Optimizing airflow therefore has implications not only for mushroom productivity but also for the operational efficiency and scalability of the cultivation system.

Summary and Research Gaps. The reviewed literature establishes that controlled temperature, humidity, ventilation, and other environmental conditions are fundamental to successful oyster mushroom cultivation. Previous studies have also demonstrated that air velocity can influence the growth and yield characteristics of Pleurotus ostreatus, while research on fogponic and other controlled cultivation systems has shown that fan-driven air circulation can contribute to environmental regulation. At the same time, advances in IoT and microcontroller-based systems have enabled increasingly precise monitoring and automated control of cultivation environments.

Despite these advances, an important gap remains at the intersection of these research areas. Existing mushroom studies have largely examined environmental conditions such as temperature, humidity, substrate characteristics, and ventilation, whereas fogponic studies have primarily focused on mist generation, environmental monitoring, and automated control. Limited research has directly evaluated fan speed as an experimentally controlled variable within a fogponic oyster mushroom cultivation system and determined its effects on harvest performance and biological efficiency.

The present study addresses this gap by integrating controlled airflow with an automated fogponics system and comparing two fan-speed conditions, 1,500 rpm and 3,000 rpm. By examining their effects on harvest weight, fruiting-body count, and biological efficiency, the study extends existing controlled-environment and mushroom cultivation research toward a better understanding of airflow regulation in fogponic mushroom production.

DESIGN AND METHODOLOGY

Design. The study employed an experimental research design to evaluate the effects of two fan-speed conditions on the production performance of fogponically cultivated oyster mushrooms. The independent variable was fan speed, with treatments set at 1,500 rpm and 3,000 rpm. The dependent variables were cumulative harvest weight, fruiting-body count, and biological efficiency. Two replicate growing chambers were used for each fan-speed condition.

Population and Sampling. The experimental units consisted of 120 pre-inoculated oyster mushroom fruiting bags sourced from the Mushroom and Biotech Research and Development Center of Rizal Technological University. The bags were allocated equally between two fan-speed treatments, with 60 bags assigned to the 1,500-rpm treatment and 60 bags to the 3,000-rpm treatment. Each treatment was implemented in two identical insulated growing chambers, with 30 distinct fruiting bags placed in each chamber. Thus, the experiment consisted of four growing chambers: two operated at 1,500 rpm and two at 3,000 rpm. The chambers were predetermined for their respective fan-speed treatments rather than randomly assigned. All fruiting bags contained a standardized substrate composition of 78% sawdust, 20% rice bran, and 2% pH equalizer, with a moisture content of 65% and an average bag weight of 900 g.

Experimental Control and Treatment Assignment. Two replicate growing chambers were used for each fan-speed treatment, with 30 distinct fruiting bags maintained in each chamber. The fan-speed conditions were predetermined, with two chambers operated at 1,500 rpm and two at 3,000 rpm. Chamber assignment was not randomized. To minimize variation unrelated to fan speed, the chambers were maintained using the same chamber configuration, substrate composition, misting and ventilation schedule, cultivation duration, and environmental monitoring procedures. Fan speed was the principal experimental factor varied between the two treatment conditions.

Instrumentation. A custom-built, microcontroller-based fogponics system was developed using an Arduino Mega 2560 as the central processing unit and a DS1307 Real-Time Clock (RTC) module for time-based automation. Environmental conditions were monitored using DHT11 sensors for real-time measurement of temperature and relative humidity. Mist was generated using ultrasonic transducers (24 V, 800 mA), while axial DC fans regulated mist dispersion at the designated fan speeds of 1,500 rpm and 3,000 rpm.

A programmable control sequence maintained a 12-hour diurnal cycle. From 6:00 AM to 6:00 PM, the system alternated between 20 minutes of misting and 40 minutes of ventilation. From 6:00 PM to 6:00 AM, ventilation was maintained according to the programmed operating cycle. All components were installed in insulated growing chambers lined with polyethylene plastic to minimize external environmental interference.

Sensor Accuracy and Limitations. The DHT11 sensors were used for real-time monitoring of temperature and relative humidity within the growing chambers. No formal calibration against a laboratory-grade reference instrument was performed prior to the experiment. The sensors were primarily used to monitor general environmental conditions and support the automated operation of the prototype fogponics system. As low-cost environmental sensors, DHT11 sensors have limitations in measurement accuracy and resolution compared with higher-grade temperature and humidity sensors. Consequently, small variations in the recorded environmental conditions should be interpreted with caution. Future studies should employ calibrated, higher-accuracy sensors to improve the precision and reliability of microclimate measurements.

Contamination Control. Prior to the experiment, the growing chambers and internal surfaces were cleaned and disinfected to minimize contamination risk. The pre-inoculated oyster mushroom fruiting bags were visually inspected before placement in the chambers for signs of contamination. During the cultivation period, the bags were regularly inspected, and when localized contamination was observed, the visibly affected portion was carefully removed to minimize further spread while retaining the unaffected portion of the fruiting bag. Sanitary handling practices were observed during routine monitoring and harvesting to minimize the introduction and transfer of contaminants among the experimental units.

Data Collection Procedures. Data collection was conducted over a 60-day cultivation period. Upon pinhead formation, the fruiting bags were opened to expose the substrate surface. Harvesting was performed at each flush following the emergence and maturation of fruiting bodies and continued for up to six flushes or until production approached zero.

For each fruiting bag, harvest weight and fruiting-body count were recorded across successive flushes. Harvest weight was measured as the fresh weight, in grams, of harvested mushrooms, while fruiting-body count was determined as the cumulative number of harvested fruiting bodies per bag during the cultivation period. Measurements obtained across the cultivation period were accumulated for each individual fruiting bag.

Biological efficiency (BE) was determined from the cumulative fresh harvest weight relative to the dry substrate weight. Based on an average initial bag weight of 900 g and a moisture content of 65%, a dry substrate weight of 315 g per fruiting bag was used in calculating biological efficiency. All measurements were manually recorded and cross-verified against system timestamps.

Statistical Analysis. Descriptive statistics, including the mean and standard deviation, were calculated for harvest weight, fruiting-body count, and biological efficiency. Biological efficiency was calculated as follows:

$$BE\% = \frac{Total\ fresh\ mushroom\ weight\ (g)}{Dry\ substrate\ weight\ (g)} \times 100$$

Differences between the 1,500-rpm and 3,000-rpm treatments were evaluated using Welch's independent-samples t-test at a significance level of $\alpha = 0.05$. Mean differences and corresponding 95% confidence intervals were reported to indicate the magnitude and precision of the estimated treatment effects. Cohen's d was calculated as a standardized measure of effect size.

Chamber-Level Analysis. Chamber-level descriptive statistics were calculated for harvest weight, fruiting-body count, and biological efficiency to examine the consistency of production responses across the two replicate chambers assigned to each fan-speed condition. The chamber-level analysis was used descriptively to determine whether the observed treatment pattern was evident across both replicate chambers.

RESULTS

This section summarizes the quantitative outcomes of oyster mushroom production under two fan speed settings: 1,500 rpm and 3,000 rpm. Metrics evaluated include total harvest weight, fruiting-body count, and biological efficiency.

Table 1
Comparison of Production Parameters Between Fan-Speed Treatments.

Parameter	1,500 rpm (n = 60), Mean ± SD	3,000 rpm (n = 60), Mean ± SD	Mean Difference	95% CI	*p*	Cohen's *d*
Harvest weight (g/bag)	157.68 ± 44.33	188.38 ± 38.64	30.70	15.66–45.74	<.001	0.74
Fruiting-body count (fruiting bodies/bag)	31.52 ± 11.38	37.27 ± 9.57	5.75	1.95–9.55	.003	0.55
Biological efficiency (%)	50.06 ± 14.07	59.80 ± 12.27	9.75	4.97–14.52	<.001	0.74

Note: Values are presented as mean ± standard deviation (SD). Each fan-speed treatment consisted of 60 fruiting bags distributed across two replicate growing chambers, with 30 bags per chamber. CI = confidence interval.

Harvest Weight. The 1,500-rpm treatment produced a cumulative harvest weight of 9,461 g, corresponding to a mean harvest weight of 157.68 ± 44.33 g per fruiting bag. The 3,000-rpm treatment produced 11,303 g, corresponding to 188.38 ± 38.64 g per bag. The mean difference of 30.70 g per bag was statistically significant, Welch's $t(115.84) = 4.04$, $p < .001$, 95% CI [15.66, 45.74], with Cohen's d = 0.74.

Fruiting-body count. The 1,500-rpm treatment produced 1,891 fruiting bodies, corresponding to a mean fruiting-body count of 31.52 ± 11.38 per bag, while the 3,000-rpm treatment produced 2,236 fruiting bodies, corresponding to 37.27 ± 9.57 per bag. The mean difference of 5.75 fruiting bodies per bag was statistically significant, Welch's $t(114.63) = 3.00$, $p = .003$, 95% CI [1.95, 9.55], with Cohen's $d = 0.55$.

Biological efficiency. Mean biological efficiency was 50.06 ± 14.07% under the 1,500-rpm treatment and 59.80 ± 12.27% under the 3,000-rpm treatment. The difference of 9.75 percentage points was statistically significant, Welch's $t(115.84) = 4.04$, $p < .001$, 95% CI [4.97, 14.52], with Cohen's $d = 0.74$.

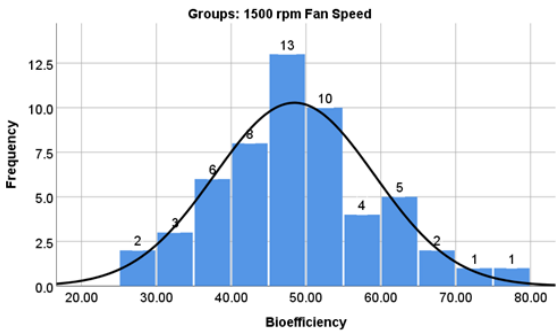

Figure 1
Distribution of biological efficiency among oyster mushroom fruiting bags under the 1,500-rpm fan-speed treatment (n = 60).

Figure 1 shows the distribution of biological efficiency among fruiting bags under the 1,500-rpm treatment. Values were generally concentrated around the middle portion of the distribution, with a mean biological efficiency of 50.06 ± 14.07%. The observed spread indicates considerable bag-to-bag variability in production performance.

Figure 2 shows a shift in the distribution of biological efficiency toward higher values under the 3,000-rpm treatment. Mean biological efficiency was 59.80 ± 12.27%, compared with 50.06 ± 14.07% under the 1,500-rpm treatment. The slightly lower standard deviation indicates somewhat lower bag-to-bag variability under the higher fan-speed condition.

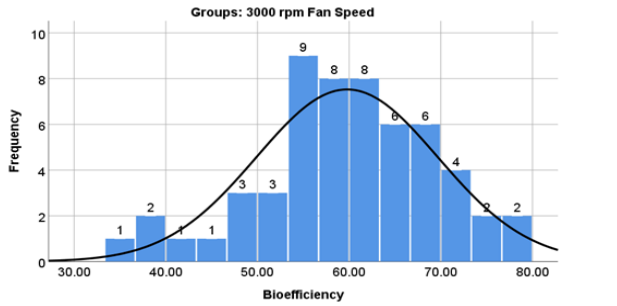

Figure 2
Distribution of biological efficiency among oyster mushroom fruiting bags under the 3,000-rpm fan-speed treatment (n = 60).

Flush-wise Yield Analysis. To assess the productivity trend throughout the cultivation cycle, mushroom yields were recorded per flush across two experimental setups. Each treatment consisted of 60 fruiting bags, observed over six consecutive flushes.

Table 2
Harvest Weight Across Six Successive Flushes.

Flush	1,500 rpm (g)	3,000 rpm (g)
First	2,155	2,498
Second	1,974	2,347
Third	1,810	2,098
Fourth	1,428	1,926
Fifth	1,010	1,334
Sixth	1,084	1,100
Total	9,461	11,303

Note. Values represent cumulative fresh harvest weight obtained from 60 fruiting bags per fan-speed treatment during each harvest flush.

Table 2 presents the harvest weight of oyster mushrooms across six successive flushes during the 60-day cultivation period. The 3,000-rpm treatment produced higher harvest weight than the 1,500-rpm treatment in all six flushes. The largest absolute difference occurred during the fourth flush, when the 3,000-rpm treatment produced 1,926 g compared with 1,428 g under the 1,500-rpm treatment. By the sixth flush, the difference had narrowed considerably to 16 g.

Figure 3 shows an overall decline in harvest weight across successive flushes under both fan-speed treatments. The 3,000-rpm treatment maintained higher harvest weight during the first five flushes, while the difference between treatments narrowed considerably during the sixth flush.

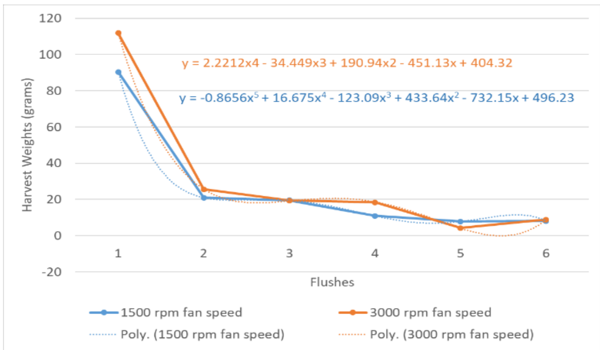

Figure 3

Flush-wise harvest weight of oyster mushrooms under the 1,500-rpm and 3,000-rpm fan-speed treatments across six successive harvest flushes. Values represent cumulative harvest weight from 60 fruiting bags per treatment for each flush.

Table 3

Chamber-Level Production Performance

Fan Speed	Chamber	n	Mean Harvest Weight (g/bag)	Mean fruiting-body count	Mean BE (%)
1,500 rpm	Chamber 1	30	156.70	30.93	49.75
1,500 rpm	Chamber 2	30	158.67	32.10	50.37
3,000 rpm	Chamber 3	30	192.50	37.27	61.11
3,000 rpm	Chamber 4	30	184.27	37.27	58.50

Note. Values represent descriptive means based on 30 distinct fruiting bags per chamber. Two replicate chambers were used for each fan-speed condition.

Chamber-Level Consistency. Chamber-level descriptive analysis showed a consistent treatment pattern across the replicate chambers. Mean harvest weights for the two 1,500-rpm chambers were 156.70 and 158.67 g per bag, compared with 192.50 and 184.27 g per bag for the two 3,000-rpm chambers. Mean fruiting-body counts were 30.93 and 32.10 fruiting bodies per bag at 1,500 rpm and 37.27 and 37.27 fruiting bodies per bag at 3,000 rpm. Similarly, mean biological efficiencies were 49.75% and 50.37% in the two 1,500-rpm chambers compared with 61.11% and 58.50% in the two 3,000-rpm chambers. These descriptive results show that the higher production pattern under the 3,000-rpm condition was observed across both replicate chambers rather than being driven by a single chamber.

DISCUSSION

The findings demonstrate that fan-speed condition was associated with significant differences in the production performance of fogponically cultivated oyster mushrooms (*Pleurotus ostreatus*). The 3,000-rpm treatment produced a mean harvest weight of 188.38 ± 38.64 g per fruiting bag compared with 157.68 ± 44.33 g under the 1,500-rpm treatment, corresponding to an approximately 19.5% increase in cumulative harvest weight. Fruiting-body count and biological efficiency were likewise higher under the 3,000-rpm condition. The moderate-to-large effect sizes for harvest weight and biological efficiency and the moderate effect for fruiting-body count indicate that the differences were meaningful in terms of production performance.

The improved performance under the 3,000-rpm condition may be associated with greater air circulation and more effective distribution of fog within the growing chamber. Increased airflow may promote more uniform movement of suspended moisture and reduce localized differences around the fruiting bags. However, because the DHT11 sensors were not formally calibrated against laboratory-grade reference instruments, the contribution of specific microclimatic changes to the observed production improvement should be interpreted cautiously. The results therefore establish an association between higher fan speed and improved production but do not independently establish the precise microclimatic mechanism responsible.

The observed response is consistent with the findings of Oh et al. (2019), who reported that differences in air velocity influenced fruiting-body characteristics and commercial yield of *Pleurotus ostreatus*. This supports the interpretation that airflow is not merely a ventilation requirement but an environmental variable that may influence mushroom production. The present study extends this concept to an automated fogponic cultivation environment, where fan-driven airflow also contributes to the distribution of suspended mist. Nevertheless, direct air velocity was not measured in the present experiment; therefore, the relationship between fan rotational speed, actual air velocity, and mushroom productivity requires further investigation.

The chamber-level results further support the consistency of the observed treatment pattern, with both 3,000-rpm chambers exhibiting higher mean harvest weight and biological efficiency than the two 1,500-rpm chambers. This consistency suggests that the observed production advantage under the higher fan-speed condition was not driven by a single unusually productive chamber. Nevertheless, because the fan-speed treatments were predetermined rather than randomly assigned to chambers, potential chamber-specific effects cannot be completely excluded. Future studies should employ randomized treatment assignments and additional independent chamber replicates to strengthen treatment-level inference.

Contrary to the possibility that higher airflow might increase production variability, the 3,000-rpm treatment showed slightly lower bag-level variability. Harvest-weight SD decreased from 44.33 g at 1,500 rpm to 38.64 g at 3,000 rpm, while biological-efficiency SD decreased from 14.07% to 12.27%. Thus, within the conditions evaluated, the higher fan speed did not appear to increase production variability.

Although 3,000 rpm produced better results, progressively increasing fan speed should not automatically be expected to further improve production. Excessive airflow may potentially create localized turbulence, uneven fog distribution, accelerated moisture loss from fruiting surfaces, or other unfavorable conditions. These effects were not directly measured. Accordingly, 3,000 rpm should be interpreted as the better-performing condition among the two fan speeds tested rather than as an absolute optimum.

The 50.06% biological efficiency obtained at 1,500 rpm was comparable to the approximately 50.9% reported by Yang et al. (2013), while the 59.80% obtained at 3,000 rpm exceeded this benchmark. Miah et al. (2016), however, reported biological efficiency reaching approximately 82% under different substrate conditions. These comparisons indicate that the present results fall within values reported for oyster mushroom cultivation while remaining below some higher-performing substrate systems. Such comparisons should be interpreted cautiously because biological efficiency is also influenced by mushroom strain, substrate composition, supplementation, environmental conditions, cultivation duration, and harvesting procedures.

The production advantage of the 3,000-rpm treatment should also be considered in relation to potential energy requirements. Increasing cumulative harvest from 9.461 kg to 11.303 kg provided an additional 1.842 kg of mushrooms, equivalent to an approximately 19.5% improvement. However, electrical energy consumption was not monitored during the experiment. Consequently, the present study cannot determine whether the additional production offsets any increase in electrical energy required for higher-speed fan operation. The results therefore demonstrate a production advantage but do not establish that the 3,000-rpm condition is more energy-efficient or economically advantageous.

The experiment was conducted using 120 fruiting bags distributed across four controlled chambers. Direct application of the 3,000-rpm condition to commercial facilities should therefore be approached cautiously. Increasing chamber volume and fruiting-bag density may alter airflow patterns, fog distribution, temperature and humidity gradients, and ventilation requirements. Consequently, commercial-scale applications should be based on required air velocity and spatial airflow distribution rather than fan rotational speed alone.

Larger facilities may require multiple strategically positioned fans, distributed fogging units, independently controlled airflow zones, and multiple environmental sensing points. The automated architecture developed in the present study provides a potential basis for such expansion, but larger systems would also increase equipment investment, electrical consumption, maintenance requirements, and system complexity. Progressive scale-up trials are therefore necessary to determine whether the productivity advantage observed under experimental conditions can be maintained economically on a commercial scale.

Several limitations should be considered when interpreting the findings of this study. First, only two fan-speed conditions, 1,500 rpm and 3,000 rpm, were evaluated; therefore, the 3,000-rpm condition should not be considered an absolute optimum. Second, the fan-speed treatments were predetermined and applied at the chamber level rather than randomly assigned. Although two replicate chambers were used for each fan-speed condition, the individual fruiting bags within each chamber represented subsamples under the same chamber-level treatment. Accordingly, the bag-level inferential results should be interpreted together with the chamber-level descriptive analysis, which showed a consistent production pattern across the replicate chambers. Third, the DHT11 sensors were not formally calibrated against laboratory-grade reference instruments, which limits the precision with which small differences in temperature and relative humidity can be interpreted. Fourth, electrical energy consumption and operating costs were not measured; consequently, the study cannot determine whether the increased production observed under the 3,000-rpm condition resulted in greater energy efficiency or economic benefit. Finally, the experiment was conducted at a relatively small scale using 120 fruiting bags distributed across four controlled chambers. Larger-scale studies with randomized treatment assignment, additional independent chamber replicates, calibrated environmental sensors, direct airflow measurements, and energy monitoring are therefore necessary before the findings can be generalized to commercial-scale fogponic mushroom production.

Overall, increasing fan speed from 1,500 rpm to 3,000 rpm was associated with improved harvest weight, fruiting-body count, and biological efficiency under the experimental conditions evaluated. Nevertheless, the production advantage should be interpreted within the tested fan-speed range and chamber configuration. Further investigation incorporating multiple airflow levels, randomized chamber assignment, calibrated sensors, direct airflow and energy measurements, and progressively larger cultivation systems is necessary to establish the technical, energetic, and economic feasibility of controlled airflow fogponic mushroom production.

Conclusion. This study addressed the limited empirical evidence regarding the influence of controlled fan speed on the production performance of fogponically cultivated oyster mushrooms (*Pleurotus ostreatus*). Under the experimental conditions evaluated, the 3,000-rpm treatment produced significantly higher harvest weight, fruiting-body count, and biological efficiency than the 1,500-rpm treatment. These findings demonstrate that airflow regulation is an important operational consideration in fogponic mushroom cultivation and provide evidence that fan-speed management can contribute to improved production when integrated with controlled misting and environmental monitoring.

The findings also contribute to the broader development of controlled-environment cultivation systems by demonstrating the potential of microcontroller-based airflow and fogging control using accessible electronic components. Such systems may support urban and resource-efficient agricultural production by enabling more controlled cultivation environments where conventional agricultural space is limited. However, because electrical energy consumption, operating costs, and commercial-scale performance were not evaluated, the higher productivity observed at 3,000 rpm should not be interpreted as evidence that this condition is the most energy-efficient, economically optimal, or universally applicable fan speed.

Further validation using multiple airflow conditions, calibrated environmental sensors, direct airflow and energy measurements, randomized chamber assignment, and larger cultivation systems are necessary to determine the technical, environmental, and economic sustainability of controlled airflow fogponic oyster mushroom production.

Recommendations. appropriates should evaluate a wider range of fan speeds, including intermediate settings between 1,500 and 3,000 rpm and, where appropriate, conditions above 3,000 rpm, to establish the airflow-response relationship and determine an optimal operating range. Variable-speed fan control should be investigated so that airflow can be adjusted according to cultivation stage and real-time environmental conditions rather than maintained at a single fixed speed.

Direct air-velocity measurements should be conducted at multiple locations within the growing chamber to characterize spatial airflow and fog distribution. For larger cultivation facilities, zoned airflow systems using multiple independently controlled fans and fogging units should be evaluated to reduce stagnant zones, excessive airflow, and uneven moisture distribution.

Future experiments should incorporate direct electrical power and energy monitoring. Relevant indicators should include fan and fogger power consumption, cumulative energy consumption per cultivation cycle, energy consumption per kilogram of harvested mushrooms, and electricity cost per kilogram of production. These measurements should be combined with equipment, maintenance, labor, and production revenue data to perform a comprehensive cost-benefit analysis.

Future studies should also employ randomized chamber assignments, additional independent chamber replicates, and calibrated higher-accuracy temperature and humidity sensors. Alternative substrate formulations and cultivation conditions may also be evaluated to determine how airflow interacts with other production variables.

Finally, progressive scale-up trials should be conducted beyond the 120-bag experimental configuration. Intermediate and commercial-scale systems should be evaluated for productivity, airflow uniformity, environmental stability, energy consumption, operating cost, equipment reliability, and maintenance requirements before recommendations are made for large-scale adoption.

Author contributions. (Not available)

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Data availability statement. All data supporting the findings of this study are included within the manuscript.

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