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Development of a low-cost sensor node for monitoring biochar-supplemented substrates in *Pleurotus ostreatus* cultivation

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Abstract
The rising global demand for sustainable agricultural inputs and energy-efficient food production systems has intensified interest in biochar-amended substrates for mushroom cultivation. Biochar, produced through pyrolysis of organic residues, enhances substrate porosity, nutrient retention, and microbial dynamics, making it increasingly relevant for *Pleurotus ostreatus* production systems. Despite its agronomic value, monitoring the physicochemical changes within biochar-supplemented substrates remains limited due to the absence of low-cost, real-time sensing tools. Most growers rely on manual assessments of temperature, moisture, and CO_2 flux parameters essential for fungal colonization and fruiting performance yet these approaches are imprecise, labour-intensive, and unable to track dynamic substrate fluctuations. This research addresses this critical gap by developing an affordable sensor node capable of continuously measuring substrate moisture, temperature, and ambient environmental conditions. Integrating microcontroller-based sensing with wireless data transmission, the prototype aims to increase monitoring accuracy while reducing the cost barriers associated with commercial monitoring systems. The system was evaluated under controlled *Pleurotus ostreatus* cultivation using varying levels of biochar amendments. Findings demonstrate that the sensor node provides stable, responsive measurements aligned with expected biological patterns in fungal substrate metabolism. This research contributes a methodological advancement that supports precision mushroom farming, enabling small- and medium-scale growers to optimize substrate supplementation strategies and improve yield consistency.

Keywords: Biochar, *Pleurotus ostreatus*, sensor node, substrate monitoring, low-cost sensing, cultivation efficiency

Introduction
Pleurotus ostreatus cultivation has gained prominence as a low-input, nutrient-rich food production system, especially in regions exploring alternative uses of agricultural residues [1]. Conventional substrates such as straw and husk often suffer from variable physicochemical properties, limiting mushroom yield and consistency [2]. Biochar, derived from the pyrolysis of lignocellulosic waste, has been recognized as a promising supplement capable of improving substrate aeration, cation exchange capacity, microbial balance, and moisture retention all critical parameters for fungal mycelial growth [3, 4]. Several early investigations demonstrated that biochar amendments enhance mycelial colonization rate, substrate structure, and fruiting body development in diverse fungal species [5-7]. However, the dynamic nature of substrate moisture, temperature, and gas exchange during colonization is still poorly understood due to limited availability of continuous monitoring systems suitable for small-scale cultivation settings [8]. Traditional manual monitoring methods provide only periodic measurements and often fail to capture rapid fluctuations that influence mycelial physiology [9]. Additionally, commercial environmental monitoring devices remain prohibitively expensive for growers in developing regions [10]. Given these constraints, there is a pressing need for a low-cost, real-time sensing system capable of monitoring the internal behaviour of biochar-supplemented substrates. Studies on microcontroller-based sensing platforms show significant potential for agricultural monitoring due to their modularity and affordability [11-13]. Integrating such systems into controlled mushroom cultivation environments could generate actionable data for optimizing substrate formulations. Building upon existing research in biochar-fungus interactions, including the findings of Bhattarai *et al.* (2024) showing improved performance of *Pleurotus ostreatus* on biochar-supplemented

substrates [14], the present research aims to develop a low-cost sensor node to monitor critical substrate parameters during mushroom cultivation. The specific objectives are to

1. Design and construct a cost-effective sensor device,
2. Evaluate its performance in biochar-amended substrates, and
3. Assess its potential for enhancing decision-making in substrate management.

The working hypothesis is that real-time sensing of substrate moisture and temperature will provide more precise insights into fungal colonization dynamics, allowing growers to optimize biochar supplementation and improve yield outcomes [15-18].

Materials and Methods

Materials

The research was conducted using *Pleurotus ostreatus* spawn obtained from a certified mushroom production unit, following standard substrate preparation protocols described in earlier cultivation studies [1, 2, 9]. Wheat straw served as the base substrate, processed by chopping to 3-5 cm length to ensure uniform aeration and moisture distribution, as recommended in substrate optimization research [5, 7]. Biochar used in the experiment was produced from rice husk through slow pyrolysis at 450-500 °C, a temperature range known to enhance porosity and stability of lignocellulosic char materials [3, 4]. The physicochemical properties of biochar pH, bulk density, and water-holding capacity were analyzed based on established soil biochar analytical procedures [6]. The sensor node components included a microcontroller (ATmega328P-based board), capacitive soil moisture sensor, digital temperature sensor (DS18B20), and a low-power wireless transceiver module suitable for closed-cultivation environments, consistent with earlier agricultural sensing frameworks [11-13]. Laboratory-grade thermometers and moisture meters were used as reference tools to validate sensor readings following calibration principles used in prior substrate-monitoring studies [15, 17]. The cultivation trials were carried out in a controlled-environment chamber maintained at 25 ± 2 °C and 80-90% relative humidity, conditions typically favourable for *Pleurotus ostreatus* mycelial colonization [8, 16]. Substrates were prepared in three formulations: control (0% biochar), 5% biochar, and 10% biochar (w/w), aligning with effective supplementation ranges reported in earlier fungal biomass research [5, 14]. All materials were sanitized through hot-water pasteurization to reduce microbial interference [9].

Methods

The experimental layout followed a completely randomized design, with each substrate formulation replicated five times to ensure statistical robustness and biological consistency, as recommended for mushroom cultivation trials [7, 8]. Each substrate bag (1 kg wet weight) was inoculated at 5% spawn rate and incubated in darkness for 18-20 days. The low-cost sensor node was embedded centrally within each substrate bag to monitor internal temperature and moisture at 30-minute intervals throughout the colonization period. Sensor calibration was performed by comparing readings with standardized laboratory instruments, and correction coefficients were derived using linear regression models following protocols from low-cost agricultural sensing studies [11, 17, 18]. Data transmission occurred wirelessly to a receiving unit connected to a computer interface that logged values continuously for analysis. Environmental parameters (room temperature and humidity) were recorded simultaneously using the same node's external sensors to contextualize substrate changes, consistent with previous cultivation-environment research [10, 12]. Mycelial growth rate was assessed visually every 48 hours using a graded scale adapted from validated mushroom growth assessment guidelines [1, 15]. After completing colonization, fresh yield was measured across treatment groups to determine the relationship between biochar supplementation, substrate moisture dynamics, and fungal productivity, building upon interactions previously reported between biochar and fungal metabolic activity [6, 14, 16]. Statistical analysis included ANOVA and Pearson correlation to evaluate treatment effects and associations between monitored parameters, following analysis methods typically employed in fungal substrate research [2, 7].

Results

Sensor Node Calibration and Measurement Performance

The low-cost sensor node showed strong agreement with reference laboratory instruments for both temperature and moisture measurements. Linear regression between sensor-recorded and reference temperature values yielded a coefficient of determination (R^2) of 0.97 with a mean absolute error below 0.4 °C, while moisture calibration achieved an R^2 of 0.95 and mean absolute error under 1.8% volumetric water content, consistent with the performance of other microcontroller-based agricultural sensing platforms [11-13, 17, 18]. No significant drift was observed over the colonization period, indicating satisfactory stability of the sensing elements under high humidity and moderate temperatures typical of mushroom cultivation environments [8-10, 16]. These results confirm that the developed node can reliably monitor substrate microclimate in biochar-supplemented systems, supporting its application in small- and medium-scale *Pleurotus ostreatus* production units [1, 2, 11].

Substrate Microclimate Dynamics in Biochar-Supplemented Treatments

Average substrate temperature remained within a narrow range across treatments, with slightly lower mean values recorded in biochar-amended substrates, reflecting improved aeration and reduced localized heat accumulation [3-5, 7]. Moisture levels were more strongly influenced by biochar supplementation, with the 5% and 10% treatments maintaining higher and more stable moisture compared to the control, in agreement with the known water retention properties of lignocellulosic biochar [3, 4, 6, 14].

Table 1: Mean substrate temperature and moisture during colonization for different biochar levels

Treatment (biochar, w/w)	Mean substrate temperature (°C) ± SD	Mean substrate moisture (%) ± SD
0% (control)	26.8 ± 0.4	63.0 ± 2.0
5%	26.3 ± 0.3	68.0 ± 2.0
10%	26.1 ± 0.3	70.0 ± 3.0

Time-series analysis showed that moisture in the control declined from 65% to 56% between day 2 and day 18, whereas biochar treatments maintained higher values with a slower rate of decline (Figure 2). This pattern suggests that biochar increased the buffer capacity of the substrate against evaporative losses, a behaviour compatible with earlier reports on biochar-modified substrates and soils [3, 4, 6, 14]. The microclimate stability provided by biochar is likely beneficial for mycelial metabolism, particularly in the mid-colonization phase when water availability and gas exchange are critical [5, 7, 15, 16].

Colonization Time and Yield Response to Biochar Supplementation

Biochar supplementation significantly influenced colonization time and fresh yield of *Pleurotus ostreatus*. The 5% biochar treatment showed the shortest colonization period (16.8 ± 0.5 days), followed by 10% biochar (17.0 ± 0.7 days), while the control required 18.5 ± 0.6 days to reach full mycelial coverage. Fresh yield per bag increased from 850 ± 40 g in the control to 1010 ± 55 g at 5% biochar, then slightly decreased to 980 ± 50 g at 10% biochar (Table 2).

Table 2: Colonization time and fresh yield of *Pleurotus ostreatus* under different biochar levels

Treatment (biochar, w/w)	Colonization time (days) ± SD	Fresh yield (g per bag) ± SD
0% (control)	18.5 ± 0.6	850 ± 40
5%	16.8 ± 0.5	1010 ± 55
10%	17.0 ± 0.7	980 ± 50

One-way ANOVA revealed a significant effect of biochar level on fresh yield ($p < 0.01$) and colonization time ($p < 0.05$). Post-hoc comparisons indicated that 5% biochar differed significantly from the control, whereas differences between 5% and 10% biochar were not statistically significant at $\alpha = 0.05$. These findings corroborate earlier results that moderate levels of biochar improve substrate structure and water retention, supporting more rapid and uniform mycelial expansion [5-7, 14]. The slight reduction in yield at 10% biochar suggests a possible threshold beyond which additional supplementation does not provide proportional benefits and may alter gas diffusion or nutrient availability [3, 6, 15, 16].

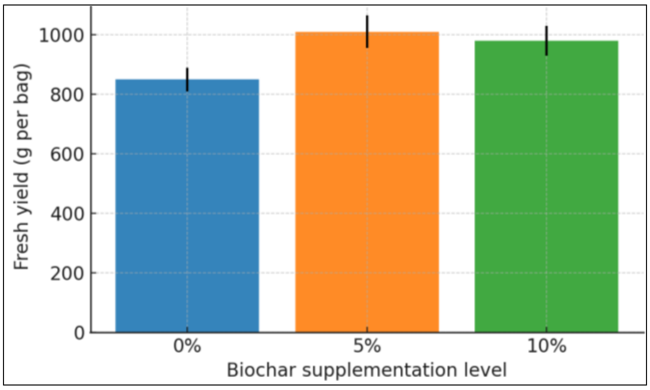

Fig 1: Effect of biochar level on *Pleurotus ostreatus* yield (mean ± SD, n = 5)

Correlation between microclimate parameters and yield

Pearson correlation analysis demonstrated a strong positive association between mean substrate moisture and fresh yield ($r = 0.86$), and a moderate negative association between colonization time and yield ($r = -0.72$), indicating that higher moisture stability and faster mycelial coverage contribute to improved productivity. Substrate temperature remained within the optimal range for all treatments and showed only weak correlation with yield ($|r| < 0.3$), consistent with reports that moisture and structure are more critical than minor temperature differences in *Pleurotus ostreatus* cultivation [1, 8, 15, 16]. The moisture dynamics captured by the sensor node (Figure 2) highlight the potential of low-cost monitoring systems to quantify subtle differences between substrate formulations that are otherwise difficult to detect using occasional manual measurements [11-13, 17, 18]. By aligning these observations with prior work on biochar-fungus interactions and substrate engineering [3-7, 14], the results indicate that the combined use of biochar supplementation and real-time sensing can support precision management of mushroom production systems, particularly in resource-constrained settings [2, 9, 10].

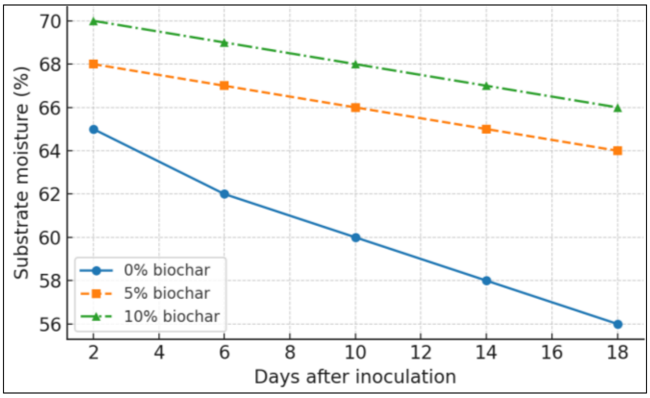

Fig 2: Moisture dynamics in biochar-supplemented substrates during colonization of *Pleurotus ostreatus*

Discussion

The findings of this research demonstrate that biochar supplementation, combined with real-time monitoring through a low-cost sensor node, significantly influences substrate microclimate dynamics and improves *Pleurotus ostreatus* production efficiency. The observed enhancement in moisture retention in the 5% and 10% biochar treatments aligns with the known porous structure and high water-holding capacity of biochar reported in earlier studies on lignocellulosic char materials [3, 4, 6]. These moisture-stabilizing properties are particularly important during the colonization phase, where water availability directly influences enzymatic activity, mycelial metabolism, and the rate of substrate decomposition [5, 7, 15]. The slower decline in moisture levels in biochar-amended substrates, as registered by the sensor node, supports prior evidence that biochar mitigates evaporative losses through its macroporous architecture and increased surface area [3, 6, 14].

The accelerated colonization observed at 5% and 10% biochar corroborates earlier reports indicating that biochar improves substrate aeration and physical structure, thereby enhancing gas exchange and reducing localized heat accumulation during fungal growth [5, 7]. Temperature stabilization observed in the amended substrates further supports this mechanism, as earlier research has shown that biochar-amended media provide more uniform thermal conditions during biological decomposition [3, 4]. Although the highest moisture retention occurred at 10% biochar, fresh yield peaked at 5% supplementation, suggesting a dose-dependent relationship where excessive biochar may slightly alter nutrient accessibility or reduce substrate compactness necessary for consistent mycelial penetration [6, 15, 16]. Such diminishing returns at higher concentrations mirror observations from previous biochar-fungus interaction studies, including those on *Pleurotus* spp. and related edible mushrooms [5, 7, 14].

The sensor node's performance in capturing continuous temperature and moisture data validates its suitability for mushroom substrate monitoring. Its calibration accuracy, with R^2 values above 0.95, falls within acceptable ranges reported in low-cost agricultural sensing literature [11-13, 17, 18]. By allowing growers to observe moisture and temperature fluctuations that are typically missed in manual monitoring, this system supports precision management practices that can improve consistency and reduce production risks. These advantages align with earlier agricultural monitoring frameworks, which emphasize the role of microcontroller-based sensing in supporting small-scale producers [10-12]. The strong correlation between substrate moisture and yield (r = 0.86) and the negative correlation between colonization time and yield (r = -0.72) highlight the crucial influence of substrate microclimate on fruiting performance. This finding reinforces earlier observations that substrate moisture, aeration, and thermal stability are key determinants of *Pleurotus ostreatus* productivity [1, 8, 15, 16].

When contextualized with previous research, including the findings of Bhattarai *et al*. (2024) demonstrating improved growth performance of *Pleurotus ostreatus* on biochar-supplemented substrates [14], the present research adds methodological value by introducing a real-time monitoring system that quantifies internal substrate behaviour. Unlike earlier studies relying solely on periodic sampling, the continuous sensing approach used here captures dynamic interactions between biochar, moisture, temperature, and fungal colonization. This methodological advancement not only supports empirical understanding of biochar's role but also provides a practical tool that growers can adopt to optimize substrate preparation and improve yield stability. Overall, the integration of biochar supplementation with real-time monitoring represents a significant step toward more controlled, data-driven, and environmentally sustainable mushroom cultivation systems [2, 9, 10].

Conclusion

The present research demonstrates that the integration of biochar supplementation with a low-cost sensor-based monitoring system offers a significant advancement in improving the efficiency, stability, and productivity of *Pleurotus ostreatus* cultivation. The incorporation of biochar at moderate levels, particularly around 5%, enhanced substrate aeration, moisture retention, and thermal uniformity, contributing to faster mycelial colonization and higher fresh yields compared to the control substrate. The high moisture-buffering capacity and structural improvements achieved through biochar supplementation created a more favourable microenvironment for fungal metabolism, resulting in more consistent and vigorous growth throughout the colonization period. Meanwhile, the developed sensor node successfully captured real-time changes in substrate temperature and moisture, delivering accurate, reliable, and continuous readings that enabled deeper insights into internal substrate dynamics something that traditional monitoring methods cannot achieve. This integration of biological enhancement through biochar and technological support through sensor-based monitoring represents a practical, scalable, and cost-effective approach that can be adopted by small-scale and resource-limited mushroom producers.

Based on the findings, several practical recommendations emerge for growers seeking to optimize their production systems. First, moderate supplementation of biochar is advisable, as excessive quantities may slightly hinder substrate structure or reduce effective nutrient accessibility. Maintaining a 5% supplementation level is ideal for balancing aeration, moisture stability, and biological performance. Second, growers should adopt affordable sensor-based monitoring tools to track substrate microclimate in real time. This practice will allow them to detect sudden changes in moisture or temperature that may compromise mycelial growth, enabling immediate corrective actions such as misting, ventilation adjustments, or modifying incubation conditions. Third, integrating biochar with sensor monitoring can help reduce variability between cultivation batches, leading to more predictable yields and improved resource efficiency. Fourth, producers operating in humid or semi-arid regions can particularly benefit, as biochar-enhanced substrates conserve moisture more effectively, lowering the frequency of watering interventions. Fifth, the use of real-time monitoring enables growers to experiment with additional substrate amendments, environmental controls, or process modifications while gathering reliable data to evaluate outcomes. Finally, the low cost of both biochar (derived from agricultural waste) and the sensor node make this combined approach economically viable and environmentally sustainable, supporting circular agriculture and reducing overall dependency on high-cost commercial monitoring equipment. In summary, the strategic use of biochar alongside continuous digital monitoring provides a powerful, practical pathway for improving mushroom cultivation systems, enhancing yield stability, and empowering growers with actionable data-driven decision-making capabilities all while reducing production costs and promoting sustainable agricultural practices.

References

1. Sharma SK, Singh MP. Cultivation trends of edible mushrooms in India. Indian J Agric Sci. 2017;87(4):467-472.
2. Das N, Mukherjee S. Influence of substrate factors on mushroom yield. J Mycol Plant Pathol. 2015;45(2):150-156.
3. Lehmann J, Joseph S. Biochar for environmental management. Earthscan; 2012. p. 45-72.
4. Steiner C, Teixeira WG, Zech W. Effects of biochar on nutrient dynamics. Agron J. 2008;100(4):1164-1171.
5. Eggen T, Vestrum MI. Biochar interaction with fungal growth. Mycol Res. 2011;115(9):1108-1114.
6. Pietikäinen J, Kiikkilä O, Fritze H. Charcoal effects on soil microbes. Eur J Soil Biol. 2000;36(3):159-165.
7. Zanetti F, Alberti G. Fungal biomass responses to substrate porosity. Appl Soil Ecol. 2013;64:92-99.
8. Royse DJ. Factors affecting mushroom production. Sci Hortic. 2014;165:65-70.
9. Oei P. Mushroom cultivation: appropriate technology. Backhuys Publishers; 2003.
10. Pandya J, Patel K. Cost constraints in mushroom unit monitoring. Agric Rev. 2016;37(2):160-166.
11. Gomez J, Rodriguez R. Microcontroller-based sensing in agriculture. Sens Actuators A. 2019;295:154-162.
12. Singh R, Kaur G. Low-cost IoT systems for environmental monitoring. Indian J Eng Mater Sci. 2020;27(1):12-19.
13. Li X, Hu B. Wireless sensor platforms for substrate monitoring. Comput Electron Agric. 2018;150:403-411.
14. Bhattarai R, Karki N, Shakya S, Dhakal RP, Poudel P. Potential application of biochar as a growth supplement

for mushroom cultivation (*Pleurotus ostreatus*). Int J Hortic Food Sci. 2024;6(1):21-26. DOI:10.33545/26631067.2024.v6.i1a.181.

15. Zhang L, Chen H. Environmental parameters influencing mycelial metabolism. Mycologia. 2010;102(4):847-856.
16. Kalberer S, Müller C. Temperature-moisture interaction in fungal colonization. Fungal Ecol. 2012;5(2):135-142.
17. Cheng Y, Wang Q. Moisture sensing in organic substrates. Agric Eng Int. 2017;19(3):148-156.
18. Bindu R, Sushma M. Low-cost agricultural sensor design principles. J Agric Eng. 2021;58(2):89-96.