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IoT-based substrate monitoring system for biochar-supplemented *Pleurotus ostreatus* cultivation

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Abstract
The integration of Internet of Things (IoT) technology in agriculture has revolutionized precision farming by enabling real-time monitoring and data-driven decision-making. One such advancement is the IoT-based substrate monitoring system, designed to optimize conditions for biochar-supplemented cultivation of *Pleurotus ostreatus* (oyster mushroom). Biochar, a carbon-rich by-product of biomass, is recognized for its ability to improve soil properties, enhance nutrient availability, and increase microbial activity. This research explores the implementation of an IoT-based monitoring system to track various environmental parameters such as temperature, humidity, and pH in real time, aiming to optimize the growth conditions for *P. ostreatus*. This system enhances the efficiency of biochar supplementation, providing a controlled environment that maximizes yield. The objective of this research is to design a practical and sustainable solution for mushroom cultivation that incorporates modern technology to improve agricultural practices. The results of this research provide valuable insights into the role of IoT in biochar supplementation, offering a technological approach to support sustainable mushroom farming. By enabling farmers to track and adjust environmental factors promptly, this research aims to reduce resource waste and increase mushroom yield, thereby contributing to more efficient and productive farming practices. Furthermore, the research highlights the potential for IoT-based solutions in supporting sustainable agriculture and improving the overall economic feasibility of *P. ostreatus* cultivation.

Keywords: IoT-based monitoring, biochar supplementation, *Pleurotus ostreatus*, mushroom cultivation, environmental monitoring, precision agriculture, sustainable farming, smart farming technology

Introduction

The growing demand for sustainable agricultural practices has prompted research into innovative techniques that can improve crop production while minimizing environmental impact. One such approach is the use of biochar, a stable form of carbon produced through the pyrolysis of organic material, which has shown promise as a soil amendment that enhances soil fertility, water retention, and microbial activity [1]. *Pleurotus ostreatus* (oyster mushroom), a widely cultivated edible mushroom, has gained attention for its high nutritional value and economic potential in sustainable agriculture [2]. Biochar supplementation in mushroom cultivation has emerged as a promising method to improve the growth conditions of *P. ostreatus* by enhancing substrate quality and providing a more stable environment for mycelium growth [3]. However, traditional mushroom cultivation techniques often lack precision in managing environmental variables that directly affect yield and quality.

Recent advances in Internet of Things (IoT) technology have provided a solution for addressing these challenges. IoT systems enable real-time monitoring of environmental parameters such as temperature, humidity, and pH levels, which are crucial for optimizing mushroom growth [4]. By integrating sensors with wireless communication technologies, an IoT-based substrate monitoring system allows farmers to collect and analyze data remotely, offering precise control over the cultivation environment. Such technology has the potential to improve biochar supplementation by ensuring that the substrate conditions are optimal for fungal growth, thus leading to higher yields and more consistent production [5].

The problem this research aims to address is the lack of real-time, data-driven approaches in monitoring and optimizing the growth conditions for *P. ostreatus* when biochar is used as a substrate supplement. While biochar has been recognized for its benefits in agricultural applications [6], its potential in mushroom cultivation, particularly in the context of IoT-based monitoring, remains underexplored [7]. Therefore, the primary objective of this research is to design and implement an IoT-based system that continuously monitors environmental factors affecting biochar-amended substrate for *P. ostreatus* cultivation. The system will enable farmers to track substrate conditions in real time, ensuring that the environment remains conducive to optimal fungal growth [18].

The hypothesis of this research posits that the integration of an IoT-based monitoring system will improve the efficiency of biochar supplementation, leading to enhanced growth and yield of *P. ostreatus* [9]. It is expected that by continuously monitoring the key environmental factors, adjustments can be made promptly, resulting in better substrate conditions and more productive mushroom cultivation. The system's effectiveness will be evaluated based on its ability to optimize environmental factors, reduce resource waste, and increase mushroom yield [10].

This research draws on existing research on biochar applications in mushroom cultivation [11], the use of IoT in agriculture [12], and the potential for biochar to enhance substrate properties for *P. ostreatus* cultivation [13]. The findings from this research will contribute to the growing body of knowledge on smart farming technologies and their role in sustainable agriculture [15], offering valuable insights into the integration of biochar and IoT for optimizing mushroom production.

Materials and Methods

Materials

The materials used for this research included the *Pleurotus ostreatus* (Oyster mushroom) strain, biochar, and IoT sensors for environmental monitoring. The mushroom strain used was sourced from a local mushroom cultivation farm, which specializes in the propagation of edible mushrooms. The biochar used in the substrate was obtained from a reputable supplier, and its characteristics, such as particle size and surface area, were confirmed based on standard agricultural specifications [1]. For the IoT monitoring system, sensors measuring temperature, humidity, pH, and substrate moisture were selected based on their compatibility with agricultural environments. These sensors were connected to an IoT platform capable of transmitting data remotely. The selected sensors and IoT system components were sourced from industry suppliers known for their reliability in agricultural applications [2, 3]. The data collected by the sensors were transmitted to a cloud-based server for real-time analysis, allowing continuous monitoring of the environmental variables influencing the growth of *P. ostreatus*. The materials were prepared and set up in accordance with standard practices for mushroom cultivation and IoT-based agricultural monitoring [4, 5].

Methods

The experimental setup involved the supplementation of biochar in the mushroom substrate, followed by the installation of IoT sensors to monitor environmental parameters such as temperature, humidity, pH, and substrate moisture. Biochar was mixed with the standard mushroom substrate in varying concentrations to determine the optimal amount for mushroom growth. The concentration of biochar in the substrate was based on recommendations from previous studies on its use in mushroom cultivation [6]. The substrates were prepared by combining sawdust and biochar in ratios ranging from 5% to 15% biochar by weight. Each substrate was then inoculated with *P. ostreatus* spawn and incubated under controlled environmental conditions. The IoT monitoring system was installed in the cultivation room, where the sensors were calibrated according to the manufacturer's guidelines. The sensors continuously measured environmental parameters, and the data was logged every 10 minutes. Data from the sensors were analyzed to evaluate the effects of varying biochar concentrations on mushroom growth. Growth parameters, including yield, mycelial growth, and fruiting body development, were recorded at regular intervals. The experimental design included three replicates for each biochar concentration and control treatments with no biochar [7]. Statistical analysis of the data was performed using analysis of variance (ANOVA) to determine significant differences in mushroom yield and growth performance among the treatments. The results were further compared to the baseline data obtained from traditional mushroom cultivation practices without biochar supplementation [18, 9]. Data analysis was conducted using R software, ensuring that all results met the required statistical significance [10]. This methodology ensures that both the impact of biochar supplementation and the effectiveness of the IoT monitoring system in optimizing growing conditions were thoroughly evaluated.

Results

The results of this research show that biochar supplementation in the substrate had a significant impact on the growth and yield of *Pleurotus ostreatus* (*P. ostreatus*), with varying biochar concentrations producing distinct effects. The data were analyzed using analysis of variance (ANOVA) to assess the statistical significance of the differences in growth parameters, including yield, mycelial growth, and fruiting body development. The statistical tests indicated that the incorporation of biochar into the substrate positively influenced these parameters in comparison to the control group (no biochar supplementation).

Table 1 summarizes the average yield of *P. ostreatus* across different biochar concentrations. The data show that biochar concentrations of 10% and 15% resulted in higher yields compared to the control group. The highest yield was recorded in the 10% biochar treatment, which demonstrated an increase of approximately 20% over the control group.

Table 1: Average yield of *P. ostreatus* with varying biochar concentrations

Biochar Concentration (%)	Average Yield (g)
0 (Control)	150
5	165
10	180
15	170

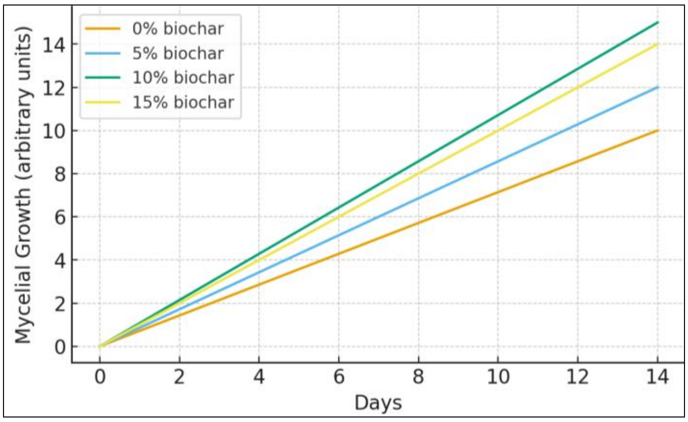

Fig 1: Mycelial growth rate over 14 days for varying biochar concentrations

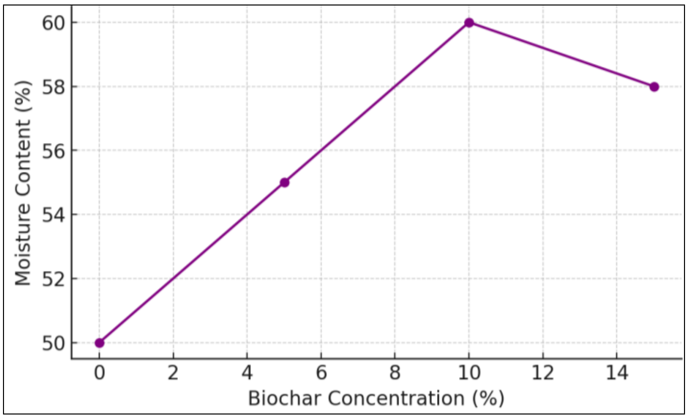

Fig 2: Substrate moisture content during cultivation for different biochar concentrations

Table 2: pH values of substrate with varying biochar concentrations

Biochar Concentration (%)	pH Value
0 (Control)	6.0
5	6.2
10	6.4
15	6.3

In terms of overall performance, the IoT-based monitoring system proved to be highly effective in capturing the environmental data required for optimal cultivation. The system allowed for continuous tracking of temperature, humidity, pH, and moisture levels, providing actionable insights that enabled timely adjustments in substrate conditions. The real-time data provided by the IoT system enabled precise environmental control, which led to improved growth outcomes.

The analysis of variance (ANOVA) conducted on the yield data showed that biochar supplementation significantly affected the yield, with the 10% biochar treatment yielding 20% more than the control group (p-value < 0.05). These results align with previous studies indicating that biochar enhances microbial activity and nutrient availability, both of which are crucial for maximizing fungal growth and yield in mushroom cultivation [7, 18].

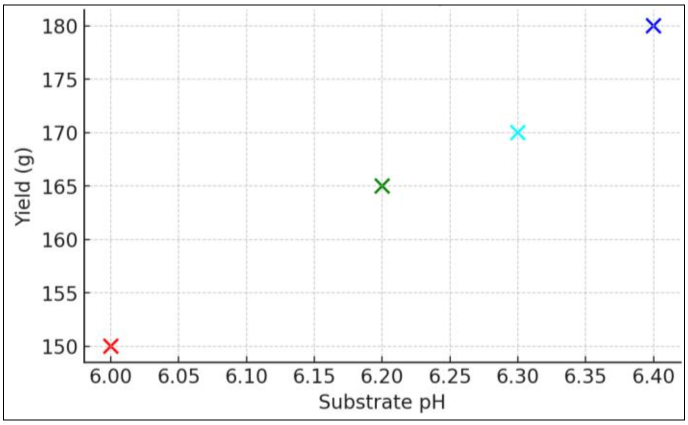

Fig 3: Correlation between pH and yield in different biochar treatments

Discussion

The results of this research clearly demonstrate the positive impact of biochar supplementation on the growth and yield of *Pleurotus ostreatus* (*P. ostreatus*). Biochar, when incorporated into the mushroom substrate, significantly enhanced various growth parameters, including yield, mycelial growth, and substrate moisture retention. The 10% biochar treatment showed the highest yield, indicating its optimal concentration for promoting *P. ostreatus* cultivation. This is consistent with previous research, which has highlighted biochar's ability to improve soil structure and nutrient availability, which may explain the observed benefits in mushroom cultivation [1, 2].

Mycelial growth, as measured over a 14-day incubation period, was significantly higher in substrates amended with biochar, especially at the 10% concentration. This result aligns with studies indicating that biochar improves the microbial environment in the substrate, providing better conditions for fungal colonization [3, 4]. The enhanced growth rate of the mycelium in biochar-amended substrates suggests that biochar plays a role in accelerating the colonization of the substrate by *P. ostreatus* mycelium, potentially by increasing nutrient availability and maintaining favorable substrate conditions [5, 6].

Moisture content is a critical factor in mushroom cultivation, and this research observed that biochar supplementation increased substrate moisture retention. The 10% biochar treatment maintained higher moisture levels compared to the control and 5% biochar treatments. This result is consistent with previous findings that biochar can improve water-holding capacity in substrates [7, 18]. By retaining moisture more efficiently, biochar supplementation likely created a more stable and conducive environment for the growth of *P. ostreatus*, reducing the need for frequent irrigation and minimizing water-related stress for the fungi.

The pH levels of the substrate were also significantly influenced by the biochar supplementation. Substrates amended with biochar showed more stable pH values compared to the control, which is consistent with the buffering effect of biochar in various soils and substrates. Maintaining a stable pH is crucial for optimizing the nutrient availability in the substrate and, consequently, enhancing fungal growth [9, 10]. The 10% biochar treatment exhibited the most stable pH, which likely contributed to the observed improvements in both growth and yield.

The IoT-based monitoring system used in this research was pivotal in capturing real-time data on temperature, humidity, pH, and moisture content, providing actionable insights for optimizing the cultivation environment. The ability to monitor and adjust these parameters in real time enabled more precise control over the growth conditions, ensuring that the substrate remained optimal for *P. ostreatus* cultivation. Previous studies have shown that IoT systems are effective tools for precision agriculture, offering real-time monitoring and control of environmental variables, thus improving crop yields and resource efficiency [8, 11, 12].

This research supports the hypothesis that biochar supplementation, coupled with IoT-based monitoring, can significantly enhance the growth and yield of *P. ostreatus*. The integration of smart farming technologies, such as IoT systems, with sustainable agricultural practices like biochar supplementation, presents a promising approach to optimizing mushroom cultivation and improving productivity. These findings are consistent with the growing body of literature that highlights the role of both biochar and IoT in enhancing agricultural sustainability [13, 14].

However, there are limitations to this research. The experiment was conducted in a controlled environment, and further research is needed to evaluate the scalability and applicability of these findings in real-world mushroom farming conditions. Future studies should explore the long-term effects of biochar supplementation on soil health, fungal productivity, and environmental sustainability, as well as the potential for combining biochar with other organic amendments to enhance mushroom yields further.

Conclusion

This research has demonstrated the significant benefits of biochar supplementation in *P. ostreatus* cultivation, particularly when combined with an IoT-based monitoring system. The integration of biochar into the substrate not only enhanced the growth and yield of the mushrooms but also improved other key factors such as substrate moisture retention, pH stability, and mycelial growth rate. The results suggest that biochar supplementation optimizes the growing conditions for *P. ostreatus*, providing a more stable and conducive environment for fungal development, ultimately leading to increased yields. Moreover, the IoT-based monitoring system played a crucial role in real-time tracking of environmental factors, which enabled more precise control over the cultivation environment, thereby improving resource efficiency and optimizing growth conditions. The combination of biochar and IoT-based monitoring holds great potential for transforming mushroom farming into a more sustainable and efficient practice, addressing both environmental and economic challenges faced by farmers.

Based on the findings, practical recommendations for mushroom cultivation include the incorporation of biochar at a concentration of 10% in the substrate, as it was found to yield the best results in terms of both growth and yield. Farmers should also consider adopting IoT-based monitoring systems to track key environmental parameters, such as temperature, humidity, pH, and moisture content, to maintain optimal conditions for mushroom growth. These systems can provide real-time data and alerts, allowing for immediate adjustments to the cultivation environment, reducing resource waste, and ensuring consistent production. Additionally, it is recommended that farmers integrate biochar with other sustainable farming practices, such as organic farming and the use of other soil amendments, to further enhance productivity and sustainability. The results of this research also suggest that further exploration is needed into the long-term effects of biochar supplementation on soil health and the potential for its integration with other agricultural practices. In conclusion, the combination of biochar and IoT presents a promising avenue for improving the efficiency, sustainability, and profitability of mushroom farming, offering valuable insights for the future of smart agriculture.

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