Review Article **Open Access**

Advances in Mushroom Cultivation Technologies: Substrate Optimization, Controlled Environment and Strategies for Yield Enhancement

Muhammad Awais Fareed [1], Muhammad Asif Shabbir [1,*], Saleha Sattar [2], Memoona Imdad [1], Humera Aslam [3], Awais Mutti [1], Summia Iqbal [1], Rabbia Nasir [1], Hafiz Muhamamad Talha Waleed [1], Umair Anwar [1], Komal Ambreen [1], Iram Bilqees [1]

[1] Department of Plant Pathology, College of Agriculture, University of Sargodha, Sargodha- 40100, Pakistan
[2] Department of Botany, University of Agriculture, Faisalabad-38000, Pakistan
[3] Department of Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Vehari, Pakistan

*Corresponding author: Muhammad Asif Shabbir
Email: shabbir.asif696@gmail.com

Cite this Article:
Fareed, M. A., Shabbir, M. A., Sattar, S., Imdad, M., Aslam, H., Mutti, A., Iqbal, S., Nasir, R., & Waleed, H. M. T., Anwar, U., Ambreen, K., & Bilqees, I. (2026). Advances in mushroom cultivation technologies: substrate optimization, controlled environment and strategies for yield enhancement. *SciNex Journal of Advanced Sciences*, 1(02), 15–23.

ABSTRACT:
Mushroom farming serves sustainable farming practices because it produces healthy food while it transforms farm waste into useful organic matter. Research studies during the last few years have concentrated on developing better substrate materials and environmental control systems and yield optimization methods to address the current restrictions of conventional cultivation methods. The review evaluates modern mushroom cultivation methods through an analysis of substrate enhancement techniques and controlled growing systems and complete yield enhancement methods. The research team used Web of Science and Scopus and Google Scholar to find relevant peer-reviewed studies which appeared during the last five years. The research findings demonstrate that optimized ligno-cellulosic substrates made from agro-industrial waste products will produce better mycelial growth and biological efficiency when researchers use suitable pre-treatment methods and add necessary nutrients. The implementation of sensor-based monitoring systems and IoT-enabled automation and IoT systems enables farmers to maintain exact control over temperature and humidity and CO_2 levels and light exposure which leads to better crop stability and enhanced product quality and decreased chances of contamination. The most effective yield enhancement results from an integrated system which selects genetic strains and implements optimized agricultural practices and stress management and bio-stimulant treatment according to substrate composition and environmental conditions. The upcoming developments in artificial intelligence-based monitoring systems and sustainable substrate technologies and smart farming methods will enhance both production levels and resource utilization efficiency. The review shows how integrated cultivation systems support sustainable mushroom farming which protects food availability and promotes circular agricultural practices.

KEYWORDS:
Mushroom cultivation; Substrate optimization; Controlled-environment systems; Yield enhancement; Sustainable agriculture.

Received: 19 Feburary 2026 / Revised: 10 May 2026 / Accepted: 25 May 2026 / Published Online: 20 June 2026

INTRODUCTION

The practice of mushroom cultivation is proved to be essential for creating environment friendly food production which meets consumer requirements and can help in farmer economic stability. The edible mushrooms contain essential bioactive compounds and micronutrients and high-quality proteins which help people maintain their health while providing dietary variety. The mushroom cultivation process enables the effective transformation of agricultural waste into useful biomass according to Moger et al. (2025). The worldwide rise in consumer demand for nutritious low-fat animal product alternatives has triggered a fast-paced expansion of edible mushroom cultivation (Badoni et al., 2025). The development of cultivation technology depends heavily on substrate optimization which involves using rice straw and wheat straw and sawdust as primary food sources for mushrooms before their combination with additional materials for enhanced biological performance and product output (Hirai et al., 2025). Research conducted recently has proven that non-sterile substrates together with different agricultural by-products can be used to show practicality for large-scale and sustainable operations in developing nations. The combination of these advanced substrates with controlled nutrient levels and moisture and carbon to nitrogen ratio enables better mycelium colonization and increased mushroom production and better nutritional content when mushrooms reach their best stage of development from three popular mushroom species *Pleurotus, Agaricus and Lentinula* (Zhang et al., 2025). The development of new substrate materials and environment control systems and yield improvement techniques has enabled mushroom farming to shift from manual work to automated precision-based cultivation methods. The Internet-of-Things (IoT) based climate-control systems function as controlled-environment systems because they track temperature and humidity and CO2 levels in real-time throughout growing facilities to establish perfect growing conditions and protect against contamination threats (Ravindran et al., 2025). The production system which operates across different locations and seasonal patterns through controlled-environments achieves better production speed and product quality than conventional farming methods (Badoni et al., 2025). The expanding body of research about mushroom culture has produced multiple evaluations which focus on separate aspects including environmental control systems and substrate development methods and specific mushroom species but these studies lack a unified technological approach. The current state of research lacks a complete analysis which effectively links controlled-environment systems to substrate enhancement methods and production enhancement strategies. The research investigates production results and substrate materials and environmental control systems to establish connections between these elements. The research establishes a connection between mushroom farming technology developments through its systematic evaluation of current research findings. The review includes all methods for improving plant growth which include climate-controlled culture systems and substrate optimization tactics and automation and smart technologies. The evaluation of commercialization potential and future possibilities and obstacles follows the assessment. The search for evaluated literature used Web of Science and Scopus and Google Scholar databases through their respective keyword terms which included "mushroom cultivation, substrate optimization, controlled-environment, yield improvement and smart farming". The research team selected peer-reviewed articles from the last five years as their main source to ensure they included the latest technological developments through online first publications and early access. The review provides a systematic resource which helps growers and industry members and researchers to find environmentally friendly mushroom cultivation methods through its evaluation of existing information.

Substrate Optimization for Mushroom Cultivation

The success of mushroom production depends on substrate optimization because substrate composition and availability and preparation methods determine mycelial colonization and fruiting behavior and yield and economic viability. Research today focuses on evaluating how different enriched lignocellulosic materials and agro-industrial leftovers compare to each other for productivity and cost and accessibility and sustainability instead of using only one substrate type. The production of mushrooms using rice straw and wheat straw as substrates remains cost-effective because these materials are widely available in many regions, although their performance often requires supplementation to match the yield and biological efficiency of sawdust-based or composted substrates, which generally involve higher processing costs (Barua et al., 2024). The study examines trade-offs between different cultivated mushroom species while presenting a summary of common substrate materials and cultivation methods and their effects on production output and biological performance (Table 1).

Table 1: Comparison of different substrates and supplementation strategies for major mushroom species

Mushroom Species	Substrate Type	Supplementation	Yield and biological efficiency	References
Pleurotus ostreatus	Rice straw	Wheat bran	70–80% BE	Zhang et al., 2025
Pleurotus ostreatus	Sugarcane bagasse	Soybean meal	75% BE	Argaw et al., 2023
Agaricus bisporus	Compost and Casing	Gypsum + Bran	85% BE	Hu et al., 2025
Lentinula edodes	Sawdust and Logs	Wheat bran	60–70% BE	Moger et al., 2025
Pleurotus eryngii	Corn cobs	Rice bran	65–75% BE	Badoni et al., 2025

Types of Substrates

The sustainability benefits of agro-industrial residues like sugarcane bagasse and corn cobs and spent coffee grounds depend on their physical characteristics and nutrient composition and their distribution across different regions (Hu et al., 2025). The mycelial growth of substrates containing high lignocellulosic content becomes possible through pre-treatment or enrichment methods which help solve nutrient-related challenges (Suwannarach et al., 2022). The use of enriched substrates which contain bran or protein-rich additives leads to better production results but makes the process more expensive while raising the chance of contamination. The research results indicate that substrate choice needs to be determined based on specific conditions because it requires a trade-off between production quantity and operational expenses and delivery costs instead of focusing solely on maximum output.

Substrate Pre-treatment Techniques

The pre-treatment process of substrates enables better control of microbial contamination which leads to enhanced nutrition and better substrate arrangement. The two primary methods for substrate treatment involve pasteurization which heats materials between 60-80°C to kill other microorganisms and sterilization through autoclaving at 121°C for 15-20 minutes (Zhang et al., 2025). The addition of organic or inorganic additives which include wheat bran and gypsum and calcium carbonate enhances both substrate nutritive value and buffering capacity. Scientists have developed pre-treatment methods which use innovative approaches to improve both substrate breakdown and mycelium growth rates. The substrate preparation process begins with selecting raw materials which then receive additions of supplements before microorganisms are introduced as shown in Figure 1. The flowchart shows that substrate selection needs a sequential approach which begins with size reduction followed by moisture adjustments and preliminary treatment and nutrition addition and inoculation. The systematic method demonstrates how biological elements interact with physical and chemical components to establish substrate compatibility which affects the results of cultivation processes

Nutrient Optimization

The process of achieving maximum mushroom development and production requires scientists to find the best possible nutrient levels. The carbon-to-nitrogen ratios function as essential factors which determine substrate compatibility because different species require different C:N ratios for growth according to Desisa et al. (2023). The enzyme activities become more effective through mineral additions which include calcium and magnesium and phosphorus while growth stimulants help speed up mycelial colonization and fruit set (Fadugba et al., 2025). The recent literature emphasizes the fact that nutrient balancing can have a considerable impact on increasing biological performance and the quality of fruit bodies in numerous edible mushroom species.

Effects on Growth and Yield

The performance of mycelial growth and fruiting initiation and total productivity depends directly on the optimization of substrates. The pre-treated substrates which have received additional nutrients and show accelerated colonization patterns produce more fruiting bodies that generate higher yields (Argaw et al., 2023). The addition of wheat grain to sawdust substrates resulted in a 25-30% higher *Pleurotus ostreatus* production compared to using extravagant substrates (Agba et al., 2021). The size of substrate particles together with their moisture levels determine how well air and water can reach the substrate which affects mycelium development and biological performance (Suwannarach et al., 2022). The production of commercial mushrooms now focuses on maximizing substrate efficiency because this approach delivers sustainable and cost-effective results with superior product quality. The process of substrate optimization requires a step-by-step approach which starts with choosing raw materials and their preparation before adding supplements and introducing microorganisms. The physical and chemical and biological elements in the process work together to determine how well the substrate supports cultivation and its overall quality (Figure 1).

Figure 1. Flowchart of substrate preparation and optimization process

Controlled Environment Technologies

Mushroom production has experienced a complete transformation because controlled-environment technologies enable growers to precisely control growth conditions which remain unaffected by outside environmental changes. The systems function to improve mycelial growth quality which results in better primordia development and fruiting body formation which leads to stable production and enhanced product quality and better biosecurity. The success of controlled agriculture depends on three critical elements which include automation-driven control mechanisms and specialized cultivation infrastructures and environmental factor management systems. The controlled-environment mushroom cultivation system has been schematically depicted to show how temperature control and humidity management and airflow systems and CO_2 tracking and lighting work together to create a stable environment which promotes both uniform growth and decreases contamination risk (Figure 2).

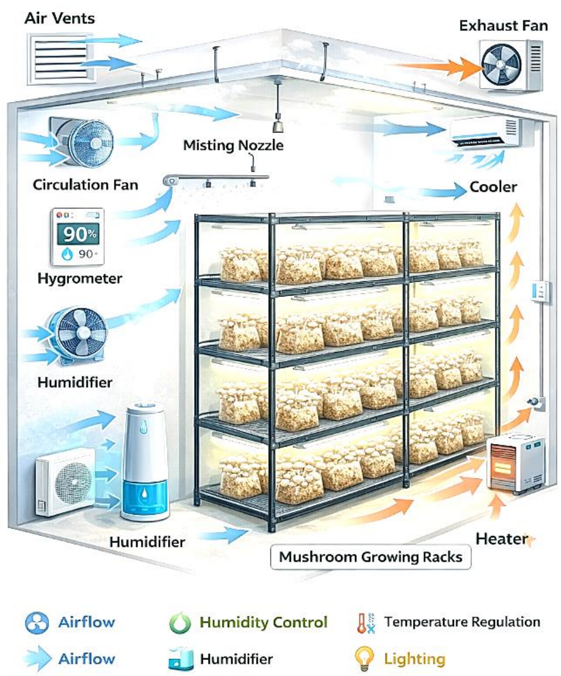

Figure 2: Controlled-environment for Mushroom Cultivation System

Environmental Parameters

Environmental conditions including temperature and relative humidity and light exposure and carbon dioxide levels determine how mushrooms develop and grow. The majority of cultivated mushroom species require specific temperature ranges for mycelial colonization and fruiting according to Kavaliauskas et al. (2022). The development of primordia requires 85–95% relative humidity to prevent fruit body desiccation while too much moisture leads to microbial contamination (Irwanto et al., 2024). The growth of caps and stems becomes more extensive when carbon dioxide levels increase in the environment which results in longer stems but produces inferior marketable quality. The light intensity and photoperiod control the production of secondary metabolites and pigmentation and photo morphogenesis in Lentinula and Pleurotus species according to Chen et al. (2022). The production of high-quality mushrooms requires exact control of these specific criteria to achieve constant high-quality mushroom production (Gundoshmian et al., 2022).

Climate-Controlled Cultivation

Climate-controlled culture systems which include greenhouses and growth chambers and indoor vertical farms maintain perfect environmental conditions throughout the entire development period. Greenhouses which require minimal infrastructure expenses enable large-scale production through their semi-controlled climate that includes heating and cooling systems and ventilation and humidification systems (Barauskas et al., 2022). The controlled-environment of growth chambers makes them suitable for research purposes and high-value mushroom species because they provide complete containment. The combination of multitier growing methods with indoor vertical farming systems enables producers to achieve maximum space utilization while maintaining uniform environmental conditions between different production levels (Zhang et al., 2025).

Automation and Smart Systems

The mushroom cultivation industry now uses automated systems which combine smart technology to enhance operational precision while reducing workforce expenses. The system tracks temperature and humidity and CO2 and substrate moisture levels through sensors which enable remote monitoring and real-time data acquisition when using an IoT enabled device. The system uses feedback-controlled systems to automatically control misting and ventilation and heating/cooling based on sensor feedback which maintains growth conditions at their optimal levels. Artificial intelligence and machine learning enable predictive modeling of growth patterns and yield optimization which helps growers maximize their production through better decision-making. The implementation of controlled-environment technologies provides multiple benefits which include maintaining consistent yields and producing high-quality fruits with minimal contamination risk. The production systems operate throughout the year because they protect against adverse weather conditions (Badoni et al., 2025). The system uses automated controls to perform environment adjustments which become necessary when the system detects any deviations or when the growth reaches its optimal point and marketable yields reach their maximum (Zhang et al., 2025). The mushroom industry operates under controlled-environments which serve as sites for scientific research into new fungal strains and substrate development and cultivation method optimization (Hu et al., 2025).

Yield Improvement Strategies

The production of mushrooms requires an integrated system which unites genetic potential with growing techniques and environmental management practices for maximum yield potential. The efficiency of agronomic techniques and stress tolerance and nutrient availability responses depend on strain selection and genetic improvement progress which determines total production levels. The effectiveness of bio-stimulants and growth promoting chemicals depends on substrate composition and nutrient dynamics so their application requires substrate optimization (Dey et al., 2024).

Genetic and Strain Improvement

The selection of high-yielding strains together with their development serves as a method to enhance total production levels. The main objective of breeding programs involves selecting mushrooms which produce fruit bodies quickly and remain disease-free while their mycelium grows efficiently through different growing materials (Nakazawa et al., 2024). The identification of superior strains and hybrids in *Agaricus Lentinula* species and *Pleurotus* now uses molecular techniques which include marker-assisted selection and genomic analysis. The genetic improvement and selective breeding of mushroom strains enable faster fruiting cycles and more efficient nutrient uptake by enhancing their responsiveness to optimized spawn rates, casing materials and controlled-environment conditions. The development of improved genetic traits related to disease resistance and environmental tolerance increases crop reliability in large-scale production systems and works in synergy with stress management strategies.

Agronomic Practices

The production of mushrooms requires specific agronomic techniques which need to be optimized to achieve maximum yield. The process of substrate colonization depends on the method used for inoculation between liquid culture and grain spawn (Dou et al., 2025) while Substrate density maintains rapid mycelial growth and avoids nutrient depletion (Badoni et al., 2025). The use of casing layers becomes essential for Agaricus species because these layers defend the fruit bodies while simultaneously promoting primordia development (Hu et al., 2021). The effectiveness of agricultural practices depends on specific traits which exist in different plant strains because these traits need appropriate cultivation techniques to reach their full potential. The strains which colonize quickly and produce high biological yields achieve their best results through optimized spawn rates and cropping cycles which demonstrate why genetic enhancement should be integrated with farming practices instead of being handled independently.

Stress management

The mushroom crop faces multiple types of stress which include pest infestations and contaminations and diseases that result in decreased total production. The prevention of these contaminants requires substrate sterilization and maintenance of clean facilities and controlled-environment conditions (Itrat et al., 2025). Biotic stresses e.g. insects can be mitigated through integrated pest management strategies as described by Hu et al. (2025) and this monitoring and management eventually increase the yield.

Bio-stimulants and Growth Promoters

The use of growth promoters and bio-stimulants enables people to produce more mushrooms while achieving better mushroom quality. The process of mycelial colonization becomes faster because enzymes such as ligninases and cellulases break down the substrate (Zhang et al., 2025). The development of fruiting bodies and stress resistance in mushrooms becomes better when they receive beneficial microbes and growth hormones and plant-based stimulants including *Bacillus* species and *Trichoderma*. The use of biostimulants in substrate and environmental management systems represents a sustainable approach to boost productivity while maintaining product quality and reducing chemical application (Hu et al., 2021). The effectiveness of bio-stimulants and growth promoters depends on two essential factors which include substrate composition and available nutrient levels. The beneficial microorganisms in the system work with substrate microorganisms to enhance mycelial health and stress tolerance. The enzyme-based additions help break down substrates and make nutrients accessible when used with suitable substrates. The connection shows that bio-stimulants function as an additional tool which enhances substrate optimization methods for yield improvement. The main elements which affect mushroom production have been combined into Figure 3 to show their mutual relationships between genetic potential and Agronomic Practices and environmental control and stress management and bio stimulant application. The various controlled-environment cultivation systems present different levels of environmental precision and scalability and energy consumption and yield production which requires producers to choose systems based on their production size and financial resources and plant species needs (Table 2).

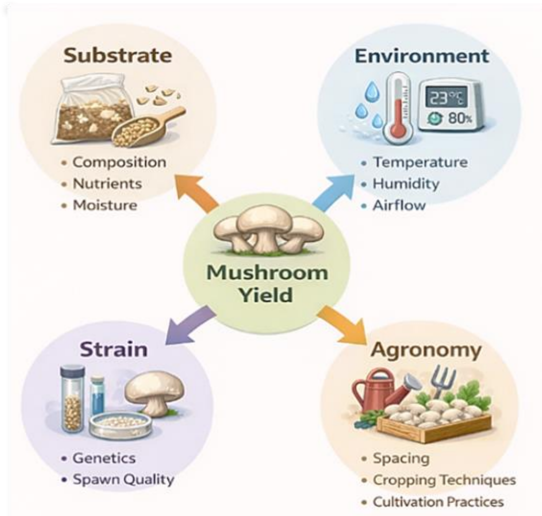

Figure 3: Factors influencing mushroom yield.

additional barriers because farmers lack proper technical knowledge and training opportunities (Zhang et al., 2025). The effectiveness of modern farming technologies becomes less important because most farmers do not understand how to control diseases or manage environmental conditions or create proper growing substrates. The knowledge gap requires extension services and capacity building programs and technology transfer initiatives to become more powerful (Chahal et al., 2024). The regulated environment fails to stop contamination and disease outbreaks from occurring. The violation of hygienic practices allows competing fungus, bacteria and pests to multiply at high density production systems. The future of research needs to focus on developing better biosecurity methods and fast diagnostic systems and biological control methods to reduce dependence on chemical treatments. The continuous technical challenges emerge from manufacturing output expansion efforts which simultaneously protect environmental stability and maintain product quality according to Zou et al. (2025). The durability and sustainable growth and broad market acceptance of advanced mushroom cultivation systems depends on solving the current technological and socioeconomic challenges.

Table 2: Comparison of Controlled-environment Cultivation Setups and their Effects on Mushroom Yield and Production Characteristics.

Environment Setup	Parameters Controlled	Advantages	Limitations	References
Greenhouse	Temperature, Light	Easy setup, year-round cultivation	Moderate control over CO_2, energy dependent	Suwannarach et al., 2022
Growth Chamber	Temperature, Humidity, Light	Full control, high yield, research-friendly	High cost, space-limited	Jarial et al., 2024
Vertical Indoor Farm	Temperature, Humidity, Light, Airflow	Maximizes space, precise control, scalable	High capital investment, technical expertise required	Zhang et al., 2025
Semi-controlled Room	Temperature, Humidity	Lower energy costs, simple design	Limited control over CO_2 and light, seasonal yield variations	Carrasco et al., 2021

Challenges and Limitations

Modern mushroom farming methods face multiple barriers which stop their widespread adoption and large-scale implementation despite having achieved major technological progress. The main socioeconomic challenge for climate-controlled infrastructure and automated monitoring systems with intelligent capabilities stems from their expensive initial setup costs (Gao et al., 2023). The expenses for small and medium sized companies operating in developing nations become too costly because they need to pay for energy and maintenance services. The solution to this problem requires two essential elements which include affordable modular technology development and policy-based financial assistance through subsidies and cooperative models and public private partnerships (Hu et al., 2025). The implementation of modern farming techniques faces

Conclusion

The review studied mushroom cultivation methods by optimizing substrates and using controlled environments and it combined different methods to enhance total yield. The review shows how these elements work together to affect productivity and resource efficiency and sustainability in contemporary mushroom farming systems instead of analyzing them separately. The research findings show that sustainable farming requires two vital components which are enhanced lignocellulosic materials and substrate optimization from agricultural waste products. The research findings show that these materials help achieve higher biological performance through waste transformation and circular economy-based approaches. The success of these substrates depends on three critical elements which include correct pre-treatment procedures and addition methods and their compatibility with particular mushroom varieties. The development of controlled-environment technologies has progressed through automated systems and climate-controlled facilities and sensor-based monitoring systems which reduce contamination risks while maintaining stable production and allowing continuous cultivation under various environmental conditions. The best productivity gains emerge when genetic potential equals substrate quality and environmental control systems operate correctly. The implementation of genetic improvement together with precision Agronomic Practices and biologically based stimulants results in enhanced yield performance according to yield enhancement initiatives. Research in the future needs to focus on creating intelligent farming systems which integrate artificial intelligence with real-time diagnostic capabilities and decision-making tools at various price points for multiple production scales and geographic locations. The research should concentrate on three critical domains which involve making affordable substrate solutions and biological disease management techniques and developing new strains which perform optimally with alternative cultivation materials and changing environmental settings. The use of modern mushroom cultivation techniques enables the production of protein through efficient methods which need minimal land space to create large amounts of waste that impact global food security and sustainable agricultural practices. Mushroom farming will gain importance for sustainable food production systems which will achieve climate resilience through research collaboration between different fields and expert knowledge sharing.

Future Prospects and Innovation of Mushroom

Mushroom farming will undergo changes in its future because new technological advancements will create more precise operations while protecting the environment and boosting production levels. Smart farming strategies that use sensor networks and Internet of Things platforms and artificial intelligence-based decision support systems will serve as essential tools to reach environmental management targets and estimate crop production and minimize operational mistakes. AI driven models use cultivation data to optimize temperature and humidity and CO2 and watering schedules through their analysis of both past and present cultivation information. The system enables production and quality prediction through its control functions which minimize resource consumption. The development of new sustainable substrates through waste to value techniques represents an exciting area of innovation. Agricultural residues and food industry wastes and spent mushroom substrates undergo pre-treatment and microbial enrichment and supplement addition to enhance biological efficiency and nutrient availability. The conversion of organic waste into food products and bioactive compounds through these methods enables both cost reduction in production and implementation of circular economy systems. The production of mushrooms at industrial levels for year-round operations with high quality results will become possible through advancements in automation systems and vertical farming technology and modular climate-controlled facilities. The combination of genetic enhancement with precision cultivation technologies enables mushroom production to achieve better nutritional and functional qualities which expands their uses in pharmaceuticals and functional food and nutraceutical markets. The complete set of developments proves that mushroom farming serves as a perfect example for modern sustainable agricultural practices which use advanced technology.

DECLARATIONS

AI Usage Declaration

In line with COPE guidelines, AI-assisted tools were used only for language editing and formatting and did not contribute to scientific content, data, analysis, or conclusions. All responsibility for the manuscript rests with the authors.

Author's Contributions

Muhammad Awais Fareed and Memoona Imdad: Writing of the original draft and preparation of figures. Muhammad Asif Shabbir: Conceptualization and finalization of the review. Saleha Sattar, Humera Aslam, Awais Mutti, Summia Iqbal, Rabbia Nasir, Hafiz Muhammad Talha Waleed, Umair Anwar, Komal Ambreen and Iram Bilqees: Resources, project administration, collecting literature, visualization, validation, writing and editing. All authors have read and approved the final version of the manuscript.

Conflict of Interest Statement

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

Data sharing does not apply to this article as no new data were created or analyzed in this study.

Acknowledgement

The authors thanks Dr. Yasir Iftikhar Department of Plant Pathology, College of Agriculture, University of Sargodha, Sargodha, Pakistan for guidance to publish this review.

Funding

Not applicable.

Ethical Statement

This article contains no studies regarding humans or animals.

Code Availability

Not applicable.

Consent To Participate

All authors participated in this research study.

REFERENCES:

Agba, M. O., Markson, A. A., Oni, J. O., & Bassey, G. A. (2021). Growth and yield impact of oyster mushroom *Pleurotus ostreatus* (Jacq.) P. Kumm. cultivated on different agricultural wastes. *Journal of Bioscience and Agriculture Research*, *27*(1), 2225–2233. https://doi.org/10.18801/jbar.270121.271

Argaw, B., Tesfay, T., Godifey, T., & Asres, N. (2023). Growth and yield performance of oyster mushroom (*Pleurotus ostreatus* (Jacq.: Fr.) Kummer) using waste leaves and sawdust. *International Journal of Agronomy*, *2023*, Article 8013491. https://doi.org/10.1155/2023/8013491

Badoni, P., & Siddiqui, S. A. (2025). Metamorphosis of mushroom production from tradition to automation. *Discover Applied Sciences*, *7*, Article 974. https://doi.org/10.1007/s44172-025-00974-3

Barauskas, R., Kriščiūnas, A., Čalnerytė, D., Pilipavičius, P., Fyleris, T., Daniulaitis, V., & Mikalauskis, R. (2022). Approach of AI-based automatic climate control in white button mushroom growing hall. *Agriculture*, *12*(11), Article 1921. https://doi.org/10.3390/agriculture12111921

Barua, B. S., Nigaki, A., & Kataoka, R. (2024). A new recycling method through mushroom cultivation using food waste: Optimization of mushroom bed medium using food waste and agricultural use of spent mushroom substrates. *Recycling*, *9*(4), Article 58. https://doi.org/10.3390/recycling9040058

Carrasco, J., Zied, D. C., Navarro, M. J., Gea, F. J., & Pardo-Giménez, A. (2021). Commercial cultivation techniques of mushrooms. In D. C. Zied & A. Pardo-Giménez (Eds.), *Advances in macrofungi* (pp. 11–40). CRC Press. https://doi.org/10.1201/9781003031687-2

Chahal, S., Sindhu, A., Singh, A., & Sindhu, S. C. (2024). Exploring extraction techniques for medicinal mushroom bioactive compounds: A comprehensive review of advantages and limitations. *The Pharma Innovation Journal*, *13*(2), 272–280.

Chen, L., Qian, L., Zhang, X., Li, J., Zhang, Z., & Chen, X. (2022). Research progress on indoor environment of mushroom factory. *International Journal of Agricultural and Biological Engineering*, *15*(1), 25–32. https://doi.org/10.25165/j.ijabe.20221501.6985

Desisa, B., Muleta, D., Dejene, T., Jida, M., Goshu, A., & Martín-Pinto, P. (2023). Substrate optimization for shiitake (*Lentinula edodes* (Berk.) Pegler) mushroom production in Ethiopia. *Journal of Fungi*, *9*(8), Article 811. https://doi.org/10.3390/jof9080811

Dey, B., Ador, M. A. H., Haque, M. M. U., Ferdous, J., Halim, M. A., Uddin, M. B., & Ahmed, R. (2024). Strategic insights for sustainable growth of mushroom farming industry in Bangladesh. *Heliyon*, *10*(17), Article e33578. https://doi.org/10.1016/j.heliyon.2024.e33578

Dou, T., Zhang, K., Shi, X., Liu, W., Yu, F., & Liu, D. (2025). Crop–mushroom rotation: A comprehensive review of its multifaceted impacts on soil quality, agricultural sustainability, and ecosystem health. *Agronomy*, *15*(3), Article 563. https://doi.org/10.3390/agronomy15030563

Fadugba, S. E., Jeeva, N., Fadugba, A. E., & Faweya, O. (2025). Mathematical modeling for the analysis and optimization of nutrient dynamics in edible mushrooms. *European Journal of Pure and Applied Mathematics*, *18*(4), 7190–7199.

Gao, Y., Wu, Z., Li, W., Sun, H., Chai, Y., Li, T., & Qin, P. (2023). Expanding the valorization of waste mushroom substrates in agricultural production. *Environmental Science and Pollution Research*, *30*(2), 2355–2373. https://doi.org/10.1007/s11356-022-22853-6

Gundoshmian, T. M., Ardabili, S., Csaba, M., & Mosavi, A. (2022). Modeling and optimization of oyster mushroom growth using artificial neural networks. *Mathematical Biosciences and Engineering*, *19*(10), 9749–9768. https://doi.org/10.3934/mbe.2022454

Hirai, M. M. (2025). *Cultivo de cogumelo Pleurotus ostreatus em resíduos da cultura de urucum* (Master's thesis). Universidade Federal do Espírito Santo, Brazil.

Hu, W., Gou, L., Hu, L., Wang, S., Liang, T., & Zhou, N. (2025). Effect of acid modification of biochar derived from spent mushroom substrate on oyster mushroom production. *Scientific Reports*, *15*, Article 30955. https://doi.org/10.1038/s41598-025-30955-4

Hu, Y., Mortimer, P. E., Hyde, K. D., Kakumyan, P., & Thongklang, N. (2021). Mushroom cultivation for soil amendment and bioremediation. *Circular Agricultural Systems*, *1*(1), 1–14. https://doi.org/10.1017/S2633903X21000042

Irwanto, F., Hasan, U., Lays, E. S., De La Croix, N. J., Mukanyiligira, D., Sibomana, L., & Ahmad, T. (2024). IoT and fuzzy logic integration for improved substrate environment management in mushroom cultivation. *Smart Agricultural Technology*, *7*, Article 100427. https://doi.org/10.1016/j.atech.2023.100427

Itrat, N., Hasanath, S. A. F., & Ali, A. (2025). Mushrooms as natural antioxidants. In *Mushroom bioactives: Bridging* *food, biotechnology, and nanotechnology for health and innovation* (pp. 45–67). Elsevier.

Jarial, R. S., Jarial, K., & Bhatia, J. N. (2024). Comprehensive review on oyster mushroom species. *Heliyon*, *10*(5), Article e27149. https://doi.org/10.1016/j.heliyon.2024.e27149

Kavaliauskas, Ž., Šajev, I., Gecevičius, G., & Čapas, V. (2022). Intelligent control of mushroom growing conditions. *Applied Sciences*, *12*(24), Article 13040. https://doi.org/10.3390/app122413040

Nakazawa, T., Kawauchi, M., Otsuka, Y., Han, J., Koshi, D., Schiphof, K., & Honda, Y. (2024). *Pleurotus ostreatus* as a model mushroom. *Applied Microbiology and Biotechnology*, *108*(1), 217–232. https://doi.org/10.1007/s00253-023-12866-7

Ravindran, S., Ramlan, N. H., Shah, A. S. M., Yudin, A. S. M., Rahman, R. A., & Faudzi, A. A. M. (2025). Enhancing mushroom cultivation through IoT-based monitoring. In *Proceedings of the IEEE 8th International Conference on Electrical, Control and Computer Engineering* (pp. 326–331). IEEE. https://doi.org/10.1109/InECCE60024.2025.10512345

Suwannarach, N., Kumla, J., Zhao, Y., & Kakumyan, P. (2022). Impact of cultivation substrate and microbial community on improving mushroom productivity. *Biology*, *11*(4), Article 569. https://doi.org/10.3390/biology11040569

Zou, G., Li, T., Mijakovic, I., & Wei, Y. (2024). Synthetic biology enables mushrooms to meet emerging sustainable challenges. *Frontiers in Microbiology*, *15*, Article 1337398. https://doi.org/10.3389/fmicb.2024.1337398