Smart Circular Bioeconomy in Medicinal Mushroom Cultivation: AI-Assisted Valorization of Agro-Waste into Nutraceutical Wealth

Aishwarya Mishra, Dr. Ajay Kumar

*Professor, Department of Biotechnology, Faculty of Engineering and Technology, Rama University, Mandhana, Kanpur-209217 Corresponding Author: drajay.fet@ramauniversity.ac.in

Abstract

The large amount of agricultural waste generated every year and the increasing interest in natural health-supporting products have led researchers to focus more on mushroom biotechnology. Mushrooms are capable of growing on different agricultural residues such as straw, sawdust, and other lignocellulosic materials that are often treated as waste. During their growth, these materials are converted into valuable fungal biomass containing important nutrients and several beneficial bioactive compounds. Because of this ability, mushroom cultivation is now being considered an effective and sustainable way to recycle agricultural by-products while also producing useful food and nutraceutical products

This review focuses on the growing importance of mushrooms in sustainable agricultural and bioeconomy systems, especially in relation to the utilization of agricultural waste, production of nutraceutical compounds, and the use of modern cultivation technologies. Various agricultural residues such as wheat straw, rice straw, sawdust, sugarcane bagasse, corn cobs, tea waste, and brewery waste have been studied as low-cost and eco-friendly substrates for cultivating mushrooms including oyster mushroom, shiitake, reishi, lion's mane, and cordyceps. These substrates not only support mushroom growth but also help in recycling agricultural by-products that would otherwise contribute to environmental pollution.

The review also discusses different bioactive compounds naturally present in mushrooms, including polysaccharides, beta-glucans, terpenoids, phenolic compounds, ergothioneine, and antioxidants, which are associated with several nutritional and health-related benefits. Along with traditional cultivation practices, recent developments in smart mushroom farming are also gaining attention. Technologies such as automated environmental monitoring, sensor-based cultivation systems, disease prediction models, image-based contamination detection, and AI-supported yield management are gradually improving cultivation efficiency and consistency

The combined use of mushroom biotechnology, sustainable waste recycling, and intelligent cultivation approaches may play an important role in the future of climate-resilient agriculture and functional food production. At the same time, there are still several areas that require further research, particularly in large-scale commercialization, standardization of cultivation systems, and integration of advanced digital technologies into mushroom farming practices.

Keywords

Medicinal mushrooms; Circular bioeconomy; Agro-waste utilization; Smart mushroom cultivation; Artificial intelligence; Nutraceuticals; Mushroom biotechnology; Sustainable agriculture; Functional foods; Precision farming; Mycelium technology; Bioactive compounds

1. Introduction

Agricultural activities generate enormous amounts of organic residues every year. Crop wastes such as rice straw, wheat straw, corn stalks, sugarcane bagasse, sawdust, and fruit processing residues are often treated as unwanted materials despite containing large amounts of biodegradable organic matter. In many regions, these residues are burned openly or disposed of improperly, resulting in environmental pollution, soil degradation, and release of greenhouse gases into the atmosphere. As concerns regarding sustainability and climate change continue to increase, researchers are now focusing on biological approaches that can convert agricultural waste into economically useful products.Among various microorganisms explored for biomass conversion, mushrooms have attracted considerable scientific and commercial attention because of their exceptional lignocellulose-degrading ability. Mushrooms possess extracellular enzymes capable of breaking down complex plant polymers such as cellulose, hemicellulose, and lignin into simpler compounds that support fungal growth. This natural biodegradation ability allows mushrooms to grow efficiently on agricultural residues that are otherwise difficult to decompose. During the past few years, medicinal mushrooms have become especially important because of their nutritional and therapeutic potential. Species such as oyster mushroom, reishi, shiitake, lion's mane, and cordyceps are now widely studied for their health-promoting properties. Various scientific investigations have shown that these mushrooms contain bioactive compounds with antioxidant, antimicrobial, anticancer, immunomodulatory, anti-inflammatory, and neuroprotective activities. Consequently, medicinal mushrooms are no longer viewed only as edible fungi but are increasingly considered valuable components of future nutraceutical and pharmaceutical industries. At the same time, the concept of circular bioeconomy has emerged as a sustainable framework for utilizing biological resources more efficiently. Instead of following the traditional "use and discard" model, circular bioeconomy promotes recycling, reuse, and continuous valorization of biomass resources. Mushroom cultivation fits remarkably well within this system because agro-industrial wastes can be converted into high-value mushroom biomass while the spent substrate generated after harvesting can further be reused for composting, vermiculture, soil conditioning, or bioenergy production. Another interesting development influencing mushroom cultivation is the advancement of smart farming technologies. Traditional mushroom farming largely depends on manual environmental management, where fluctuations in temperature, humidity, ventilation, or contamination can significantly affect production. Recent progress in artificial intelligence, Internet of Things (IoT), automated sensors, and machine learning systems has introduced precision-based mushroom farming approaches capable of improving productivity and resource efficiency.The present review therefore attempts to discuss the relationship between medicinal mushroom cultivation, agro-waste valorization, circular bioeconomy, and emerging smart technologies. Particular emphasis has been given to sustainable substrate utilization, medicinal properties of mushrooms, and future opportunities associated with AI-assisted cultivation systems.

2. Circular Bioeconomy and the Role of Mushroom Biotechnology

The growing demand for sustainable production systems has increased global interest in circular bioeconomy approaches. Unlike conventional linear economic systems where resources are extracted, consumed, and discarded, circular bioeconomy focuses on the continuous utilization and regeneration of biological resources. The primary objective is to minimize waste generation while maximizing the value obtained from biomass materials.

Mushroom cultivation is considered one of the most practical examples of circular bioeconomy because fungi can efficiently convert agricultural and agro-industrial residues into edible biomass and useful by-products. Crop residues that are usually treated as waste become valuable substrates for fungal growth. Through enzymatic degradation, mushrooms transform these lignocellulosic materials into protein-rich food products and medicinal metabolites.The environmental importance of this process is particularly significant in agricultural countries where stubble burning and improper biomass disposal contribute heavily to air pollution. Utilizing crop residues for mushroom cultivation provides an environmentally safer alternative while simultaneously generating economic benefits for farmers and small-scale industries.

Another important aspect of mushroom-based circular systems is the utilization of spent mushroom substrate (SMS). Even after harvesting, the residual substrate still contains organic nutrients and partially degraded biomass. Researchers have explored the use of SMS as organic manure, animal feed supplement, biofertilizer, vermicompost substrate, and raw material for biogas production. Such multi-stage utilization improves overall sustainability and reduces waste generation.

Interestingly, recent studies have suggested that mushroom biotechnology may also contribute to climate-smart agriculture because mushrooms require comparatively lower land area and water resources than many traditional protein-producing systems. In addition, fungal proteins and mycelium-based food products are increasingly being considered sustainable alternatives to animal-derived proteins.

3. Agro-Waste Utilization in Medicinal Mushroom Cultivation

The selection of an appropriate substrate is one of the most important factors influencing mushroom growth, biological efficiency, and bioactive compound production. Agricultural residues are widely preferred as substrates because they are inexpensive, easily available, and rich in lignocellulosic components required for fungal metabolism.

Wheat straw is among the most commonly used substrates for oyster mushroom cultivation because it supports rapid mycelial colonization and good fruiting body development. Rice straw has also shown excellent potential, especially in Asian countries where large quantities are produced annually. Similarly, sugarcane bagasse generated from sugar industries provides suitable fiber content and moisture retention properties for fungal growth.

Sawdust is extensively utilized for cultivating woody medicinal mushrooms such as shiitake and reishi because these fungi naturally prefer lignin-rich substrates. Corn cobs, cotton waste, tea residues, banana leaves, coffee pulp, coconut coir, and brewery wastes have also demonstrated promising applications in mushroom farming.

Several researchers have reported that combining different agro-wastes can improve substrate quality and mushroom productivity. Supplementation with wheat bran, rice bran, soybean meal, or mineral additives may further enhance nutritional composition and yield performance. However, substrate composition can also influence the concentration of medicinal metabolites produced by mushrooms.

Recent developments in smart agriculture have introduced AI-assisted substrate optimization systems where machine learning models analyze substrate composition, moisture levels, pH, temperature, and fungal growth characteristics to predict cultivation performance. Such technologies may help improve production efficiency and reduce crop losses in commercial mushroom farming systems.

The conversion of agricultural waste into medicinal mushroom biomass therefore represents a sustainable “waste-to-value” strategy capable of generating economic, nutritional, and environmental benefits simultaneously.

4. Medicinal Importance and Bioactive Compounds of Mushrooms

Medicinal mushrooms are rich sources of biologically active compounds with diverse therapeutic properties. The increasing demand for natural health-promoting products has significantly expanded research interest in mushroom-derived nutraceuticals during the last decade.

Polysaccharides, particularly beta-glucans, are among the most extensively studied compounds present in medicinal mushrooms. These molecules are known to modulate immune responses by stimulating macrophages, natural killer cells, and cytokine production. Various studies have associated mushroom beta-glucans with improved immunity and potential anticancer activities.

Reishi mushroom contains triterpenoids and ganoderic acids that exhibit antioxidant, hepatoprotective, anti-inflammatory, and antitumor properties. Lion’s mane mushroom has attracted attention because of compounds such as hericenones and erinacines that may support nerve regeneration and cognitive function. Similarly, cordyceps species are widely studied for

their adaptogenic properties and possible roles in improving energy metabolism and reducing fatigue.Mushrooms are also rich in phenolic compounds, flavonoids, vitamins, minerals, dietary fibers, and ergothioneine, a sulfur-containing antioxidant associated with cellular protection against oxidative stress. Because of these compounds, medicinal mushrooms are increasingly being incorporated into functional foods, dietary supplements, herbal beverages, and nutraceutical formulations.Although significant progress has been made in identifying mushroom bioactive compounds, further studies are still needed to understand their bioavailability, molecular mechanisms, clinical effectiveness, and long-term therapeutic applications.

5. Artificial Intelligence and Smart Mushroom Farming

Modern mushroom cultivation is gradually shifting toward precision farming systems supported by artificial intelligence and digital technologies. Traditional mushroom farming requires careful monitoring of environmental conditions because even small changes in temperature, humidity, carbon dioxide concentration, or ventilation can influence mycelial growth and fruiting body formation.

IoT-based environmental sensors are now being used to monitor cultivation chambers continuously and provide real-time data regarding humidity, substrate moisture, temperature, and gas concentration. These systems help farmers maintain stable environmental conditions and reduce manual errors.

Machine learning algorithms are also being explored for predicting mushroom yield, identifying contamination risks, and optimizing harvesting schedules. Image-processing technologies can detect fungal diseases, bacterial infections, and abnormal growth patterns before they become severe enough to affect productivity.

Another promising area is automated climate control systems that regulate ventilation, irrigation, and humidification according to fungal growth requirements. Such technologies not only improve production efficiency but also reduce energy and water consumption.

Although AI-assisted mushroom cultivation is still developing, especially in developing countries, its future potential appears highly promising. Smart cultivation systems may become particularly important for medicinal mushroom production where environmental precision directly affects the concentration of bioactive compounds.

6. Future Prospects

The future scope of mushroom biotechnology extends beyond food production alone. Mycelium-based materials are increasingly being explored as eco-friendly alternatives to plastics, leather, packaging materials, and construction products. Fungal biomaterials are biodegradable, lightweight, and renewable, making them attractive for sustainable industrial applications.The development of mushroom-derived meat alternatives and mycoprotein products is another rapidly growing field because of increasing interest in sustainable protein sources. Researchers are also exploring the role of medicinal mushrooms in personalized nutrition, gut health management, neuroprotection, and preventive healthcare.

Future advancements may involve integration of artificial intelligence, robotics, genomics, metabolomics, and nanotechnology into mushroom biotechnology systems. Interdisciplinary collaboration between microbiologists, agricultural scientists, food technologists, and AI specialists will therefore be essential for further development of this field.

Conclusion

Medicinal mushroom cultivation represents a sustainable biotechnological approach capable of converting agricultural waste into nutritionally and therapeutically valuable products. Through the principles of circular bioeconomy, agro-residues can be transformed into edible biomass, nutraceutical compounds, and eco-friendly biomaterials while simultaneously reducing environmental pollution and promoting resource efficiency.

The incorporation of artificial intelligence and smart cultivation technologies is further improving precision farming practices and supporting sustainable mushroom production systems. As global interest in functional foods, climate-smart agriculture, and sustainable biotechnology continues to increase, medicinal mushrooms are expected to play an increasingly important role in future food, healthcare, and environmental management systems.

References

Aso-Campos H, Zolla G. The potential of edible and medicinal mushrooms in promoting the circular economy and enhancing food security. Frontiers in Sustainability. 2025;6:1683332.

Dhiman S, Kaur P, Narang J, et al. Fungal bioprocessing for circular bioeconomy: Exploring lignocellulosic waste valorization. Mycology. 2024;15(2):115–129.

Fernandez M, Costa J, Silva P. Mycelium biotechnology for sustainable packaging and biomaterials. Sustainable Materials Research. 2024;9(1):44–58.

Gupta A, Meena R, Tiwari N. Precision farming technologies in medicinal mushroom production systems. Agricultural AI and Biotechnology. 2025;4(2):88–104.

Jacob MS, Xu A, Qian K, et al. Artificial intelligence in edible mushroom cultivation, breeding, and classification: A comprehensive review. Journal of Fungi. 2025;11(11):758.

Károly AI, Galambos P. Synthetic image datasets and mushroom segmentation for precision farming applications. Computational Agriculture. 2025;7(3):201–214.

Leavy S, Allegretti G, Presotto E, et al. Bioeconomy indicators and sustainable biomass utilization systems. Bioeconomy Studies. 2024;12(1):56–72.

Li X, Huang Y, Chen F, et al. IoT and AI-assisted environmental control systems in mushroom farming. Journal of Smart Agriculture. 2025;5(4):144–159.Madusanka C, Udayanga D, Nilmini R, et al. Recent advances in fungal mycelium-based composites and biomaterials. Discover Materials. 2024;4(1):36–49.

Malakar S, Sutaoney P, Singh P, et al. Systems biology approaches in mushroom cultivation for sustainable agriculture. Circular Agricultural Systems. 2025;3(2):91–108.

Roy S, Banerjee D, Mukherjee P. Bioactive compounds of medicinal mushrooms and their nutraceutical potential. Functional Foods and Human Health. 2026;8(1):11–29.

Sharma R, Patel V, Kumar S. Agro-industrial waste utilization for sustainable mushroom cultivation. Environmental Biotechnology Reviews. 2024;10(2):77–93.

Shin HJ, Ro HS, Kawauchi M, et al. Review on mushroom mycelium-based products and their production process. Bioresources and Bioprocessing. 2025;12(1):65–81.

Vishnoi M, Sindhu VL, Pallavi H, et al. Edible and medicinal mushrooms in global food systems and circular bioeconomy: A comprehensive review. Microbiology Research Journal International. 2026;36(1):1–18.

Report provided by the «eAarjav» service
http://ramauniversity.eaarjav.com

Check Report

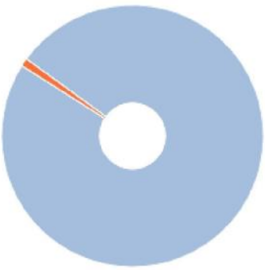
Author: Mr Jitendra Verma

Document: Aishwarya review paper

Checked by: Mr Jitendra Verma

Organization: Rama University

CHECK RESULTS



Matches:
0.63%

Originality:
99.37%

Quotes:
0%

Text recycling:
0%

AI content:
42.88%

Matches, Text Reuse, Text Recycling, and Originality are individual indicators displayed as percentages. Their sum is equal to 100%, which is the entire text of the checked document.

The following reuse hiding methods may have been used: Generated text on pages: 1, 2, 4, 5

- **Matches** — segments in the checked text that are fully or partially similar to identified sources, except for those that the system has classified as text reuse or recycling. The Matches value reflects the share of the checked text segments classified as matches in the overall text volume.
- **Text recycling** — includes segments in the checked text that are identical or nearly identical to a source text fragment whose author or co-author is the author of the document being checked. The Text Recycling value reflects the share of the checked text segments classified as text recycling in the overall text volume.
- **Quotes** — includes segments in the checked text that are not original, but which the system considers correctly formulated. Text reuse also includes boilerplate phrases, bibliographies, and text segments found by the Garant Legal Information System: Regulatory Documents search module. The Text Reuse value reflects the share of the checked text segments classified as text reuse in the overall text volume.
- **Text crossing** — text fragment of a checked document which is identical or almost identical to a fragment of the source text.
- **Source** — document indexed by the system and contained in the search module which is used for the check.
- **Original text** — includes segments in the checked text that are not found in any source or tagged by any of the search modules. The Originality value reflects the share of the checked text segments classified as original text in the overall text volume.

Please note that the system finds overlapping texts in the checked document and text sources indexed by the system. At the same time, the system is an auxiliary tool. Correctness and adequacy of reuse or quotes, as well as authorship of text fragments in the checked document must be determined by the verifier.

DOCUMENT INFORMATION

Document No.: 606

Document type: Thesis

Check start: 29.04.2026 13:31:24

Date of correction: No

Number of pages: 6

Number of characters: 13139

Number of words: 1595

Number of sentences: 78

Comment: not specified