

Mushrooms as a Sustainable Resource: Biocatalysis, Health Benefits and Waste Utilization

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ABSTRACT

Mushrooms have emerged as a versatile resource with applications in biocatalysis, human health, and waste management. This review explores the multifaceted role of mushrooms, highlighting their enzymatic potential in organic synthesis, their prebiotic and medicinal properties, and their contributions to sustainable waste utilization. We provide a comprehensive synthesis of recent advancements in mushroom-based biocatalysis, gut microbiota modulation, therapeutic applications, and the recycling of spent mushroom substrate (SMS). By integrating insights from 30

key research papers, this review underscores the significance of mushrooms in various scientific and industrial domains while identifying future research directions.

Keywords Mushroom, Biocatalyst, Recycling, Microbiota.

INTRODUCTION

Mushrooms, a diverse group of fungi, have gained attention for their ecological, nutritional, and pharmaceutical significance. They function as biocatalysts in organic synthesis, serve as a prebiotic source for gut health, offer medicinal benefits for neurodegenerative and cancer treatment, and contribute to sustainable agricultural practices through waste recycling (Yang *et al.* 2024, Kulshreshtha 2023). Given the increasing focus on sustainable biotechnological applications, this review aims to consolidate recent research on mushroom biocatalysis, human health benefits, and the utilization of mushroom by products.

Mushrooms have long been utilized in traditional medicine and food culture across various civilizations. However, their scientific exploration has intensified in recent decades due to their enzymatic properties and bioactive compounds (Fonseca *et al.* 2024). The enzymatic processes driven by mushrooms have opened new doors for green chemistry,

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reducing reliance on synthetic catalysts. Additionally, their role in promoting gut microbiota diversity has gained prominence, showing promising implications for human health (Araújo-Rodrigues *et al.* 2024).

Apart from their enzymatic and health-promoting capabilities, mushrooms have become a focal point of sustainability discussions. The mushroom industry generates large quantities of by-products, and their efficient recycling holds potential for achieving zero-waste systems (Luo & Chen 2024). By examining these three critical areas—biocatalysis, health benefits, and waste utilization—this review provides a comprehensive perspective on the growing significance of mushrooms in biotechnology and sustainable development.

Mushroom-mediated biocatalysis

Mushrooms possess unique enzymatic systems that facilitate redox reactions, including oxidation, reduction, and epoxidation, making them valuable biocatalysts in green chemistry (Yang *et al.* 2024). Their ligninolytic enzymes, such as peroxidases and laccases, play a crucial role in breaking down complex organic compounds. Research has demonstrated their effectiveness in the hydroxylation of aromatic compounds and oxidative cleavage of alkenes (Pretzler & Rompel 2024). The potential for mushroom-mediated enzymatic transformations in pharmaceutical and industrial settings remains a promising area for future exploration.

Mushroom-derived enzymes, including cytochrome P450 monooxygenases, have shown remarkable efficiency in modifying organic molecules, providing a sustainable alternative to chemical catalysts (Zhang *et al.* 2021). These enzymes enable regio- and stereoselective transformations, enhancing their value in pharmaceutical production (Fonseca *et al.* 2024). For example, certain *Basidiomycota* species are known to catalyze hydroxylation reactions that are difficult to achieve with traditional synthetic methods (Babot *et al.* 2015).

Moreover, mushrooms have demonstrated the ability to degrade persistent environmental pollutants (Ma *et al.* 2025). Their enzymatic systems can

break down pesticides, dyes, and even microplastics, offering solutions to industrial and environmental challenges. These biodegradation capabilities position mushrooms as an essential tool for ecological sustainability and pollution mitigation (Luo & Chen 2024). Ongoing research is aimed at optimizing mushroom-mediated biocatalytic processes for large-scale industrial applications, with promising results in biopolymer synthesis and pharmaceutical compound development.

Prebiotic and health benefits of mushrooms

Mushrooms are rich in polysaccharides, particularly beta-glucans, which act as prebiotics and modulate gut microbiota (Araújo-Rodrigues *et al.* 2024). Studies indicate that mushroom-derived polysaccharides enhance the growth of beneficial bacteria, improve gut barrier function, and regulate lipid metabolism. Additionally, specific mushroom species, such as *Ganoderma lucidum*, have demonstrated neuroprotective and immunomodulatory effects (Chen *et al.* 2024). Clinical studies suggest that dietary mushroom intake is associated with a reduced risk of cognitive decline and neurodegenerative disorders (Aoki *et al.* 2024).

The mechanism behind the prebiotic benefits of mushrooms lies in their complex polysaccharides, which resist digestion in the upper gastrointestinal tract and reach the colon intact (Araújo-Rodrigues *et al.* 2024). Once there, they serve as substrates for beneficial gut bacteria, promoting the growth of *Bifidobacteria* and *Lactobacillus* species. This shift in microbiota composition has been linked to improved metabolic health, reduced inflammation, and enhanced immune function.

Beyond their gut health advantages, mushrooms exhibit cholesterol-lowering properties. Certain bioactive compounds in mushrooms interfere with cholesterol absorption, leading to improved lipid profiles. Additionally, mushrooms contain antioxidants, such as ergothioneine and polyphenols, which contribute to reduced oxidative stress and inflammation in the body. These compounds have been studied for their potential role in preventing cardiovascular diseases and metabolic disorders (Kulshreshtha 2023).

Recent research also suggests that mushrooms may have adaptogenic properties, helping the body manage stress and enhance cognitive resilience. This aligns with findings that certain mushroom species can modulate the gut-brain axis, potentially alleviating symptoms of anxiety and depression. Further investigations are needed to explore these neurological benefits and validate them through human clinical trials (Chen and Xu 2024).

Medicinal applications of mushrooms

The bioactive compounds in mushrooms, including triterpenoids and polysaccharides, have been explored for their anticancer properties (Yang *et al.* 2024). Mushroom extracts have been shown to enhance chemotherapy efficacy by modulating apoptosis pathways and inhibiting drug resistance mechanisms in cancer cells (Fonseca *et al.* 2024), also promotes beneficial gut microbes, suppresses harmful ones, and protects intestinal barrier function, indicating its strong potential for improving gut health through microbiota modulation (Li *et al.* 2024a).

Moreover, compounds derived from Chaga and Shiitake mushrooms exhibit antimicrobial, anti-inflammatory, and antioxidant properties, further supporting their therapeutic potential (Wang *et al.* 2024). The role of psychedelic mushrooms in mental health treatment has also garnered interest, with studies exploring their effects on neuroplasticity and mood disorders (Shahar *et al.* 2024).

Certain mushrooms have shown promise in enhancing immune system activity. Extract from Chaga mushroom impedes oral cancer cell progression by inhibiting cell cycle and proliferation. The extract is a promising medicine for oral cancer treatment (Yeo *et al.* 2024). Numerous *in vitro* and *in vivo* studies using diverse biological models have explored their immunomodulatory, antioxidant, and gut health benefits, highlighting the need to further understand their mechanisms for future medicinal applications (Sharika *et al.* 2024).

Additionally, research is growing on the neuroprotective effects of mushrooms in Alzheimer's disease (Aoki *et al.* 2024). Bioactive compounds

such as hericenones from *Hericium erinaceus* have demonstrated the ability to promote nerve growth factor (NGF) synthesis, aiding in neuroregeneration and cognitive function improvement (Wang *et al.* 2024). *Meripilus giganteus* is an ecologically important mushroom with diverse bioactive properties, making it promising for bioremediation and biofuel applications (Sulkowska-Ziaja *et al.* 2025). Mushrooms possess bioactive compounds with antioxidant and anti-inflammatory properties, and a review of 34 human studies have also suggested their inclusion in the diet may benefit cognition and mood, in both healthy and at-risk populations (Cha *et al.* 2024).

Sustainable waste utilization: Recycling spent mushroom substrate

The large-scale cultivation of mushrooms generates significant by-products, including spent mushroom substrate (SMS), which poses an environmental challenge. SMS consists mainly of lignocellulosic material, residual fungal biomass, and nutrients, making it a valuable resource if properly managed. Rather than being discarded as waste, SMS can be repurposed in several sustainable applications, including soil enrichment, biofertilizers, animal feed, and biofuel production (Phan and Sabaratnam 2012).

In agriculture, SMS improves soil structure and fertility by enhancing organic matter content and microbial diversity (He *et al.* 2024). Research has shown that incorporating SMS into soil can increase crop yield and improve resistance to plant pathogens (Ma *et al.* 2025). Additionally, SMS serves as an efficient substrate for vermicomposting, supporting the growth of earthworms and producing nutrient-rich compost that benefits plant growth (Aira *et al.* 2002).

Apart from its agricultural applications, SMS has potential uses in bioremediation (Mayans *et al.* 2024) (He *et al.* 2024). Studies have demonstrated its ability to degrade pesticides, and neutralize pollutants in contaminated environments (Zhao *et al.* 2025). These properties make it a promising tool for ecological restoration efforts. In a study SMS was efficiently fibrillated with low energy input, showing antioxidant properties and environmental benefits over chemically treated materials, making it suitable for eco-friendly applications like packaging

(Berglund *et al.* 2024).

Furthermore, SMS is being explored as a renewable energy source. Its high lignocellulosic content makes it suitable for bioethanol and biogas production, contributing to the development of a circular economy (Shu *et al.* 2024). Optimizing SMS utilization through innovative processing techniques could reduce waste accumulation while promoting sustainable energy solutions (Ravlikovsky *et al.* 2024).

Future perspectives and research directions

While mushrooms hold immense potential in biotechnology, medicine, and sustainable agriculture, several research gaps remain. Further studies should focus on optimizing mushroom-derived enzymes for industrial applications, enhancing their stability, and scaling up production processes to meet commercial demands (Pretzler & Rompel 2024). Additionally, advancements in genetic engineering could enable the development of high-yield, high-potency mushroom strains with enhanced enzymatic and bioactive properties (Li *et al.* 2024b). *Cortinarius* mushrooms discovered a new class of polyketide synthase to produce anthraquinone pigments. A previously unknown biosynthetic pathway in mushroom was revealed expanding opportunities for drug discovery and evolutionary biology (Löhr *et al.* 2022). Mushrooms are also reported to generate polyketides found in other diverse organisms like plants, bacteria revealing the connection across various lifeforms (Lohr *et al.* 2024).

From a health perspective, large-scale clinical trials are necessary to validate the therapeutic effects of mushroom-derived compounds. Although preliminary studies have demonstrated promising results in cancer treatment, neurodegenerative diseases, and metabolic disorders, standardized dosages, safety assessments, and long-term effects require further exploration (Fonseca *et al.* 2024). Research on the gut-brain axis and its link to mushroom consumption could also open new avenues for understanding their role in mental health and cognitive function (Aoki *et al.* 2024). Innovations in biofuel production, eco-friendly packaging materials derived from

mycelium, and waste-to-resource strategies could significantly reduce environmental impact while contributing to a circular economy. Moreover, policy initiatives and industry collaborations will be vital in promoting the commercial viability of mushroom-based products and ensuring their accessibility to a broader population (Luo & Chen 2024).

CONCLUSION

Mushrooms serve as a valuable biological resource with applications spanning biocatalysis, health sciences, and environmental sustainability. Their enzymatic capabilities enable green chemistry transformations, their polysaccharides support gut and brain health, and their waste by-products contribute to circular economy models (Yang 2025). Through their medicinal properties, mushrooms have demonstrated promising therapeutic effects against cancer and neurodegenerative diseases (Chen and Xu 2024).

The integration of mushroom-based solutions in biotechnology, medicine, and waste management represents an emerging field with vast potential. However, addressing existing research gaps and enhancing industrial scalability remain critical for broader adoption (Fonseca *et al.* 2024). By investing in interdisciplinary research, technological advancements, and sustainable policies, mushrooms can play a transformative role in creating a healthier and more sustainable future (Ma *et al.* 2025).

Ultimately, the convergence of science, industry, and environmental stewardship will determine the extent to which mushrooms can be harnessed to address contemporary challenges in human health and ecological conservation. As further discoveries unfold, the potential of mushrooms as a sustainable resource will continue to expand, shaping the future of biotechnology and environmental resilience (Luo & Chen 2024).

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