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VALORIZATION OF SPENT MUSHROOM SUBSTRATE FOR SUSTAINABLE AGRICULTURE AND ALLIED SECTORS

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ABSTRACT

The global mushroom industry is expanding rapidly, with production in India reaching approximately 3.51 lakh tonnes by 2024. This increased production generates a substantial quantity of spent mushroom substrate (SMS), a byproduct obtained at 3 to 5 times the amount of mushrooms themselves. If managed unscientifically, SMS poses significant environmental risks, including leaching, foul odors, and greenhouse gas emissions etc. However, SMS is a nutrient-rich lignocellulosic material containing essential minerals, bioactive compounds, and beneficial microflora. In agriculture, it serves as a cost-effective casing material, soil amendment, and organic mulch that suppresses soil-borne pathogens. Its high microbial activity also aids in the degradation of pesticides and petroleum hydrocarbons during bioremediation. Furthermore, SMS shows potential as a palatable animal feed supplement and a feedstock for renewable energy production, including biogas and bioethanol. Despite challenges like compositional variability and high transportation costs, the projected global production of 100 million tonnes by 2026 necessitates standardized processing to transform SMS from a waste product to a crucial resource in a circular economy.
***Keywords* :** spent mushroom, substrate, compost, circular economy, valorization

Introduction

Mushrooms, belonging to the phylum Basidiomycota and class Agaricomycetes, are fleshy fungi which are characterized by a stem, cap and gills. They may be edible or wild, while some species are toxic. It contains more than 90 per cent water and less than 1 per cent fat. Mushrooms are rich in proteins, dietary fiber, vitamin B and minerals like copper and selenium. (Ramamurthi *et al.*, 2015). The global mushroom production is increasing at an average annual rate of 6–7per cent (Abak, 2024). The mushroom cultivation is an ecofriendly activity as it utilizes agricultural wastes especially the crop residues, underutilized wood shavings or saw dust which would otherwise be burned or dumped. The mushroom industry is flourishing day by day and in India and its production has reached 3.51 lakh tonnes by 2023-2024 (Sree *et al.*, 2024). Spent mushroom substrate (SMS) refers to describe the substrate that is left after mushroom cultivation and is the main byproduct of mushroom industry. The quantity of SMS generated is typically 3-5 times higher than the quantity of mushrooms produced. For instance, it is 5 times greater for button mushrooms, 3 times greater for oyster mushrooms, and 3–8 times greater for paddy straw mushrooms (Chamoli *et al.*, 2023). It is reported that approximately 5 kg of SMS is released for each kg of mushrooms produced, regardless of the mushroom species (Jasińska, 2018). By 2026, the mushroom industry is expected to produce more than 100 million tonnes of SMS globally (Atallah *et al.*, 2021). In India, nearly 5 lakh tonnes of discarded mushroom substrate were produced during the year 2022 (Chamoli *et al.*, 2023). However, spent mushroom substrate (SMS), comprising partially degraded paddy or wheat straw, sawdust, and other agricultural residues remaining after mushroom cultivation, may pose environmental concerns, including leaching, foul odor generation, and greenhouse gas emissions, if not properly managed.

Environmental consequences of unmanaged SMS

The substantial volume of SMS, coupled with its environmental pollution risks, poses significant challenges to mushroom growers. Due to its bulky nature, low density, and high water content, it is extremely challenging to transport huge quantities of SMS to the disposal sites. The unscientific disposal or dumping of SMS can lead to:

1. **Environmental pollution:** Leaching of harmful chemicals into soil and water sources can lead to contamination, while the accumulation of SMS in large piles results in foul odors.
2. **Greenhouse Gas Emissions:** Decomposing organic matter in landfills produces methane, a potent greenhouse gas contributing to climate change.
3. **Water Pollution:** Dumping SMS near water sources can contaminate groundwater and surface water, posing risks to human health, aquatic life, and eutrophication. The runoff from such heaps contaminates adjacent water sources, leading to water pollution (Beyer, 1996)
4. **Pathogen and Pest Risks:** SMS can harbor pathogens and pests, which can spread to other crops or areas if not managed properly. Besides, these heaps act as a breeding site for mosquitoes and rats, leading to outbreaks of diseases (Martin *et al.*, 2023).

In recent years, mushroom growers are facing increasing pressure from environmental regulations, necessitating the development of sustainable approaches for managing SMS. Hence, it is imperative to develop sustainable solutions for the safe disposal of SMS at the source itself as centralized disposal of SMS is costly and time consuming.

Characteristics of SMS

Spent mushroom substrate (SMS) is a lignocellulosic by-product characterized by a brown to straw-like color. It typically exhibits a pH ranging from 6.0 to 8.0, organic matter content of 40–60%, and moisture levels between 30–65% (Medina *et al.*, 2009). It contains a variety of components including proteins, organic acids, polysaccharides, essential plant nutrients such as Fe, Zn, Mn, Cu, and Mg, as well as beneficial elements like selenium and other bioactive compounds. SMS also contains gypsum powder, or lime which effectively regulates pH (Ma *et al.*, 2021)Due to its porous structure and large surface area, SMS has a strong capacity to adsorb heavy metals from aqueous environments, making it a promising material for pollution mitigation (Chang *et al*., 2022). It is also rich in carbon (typically ≥50%) and contains significant levels of plant nutrients. The raw materials commonly used in mushroom substrates such as sawdust, rice straw, and wheat straw generally consist of 40-55per cent cellulose, 20-40 per cent hemicellulose, and 10-30 per cent lignin (Jayakumar *et al.,* 2023). On the other hand, SMS typically contains 20-30 per cent cellulose, 20- 30 per cent hemicellulose, and 10- 20 per cent lignin.

Utilization of spent mushroom substrate

SMS has gained considerable attention as a valuable by - product of mushroom cultivation, with diverse applications in agriculture, livestock feed, environmental management, and renewable energy production (Kousar *et al.*, 2024).

New mushroom cultivation

Cultivated mushrooms are generally classified as primary decomposers (e.g. *Pleurotus ostreatus*, *Lentinus edodes*) that are produced directly on previously untreated (or partly treated/composted) lignocellulosic substrates, or as secondary decomposers like *Agaricus bisporus*, *Volvariella volvacea)* which are cultivated on composted substrates prepared from various agricultural residues, including manures. Primary decomposers require materials with higher C:N ratio and lignin content and lower nitrogen content (sawdust, sugarcane bagasse and straw), whereas secondary decomposers require materials with lower C:N ratio and higher cellulose and hemicellulose. SMS can be effectively recycled for new mushroom cultivation (Suwannarach *et al.*, 2022). If it contains the necessary nutrients for the growth of mushroom, it can be used for further cycles of mushroom culture but it requires proper processing. When bacteria or other fungi break down SMS, *Agaricus* species can flourish (Ahlawat and Sagar, 2007). When 30 per cent of wheat straw was replaced with *A. bisporus* SMS, the system showed higher levels of cellulose, nitrogen, phosphorus, and potassium, along with a reduced C:N ratio, which resulted in higher yield (Ahlawat and Sagar, 2007).

The effective reuse of spent mushroom substrate (SMS) in subsequent mushroom cultivation primarily depends on factors such as the original substrate composition, the duration of cultivation cycle, and the number of flushes harvested. Key parameters to be considered in such applications include the type of substrate pretreatment adopted (e.g., chopping, composting etc.), the incorporation rate of SMS into the main substrate of the new crop, additional nutrient supplementation, and the choice of species or strain used for cultivation.

Casing material

Casing is a process carried out after the spawn run, in which a thin layer of soil is applied over the substrate. Traditionally, peat is the most commonly used casing material; however, it is expensive and not readily available, making it difficult for growers to the material. SMS can serve as a potential casing material, but it needs to be composted for a certain period. Composting reduces the electrical conductivity (EC) and facilitates the breakdown of organic matter into humic substances. The reuse of SMS as a casing material has been successfully applied in the cultivation of milky white mushrooms (Ashrafi *et al.*, 2017). The Spent Mushroom Compost alone or mixed with sand (3:1) as casing material for milky white mushroom resulted in faster primordial initiation and enhanced the development of stalk and pileus traits. Since FYM is not needed, SMC or SMC + sand (3:1) can be recommended as cost-effective casing options. Reusing SMS not only contributes to waste recycling but also enhances environmental sustainability while reducing the actual cost of cultivation, making it economically viable (Chamoli *et al.*, 2023)

Spent mushroom compost (SMC)

SMS can be directly applied to the soil as a fertilizer or amendment, as it increases organic carbon and nitrogen levels, modifies the soil micro-ecosystem, and enhances its physical, chemical, and overall quality (Ma *et al.*, 2025) However, because of its high C:N ratio, direct application of spent mushroom substrate in the field has not been very successful (Sangwan *et al.*, 2002). Spent mushroom substrate normally contains 1.9 per cent N_2, 0.4 per cent P_2O_5 and 2.4 per cent K_2O before composting and after normal composting for a period of 8-16 months, it contains 1.9 per cent N_2 0.6 per cent P_2O_5 and 1.0 per cent K_2O (Ahlawat and Sagar, 2007). SMS is a good composting substrate since it is rich in organic materials. In aerobic composting, microorganisms in SMS break down organic matter in the presence of oxygen to form stable humus. The microbial agents can remarkably increase the metabolic activities of specific functional microorganisms, thus influencing the various compost indices. SMS is used as a compost substrate, where microbes break down cellulose, hemicellulose, and other complex compounds in SMS into simple, soluble molecules that plants can readily absorb and utilize (Ma *et al*., 2021). Natural aerobic and anaerobic composting of spent mushroom substrates takes a longer period to complete the process. Vermicompsting is one of the technologies for the composting of SMS. However, the farmers are reluctant in the adoption of vermi technology due to the attack of rodnts, birds, and ants, which ultimately results in the loss of earthworms. Nowadays microbial consortiums have been widely used in composting (Xu *et al.*, 2022) which accelerates the process. During composting processes, pests and parasites present in the SMS are reduced due to the high temperature, ensuring its safe application (Xu *et al.*, 2023).

The composting process of SMS involves three stages (Batool *et al.*, 2024; Xu *et al.*, 2023). The first stage, known as the warming phase, is characterized by temperatures ranging from 15 to 45 °C. During this time, mesophilic aerobic microbes are more prevalent and need a lot of oxygen to grow quickly. This stage involves the conversion of readily decomposable organic materials into tiny molecules. Compost pile temperatures range from 50 to 70°C as the process moves into the high temperature stage. Because they can efficiently break down complex organic matter like cellulose and hemicellulose into humus and achieve stability, thermophilic bacteria take the role of mesophilic ones. The cooling phase, also known as the maturity stage, is the last phase. High quality organic fertilizers are produced when the temperature falls below 40°C because thermophilic microorganisms become less active, decreasing the pace of breakdown and deepening the formation of humus.

Factors affecting composting of spent mushroom substrate

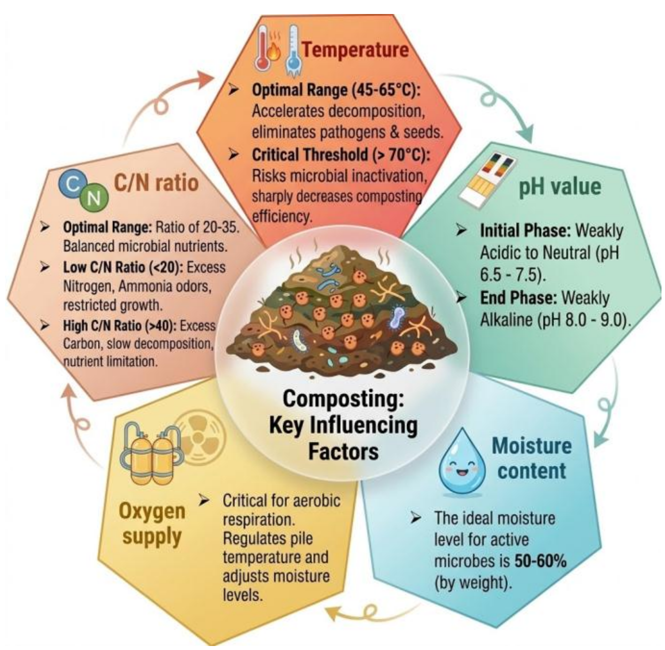

Fig. 1 : Factors affecting the SMS composting.

The efficiency of SMS composting is influenced by several interrelated physical, chemical, and biological factors, including temperature, C: N ratio, pH, moisture content, and oxygen

Substrate for crop production

Spent mushroom substrate serves as a nutrient rich growth medium for plants as it improves soil structure, fertility, and microbial activity, thereby enhancing crop growth and yield. Studies on leafy vegetables and spinach confirmed significant improvements in germination, growth, yield, nutrient uptake and soil health under SMS application (Verma *et al.*, 2020). However, high salt concentration can be a problem; Rinker (1994) suggested the trickle irrigation to leach out the excess salts. SMS is rich in nutrients and is always applied to agriculture land to enhance soil organic matter and nutrient contents (Lou *et al.*, 2015).

Table 1 : Reuse of spent mushroom substrate (SMS) as soil amendment

Source of SMS	Type of SMS and incorporation rate to soil (field or pot experiments)	Observed effects on soil and /or crops	Reference
Agaricus bisporus	SMS incorporated into soil at 25 and 100 mg ha^{-1} (dry weight)	Enhanced dehydrogenase activity, soil respiration, and microbial biomass in degraded vineyard soils	Hernandez *et al.*, 2022
Agaricus bisporus and *Pleurotus ostreatus*	Composted SMS (7:3 ratio) used as a peat substitute in pots	Higher yields of baby leaf lettuce. i.e., 3–7 times more than that obtained by peat	Hernandez *et al.*, 2021
Agaricus bisporus	Composted SMS (5 to 75 g L$^{-1)}$ in pots	Improved yield of *Lolium multiflorum* (up to 300% over control without NPK fertilization)	Paula *et al.*, 2019
Agaricus bisporus	SMS applied @ 45 and 85 ton ha^{-1} in pots	Promoted the presence of fungi in the highly connected fraction of the active microbial community	Paula *et al.*, 2019

*NPK: N, P, K

Greenhouse crop production

The utilization of SMS in greenhouse crop production is a sustainable approach to enhance soil quality and crop yield. SMS, rich in nutrients and beneficial microorganisms, can significantly improve the growth conditions for various crops in green house. Spent mushroom compost and substrate enhance soil properties and microbial diversity in greenhouse, providing higher nutrient content and beneficial microorganisms (Parihar *et al.*, 2026)

SMS are commonly used as growth media in greenhouse and horticulture production. The use of SMC as a growth medium provides an eco-friendly strategy for enhancing greenhouse tomato production by improving initial soil nutrient status and microbial diversity (Huang *et al.*, 2023).

However, these beneficial effects on physicochemical properties and enzyme activities diminish over time. Apart from these, the presence of SMC promotes beneficial microbial communities in contrast to the abundance of pathogens observed in continuously cropped soil

Mulching material

Mulching with spent mushroom substrate (SMS) acts as an effective physical barrier that inhibits weed seed germination and growth, thereby managing the weeds in crop fields (Remya and Beena, 2023). SMS derived from shiitake mushroom (*Lentinus edodes*) has shown potential in enhancing pesticide degradation when used as mulch (Gao *et al.*, 2018). Besides, it is rich in organic and essential plant nutrients that make it a useful material for soil improvement. When used as mulch, SMS helps to retain soil moisture and protects seeds from being eaten by birds. However, it is not suitable for vegetables that are sensitive to salt. SMS is most effective as a mulch during spring and summer (Sagar *et al.*, 2009). Furthermore, it is free from pests and weed seeds due to the high temperatures employed during pasteurization, composting, and post-harvest treatment. Its physical presence alone can also suppress weed growth (Mwangi *et al.*, 2024).

Disease management

SMS is unique in its chemical composition and the microflora present in it, which includes fungi, bacteria and actinomycetes, and hence, has a potential to suppress the pathogens in the soil ecosystem. Several studies revealed that the SMS can be effectively used for disease management. It enhances the plant growth and suppressing soil-borne diseases in vegetable crops by promoting antagonistic microorganisms, reducing pathogenic fungi, and stimulating natural plant defense mechanisms, thereby mitigating various soilborne pathogens and nematodes (Prasad and Srinivasaraghavan, 2019).

Spent mushroom compost can effectively manage crop diseases by inducing microbiostasis, direct toxicity, or systemic resistance in host plants. It serves as a natural alternative to chemical pesticides, enhancing soil properties and promoting sustainable agricultural practices (Mwangi *et al.,* 2024). Numerous studies have demonstrated that the incorporation of SMS into soil not only enhances crop yield but also promotes the proliferation of nitrogen-fixing bacteria and reduces various diseases in crops.

Table 2 : Effect of spent mushroom substrate (SMS) on disease management in various crops

S.No	Crops	SMS Application Rate (t ha^{-1})	Diseases managed
1	*Lycopersicon esculentum*	18.5	Buckeye rot, leaf curl, fruit borer in FYM
2	*Capsicum annum*	25	Fruit rot, chilli mottle virus
3	*Pisum sativum*	20	Fusarium wilt and powdery mildew
4	*Brassica oleracea*	25	Black rot and caterpillar
5	*Zingiber officinale*	30-32	Lower rotting

SMS offers an environmentally friendly and cost effective approach to disease management. It's application reduces the activity of pathogens, thereby contributing to improved crop yield (Adedeji and Modupe, 2016; Kang *et al.,* 2017; Shitole, 2014).

Reducing the effect of pesticides

SMS enhances the degradation of pesticides in soil. Studies showed the faster pesticide dissipation rates in SMS amended soils compared to unamended soils which is due to increased microbial activity present in the SMS. The application of SMS at a lower rate as an organic amendment to soils could help to prevent water pollution caused by the frequent use of pesticides in agriculture (Marín-Benito *et al.,* 2009).

Animal nutrition

Mushrooms efficiently degrade cellulose, hemicellulose, and lignin during its growth, making the nutrients in SMS more readily digestible for animals (Phan and Sabaratnam, 2012). SMS is a valuable feed resource as it contains crude protein, lipids, essential amino acids, and vitamins essential for animal health. It also has a pleasant aroma, soft texture, and high palatability. Moreover, the probiotics present in SMS can enhance the immunity of livestock. SMS can be incorporated into animal feed by drying and milling to facilitate uniform blending with feed formulations. Due to its loose and fragile structure, SMS has low mechanical strength, which makes feed production convenient and reduces costs. However, its effectiveness as a feed is still constrained by indigestible fibers, high molecular weight compounds, and anti-nutritional factors that often remain untreated (Ma *et al.,* 2024).

Animal feed prepared from SMS has significant positive effects in enhancing feed digestibility, product quality, and animal immunity based on the proportion of SMS. Yeast and lactic acid bacteria (LAB) fermentation are the most effective methods for feed processing (Gal *et al.*, 2011). Biological fermentation helps improve the digestibility of crude protein and carbohydrates in SMS, aiding in better intestinal digestion for animals. However, SMS may become contaminated with undesirable microorganisms during storage, potentially leading to animal health issues or toxicity; therefore, proper cleaning and sterilization are essential before its use as animal feed (Tasaki *et al.,* 2014).

In poultry farming, the waste of oyster mushroom left from the mushroom industry was used as supplement and 1per cent supplementation showed a positive response on the health of broiler chicken (Fard *et al.,* 2014).

In fisheries, the use of spent mushroom substrate supplemented feed has gained increasing attention, with several studies reporting its positive effects on fish culture. Mohd-Din *et al.* (2012) used spent mushroom substrate as a probiotic compound in red Tilapia fingerlings and observed a significant increase in weight gain compared to the control group. Similarly, replacing 64–80% of dietary fish meal with fermented SMS enhanced growth, digestive enzyme activity, and antioxidant capacity in allogynogenetic crucian carp (Zhang *et al.*, 2017). Furthermore, Dube and Dwivedi (1996) reported that supplementing the water of *Cirrhinus mrigala* tanks with oyster mushroom waste not only provided highly nutritive colonized detritus as a direct feed but also promoted the production of rich plankton in the treated tanks compared to controls.

Utilization of SMS in Bioremediation

The utilization of SMS for bioremediation presents a promising approach to address environmental contamination, particularly in soils polluted with petroleum hydrocarbons. SMS, a byproduct of mushroom cultivation, is rich in valuable microbiota and possesses unique physical and chemical properties that enhance its effectiveness as a bioremediation agent. Due to its organic composition and ability to support microbial growth, SMS can act as a bioremediation agent. It facilitates the degradation of organic and inorganic pollutants in contaminated soils, thereby enhancing soil health and environmental sustainability (Antón-Herrero *et al.*, 2022).

SMS enhances bioremediation of petroleum contaminated soils by providing valuable microbiota. SMS from species like *Agaricus bisporus* and *Lentinula edodes* significantly improves the degradation of total petroleum hydrocarbon, demonstrating its potential as an effective and sustainable remediation strategy. The re use of SMS in environmental remediation is a promising way to covert this agricultural waste into a sustainable bioresource promoting the green development of the global mushroom industry (Leong *et al.,* 2022).

Different spent mushroom substrates were used to adsorb organic and inorganic contaminants or to degrade organic contaminants from water (Ghose *et al.,* 2022). The composted SMS is an effective adsorbent to minimize the availability of metals in soil and enhanced the phytoremediation of mining soil, reduced the leaching of pesticides from soil and minimized the impact of herbicides in soil microbial community (Carpio *et al.*, 2020).

Utilization of SMS in Renewable Energy Production

The traditional method of using SMS in energy production involves its direct combustion as fuel. However, the combustion process releases green house gases and ash, which aggravate environmental pollution. The utilization of SMS for energy production not only offers a sustainable management solution but also helps to divert SMS from landfills. This approach contributes to minimizing environmental impact, as the energy production from SMS generally produces minimal acid gas emissions such as nitrogen oxides (NOx), sulfur oxides (Sox), and hydrogen chloride (HCl). SMS can be utilized in green technology projects, including renewable energy applications. Its enzymes may aid in bioremediation and industrial processes, positioning

SMS as a valuable renewable resource rather than mere waste. (Remya and Beena, 2023). SMS can be utilized for bioenergy generation. It serves as a feedstock for biogas, bioethanol and biohydrogen production, contributing to renewable energy development (Kousar *et al.,* 2024)

Challenges and Future Prospects

Despite its potential, the utilization of SMS faces key challenges. Its composition varies with mushroom species, substrate, and number of harvest cycles, leading to a lack of standardization and inconsistent quality as a growth medium or fertilizer. Large scale adoption is hindered by economic and logistical issues, since bulkiness and high moisture enhance the cost collection, processing, and transportation. Concerns also exist over contamination with heavy metals, herbicides, pesticides or pathogens, while elevated salt levels can harm salt sensitive crops, require composting before application. However, SMS is rich in organic matter, nutrients, and beneficial microbes that improve soil health and productivity, and its prospects extend beyond agriculture into areas such as bioremediation of soil and water, biofuel production, and extraction of industrially valuable enzymes and bioactive compounds

Conclusion

SMS represents a valuable resource with a wide range of applications in agriculture, environmental management, animal nutrition, and renewable energy production. Its benefits as a soil amendment or conditioner, compost, animal feed, and bioremediation agent contribute to enhanced soil health, improved crop productivity, pollution mitigation, and sustainable waste management. Moreover, its potential applications in bioenergy expands its relevance beyond agriculture, highlighting its role in advancing a circular economy. However, challenges such as salinity, compositional variability, and unscientific disposal highlight the need for standardized processing methods and tailored application guidelines. With global SMS production projected to exceed 100 million tonnes by 2026, valorization of SMS presents both an environmental necessity and a transformative opportunity. Strategic collaborations among researchers, policymakers, farmers, and industry stakeholders will be crucial to unlock its full potential, ensuring its effective integration into sustainable resource management strategies.

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Competing Interests

The authors declare no competing interests.

References

Abak, K. (2024). *The place of mushrooms in human life, production and importance in terms of nutrition* (pp. 3–52). Iksad Publishing House.

Adedeji, K. O. and Aduramigba, M. O. A. (2016). In vitro evaluation of spent mushroom compost on growth of *Fusarium oxysporum* f. sp. *lycopersici*. *Advances in Plants & Agriculture Research,* ***4***(4), 332–339.

Ahlawat, O. P. and Sagar, M. P. (2007). *Management of spent mushroom substrate*. National Research Centre for Mushroom, Indian Council of Agricultural Research.

Antón-Herrero, R., García-Delgado, C., Baena, N., Mayans, B., Delgado-Moreno, L. and Eymar, E. (2022). Assessment of different spent mushroom substrates to bioremediate soils contaminated with petroleum hydrocarbons. *Applied Sciences*, ***12***(15), 7720.

Ashrafi, R., Mian, M. H., Rahman, M. M. and Jahiruddin, M. (2017). Reuse of spent mushroom substrate as casing material for the production of milky white mushroom. *Journal of Bangladesh Agricultural University,* ***15***(2), 239–247.

Atallah, E., Zeaiter, J., Ahmad, M. N., Leahy, J. J. and Kwapinski, W. (2021). Hydrothermal carbonization of spent mushroom compost waste compared against torrefaction and pyrolysis. *Fuel Processing Technology,* ***216***, 106795.

Batool, F., Kurniawan, T. A., Mohyuddin, A., Othman, M. H. D., Aziz, F., Al-Hazmi, H. E., Goh, H. H. and Anouzla. (2024). Environmental impacts of food waste management technologies: A critical review of life cycle assessment (LCA) studies. *Trends in Food Science & Technology*, ***143***, 104287.

Beyer, S. and Kilsby, M. (1996). The future of employment for people with learning disabilities. *British Journal of Learning Disabilities,* ***24***, 134–137.

Carpio, M. J., Marin-Benito, J. M., Garcia-Delgado, C., Sanchez-Martin, M. J. and Rodriguez-Cruz, M. S. (2020). Soil microbial community changes in a field treatment with chlorotoluron, flufenacet and diflufenican and two organic amendments. *Agronomy,* ***10***, 1166.

Chamoli, V., Singh, K., Kaushik Parashar, G. and Pant, A. (2023). The usage of spent mushroom substrate. *International Journal of Plant Pathology and Microbiology,* ***3***(2), 48–50.

Chang, H., Chen, I. G., Yu, H., Tsai, M. Y., Wu, K. T. and Liu, S. (2022). Spent mushroom substrate and electric arc furnace dust recycling by carbothermic reduction method. *Materials,* ***15***(7), 2639.

Dube, K. and Dwivedi, A. (1996). Oyster mushroom waste as manure in fish culture. *Journal of Indian Fisheries Association,* ***26***, 111–114.

Fard, S. H., Toghyani, M. and Tabeidian, S. A. (2014). Effect of oyster mushroom wastes on performance, immune responses and intestinal morphology of broiler chickens. *International Journal of Recycling of Organic Waste in Agriculture,* ***3***(4), 141–146.

Gal, S., Moon, Y. and Cho, S. (2011). Effect of the dietary supplementation of fermented spent mushroom (*Pleurotus eryngii*) substrates on the growth performance and carcass characteristics in Hanwoo steers. *Journal of Life Science,* ***21***(12), 1705–1709.

Gao, W., Liang, J., Pizzul, L., Feng, X. M., Zhang, K. and del Pilar Castillo, M. (2015). Evaluation of spent mushroom substrate as substitute of peat in Chinese biobeds. *International Biodeterioration & Biodegradation,* ***98***, 107–112.

Ghose, A. and Mitra, S. (2022). Spent waste from edible mushrooms offers innovative strategies for the remediation of persistent organic micropollutants: A review. *Environmental Pollution,* ***305***, 119285.

Hernandez, D., Ros, M., Carmona, F., Saez-Tovar, J. A. and Pascual, J. A. (2021). Composting spent mushroom substrate from *Agaricus bisporus* and *Pleurotus ostreatus* production as a growing media component for baby leaf lettuce cultivation under *Pythium irregulare* biotic stress. *Horticulturae,* ***7***(2), 13.

Herrero-Hernandez, E., Andrades, M. S., Eguren, G. V., Sanchez-Martin, M. J., Rodriguez-Cruz, M. S. and Marin-Benito, J. M. (2022). Organic amendment for the recovery of vineyard soils: Effects of a single application on soil properties over two years. *Processes,* ***10***(2), 317.

Huang, C., Han, X., Luo, Q., Nie, Y., Kang, M., Chen, Y., Tang, M., Fu, Y., Li, X. and Chen, Y. (2023). Agro-based spent mushroom compost substrates improve soil properties and microbial diversity in greenhouse tomatoes. *Agronomy,* ***13***(9), 2291.

Jasinska, A. (2018). Spent mushroom compost (SMC)—Retrieved added value product closing loop in agricultural production. *Acta Agraria Debreceniensis,* ***150***, 185–202.

Jayakumar, M., Gindaba, G. T., Gebeyehu, K. B., Periyasamy, S., Jabesa, A., Baskar, G., John, B. I. and Pugazhendhi, A. (2023). Bioethanol production from agricultural residues as lignocellulosic biomass feedstock waste valorization approach: A comprehensive review. *Science of the Total Environment,* ***879***, 163158.

Kang, D. S., Min, K. J., Kwak, A. M., Lee, S. Y. and Kang, H. W. (2017). Defense response and suppression of *Phytophthora* blight disease of pepper by water extract from spent mushroom substrate of *Lentinula edodes*. *The Plant Pathology Journal,* ***33***(3), 264.

Kousar, A., Khan, H. A., Farid, S., Zhao, Q. and Zeb, I. (2024). Recent advances on environmentally sustainable valorization of spent mushroom substrate: A review. *Biofuels, Bioproducts and Biorefining,* ***18***(2), 1–10.

Leong, Y. K., Ma, T., Chang, J. and Yang, F. (2022). Recent advances and future directions on the valorization of spent mushroom substrate (SMS): A review. *Bioresource Technology,* ***344***, 126157.

Lou, Z., Zhu, J., Wang, Z., Baig, S. A., Fang, L., Hu, B. and Xu, X. (2015). Release characteristics and control of nitrogen, phosphate and organic matter from spent mushroom compost amended soil in a column experiment. *Process Safety and Environmental Protection,* ***98***, 417–423.

Ma, X., Li, S., Tong, X. and Liu, K. (2024). An overview on the current status and future prospects in *Aspergillus* cellulase production. *Environmental Research,* ***244***, 117866.

Ma, X., Yan, S. and Wang, M. (2025). Spent mushroom substrate: A review on present and future of green applications. *Journal of Environmental Management,* ***373***, 123970.

Ma, Y., Wang, Q., Sun, X., Wang, X., Su, W. and Song, N. (2021). A study on recycling of spent mushroom substrate to prepare chars and activated carbon. *BioResources,* ***9***(3), 3939–3954.

Marin-Benito, J. M., Rodriguez-Cruz, M. S. and Sanchez-Martin, M. J. (2009). Effect of spent mushroom substrate amendment of vineyard soils on the behavior of fungicides: Mobility of penconazole and metalaxyl in undisturbed soil cores. *Journal of Agricultural and Food Chemistry, **57***, 9643–9650.

Martin, C., Zervakis, G. I., Xiong, S., Koutrotsios, G. and Straetkvern, K. O. (2023). Spent substrate from mushroom cultivation: Exploitation potential toward various applications and value-added products. *Bioengineered, **14***(1), 2252138.

Medina, E., Paredes, C., Perez-Murcia, M. D., Bustamante, M. A. and Moral, R. (2009). Spent mushroom substrates as component of growing media for germination and growth of horticultural plants. *Bioresource Technology, **100***(18), 4227–4232.

Mohd Din, A. R. J., Razak, S. A. and Sabaratnam, V. (2012). Effect of mushroom supplementation as a prebiotic compound in super worm based diet on growth performance of red tilapia fingerlings. *Sains Malaysiana, **41***(10), 1197–1203.

Mwangi, R. W., Mustafa, M., Kappel, N., Csambalik, L. and Szabo, A. (2024). Practical applications of spent mushroom compost in cultivation and disease control of selected vegetable species. *Journal of Material Cycles and Waste Management, **26***, 1918–1933.

Parihar, N. S., Sabharwal, U. and Bisen, J. S. (2026). The role of spent mushroom substrate in sustainable agriculture, environmental management and circular economy development. *Discover Sustainability, **7***, 505.

Paula, F., Tatti, E., Thorn, C., Abram, F., Wilson, J. and O'Flaherty, V. (2019). Organic soil amendment with spent mushroom substrate results in fungal colonisation, alters bacterial-fungal co-occurrence patterns and improves plant productivity. *[Journal name and publication details not provided]*.

Phan, C. and Sabaratnam, V. (2012). Potential uses of spent mushroom substrate and its associated lignocellulosic enzymes. *Applied Microbiology and Biotechnology, **96***(4), 863–873.

Prasad, D. and Srinivasaraghavan, A. (2019). *Management of soilborne diseases of vegetable crops through spent mushroom substrate*. Apple Academic Press.

Ramamurthi, K. and Geethalakshmi, R. (2021). Food: Nutritive value and health benefits of mushroom. *International Journal of Agricultural Sciences, **17***(2), 745–750.

Remya, J. S. and Beena, S. (2023). Spent mushroom substrate: A ruby in the rubble. *European Issues in Agricultural Sciences, **5***, 122–137.

Rinker, D. L. (2017). *Edible and medicinal mushrooms: Technology and applications*. Wiley-Blackwell.

Sagar, M. P., Ahlawat, O. P., Raj, D., Vijay, B. and Indurani, C. (2009). Indigenous technical knowledge about the use of spent mushroom substrate. *Indian Journal of Traditional Knowledge, **8***(2), 242–248.

Sangwan, P. S., Swami, S., Singh, J. P., Kuhad, M. S. and Dhaiya, S. S. (2002). Effect of spent mushroom compost and inorganic fertilizer on yield and nutrient uptake by wheat. *Journal of the Indian Society of Soil Science, **50***(2), 186–189.

Shitole, A. V., Gade, R. M., Bandgar, M. S. and Zalte, A. (2014). Utilization of spent mushroom substrate for management of tomato damping off. *Journal of Plant Disease Sciences, **9***(1), 271–275.

Sree, R. S., Govindasamy, R. and Kaleeswari, G. (2024). Production performance of mushroom in India. *EPRA International Journal of Agriculture and Rural Economic Research, **12***(10), 8–13.

Suwannarach, N., Kumla, J., Zhao, Y. and Kakumyan, P. (2022). Impact of cultivation substrate and microbial community on improving mushroom productivity: A review. *Biology, **11***(4), 569.

Tasaki, Y., Kozuka, K., Mochida, K. and Sugawara, M. (2014). Effect of sawdust-based spent mushroom substrate treated with steam on rat growth performance. *Food Science and Technology Research, **20***(2), 493–497.

Verma, D., Didwana, V. and Maurya, B. (2020). Spent mushroom substrate: A potential sustainable substrate for agriculture. *International Journal of Grid and Distributed Computing, **13***, 104–109.

Xu, M., Sun, H., Chen, E., Yang, M., Wu, C., Sun, X. and Wang, Q. (2022). From waste to wealth: Innovations in organic solid waste composting. *Environmental Research, **229***, 115977.

Xu, M., Yang, M., Sun, H., Meng, J., Li, Y., Gao, M., Wang, Q. and Wu, C. (2023). Role of multistage inoculation on the co-composting of food waste and biogas residue. *Bioresource Technology, **361***, 127681.

Zhang, D., Zhang, Y., Liu, B., Jiang, Y., Zhou, Q., Wang, J. and Kuang, Q. (2017). Effect of replacing fish meal with fermented mushroom bran hydrolysate on the growth, digestive enzyme activity and antioxidant capacity of allogynogenetic crucian carp (*Carassius auratus gibelio*). *Turkish Journal of Fisheries and Aquatic Sciences, **17***, 1039–1048.