

Circular Economy of Mushroom Cultivation and Used Substrate Potential for Various Valuable Products

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Abstract

Mushroom is one of the fastest-growing and most dynamic industries within the world agricultural sector, as the mushroom industry is continuously being industrialized in Asia, Europe and North America, and as mushroom consumption keeps increasing as a source of high-quality and low-impact protein. In fact, this growth creates an ever-increasing by-product which is spent mushroom substrate (SMS) the lignocellulosic material that remains after mushroom fruiting bodies are collected. When not re-used, SMS is a lost resource and an environmental burden, increasing GHG emissions, leachate pollution and disposal expenses. This review brings together current knowledge of the production trends and mushroom potential for global and regional production, mushroom properties and nutritional benefits in human nutrition as well as the mushroom valorisation process and possibilities. Its applications in the soil as compost and biofertiliser for enhancing soil structure and fertility, as a poultry and ruminant feed ingredient, as a feed ingredient for aquaculture species and farmed insects as a second-generation feedstock for bio-organic production of bio-gas, bio-ethanol and bio-char and as a source of residual lignocellulolytic enzymes and recovered bioactive compounds for nutraceutical and pharmaceutical applications. In all these applications, the evidence is mounting for an integrated biorefinery strategy where several value streams are extracted from a single substrate before any waste product is returned to the soil, instead of SMS being considered as a single-use waste product. However, this potential needs to be realised on a wider scale, including the need to standardize the characterization of the substrate, increase investment in large-scale field and techno-economic studies and integrate better the mushroom farms with the surrounding agricultural, livestock and energy sectors. This review brings together recent developments in these areas and reconsiders the role of spent mushroom

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substrates as an agricultural waste problem rather than a solution. This review has consolidated the latest developments in these areas and rethought the role of spent mushroom substrates as a contribution to a circular bioeconomy rather than the problem of agricultural waste.

Keywords: Spent mushroom substrate; Mushroom industry; Lignocellulosic waste; Waste valorization; Circular bioeconomy; Biofertilizer; Animal feed; Aquaculture feed; Biorefinery; Bioenergy; Bioactive compounds; Sustainable agriculture.

1 Introduction

As visible spore-bearing structures known as sporocarps, mushrooms can play an important part in the sexual reproduction stage of many fungi's life cycles (Mayirnao et al., 2026). Because they are low in anti-nutrients and free of toxins, many mushrooms are regarded as edible. They are also high in proteins, vitamins, minerals, dietary fiber or many other nutrients (El-Ramady et al., 2022). The species of mushroom fungi regulate their specific composition. As much as 30% w/w of protein crude can be found in mushrooms, but some species of mushroom have up to 28%, 8%, and 95% (w/w) of fat, crude fiber, and carbs (Gargano et al., 2025). Edible mushrooms are a high in protein, low-carbon food source that can moderately replace meat, whose production has a major effect on the environment. Moreover, because of their high concentration of several components that promote health, such as peptides, proteins, phenolic compounds and β -glucans (González-Ibáñez et al., 2023). It is commonly known that eating mushrooms improves wellbeing and human health. As a result, there is now a much bigger demand for edible mushrooms across all continents, and the industry has been grown to be global in scope. Since 1978, the production of mushrooms has expanded more than thirty times, and industrial activity is rapidly growing. Despite the fact that most of the global population of mushroom production is concerted in Asia, where China holds a 90% market share, the processing of growing mushroom in the Americas and European Union, headed by the Netherlands and Poland has increased significantly in recent decades (Braat et al., 2022). Mushrooms are grown on plant biomass-based substrates, such as underutilized wood waste and crop leftovers which are becoming more abundant due to the increase in agricultural output brought on by the world's growth population. Presently, Burning is among the most common ways to deal with the buildup of plant waste. The idea of the circular economy has evolved from an idea to the devising of authentic policies. Agricultural waste streams are now seen as a valuable resource sooner than as debit entries in this perspective. The 0.25 billion tons of straw are burned in China 2009 (Li et al., 2026). Over Fifty different varieties of mushrooms are grown for commercial purposes. Together, these four genera account for 74% of the global market: *Lentinula* (*L. edodes*), also called shiitake, *Agaricus bisporus* (also called button mushrooms) *Pleurotus* (also called oyster mushrooms), *Auricularia* (also called wood ear mushrooms). In 2013, the market of mushrooms was valued at 63 billion dollars in the US (Royse, 2017). In this market place, 8% are wild mushroom, 54% are grown edible mushrooms and 38% are medicinal mushrooms. The amount of cultivated edible mushrooms expended per person worldwide greater than before from 1 to 4.7 kg between 1997 and 2013 (Jesus et al., 2023). Since it's necessary to locate appropriate removal sites and deal with great cost of transporting a bulky material with a low density and high moisture content intensive activity that is hardly feasible-drying fresh SMS is an energy the vast amounts of SMS that are generated which are presently considered a waste product that isn't particularly valuable and a major obstacle for mushroom growers. Furthermore, the handling and disposal of SMS poses a major environmental risk because it releases greenhouse gases into the atmosphere through spontaneous anaerobic digestion which are frequently occurs in the piles created during temporary storage, leachate flow to water responsive areas and foul smells which results in pollution and eutrophication. The kind of supplements and raw materials that are utilized in to make the initial substrate of mushroom have a major impact on the characteristics and composition of SMS. Many lignocellulosic by products

of mushrooms, such residues, agro-industrial, agricultural and forest as substrate are utilized bases for the farming of edible mushrooms that belong to genera *Pleurotus*, *Auricularia*, *Lentinula*, which account for 60% of the production worldwide (Gong et al., 2022). For other mushroom species (like those in the genus *Agaricus*) that need decomposed substrates such as manure of chicken is also a key ingredient. Ingredients high in starch and nitrogen such as legume flour cereal bran along with mineral salts, are utilized as supplement (Chen et al., 2022). Enzymatic degradation of substrate components occurs during cultivation; the resulting nutrients, along with those already present in the substrate, are utilized for mushroom production and fungal development. According to reports that *P. pulmonarius*, *Pleurotus ostreatus*, and *Lentinula edodes* exhibit mass losses ranging from 57–77% initial cellulose, 61–75% hemicelluloses, 26–46% of the lignin respectively (Li et al., 2022). Ultimately, the cultivated species and the original characteristics of substrate's possess a noteworthy impact on the composition of SMS. In this review, we'll talk about the processing of growing mushroom and prospective application of Spent mushroom substrates in circular economy, we we'll talk overview on probable Spent mushroom substrates applications and products linked to agriculture and animal husbandry, production of enzymes and bioactive compounds, new cycles of mushroom cultivation.

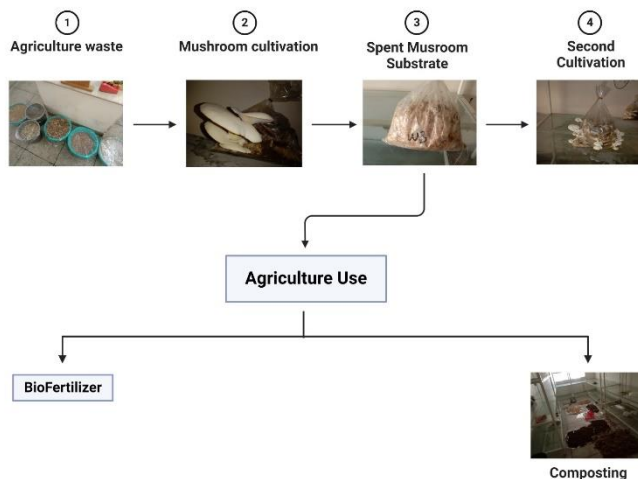


Figure 1: Spent mushroom substrate for mushroom cultivation

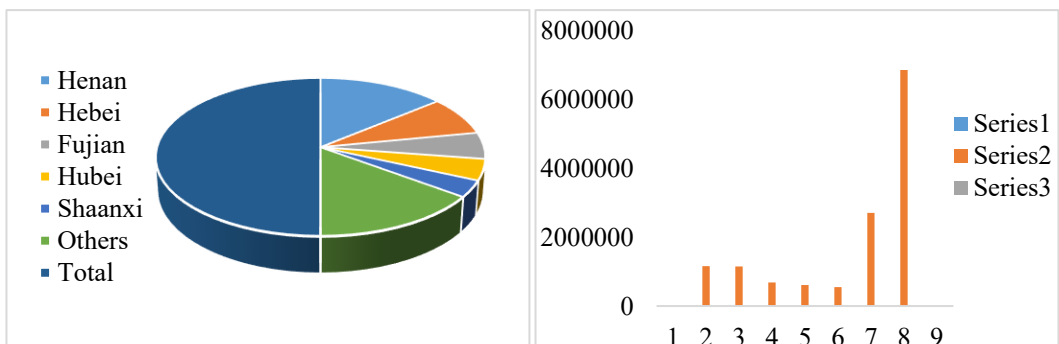
2 Mushroom production

Mushrooms were obtained by the collection of naturally occurring mushrooms. The development of numerous production techniques utilizing bags, wooden logs, beds, and bottles. All of which take advantage of the mushrooms' natural ability to breakdown in ecosystems has reinforced the significance of mushrooms as food sources (Dhar, 2024). Currently, Hardwood and sawdust logs both agricultural and forestry agricultural byproducts are used in the mushroom industry (Grimm & Wosten, 2018). Over the 30 years from 1990 to 2020, the number of mushrooms produced worldwide has grown to 42.8 million tons, a 13.8-fold rise (Girado et al., 2022). In Japan, the second biggest mushroom grower in the world, processing of growing mushrooms has reached a ten-year plateau (MAFF, 2021). In Japan using woods that cover about 70% of the state's area, the forestry sector in Japan generates 44% of its production value from mushrooms (Okuda et al., 2022). Additionally, mushrooms make up more than 80% of the value of forest products other than

wood, such as edible wild plants, nuts, firewood, charcoal, bamboo, and Japanese lacquer. In gardening of mushrooms, fresh mushrooms are the law of thumb. Alternatively, fruiting efficiency and colonization will be significantly influenced by the structure of the substrate. The substance for substrate formulation is determined by the availability of substrates in the area, while straw and animal dung are frequently combined. For example, the colonization of *Pleurotus Florida* decreases the dry weight of rice straw by 12% and pea straw by 20%, respectively (Mayirnao et al., 2026). On substrates that have been self-pasteurized, button mushrooms can be grown for example corn cob and Pongola grass, primavera tree, the latter has the maximum production levels, yielding 7.6 kg m⁻² and a biological efficiency (BE) of 52% (Cruz et al., 2022). In profound research has been done on the revolution of a substrate based on horse manure during composting and *Agaricus bisporus*'s vegetative development (Suwannarach et al., 2022). About 15 g of HDPE bags are useless each 900 grams of shiitake mushrooms production. According to latest research, this indicates that if the world produces 10 million tons of shiitake mushrooms. Every year, over 160,000 tons of mushroom waste are generated. In a similar way, 18 g of waste is converted into 450 g of oyster mushrooms. Numerous studies demonstrate that mushroom growing can be a lucrative industry when low-value forestry and agricultural byproducts are used instead of being burned. The contribution of different kinds of mushroom species to global mushroom output has reformed throughout the time, and a variety of mushrooms have been cultivated. 90% of the world's mushroom production in 2013 came from five genera *Pleurotus*, *Lentinula*, *Auricularia*, *Flammulina* and *Agaricus*. Global output of mushroom reached 43 million tons in 2018–19, and by 2025, it may approach 50 MT. We provide species and region which specific mushroom production data for the main mushroom-producing nations, which include Japan, China, the USA and Canada. (Bijla et al., 2023).

2.1 Production in China

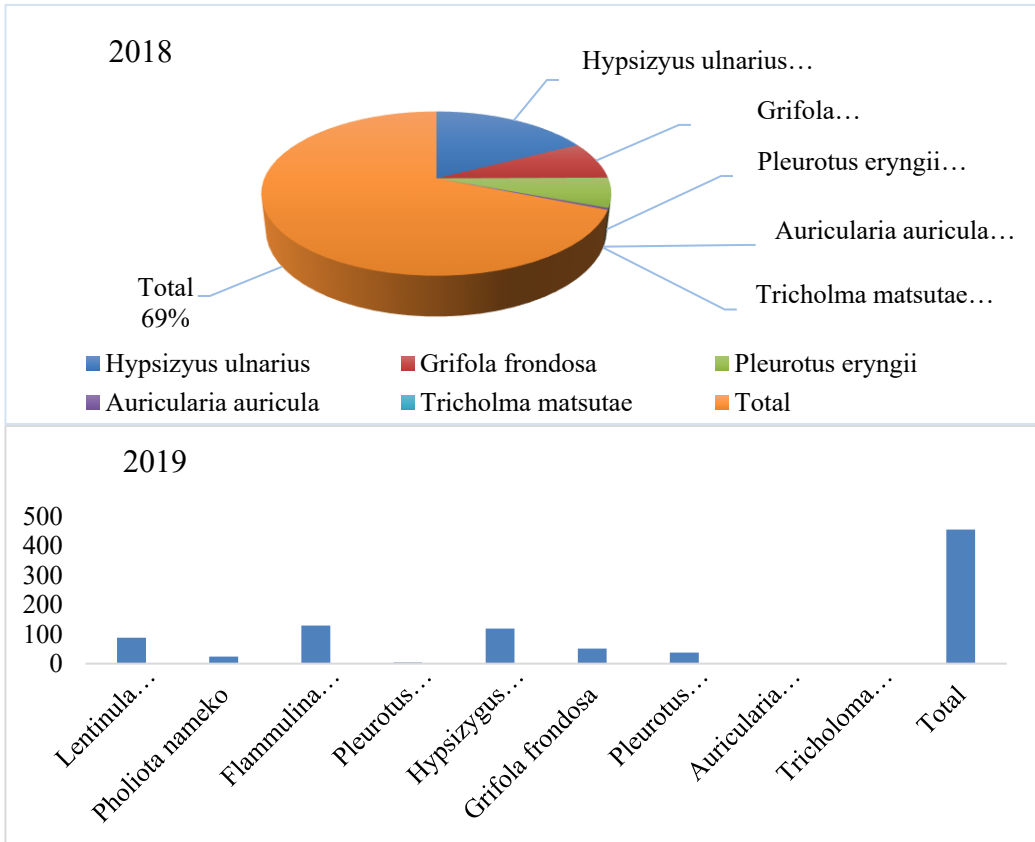
According to reports, 798 medicinal fungus and around 1789 edible fungi coming from China (Wang et al., 2024). More than two hundred species have been successfully grown in labs, hundred species have undergone domestication, and over sixty species have been grown for profit (Li, 2021). Even with the large production of mushrooms, not all provinces have the same level of mushroom farming. In 2019 50% of the overall output come from five provinces Fujian, Henan, Shandong, Hebei and Heilongjiang. Out of over 30 years. Sichuan, Jilin, Jiangsu, Hubei, and Jiangxi were the other five provinces that contributed about 25%.



2.2 Production in Japan

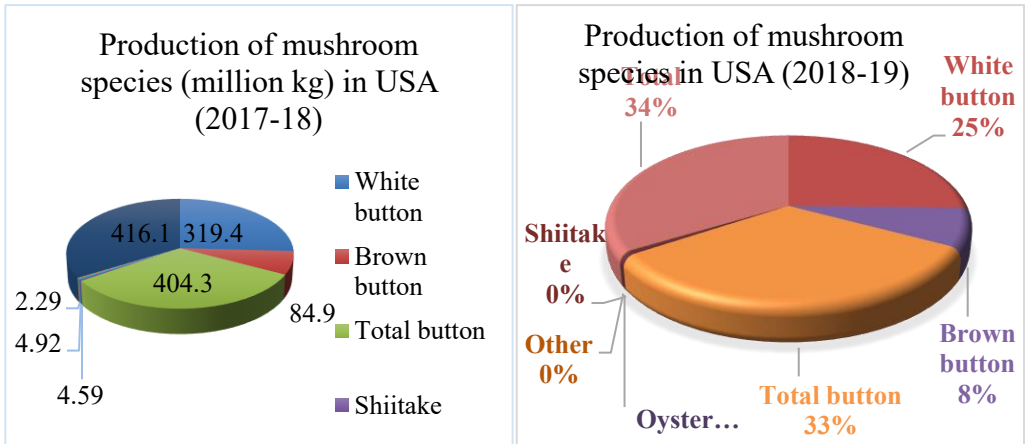
Six important species are cultivated in Japan: *Pleurotus eryngii*, *Grifola frondosa*, *Hypsizygus ulnarius*, *Flammulina velutipes*, *Lentinula edodes* and *Pholiota nameko*. While there has been some drop in Shiitake mushroom output throughout the years, the global production has stabilized

at about 460 million kg. While shiitake is grown for drying more frequently in southern locations like Miyazaki and Oita prefectures, fresh shiitake mushrooms is grown throughout the country specially Tokushima and Hokkaido producing the most. Niigato and Nagano were among the biggest growers and these two provinces including 47 made up 55.6% of the entire output (Bijla et al., 2023).



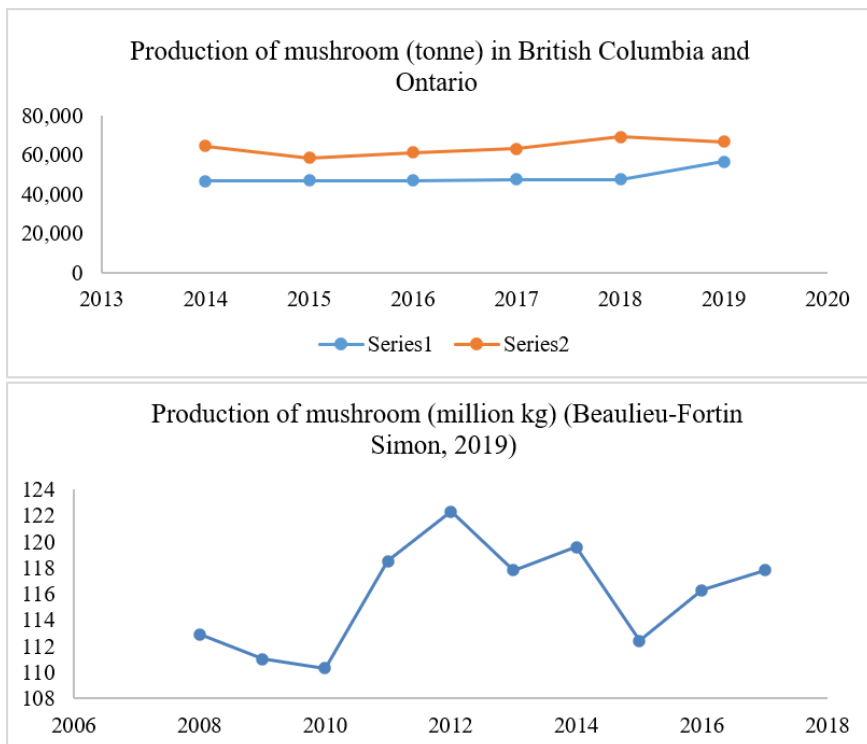
2.3 Production in USA

Over the past ten years, the production of mushroom in the USA's 400 million kg weight has stabilized. Productivity decreased from the 2019 to 2020 season, especially in California, due to COVID (Bijla et al., 2023). Mushrooms production in Pennsylvania accounts for around 66% of the country's output, while, Chester County contributing 48% of that total.



2.4 Production in Canada

Two provinces in Canada that produce the majority of mushrooms. In 2018/2019, British Columbia accounted for 42.7 percent of the entire production whereas Ontario accounted for 50.5%. The beginning of COVID in 2019 to 2020 has an immediate effect of increasing canning (Bijla et al., 2023).



3 Dietary component of mushroom and significance

As a well-balanced food item, mushrooms provide people with important nutrients and health advantages (Rathore et al., 2022). Because of their distinct flavor and widespread recognition as a culinary marvel, mushrooms are used in gourmet cuisine all over the world. Apart from this, they are highly known for their useful dietary properties (Cho et al., 2024). Steroids, amino acids, Proteins, polysaccharides, vitamins, nucleotides, carbohydrates, enzymes, glycoproteins, flavonoids, phenols, oxidized polyphenols and tannins are just a few of the mycochemicals found in mushrooms. Mushrooms are high in minerals, protein, low in fat, vitamins and fiber all of which have been shown to strengthen the immune system. Alkaloids, tannins, and flavonoids are also present in mushrooms (Shameem et al., 2023). Because they provide all the essential amino acids for adult needs and because mushrooms have higher protein levels than most other vegetables and leaves, they are advantageous for vegetarian diets. One of the essential components of the diet is the mineral component. It has been shown that some edible wild mushroom species include higher concentrations of minerals; both magnesium and calcium are the most common minerals among them. In addition to minerals, unsaturated fatty acids and vitamins particularly B and C can be found in abundantly in mushrooms (Shallal et al., 2026). There have been reports of the traditional usage of mushrooms such as *Lentinus edodes*, *Ganoderma lucidum*, *Coriolus versicolor* and *A. blazei*, for medicinal purposes. In Korea, Japan and China, *A. blazei* extracts have been utilized as supplements to radiation and chemotherapy treatments. Potential source of antibacterial medications could be mushrooms. In addition, it may possess antifungal qualities (Agnihotri et al., 2024). Because they contain vitamin C which helps to form blood, mushrooms are used to cure anemia. Mycochemicals are substances that stop the activity of free radicals, shielding the organism from oxidative harm. Free radicals are autonomous molecules that possess one or more unpaired electrons. They cause biological harm and are implicated in a number of non-communicable illnesses. Mushrooms possess potent antioxidant properties due to their high vitamin C, polyphenol, and other component levels, which help prevent chronic diseases such as cancer, diabetes, and heart disorders (Iqbal et al., 2024). By speeding up the creation of T cells, vitamin D and the mineral selenium, which is present in some mushrooms, assist in eliminating substances that cause cancer and improve immunity. The fibers found in a variety of mushrooms are perfect materials to use for treating digestive issues and managing weight (Krishnamoorthi et al., 2022). Bioactive substances produced from mushrooms, including ergosterol, velutin, helianthiol F, colossolactone VIII, lentinan, C and E, have shown promise as SAR-CoV-2 primary protease inhibitors for treating multiple drug conditions, including hyperglycemia, immunodeficiency, tuberculosis and HIV infection (Rukhiran et al., 2023).

4 Traditional and latest approach of mushroom production

4.1 Innovations in the environmentally friendly extraction of value from discarded mushroom substrate

According to statistics, the global mushroom economy is expected to grow to 20.84 million tons by 2026. The mushroom industry is expanding swiftly, which leads to the generation of a large volume of spent mushroom substrates (SMS). Every year, about 60 million tons of SMS are produced. Inadequate waste management could lead to improper disposal of this trash, which might pollute the soil and water and cause other environmental problems (Baptista et al., 2023). It is now necessary to use SMS more effectively and accurately due to the mushroom industry's growth and the consequent increase in SMS generation. The lignocellulosic biomass from mushroom culture that is only 40–80% degraded, as in the instance of *Pleurotus eryngii*, is what makes composed spent mushroom substrate. SMS are numerous, affordable, and renewable producers of many useful byproducts, such as proteins, sugar polymers, and phenolic compounds (Sarkar et al., 2024). It matters to keep in mind that the area, species of mushrooms, and other

characteristics of mushroom farming greatly affect the structure and content of SMS. Researchers have sought to create ways to use SMS successfully, such as using it as animal food and as a substitute for fertilizers and soil additives (Ayuso et al., 2025). Recycling the SMS and adding additional nutrients for a new mushroom species' growth cycle is another viable option. Additionally, spent mushroom substrate can serve as the foundation for the production of bioenergy, particularly solid biofuel, biogas, bioethanol, bio-oil, and biohydrogen. One of the most significant reuse potentials for SMS is pollution control which helps with land reclamation through improved soil health and promoting vegetation establishment in addition to bioremediating contaminant-polluted soil (Silva et al., 2024).

4.2 Used substrate of mushroom as compost

Mineral fertilizers are a major component of modern agriculture practices. Over 50% of the energy utilized in commercial agriculture comes from nitrogen fertilizer, the manufacturing process for these fertilizers has a significant environmental effect (Suwannarach et al., 2022). A 50% boost in barley output in the same year was obtained by applying 100 tons of SMS per hectare, which is comparable to the effect of inorganic fertilizer. By using pyrolysis to turn SMS into charcoal, leaching can be minimized. Thus, when large volumes of SMS are utilized by this, water bodies and groundwater may not become contaminated. Not only may in addition to being utilized as a pure fertilizer, spent mushroom substrate also utilized to raise the caliber of compost made from pig dung (Ma et al., 2023). Using SMS as a thickening agent while pig manure is composting decreases the amount of time that the compost takes to break down. In addition, SMS lowers emissions of N_2O and NH_3 36 and 46%, correspondingly in comparison to stover corn. SMS is a good thickening agent for lowering the emissions of gaseous and improving the quality of compost even if it raises CH_4 emissions by 10%. SMS treatment also results in a 34% reduction in CH_4 and N_2O 's capacity to cause global warming. When SMS is applied to a composting sewage sludge, similar outcomes have been observed. Biofertilizer can also be made with SMS (Zeng et al., 2023). By increasing crop output, biofertilizers support the development of sustainable agriculture. A stress-tolerant yeast that can be utilized as a biofertilizer is called *Pichia farinose*. It increases soybean growth as a result SMS residue, *P. ostreatus* and a portion of the unbound reducing sugars that comes from enzymatic plus chemical treatment can be used to generate *P. farinose* biofertilizer (Lin et al., 2022).

4.3 Used substrate of mushroom for energy production

Pleurotus eryngii or *Flammulina velutipes* SMS and dairy manure were combined to produce methane. More methane was produced this combination than either dairy or SMS manure alone, demonstrating the beneficial effects of co digestion. SMS can potentially be a source of sugars for the production of bioethanol (Hu et al., 2022). SMS of *Agricus bisporus* comprises of 9% cellulose, 30% sugar, most of which consists of (8%) xylan and (19%) glucans. Nearly all of the glucose and more than 40% of the xylose were liberated through chemical and enzymatic hydrolysis. about 300 mg of reducing sugar for every gram of SMS can be released. It has also been investigated to *P. ostreatus* SMS originating from a substrate that consisting of wheat straw, hay cotton seed and corn cobs and for the synthesis of bioethanol used as a source of sugars. About 40% of the cellulose and 20% of the hemicellulose in this SMS remain. About 40% of the SMS residue and 25% of total dropping sugars mostly xylose or glucose were produced by chemical and enzymatic treatment. These sugars can be transformed from one gram to roughly ethanol 0.5 g (Santos et al., 2022). Therefore, 150 kg ethanol might be produced from 1 ton of SMS in these scenarios. *P. ostreatus* SMS, which was generated from sorghum chaff, really produced ethanol content of 187 g per kilogram dry matter (Ye et al., 2023).

The effects of change of climate are knowledgeably affecting the environment in which we live, the resources becoming more limited and ecosystems are under attack. As a effect, plans for

sustainable manufacturing are being put out right now. Mushrooms require materials, water input, and energy for their production, much like any other food product. Critical energy loss points (CEPs) linked to physical and chemical energy losses were discovered to be the SMS's cooking-out procedure and the first stage of composting respectively, during the evaluation of the industrial mushroom production chain's efficiency. Since spent mushroom substrate is highly microbially diverse and has previously undergone degradation that utilities in the beginning of the phase I compost process's fermenting phase., when combined with other ingredients to create new cultivation substrates will effective in this sense (Bigolin et al., [2026](#)). Transportation remains a significant production expenses in mushroom industry. According to many researches, the perfect raw material for making compost must to be year-round and accessible to mushroom farms. However, 36% of the overall cost of transportation for mushroom farms are incurred in the process of transporting raw material. Lastly, utilizing SMS in new mushroom harvests has the advantage of avoiding long term distance transportation as a soil conditioner for disposal, and in the Netherlands, which produces around SMS of 800,000 tonnes annually (Phan et al., [2023](#)).

4.4 Used substrate of mushroom as feed

In order for agriculture to supply food to the growing global population which is predictable to reach 9.7 billion by 2050 agricultural production will eventually want to increase by 70–100% . The protein sources and leading energy exploited by the livestock breeders for producing poultry, meat and milk are soybeans and corn. These products are the primary sources of protein in the diets of humans (Xavier, [2024](#)). While their protein content may be low, the major raw materials employed in manufacturing mushrooms are rich in fiber, hemicelluloses and lignin (Martín et al, [2023](#)). The substrate polymers are by enzymatic torn apart via a solid-state fermentation caused by fungus that forming mushroom, drastically improving the palatable potential of plant remnants. likewise, whenever mycelial biomass develops the substrate develops superior due to the fact it incorporates a greater number of proteins and bioactive elements like a substance polysaccharide and ergosterol. In addition, *P. ostreatus* growth broadened the test specimen in 14 of the 16 amino acids investigated and heavily lowered the amount of anti-nutritional contaminants like vicine, tannin and acquit. SMS from multiple types of mushrooms is also prevalent in substances that have the potential to be used to make it better the feed rations' quality. SMS from *L. edodes* has a great deal of the 151.6 mg of ergosterol in pro vitamin D. While spent mushroom substrates from numerous other species of mushrooms holds a great polysaccharides deal, with glucans as, β -glucan. likewise, the major result of each investigation being concisely presented and discussed more under, ended in increased the levels of immunoglobulins G and B, as well as the levels of glutathione and peroxidase events, whereas cholesterol, malondialdehyde contents and leukocytes were decreased (Boontiam et al., [2022](#)).

4.5 Used substrate of mushroom as animal feed

SMS can also be used to fodder poultry, fish, cows and pigs directly. Several studies have been directed on using mushroom cloud extracts or mushrooms themselves as feed. Interesting to think that conclusions can applied to Spent mushrooms substrates. *Hemigrammus caudovittatus* and *Labeo rohita* fingerlings were nourished a food a 9% mushroom meal, of 9% fish meal, 9% fishmeal, 9% worm meal or 18% fish meal. When associated to the diet of fish meal, the meal of earth worm diet exposed a two-fold increase in the development rate, while the diet of mushroom diet exhibited 1.2 to 1.7-fold increase in rate. These findings suggest that both mushroom and earthworm meal can be used as an addition cutting-edge fish diet, hypothetically plummeting the need for meal of fish (Quaicoe et al., [2024](#)). The rainbow trout diet was supplemented with 2% shiitake mushroom extract. Mykiss, *Oncorhynchus* When visible *Lactococcus garvieae* to the pathogen of bacteria, the fish's immunological limitations better quality and their existence rate increased (Gao et al., [2023](#)). The presence of fungal mycelium may counterbalance the enhanced

digestibility of stubble. Agitating spent mushroom substrate with lactic acid bacteria had an optimistic effect on development. The accumulation of 10% made from fermented sawdust on SMS of *P. ostreatus* that can upgrade the post weaning calves development recital by 8 percent (Raman et al., [2022](#)).

4.6 Used substrate of mushroom in the diet of edible insects and fish

There is a lot of attention in using SMS in pisciculture. Related to lucrative foods, spent mushroom substrates from, *G. lucidum*, *P. ostreatus* and *Pleurotus cystidiosus* looks to provoke catfish development and considerably rise its digestive ability and survival rate (Lai et al., [2024](#)). When *C. militaris* SMS was added to the diet of *Oreochromis niloticus* tilapia, up to 40 g kg⁻¹, the fish's growth performance and skin condition were enhanced serum, peroxidase activities and mucus lysozyme (Hilali et al., [2025](#)). These structures were further enhanced by the adding of *L. plantarum* to SMS. Additionally, enrichment A diet of Nile tilapia supplemented with 1% w/w *A. blazei* SMC offered important defense against the infection of *Streptococcus agalactiae*. In light of the imperative to reduction dependence on plant-based feeds, the utilization of insects *12 C. Martin* et al appears to be a viable substitute because of their high fat up to 59% content and crude protein up to 76% content, 20–30 MJ/kg DM of energy, low-cost growth and brief life cycle necessities (Melise et al., 2025). A recent appraisal measured the ability of 6 Spent mushrooms substrates produced from *L. edodes*, *P. eryngii*, *Auricularia heimuer*, *Pleurotus citrinopileatus*, *P. ostreatus* and *Auricularia cornea* to rear black soldier fly and *Tenebrio molitor* larvae. It was exposed that SMS from *Lentinula edodes* was the best contender towards substitute the insects outdated diet (Lai et al., 2024).

4.7 Used substrate of mushroom for isolation of bioactive molecules and enzymes

When fungi form mushrooms, they secrete lignocellulosic enzymes like lignin peroxidase, xylanase, cellulase, and laccase that break down their substrate into molecules that can be ingested as nutrients. These enzymes can be taken out of SMS and used in processes like the making of biofuel and marsh gas (Sabaratnam et al., [2024](#)). For the creation of second-generation biofuels, biomass is first treated with fungi more energy and efficient environmentally than physical and chemical pre-treatments of biofuel unprocessed materials. But the cost for manufacturing enzymes has been predicted to be between US\$0.6 and 1.3 per gallon of bioethanol, this represents 40–87% of the biofuel's retail price. Reducing the period of fermentation and the intricacy of the enzyme production process might reduce the substantial cost related to the production of bioethanol (da Silva et al., 2025). Since the extraction process can be simple and there is no need for a fermentation period, SMS's enzymes could be a good substitute. For example, using water, it is easy to separate the enzymes from SMS. These removes can be utilized straight, solely in combination with other sources of enzymes, to provide sugars for second-generation biofuels, such as converting lignocellulosic waste streams. They can also be partially separated from the extract by employing a poly-ethylene glycol salt system in an easy two-phase isolation process. For example, with such a system, 95% of laccase activity could be retrieved (Barua et al., [2024](#)). Future studies ought to evaluate which SMS subtypes exhibit the highest levels of active enzymes for specific lignocellulosic raw material. The unrefined SMS enzyme extracts may also be utilized to absolve particular enzymes for use in food and feed, as well as for scientific research. Whether this is economically feasible will depend on the processes that are obtained.

5 Conclusion and future aspects

This collection of evidence clearly demonstrates that mushroom farming and the key by-product of spent mushroom substrate are no longer just on the sidelines of agricultural waste management but at its heart of the true circular economy. Global production continues to grow with the vast majority of this production situated in Asia, but steadily industrialising and diversifying elsewhere

and the amount of substrate to be managed is growing accordingly. The valorisation pathways explored here such as substrate reuse as compost and biofertiliser as livestock and aquaculture and insect feed as a feedstock for biogas, bioethanol and biochar and as a source of extractable enzymes and bioactive compounds, are no longer laboratory curiosities. They are moving towards an integrated biorefinery approach where multiple value streams are recovered from the same raw material with no residual streams being released back into the soil, linking the primary cultivation to the agricultural, energy and nutraceutical sectors. The translation of laboratory science to field application is what now holds back the spread of the use. Recycling rates of spent mushroom substrate are still comparatively low for mushroom production on a global scale the composition of mushroom substrates is highly variable between mushroom species and throughout growing media and mushroom farming practices, and this variability is still a major limitation for the standardisation necessary for successful and reliable valorisation at the farm level. While there is relatively limited large-scale, multi-season field testing and robust techno-economic and life-cycle analysis investment for scaling up laboratory processes to larger-scale industrial applications is still low in comparison to the opportunity. Therefore, four directions should be given priority as future work. In the first place, the harmonisation of regionally and system dependent characterisation of spent mushroom substrate would enable valorisation pathways to be matched reliably to the mushroom substrate composition, instead of being treated generically. Second, the integrated biorefinery pilots aiming for the sequential extraction of feed, fertilizer energy and bioactive fraction from one substrate stream warrant much more investment than single application studies. Thirdly, there is a need to reduce distances to transport mushrooms decrease disposal costs and augment local circular-economy networks by getting the mushroom farms closer to other horticultural, livestock and aquaculture activities. Fourth, the financial and environmental trade-offs for each of the valorisation routes would be clear to growers, investors and policy makers as the result of consistent application of techno-economic and full life-cycle assessment across the range of candidate technologies enabling uptake at the rate that the scale of the challenge requires. Combined these directions could make the industry's own waste stream a more manageable and near-term contribution to a truly circular bioeconomy.

Author Contributions

Muhammad Awais Fareed, Mazeera Fatima, Shahzaib Asghar, Zara Zahid, Muhammad Tayab Mateen, Abdul Basit Latif, Iram Bilqees, and Sonum Bashir contributed to the conceptualization, literature search, review and synthesis of relevant evidence, interpretation of the literature, organization of the scientific content, and preparation of the manuscript. All authors contributed to writing—original draft and writing—review and editing. All authors read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of Interest

The authors declare that they have no financial, professional, commercial, institutional, or personal conflicts of interest that could have influenced the content, interpretation, or conclusions presented in this article.

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Data Availability

No new experimental or primary dataset was generated or analysed for this study. All information supporting the discussion and conclusions was obtained from the published scientific literature and publicly available sources cited in the manuscript.

Informed Consent

Not applicable. The study did not involve human participants or the collection of primary personal data.

Use of Generative AI

The authors declare that no generative artificial intelligence tools were used to conduct the literature analysis, generate the scientific content, interpret the evidence, or formulate the conclusions presented in this article.

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