International Journal of Agriculture and Food Science 2026; 8(5): 624-627

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(5): 624-627
www.agriculturaljournals.com
Received: 06-04-2026
Accepted: 11-05-2026

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From Waste to Wealth: A Critical Review on Spent Mushroom Substrate

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DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i5h.1567

Abstract
The residual biomass produced following mushroom growing is known as spent mushroom substrate (SMS) and it is produced in significant amounts all over the world. SMS was once thought of as an agricultural waste, but because of its rich organic matter, partially decomposed lignocellulosic chemicals and vital nutrients, it is now acknowledged as a valuable resource. This review provides an overview of SMS's production, nutritional properties, decomposition techniques and numerous applications as well as its benefits, limitations and future prospects. SMS has shown great potential in the production of bioenergy through the creation of biogas and biochar, in environmental remediation for the elimination of contaminants and in agriculture as a soil supplement and compost material. Despite its advantages its large-scale use is constrained by issues like high moisture content, compositional unpredictability and handling concerns.

Keywords: Spent mushroom substrate, agricultural waste, bioenergy, compost, Soil supplement

Introduction
Over the past few decades, the global mushroom business has grown rapidly, which has significantly increased the production of agro-industrial residues, especially Spent Mushroom Substrate (SMS). Straw, sawdust, corncobs and other agricultural wastes are examples of lignocellulosic materials that are used to grow mushrooms. During fungal growth, these materials partially biodegrade. The leftover substrate also known as SMS, is thrown in massive amounts after multiple harvesting cycles, creating serious management and environmental issues [1]. The accumulation of SMS has grown in importance in both developed and emerging nations due to the ongoing increase in global mushroom output.

SMS was traditionally disposed of via landfilling, open dumping or incineration since it was seen to be a low value by product or waste item. Nevertheless, these actions lead to damage of the environment, including emissions of greenhouse gases, nutrient leaching and contamination of water and soil [2]. There is a critical need for sustainable disposal and use options because recent research demonstrate how mismanaged SMS can worsen waste management issues and have a detrimental effect on nearby ecosystems.

SMS is now seen as a useful bioresource rather than as garbage, a paradigm shift that has occurred in recent decades. SMS is rich in organic matter, lignocellulosic components, mineral nutrients and various microbial communities, all of which are considerably altered during mushroom production, according to recent research [3]. Its appropriateness for a variety of uses, such as soil amendment, composting, bioenergy generation, animal feed and environmental remediation is improved by these physicochemical and biological changes. As a result, SMS is becoming more widely acknowledged as a crucial element of circular bioeconomy and sustainable agriculture models. The versatile properties of SMS that facilitate its integration into eco-friendly technology. It is a desirable resource for waste valorisation because of its potential uses in pollution management, agriculture, renewable energy and bioproduct development [4]. Additionally, innovative methods to transform SMS into valuable products like enzymes, bioactive chemicals and biosorbents have been made possible by developments in biotechnology and biorefinery techniques [5]. Despite these encouraging advancements, a number of issues still need to be resolved, such as composition variability, a lack of standardized processing techniques and limited large-scale implementation.

To properly utilize SMS within sustainable development frameworks, these restrictions must be addressed through interdisciplinary research and technical innovation. Thus, the purpose of this paper is to give a thorough understanding of the production, properties and most recent developments in the use of spent mushroom substrate. Its contribution to the advancement of circular economy, sustainable agriculture and environmental management is highlighted.

Type of substrates used for mushroom cultivation

The production of mushrooms depends on a variety of organic and lignocellulosic substrates that supply vital nutrients for fungal growth. Because of their abundance and appropriate carbon to nitrogen ratio, agricultural leftovers like wheat straw, paddy straw, maize stalks and sugarcane bagasse are frequently used materials. For species like *Lentinula edodes* and *Ganoderma lucidum*, wood-based substrates like sawdust and logs are usually utilized whereas *Agaricus bisporus* cultivation requires composted combinations of straw and animal dung. Additionally, agro-industrial wastes including brewery dregs, coffee husk and tea trash are being used more and more to encourage sustainable waste recycling. These substrates are frequently enhanced with nutrient rich additions such as soybean meal and wheat bran to increase production. A growing focus on sustainability and circular bioeconomy approaches in mushroom farming is shown in recent research, which also emphasizes the use of alternative materials including coconut coir, banana wastes and water hyacinth [6-10].

Total quantity of spent compost generated from different mushrooms

Large amounts of spent mushroom substrate (SMS) are produced during the growing of mushrooms; according to recent studies, depending on the species and culture methods, 4-6 kg of SMS are produced for every kg of fresh mushrooms [1-4]. Due to its intense culture on composted substrates, *Agaricus bisporus* (button mushroom) produces the largest volume among various mushrooms, while *Pleurotus* spp. (oyster mushrooms) also produce significant quantities (3 kg) from lignocellulosic agricultural leftovers [1, 2]. Similar to this, *Ganoderma lucidum* and *Lentinula edodes* (shiitake) generate a significant amount of SMS, especially in bag-based culture systems with greater turnover rates [2, 5]. Millions of tons of SMS are produced globally each year as a result of the mushroom industry's explosive growth, making its management and valorization essential to the development of sustainable agriculture and the circular bioeconomy [1-5].

Fig 1: Spent Mushroom Substrate of Oyster Mushroom

Nutritional status of SMS generated from different mushrooms

Spent Mushroom Substrate (SMS) is nutrient rich by product rather than waste since it retains a significant quantity of organic matter and nutrients even after cultivation. Depending on the type of mushroom and substrate utilized, SMS typically includes 30-50% organic carbon, 22-35% cellulose, 18-32% hemicellulose and 10-25% lignin on a dry weight basis [1-4]. Additionally, it preserves quantifiable levels of calcium (5-15 g/kg), phosphorus (2-8 g/kg), potassium (10-25 g/kg) and nitrogen (approximately 1.0-2.0%) with higher mineral content being seen in SMS from manure-based systems like *Agaricus bisporus* [2, 5]. On the other hand sawdust based systems like *Ganoderma lucidum* have more lignin and delayed nutrient release, whereas SMS from *Pleurotus* spp. and *Lentinula edodes* has higher proportions of partially decomposed lignocellulosic Fibers and a moderate protein content (around 10-14%) [1-4]. Reusing SMS from various mushrooms in agriculture and other value-added applications is supported by its generally diverse but consistently nutrient-rich composition [1-5].

SMS decomposition methods

In order to improve its stability, reduce environmental risks and recover important nutrients, Spent Mushroom Substrate (SMS) can be efficiently decomposed and valorized using a variety of biological, chemical and physical treatment. According to recent research, the most popular technique is composting, which improves humification and nutrient stabilization by aerobically decomposing SMS either on its own or in combination with other organic wastes such animal manure or agricultural residues [1, 11]. It has been demonstrated that co-composting SMS with materials like pig manure improves compost maturity and organic matter degradation [11]. Anaerobic digestion is another important method that turns SMS into biogas in the absence of oxygen. By breaking down of lignocellulosic structures and increasing methane output, pretreatment techniques including thermal, mechanical or hydrothermal processing greatly increase biodegradability [3]. Vermicomposting and insect-based bioconversion, such as using black soldier fly larvae are also new biological methods that speed up the degradation of SMS while generating biomass or nutrient rich biofertilizers [3]. Long-term carbon sequestration and soil amendment applications are made possible by advanced thermochemical processes like hydrothermal liquefaction and biochar production, which transform SMS into stable carbon-rich materials or bio-oil at regulated high temperatures [2, 5]. In a circular bioeconomy paradigm, these decomposition methods work together to enable the conversion of SMS from waste into useful resources [1-5,11].

Uses of Spent Mushroom Substrate

- **Agricultural uses (Soil amendment and fertilizer)**
  Because of its high organic matter content and residual nutrients including potassium (K), phosphorus (P) and nitrogen (N) SMS is often used as an organic fertilizer and soil conditioner. Plant growth and agricultural output are increased when SMS is applied to soil because it increases soil structure, porosity, aeration and water-holding capacity. Additionally, as SMS contains beneficial microbes and enzymes produced during mushroom cultivation, it helps restore soil microbial diversity. Studies have shown that SMS can partially replace chemical fertilizers, enable sustainable agricultural practices and lower input costs and environmental effects [1, 2].

- **Bioenergy Production**
  SMS is a viable fuel for the creation of renewable energy, especially because of its lignocellulosic content. Although pretreatment techniques (such as thermal, chemical or mechanical) are frequently needed to increase biodegradability and gas yield, SMS can be converted into biogas (methane) through anaerobic digestion. SMS can also be used to produce bioethanol after being hydrolysed into sugars that can be fermented. Biochar, natural gas and bio-oil can be produced from SMS using thermochemical conversion processes such gasification and pyrolysis. These methods of energy recovery reduce dependency on fossil fuels and help value trash [2, 5].

- **Composting and Vermicomposting**
  SMS is frequently utilized as a feedstock in vermicomposting and composting systems. SMS decomposes more quickly than raw agricultural wastes because it is partially degraded lignocellulosic. In order to produce stable, nutrient-rich compost, co-composting SMS with animal manure or green wastes improves nutritional balance (C:N ratio) and speeds up humification. By converting SMS into vermicast rich in microbial biomass and plant-available nutrients, vermicomposting using earthworms further enhances nutrient availability. These procedures not only create high-quality organic fertilizers appropriate for horticultural and agricultural uses, but they significantly reduce the amount of trash [3, 4].

- **Environmental Remediation**
  SMS has drawn interest as a low-cost, efficient material for environmental remediation. It may absorb heavy metals, dyes, pesticides and other xenobiotic substances from contaminated water and soil thanks to its porous structure and functional groups (such as hydroxyl and carboxyl). Additionally, SMS is appropriate for bioremediation applications since the microbial populations it contains, promote the biodegradation of contaminants. Its ability to cure industrial effluents and restore contaminated ecosystems has been demonstrated by recent investigations, especially when paired with chemical or microbial alteration approaches [1, 5].

- **Animal feed supplements**
  SMS can be used to animal feed after the proper processing (such as fermentation, drying or ensiling). It has moderate amounts of fiber, protein and leftover elements that can help with animal nutrition. However, pretreatment is necessary to increase its nutritional value and taste because of its high lignin content and poor digestion. Research has demonstrated that adding processed SMS to animal diets can lower feed costs without sacrificing ruminant and other livestock growth performance [2, 3].

- **Industrial and Biotechnological Uses**
  SMS is an important raw material used in many biotechnological and industrial operations. Because of the leftover fungal biomass, it can be utilized to produce organic acids, bioactive chemicals and enzymes (such as cellulases and ligninases). SMS is also being investigated for the creation of bio-based composites, packaging items and biodegradable materials. It has also been extensively researched as a growing medium in horticulture, providing an environmentally friendly substitute for peat in nursery production systems [4, 5].

Advantages of SMS

Spent Mushroom Substrate (SMS) is a valuable resource in circular bioeconomy systems and sustainable waste management due to its many economic, agricultural and environmental benefits. When utilized as an organic amendment, SMS's high organic matter content (30–50%) and residual nutrients (nitrogen, phosphorus and potassium) improve soil fertility and promote plant development [1, 2]. By enhancing soil structure, aeration and water-holding capacity, its application promotes improved root development and higher crop yields [3].

Its contribution to environmental sustainability and trash recycling is another important benefit. Large amounts of SMS are produced and their reuse lowers environmental pollution, greenhouse gas emissions and landfill disposal. Utilizing SMS in bioremediation, composting and bioenergy production reduces ecological impact and promotes effective resource recovery [1, 4]. Furthermore, SMS has enzymes and beneficial bacteria that promote nutrient cycling and increase soil microbial activity [2, 5].

SMS is also beneficial since it can be used as a substrate for composting, the manufacturing of biofertilizer, animal feed (after treatment) and the production of bioenergy. It can be converted into value-added products like charcoal, biogas and enzymes because of its lignocellulosic nature [4, 5]. Additionally, SMS is an affordable substitute for traditional inputs like peat and chemical fertilizers because it is an easily accessible and affordable resource, especially in areas where mushrooms are produced on a big scale [3, 5]. The ability of SMS to turn agricultural waste into a useful resource, promoting sustainable agriculture, environmental preservation and the growth of the circular economy is the main advantage [1-5].

Limitations and challenges of SMS

Spent Mushroom Substrate (SMS) has several uses, but its widespread acceptance is hampered by a number of restrictions and difficulties. Its bulkiness and high moisture content (60–70%) are two of its main limitations, making handling, storage and transportation expensive and logistically challenging [1, 2]. Furthermore, the chemical composition of SMS varies based on the kind of mushroom, the formulation of the substrate and the culture conditions, which causes uneven performance in industrial and agricultural applications [2, 3]. The high lignin content and poor biodegradability of some SMS types, especially those produced from wood-based substrates, present another major obstacle that restricts their direct use and frequently calls for pre-treatment or composting to increase nutrient availability and stability [3, 4]. Additionally, SMS may contain heavy metals, ammonia or residual salts, particularly from manure-based substrates. If these substances are given in excess without being properly treated, they may have a detrimental effect on plant growth [1, 4]. Moreover, biosecurity issues in agricultural applications may arise from the possibility of infections, pests and weed seeds in incorrectly handled SMS [2]. Its efficient use at commercial scale is further limited by low knowledge, a lack of standardized processing technology and inadequate legislative backing [3, 5]. Its widespread adoption is further hampered by economic issues, such as the high cost of processing technology and the absence of well-established markets for SMS based products [4, 5]. All things considered, SMS has a lot of potential as a renewable resource, but in order to fully reap its benefits in sustainable agriculture and circular bioeconomy systems, these technological, environmental and financial issues must be resolved [1-5].

Future Prospectives of SMS

The effective conversion of Spent Mushroom Substrate (SMS) into a valuable resource using cutting edge and environmentally friendly technologies is the key to its future. SMS can be used more frequently in integrated systems for the production of bioenergy, organic fertilizers and biodegradable materials as waste to wealth approaches gain more attention. It is anticipated that biotechnology advancements would increase its conversion efficiency, especially by improving the breakdown of complicated lignocellulosic components. Refined processing techniques can aid in the creation of standardized, nutrient balanced agricultural products that can be applied consistently in the field. Its importance will also be increased by broadening its function in environmental management, such as soil restoration and pollution control. Ultimately, realizing SMS's full potential as a sustainable resource would require enhanced processing, better use techniques and greater industrial acceptance.

Conclusion

Rich in organic matter and nutrients, Spent Mushroom Substrate (SMS) is a significant agro-industrial by-product that can be used for a variety of purposes in agriculture, energy generation and environmental management. Despite obstacles such high moisture content and composition unpredictability, appropriate handling and treatment can greatly improve its usefulness. Overall, by encouraging resource recovery, trash recycling and circular bioeconomy practices, SMS has a significant potential to help sustainable development.

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