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Chapter- 29

Unlocking the Potential: A Comprehensive Review of Environmentally Sustainable Applications for Agro-Based Spent Mushroom Substrate (SMS)

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Keywords: Spent Mushroom Substrate (SMS), Agro-waste Utilization, Animal Feedstock, Environmental application, Sustainable agriculture.

Abstract:

Agro-industrial residues represent both a challenge and an opportunity in sustainable agriculture. Spent mushroom substrate (SMS), a byproduct of mushroom cultivation holds immense potential for various environmentally sustainable applications. This review critically examines the current state of knowledge regarding the utilization of SMS in agriculture and related fields. The potential of SMS as a soil amendment to enhance soil fertility and productivity is explored, highlighting its role in improving soil structure, nutrient availability, and microbial diversity. Additionally, the suitability of SMS as a substrate for the cultivation of various crops, including vegetables, ornamentals, and medicinal plants, is evaluated, emphasizing its contribution to sustainable crop production and resource conservation. Furthermore, the utilization of SMS in bioenergy production, bioremediation, and waste management are discussed, underscoring its role in promoting circular economy principles and mitigating environmental pollution. The review also addresses key considerations and challenges associated with the widespread adoption of SMS-based practices, including nutrient management, potential contaminants, and economic feasibility. Moreover, emerging trends and innovative approaches for maximizing the value of SMS are identified, such as its utilization in biopolymer production, nanotechnology applications, and integrated agroecosystem management. The review concludes by highlighting the importance of interdisciplinary collaboration and holistic approaches to harness the full potential of SMS for sustainable agriculture and environmental conservation. Overall, this review provides valuable insights into the diverse applications of SMS and offers recommendations for future research directions and policy interventions to promote its widespread adoption and integration into agroecological systems.

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Introduction:

Mushrooms are fascinating macro-fungi with distinguishing sporocarp that may be either hypogeous (underground) or epigeous (aboveground) and big enough to be viewable in unaided sight and to be plucked by hand. Agricultural waste refers to the residues left behind after various agricultural activities, and it can be generated both before and after processing. The term "lignocellulosic" is often used to describe such waste because it primarily consists of three main polymers: cellulose, hemicellulose, and lignin (Treuer et al., 2018). The composition of agricultural waste can vary depending on the type of crop, farming practices, and processing methods (Banerjee Banerjee et al., 2021). Examples of agricultural waste include crop residues (such as stalks, leaves, and husks), straw, bagasse, and other by-products of farming and processing activities (Adebayo & Martinez-Carrera, 2015). With around 160,000 of the 1.5 million known fungi species producing study-worthy sporocarps (Hawksworth, 2012; Murugesan, 2017), approximately 7,000 of the 16,000 recognized mushroom species are edible (Hawksworth, 2012). Among them, 3,000 are primary edible mushrooms, and around 700 are recognized for their health benefits (Chang & Wasser, 2017; Li et al., 2021). Interestingly, 200 mushroom species are considered super-foods globally (Kalac, 2016), but only 35 are commercially cultivated, with 10 reaching the status of industrial production in various countries (Aida et al., 2009; Xu et al., 2011; Chang & Wasser, 2017). Many Asian countries generate substantial amounts of agricultural waste, and the list of examples includes palm oil waste, paddy straw, sugarcane bagasse, corncob, EFB, cottonseed hulls, wheat straw, hay, and cocoa hulls (Yadav & Samadder, 2018; Bhattacharyya et al., 2020). China is indeed one of the largest producers of mushrooms globally, India is a significant producer of mushrooms, with both edible and medicinal varieties being cultivated, Malaysia has been actively involved in mushroom production, and Ireland has also been recognized as a notable producer of mushrooms (Saha & Khatua, 2024). A significant gap between the demand and production of mushrooms in Malaysia leads to substantial imports from China. Demand for mushrooms in Malaysia is reported to be around 50 tons per day, and the current local production is stated to be 24 tons per day. In 2012, Malaysia imported a considerable quantity of mushrooms from China: Approximately 2.71 million tons of fresh mushrooms, and Approximately 3.11 million tons of dried mushrooms (Lee et al., 2009b; Amin et al., 2014). The average production from each mushroom farm in Malaysia is 100 tons of fresh mushrooms annually (Phan & Sabaratnam, 2012). China produces 1.5 million tons of mushrooms per year and is expected to increase production by 65% in the next 10 years (Royse et al., 2017). Mushroom production in Ireland gained momentum in the 1980s. The key breakthrough was the development of a method for producing high-quality mushrooms at a low cost. This made Irish mushroom production competitive in European markets (Williams et al., 2001). The agricultural waste generated in these countries provides a valuable resource that can be repurposed as substrates for mushroom cultivation. Mushroom cultivation typically involves the use of organic materials as substrates or growing mediums. The lignocellulosic nature of many agricultural residues makes them suitable for breaking down into a nutrient-rich substrate for growing mushrooms. The production rate of agricultural waste in mushroom-producing countries can vary and may not always be readily available. This review provides a general overview of how agricultural waste is generated and can be used in the context of mushroom cultivation (**Table 1**).

Table 1: The production rate of agricultural wastes in mushroom-producing countries.

Types of agricultural waste	Production rate (million tonnes)	Management methods	Year	Country	References
Food waste	11	Disposed	2019	Canada	Tsa et al., 2023
SMS	4	Burning	2007	China	Kim et al., 2011a
Sugarcane bagasse	620	Disposed, burning	2018	India	Sadh et al., 2018
Empty fruit bunch	76.9	Disposed	2012	Indonesia	Embrandiri et al., 2013
Wasted crops	30	Burning	2022	Iran	Khouzani & Ghahfarokhi, 2022
Food waste	60	Disposed	2004	Ireland	Saba et al., 2016
Food waste, manure, maize waste	5.3	Disposed	2022	Poland	Hajdu et al., 2022
Livestock, poultry, and food	292.4	Landfilling	2012	USA	Loehr, 2012
Manures and slurry	43	Landfill	2021	United Kingdom	Chancharoonpong et al., 2021

Agricultural residues and waste, often referred to as Agro-based SMS (Sustainable Management Systems), present a significant yet underexplored resource with vast potential contributions to soil health, agricultural practices, and waste management (Van Zuydam, 2021). Agricultural activities generate substantial amounts of waste in the form of crop residues, by-products, and post-harvest remnants (Aruya et al., 2016). While traditionally considered as a challenge for disposal, there is a growing recognition of the multifaceted benefits embedded in these agricultural residues (Aruya et al., 2016). One of the primary focuses of this review is the potential of Agro-based SMS to enhance soil health and fertility (Leong et al., 2022). The organic matter content, nutrient composition, and microbial activity found in many agricultural residues can contribute significantly to soil structure and fertility (Bhupinderpal-Singh & Rengel, 2007). Exploring methods to harness these benefits can lead to improved soil water retention, reduced erosion, and enhanced nutrient availability, ultimately fostering sustainable and resilient agricultural ecosystems (Hou et al., 2020). The utilization of Agro-based SMS extends beyond soil health to impact overall agricultural productivity (Sarkar et al., 2022). Integrating these residues into innovative farming practices, such as organic mulching, cover cropping, or bioenergy production, can optimize resource utilization and promote sustainable intensification (Sarkar et al., 2020). The high production rate of agricultural waste, especially when it reaches critical levels, poses significant challenges and can have adverse effects on the environment. The challenge of managing and properly utilizing large amounts of agricultural waste is indeed a critical environmental concern. Discarding agricultural waste through disposal and burning methods can lead to environmental pollution and other negative impacts. Developing alternative methods for utilizing agricultural waste is crucial for sustainable waste management and environmental conservation (Barh et al., 2018). Mushroom cultivation involves several processes, from substrate preparation to harvest (**Figure 1**).

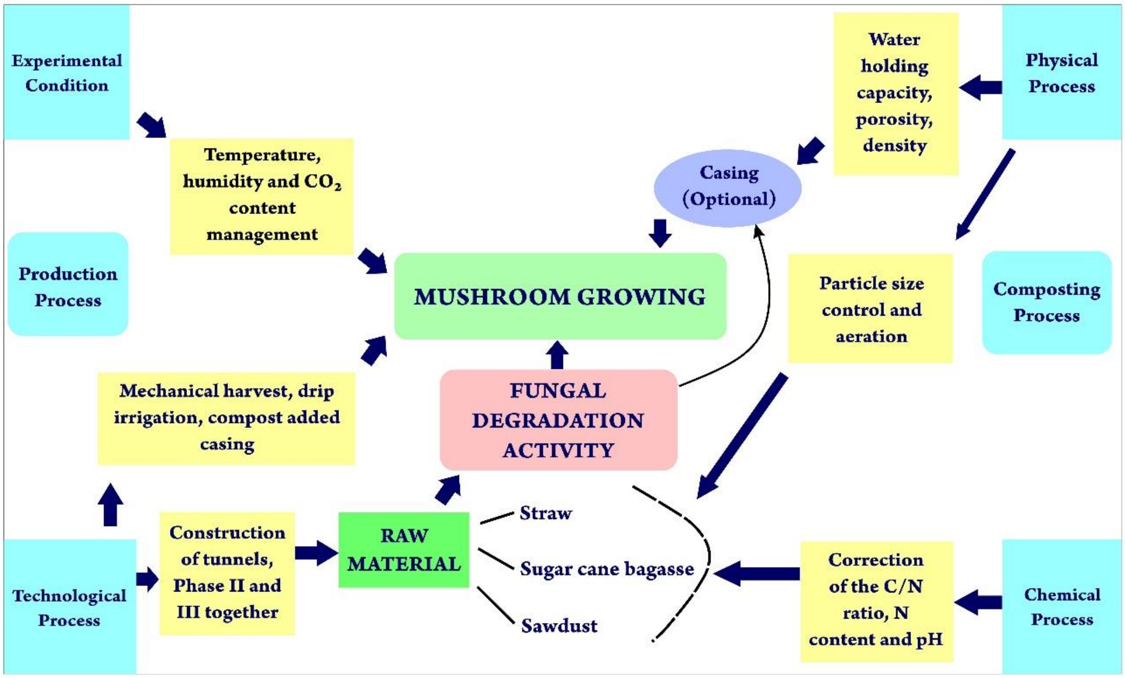

Figure 1. Scheme of mushroom cultivation and various processes.

Spent Mushroom Substrate (SMS):

Spent Mushroom Substrate (SMS) refers to the substrate or growing medium that has been used for mushroom cultivation and has completed its lifecycle, no longer supporting mushroom growth. This substrate is "spent" because the mycelium has consumed the available nutrients, and the substrate is exhausted. Spent Mushroom Substrate (SMS) is abundantly generated in mushroom farms after the harvesting period of mushroom fruiting bodies (Moon et al., 2012). SMS refers to the residual biomass waste that is generated from the process of mushroom production. For every 1 kilogram of fresh mushrooms harvested, the cultivation process results in the generation of approximately 5 kilograms of SMS (Lin et al., 2014; Zisopoulos et al., 2016). The residue from Spent Mushroom Substrate (SMS) is often treated as waste and discarded after the harvesting of mushrooms in many countries (Chiu et al., 1998). The challenge of managing the substantial amount of Spent Mushroom Substrate (SMS) in mushroom farms is a common issue faced by cultivators (Rasib et al., 2015) (**Figure 2**).

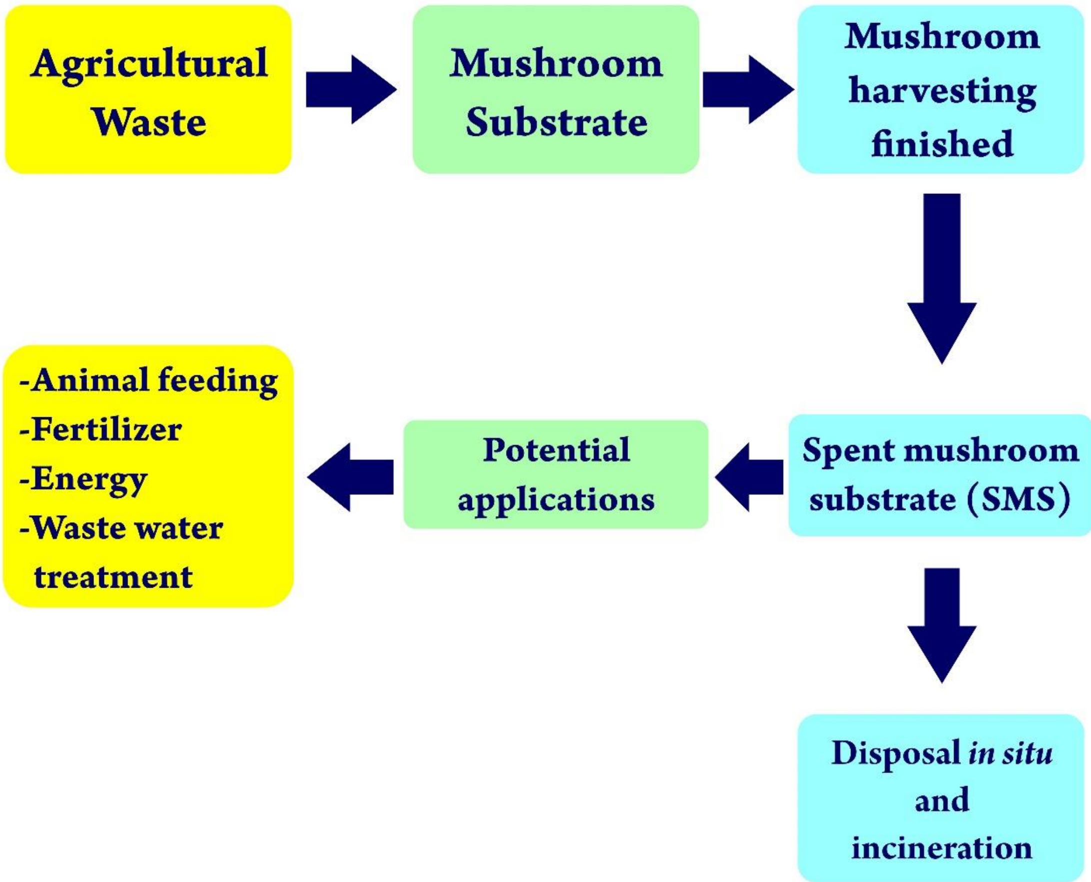

Figure 2. The management of SMS in the mushroom industry.

Concerns regarding the disposal of Spent Mushroom Substrate (SMS) have persisted and intensified over recent decades. The escalating trend of mushroom production, alongside the substantial generation of SMS as solid waste, underscores the challenges and opportunities inherent in managing agricultural residues. With an estimated annual production of around 5 million tons of SMS as solid waste, effective and sustainable waste management practices within the mushroom cultivation industry are imperative (Chiu et al., 1998). The annual production of approximately 660,000 tons of *Pleurotus eryngii* Spent Mushroom Substrate (SMS) in Korea serves as a testament to the magnitude of mushroom cultivation in the country. *Pleurotus eryngii*, commonly referred to as king oyster mushroom or king trumpet mushroom, stands as a popular edible mushroom species cherished for its culinary excellence and nutritional richness (Kim et al., 2012). Traditional methods of managing agricultural residues, such as employing SMS on farmland as fertilizer or disposing of it on land or through incineration, are still prevalent. However, each practice bears its own set of implications, with the choice often influenced by factors like local regulations, farm practices, and environmental concerns (Williams et al., 2001). The active pursuit by mushroom industries and researchers of low-cost potential applications for Spent Mushroom Substrate (SMS) with minimal environmental impact underscores ongoing efforts to tackle waste management challenges and discover sustainable solutions. The reviewed literature primarily delves into the major applications of SMS, which encompass animal feedstock, fertilizer, energy production, and wastewater treatment.

Utilization of Agricultural Waste for Mushroom Cultivation:

Mushroom cultivation using agricultural wastes as substrates offers several environmental benefits and can contribute to minimizing pollution in plantations and farms. The cultivation techniques for mushrooms can vary significantly between countries and even among different types of mushroom substrates. The choice of cultivation technique depends on factors such as the type of mushroom species, the availability of resources, climate conditions, and local agricultural practices (Marlina et al., 2015; Yang et al., 2016). The emphasis on utilizing low-value agricultural waste to enhance the nutritional quality of mushrooms underscores the growing importance of sustainable and innovative agricultural practices (Sardar et al., 2017). The research focuses on mushroom cultivation using agricultural waste and extends to various mushroom species, each with its unique characteristics and requirements. *Pleurotus spp.* (Oyster mushrooms), *Flammulina velutipes* (Enoki mushrooms), *Volvariella volvacea* (Straw mushrooms), and *Lentinula edodes* (shiitake mushrooms) are among the key species that researchers investigate for their potential in utilizing agricultural waste (Reis et al., 2012; Pala et al., 2012). The cultivation of mushrooms on various types of agricultural waste has been demonstrated and has gained significant attention in recent years. Corn waste, in particular, is recognized as a good substrate for mushroom production (Chukwurah et al., 2012). The use of corn cob as a main substrate for mushroom cultivation in India, and the reported high biological efficiency of approximately 93.75%, highlight the success and suitability of this agricultural waste material for mushroom production (Naraian et al., 2009). The use of paddy straw as a mushroom substrate, particularly in the cultivation and production of *Pleurotus spp.* (oyster mushrooms), has indeed been a common and established practice for many years (Thiribhuvanamala et al., 2017). Mushroom cultivation is indeed a widespread agricultural practice, and mushrooms are cultivated in numerous countries around the world. The countries you mentioned—China, Japan, The Netherlands, Spain, Malaysia, and others—are notable for their significant contributions to the global mushroom cultivation industry. China holds a prominent position as the world's largest producer and exporter of edible mushrooms such as *Pleurotus spp.*, *Lentinula edodes*, and *Agaricus bisporus* (Phan & Sabaratnam, 2012). The estimate of around 2000 types of edible mushrooms is a general approximation (Falandysz, 2013), and the actual number of known edible mushroom species may vary. The diversity of edible mushrooms is vast, and new species continue to be discovered and studied. The genus *Pleurotus*, commonly known as "oyster mushrooms," is indeed one of the well-known and widely cultivated genera in the world of edible mushrooms (Jayakumar et al., 2011). Mushroom cultivation in India has seen growth and diversification, with various regions adopting different species based on local climatic conditions, substrate availability, and market demand (Randive, 2012). Diverse mushrooms are, with varieties like oyster, king oyster, white button, shiitake, straw, and wild mushrooms offering various flavors and textures. Each type has its unique culinary and nutritional attributes (Amin et al., 2014; Islam et al., 2009). *Pleurotus spp.*, including *P. Sajor caju*, *P. Eryngii*, and *P. florida*, are widely cultivated and popular among mushroom enthusiasts (Alam et al., 2008; Moonmoon et al., 2012). These species are favoured in Asian countries not just for their culinary appeal but also because they are relatively easy to cultivate (Phan & Sabaratnam, 2012). Pleurotus spp. thrive in tropical regions and are known for their low-maintenance cultivation. Their ability to grow on various agricultural wastes, such as straw and other plant materials, makes them economically and environmentally beneficial (Pala et al., 2012). *Agaricus bisporus* and *Lentinula edodes* hold a dominant position in mushroom cultivation worldwide. Their widespread popularity is due to their versatile culinary uses, adaptable growing conditions, and global acceptance in various cuisines (Phan & Sabaratnam, 2012). Shiitake's popularity in Asia extends beyond culinary use; it's highly regarded as a medicinal mushroom, believed to have various health benefits. While its roots are in Asia, it has indeed found its way to other regions like North America and Europe, where it's appreciated both for its distinctive flavour in cooking and potential health-promoting properties (Melo de Carvalho et al., 2010). The different types of substrates for mushroom cultivation (**Table 2**).

Composition of Spent Mushroom Substrate (SMS):

Spent mushroom substrate (SMS) composition is significant for various applications, particularly in agriculture and waste management. After mushrooms have been harvested, the remaining substrate still contains valuable organic matter. It can be repurposed as a soil amendment, contributing to soil fertility and structure. Additionally, SMS has the potential for use in bio-energy production or as a feedstock for other industrial processes. The recycling of spent mushroom substrate is a sustainable practice with multifaceted applications (Lee et al., 2009). The composition of sawdust-based spent mushroom substrate (SMS), which includes various components like NDF (neutral detergent fiber), ADF (acid detergent fiber), hemicellulose, cellulose, lignin, carbohydrates, crude protein (CP), ether extract (EE), ash, dry matter (DM), calcium (Ca), and phosphorus (P). This complex composition makes it a rich resource with potential applications in different fields, such as agriculture and bio-energy. The nutrient content, especially in terms of organic matter and minerals, can contribute to its value in soil enhancement (Kwak et al., 2008). The nutrient composition of paddy straw-based spent mushroom substrate (SMS) with higher dry matter (DM) and crude protein (CP), along with slightly lower neutral detergent fiber (NDF), suggests its potential as a valuable agricultural resource (Kim et al., 2011). These attributes can enhance soil fertility and structure, making it beneficial for crop production. Agro-waste, with its high carbon and nitrogen content, provides

Table 2: Various Types of Substrates for Mushroom Cultivation.

Substrates	Mushroom types	References
Rice straw, wheat straw, rice + wheat straw, agricultural lime + wheat straw, agricultural lime + rice straw, quicklime + rice straw	*Pleurotus floridanus*	Youssef et al., 2023
Saw dust of mango, jackfruits, jam, kadom, mahogany, shiris, and coconut.	*Pleurotus flabellatus*	Islam, 2009
Sawdust, peat of coconut husk, narrow leaf cattails, bagasse	*Pleurotus ostreatus*	Vetayasuporn, 2006
Paddy straw, wheat straw, soybean straw, sugarcane bagasse, cotton waste, coconut coir pith	*Calocybe indica*	Porselvi & Vijaykumar, 2019
Sugarcane bagasse with cow dung, horse manure, chicken manure, cotton seed hull, sugarcane trash	*Lentinus edodes*	Desisa et al., 2022
Paddy straw, wheat straw, sugarcane bagasse	*Pleurotus pulmonarias*	Pant et al., 2006
Panicum repens, *Pennisetum purpureum*, *Zea mays*	*Pleurotus citrinopileatus*	Liang et al., 2009
Paddy straw, rubber tree straw	*Pleurotus eryngii*	Moonmoon et al., 2010
Paddy straw	*Pleurotus sapidus*	Singh & Sing, 2012
Onion waste, tea waste, paddy straw, wheat straw, sugarcane bagasse	*Pleurotus sajor-caju*	Banik & Nandi, 2004
Paddy straw	*Volveriella volvacea*	Ahlawat et al., 2010

favourable conditions for the performance of mushroom fruiting bodies. This balanced carbon-to-nitrogen ratio is crucial for the growth and development of mushrooms (Harith et al., 2014). Agro-waste, such as agricultural residues and by-products, not only serves as an environmentally friendly substrate but also contributes to the sustainability of mushroom cultivation. When considering the application of spent mushroom substrate (SMS) for fertilizer, it’s crucial to assess and manage nutrient levels. Understanding the nutrient composition of SMS helps ensure that it aligns with the specific needs of the crops or plants it is being used for. Balancing nutrient ratios and considering factors like nitrogen, phosphorus, and potassium content is essential to maximize the benefits of SMS as a fertilizer. The nutrient composition of the spent mushroom substrate (SMS) can vary based on the mushroom species cultivated and the type of substrate used (Kamthan & Tiwari, 2017; Mohd Hanifi et al., 2018) (Table 3).

Table 3: Composition of Spent Mushroom Substrate (SMS).

Substrate	Composition
Bean straw	Carbohydrates (31.3%), Moisture (85.8%), Ash (9.4%), Crude protein (37.6%), Crude fat (2.6%), and Crude fiber (9.3%)
Paddy straw	Carbohydrates (42.3%), Moisture (90.4%), Ash (90.4%), Ash (1010%), Crude protein (38.1%), Crude fat (1.0%), Crude fiber (1.70%)
Wheat straw	Cellulose (40%), Hemicelluloses (39%), Lignin (13%) and Protein (1%)
Rice straw	Cellulose (41%), K_2O (0.3%), P_2O_5 (0.25%), SiO_2 (6%), total nitrogen (0.8%), and pH 6.9
Sugarcane bagasse	Ash (1-4%), Cellulose (35-40%), Hemicellulose (20-25%), Lignin (18-24%), Nitrogen (0.7%), and Waxes (0.7%)
Cotton waste	Moisture (88.1%), Ash (6.1%), Crude protein (21.6%), Crude fat (8.4%), and Crude fiber (9.3%)

Food security assurance:

The excerpt highlights the importance of food security and the role mushrooms can play in addressing nutritional, pharmaceutical, and economic aspects (WHO, 2012). The challenges of hunger, food shortages, and the “perfect storm” of scarcity predicted by 2030 underscore the need for sustainable solutions (The Guardian, 2009; The Guardian, 2011). The emphasis on awareness and cultivation, especially in regions facing high food insecurity like African and developing Asian countries, reflects a proactive approach to addressing global nutritional challenges (Pandey et al., 2018; Sustainable Development Goals, 2020). The pursuit of alternative, cost-effective, and protein-rich food sources has led to the exploration of edible fungi, particularly mushrooms of the Basidiomycetes class (Mukherjee & Nandi, 2004). Mushroom cultivation, as an indoor crop utilizing vertical space, offers advantages like land efficiency and waste utilization. Notably, mushrooms are a potent protein source, with production efficiency nearly 100 times higher than traditional agriculture (Sing et al., 2011). Approximately 50% of edible mushrooms are considered functional food, contributing to both nutrition and potential health benefits (Food Revolution Network, 2016). China leads the world in mushroom production, surpassing 20 million tons, constituting over 80% of global production. The mushroom industry continues to play a significant role in addressing protein needs and sustainable food production (Dai et al., 2009; Li, 2012). Mushroom farming has become a global phenomenon, spanning over 100 countries, and its production is steadily increasing at an annual rate of 6–7%. In developed European and American nations, mushroom cultivation has evolved into a high-tech industry marked by significant mechanization and automation (Sing et al., 2011), reflecting advancements in agricultural practices. This shift underscores the importance and widespread adoption of mushrooms as a valuable and sustainable agricultural product. The Asia Pacific region takes the lead in the global mushroom production market. China, being the largest producer of mushrooms worldwide, not only

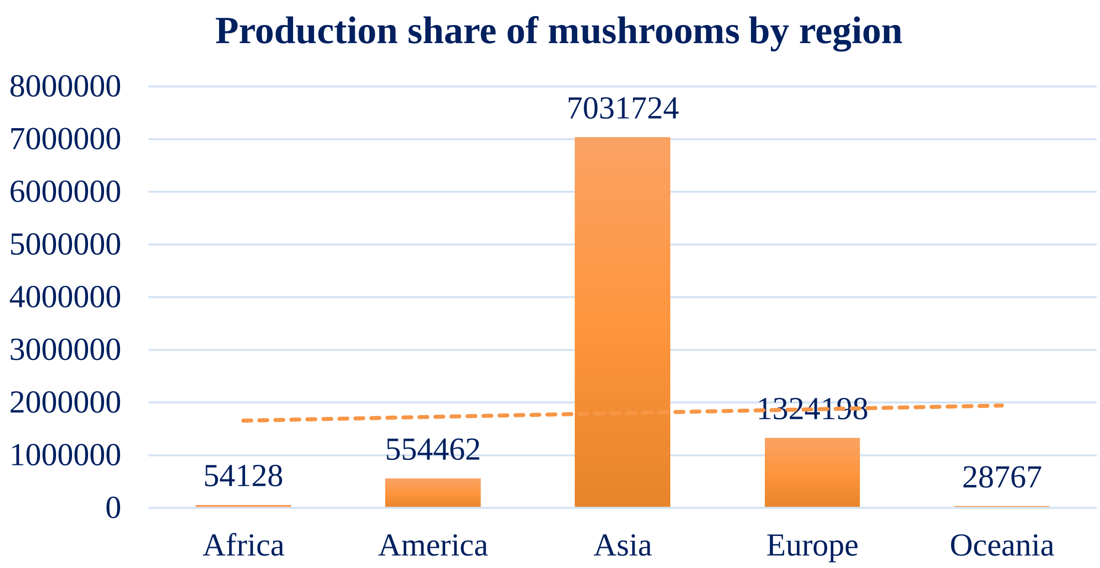

Figure 3. Region-wise production of mushrooms.

contributes significantly to the overall production but also boasts a higher per capita consumption compared to any other country (FAO, 2018; Faostat Production database, 2018) (Figure 3). This underscores the prominence of the region, especially China, in shaping the dynamics of the mushroom industry.

China stands out as a global leader in the production of various mushroom varieties, including *Lentinula edodes*, *Volvariella volvacea*, *Agaricus bisporus*, and others (Wu et al., 2013). The consumption patterns differ among countries, with China, the EU, and India relying significantly on domestic sources, while the United States, Japan, Australia, and Canada combine domestic production with substantial imports (USITC, 2010). In Africa, where food insufficiency and malnutrition persist, mushrooms emerge as a potential solution, offering a protein-enriched alternative to staple foods with low micronutrients (Ishara et al., 2018). Nigeria provides a notable example where mushrooms contribute to combating poverty, hunger, and malnutrition. Similarly, the People of Bamenda Highlands turn to mushrooms for food security during shortages (Fongnzossie et al., 2020).

International forums, such as those dedicated to edible, medicinal, and wild mushrooms, aim to uplift the global mushroom industry (Chang, 2006; Fortune Business Insights, 2019). Key players in the mushroom market include Monterey Mushrooms, Inc., Weikfield Foods Pvt. Ltd., and others (Fortune Business Insights, 2019). However, challenges like pathogenic issues, political and financial obstacles, and weak government policies hinder mushroom production in developing nations.

Sustainable use of SMS as an agro-industrial resource:

Spent mushroom substrate (SMS) refers to the residual material left after the cultivation of mushrooms. It is essentially a by-product of the mushroom farming process (Phan & Sabaratnam, 2012). Instead of being discarded as waste, SMS can be utilized in various ways to contribute to sustainable agriculture and the efficient use of agro-industrial resources (Kivaisi et al., 2010). SMS is rich in organic matter and nutrients, making it a valuable soil amendment. It can enhance soil structure, water retention, and nutrient content. SMS can be added to compost piles to enhance the nutrient content and accelerate the composting process. Mixing it with other organic materials creates a balanced and nutrient-rich compost that can be used as a natural fertilizer for plants. The spent mushroom substrate can be used as a feedstock for bioenergy production through processes like anaerobic digestion or combustion. While the substrate has been used to grow one batch of mushrooms, it may still contain residual nutrients suitable for growing other crops. Depending on the mushroom species and the cultivation process, SMS may have residual nutritional value (Mohd. Hanafi et al., 2018). The spent mushroom substrate has been explored for its potential in environmental applications, such as bioremediation (Ghose & Mitra, 2022) (Figure 4).

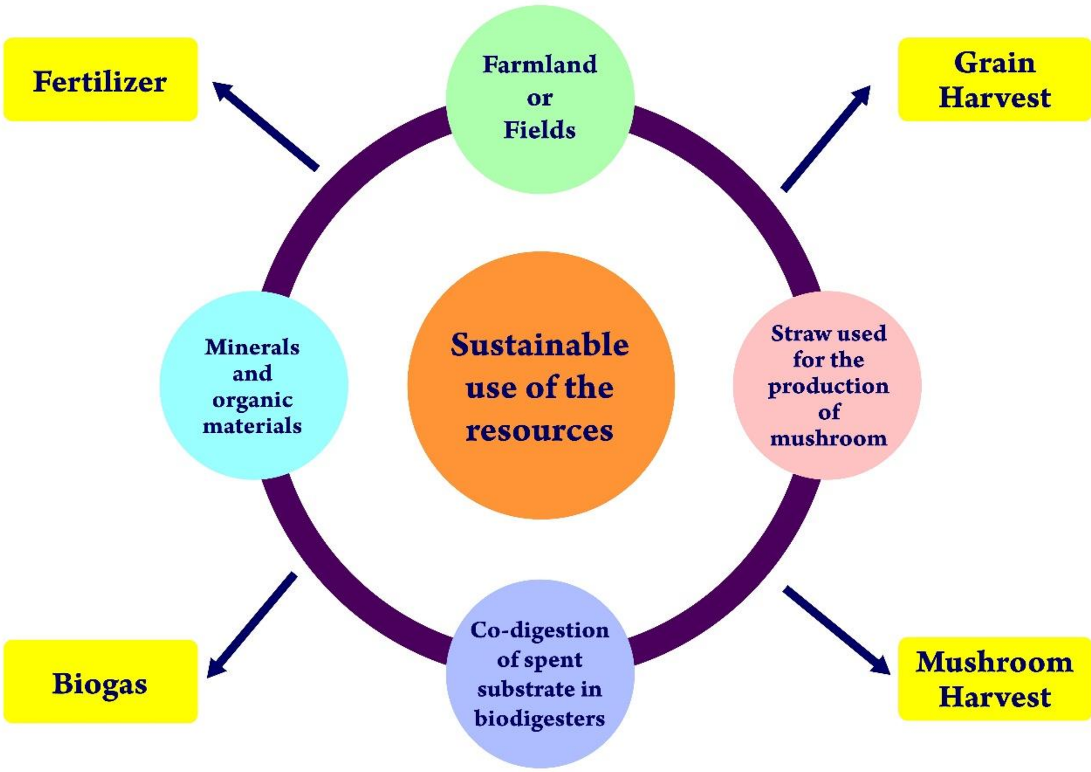

Figure 4. Sustainable use of agro-industrial resources.

Lignocellulolytic Enzyme Production by Mushroom Using Agro-Industrial Wastes:

The decomposition of lignocellulosic materials, a crucial process in the terrestrial carbon cycle, involves various decomposers such as bacteria, micro-fungi, mushrooms, earthworms, and woodlice (Eichorst & Kuske, 2012; Cragg et al., 2015; Bredon et al., 2018). Lignocellulose, consisting of cellulose, hemicellulose, and lignin, requires the collaborative action of multiple carbohydrate-active enzymes due to different bonding functions (Lombard et al., 2014; Andlar et al., 2018). The degradation process involves both hydrolytic and oxidative enzymes, with hydrolytic enzymes breaking down cellulose and hemicellulose, while oxidative enzymes participate in lignin degradation (Lopez-Mondejar et al., 2016; Madeira et al., 2017; Kumla et al., 2020) (**Figure 5**). This synergistic activity is essential for the efficient breakdown of lignocellulosic biomass in the environment.

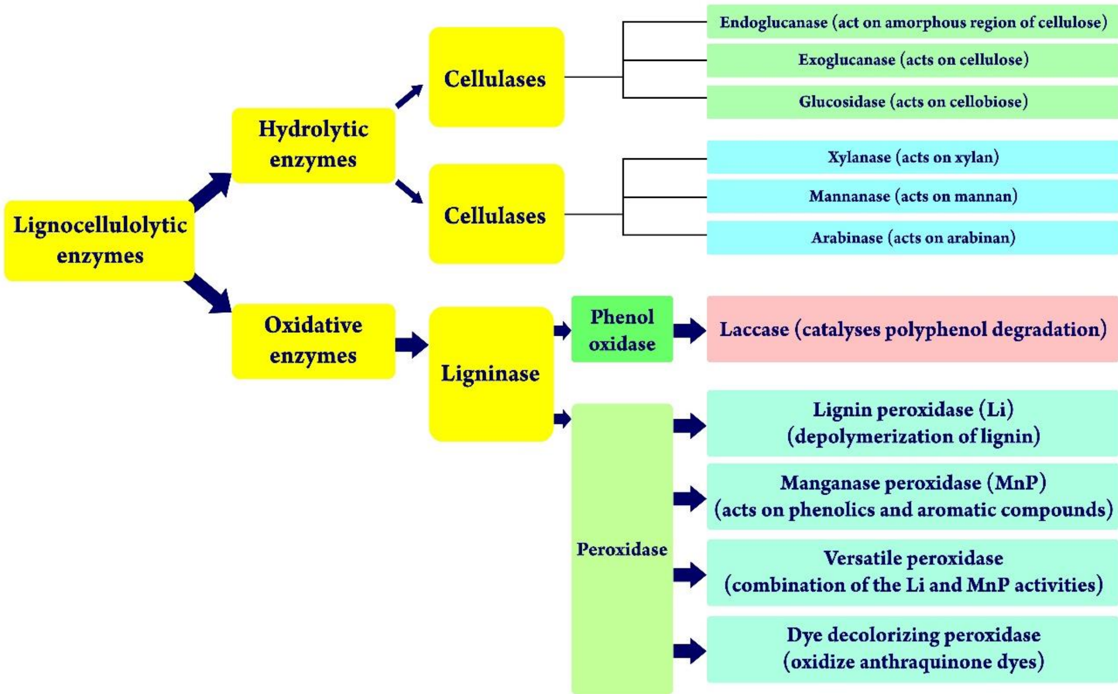

Figure 5. Scheme of enzymes involved in the lignocellulosic degradation process.

Application of Spent Mushroom Substrate (SMS):

SMS as Animal feedstock:

The lignocellulosic biomass such as paddy straw, wheat straw, and barley straw is utilized as a ruminant feedstock due to its rich nutrient content. These agricultural residues are excellent sources of fiber, providing energy and promoting digestive health in ruminants. The high fiber content, including cellulose and hemicelluloses, supports the complex digestive systems of animals like cows and sheep (Rezaei et al., 2015; Amerah, 2015). Ruminants are herbivores with a specialized digestive system that allows them to efficiently break down and extract nutrients from plant materials. Their stomach is divided into multiple compartments, including the rumen, where microbial fermentation of fibrous plant material occurs. This fermentation process helps break down complex carbohydrates like cellulose into simpler compounds that the ruminant can digest (Jami & Mizrahi, 2012). While cattle may be inclined to consume paddy straw, a challenge lies in its high silica content. Silica can negatively impact feed digestibility, affecting the overall nutritional value of the straw for cattle (Drake et al., 2002). The high silica content in paddy straw can limit its digestibility for ruminants, impacting its overall utility as a feed source. While ruminants have specialized digestive systems capable of breaking down fibrous materials, excessive silica can hinder the efficiency of this process. The nutritional value derived from paddy straw may be lower compared to other feed options (Sarnklong et al., 2010; Van Kuijk et al., 2015). Mushrooms are a nutritious food source and can be included in a balanced human diet (Furlani & Godoy, 2008; Stamets, 2011). The increasing consumption of mushrooms, whether fresh or preserved, is likely due to their versatility, nutritional benefits, and culinary appeal (Jayakumar et al., 2011). Mushrooms offer a unique flavour and texture, and they are a good source of vitamins, minerals, and protein. Optimizing the production efficiency and reducing the cost of supplemental feed for ruminants, like dairy cattle, is crucial for both smallholder and commercial farmers. Understanding and balancing components such as neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, ash, cellulose, hemicellulose, and protein in the forage or supplemental feed can contribute to improved digestibility for ruminants (Fazaeli et al., 2014; Van Wyngaard et al., 2015). Utilizing SMS in ruminant feeding is a valuable approach (Fazaeli et al., 2014). The components like fiber, cellulose, and hemicellulose in SMS contribute to the structural composition of forage, promoting proper digestion in ruminants (Rezaei et al., 2015; Amerah et al., 2015; Gimeno et al., 2015). Integrating SMS into the diet helps support the complex digestive processes of these animals, ensuring a balanced and nutritionally adequate feed for their well-being (Yang et al., 2016; Zhang et al., 1995). The higher ruminal degradability and lower neutral detergent fiber (NDF) content in agro-based SMS make it a promising candidate for developing additional supplements for ruminant animals (Aldoori et al., 2015). The SMS obtained from various mushroom species is suitable for ruminant feedstock due to its content of essential nutrients such as polysaccharides, vitamins, and trace elements like iron (Fe), calcium (Ca), zinc (Zn), and magnesium (Mg) (Medina et al., 2009; Zhu et al., 2012; Fazaeli et al., 2014). These components make mushroom-derived SMS a nutritionally valuable option for ruminants, comparable to commercial animal pellets. The content of amino acids and dietary protein is vital in the diets of ruminants. The addition of SMS to the diet of elk has been observed to enhance their physiological condition during growth. Specifically, *P. florida* straw-based SMS demonstrated a higher degradable value compared to *P. sajor-caju*-SMS. The utilization of *P. ostreatus* corn straw-based SMS has shown positive effects, improving the chemical composition of straws and enhancing the growth performance of feedlot lambs (Galaviz-Rodriguez et al., 2010; Park et al., 2012). The utilization of agro-based SMS in feeding ruminants offers a valuable approach to enhancing their diet (**Table 4**).

Table 4: Utilization of agro-based SMS in feeding ruminants.

Types of mushroom	Substrates types	Findings	Feeding trial	Remarks	References
Agaricus bisporus	SMS 15%	No remarkable differences were noticed in the carcass and internal organs of the claves that received the SMS.	Holsteins male calves	The result was taken after 170 days of SMS feeding.	Fazaeli et al., 2014
Agaricus bisporus	SMS 10%,20%,30%	Nitrogen balance and digestibility were normal up to 20% SMS.	Sheep	Above 20% may show some imbalance in nutrient uptake. The result was taken after three weeks of observation.	Fazaeli et al., 2006
Agaricus bisporus	Wheat straw, poultry manure, calcium sulfate, sugar beet molasses, and urea.	Used in the diet of finishing calves in pellet form.	calves	The total mixed ratio in marsh form can negatively affect the feed intake.	Fazaeli et al., 2014
A.blazei	SMS 0.2% - 1.0%	0.2% SMS showed the best result in weight gain, and feed conversion.	Broiler chicks	Data taken up to 42 days and above 0.4% of SMS reduced animal performance.	Machado et al., 2006

Cordyceps militaris	SMS 0.2%	Increased final body weight.	Crossbred growing pigs	Other body parameters like IgA, and IgG were the same till 6 weeks.	Boontium et al., 2019
Flammulina velutipes	fresh SMS	Decreased protozoa in the rumen.	Holstein steers.	Negatively effect. protozoa population and methane emission.	Rangubhet et al., 2017
Ganoderma lucidum	Hot water extract of SMS	It enhanced murine function.	mice	After 30 days, it was observed that 0.84g/kg dose had an optimal effect in all aspects.	Liu et al., 2018
Ganoderma lucidum	Hot water extract of SMS	It enhanced milk quantity, immunity, and antioxidant capacity.	Holstein cows	The given data was taken after 60 days of SMS feeding.	Liu et al., 2015
G. chalceum	Hot water extract of SMS	It enhanced milk protein, quantity, triglyceride level, and hematology parameters.	Chinese Holstein cows	The given data was taken after 60 days of SMS feeding.	Liu et al., 2015
Grifola frondosa	SMS	No remarkable effect on body weight, feed efficiency, or biochemical	Wistar rats	Fecal weight and protein content were slightly higher than the control.	Tasaki et., al. 2013

		parameters.			
Hypsizygus marmoreus	SMS fermented with Bacillus subtilis	Egg production, egg mass, egg white, feed conversion, and viability were the same.	Laying hens	After 12 weeks of observation feed intake increased.	Kim & Song, 2014
Lentinula edodes	SMS fermented with Bacillus subtilis	Increased final weight, daily gain, feed conversion, and immunity.	Weaned piglets	The data was reported after 33 days.	Liu et al., 2020
Pleurotus sajor-caju	Rice straw fermented with SMS	Increased nutrient content, degradability of dry matter, and milk yield.	Alpine dairy goats	The data was reported after 28 days.	Fan et al., 2023
Pleurotus sajor-caju	SMS 0.5- 2%	SMS up to 0.67% improved the weight gain till the first 21 days.	Broiler chicken	Above 0.67% may show some imbalance.	Azevedo et al., 2015
Pleurotus ostreatus	SMS 10 %	After 60 days, increased the digestibility of crude fat.	Male sika deers	It can be replaced by the intake of organic matter.	Yuan et al., 2022
Pleurotus ostreatus	SMS co-fermented with feed and whole plant rice.	No adverse effect on the slaughter.	Liuyang black goats	After feeding for 60 days the meat quality was improved.	Huang et al., 2022

Pleurotus ostreatus	SMS fermented or not with Lactobacillus brevis.	No adverse effect till 13 days.	Hanwoo steers	Could replace formulated feed concentrate.	Baek et al., 2017
Pleurotus ostreatus	SMS	Up to 5% had no effect.	geese	After 8 weeks, it favors effective sensory attributes.	Chang et al., 2016
Pleurotus ostreatus	SMS (5, 10, 15 and 20%)	SMS ratio (up to 15%) decreased slaughter, empty body, and carcass weights, dressing, and leg lean.	Awassi sheep	The data was reported after 70 days.	Kim et al., 2015
Pleurotus ostreatus	SMS substituted wheat bran	SMS improved feed intake	broilers	Til 8 weeks, SMS did not affect breast, thigh, drumstick, back, neck, wings, and shoulder weight.	Foluke et al., 2014
Pleurotus ostreatus	SMS 10% fermented or not with lactic acid bacteria	Fermented SMS enhanced the growth compared to non-fermented SMS.	Postweaning claves	Data were taken up to 60 days.	Kim et al., 2011
Pleurotus ostreatus	SMS with rice bran and	3% SMS enhanced the	Berkshire pigs	After 7 weeks daily feed	Song et al., 2007

	barley bran 3,5,7%	growth, carcass trait, meat quality, and fatty acid concentration of meat.		intake and feed conversion increased.	
Pleurotus ostreatus	Fresh SMS	No negative effect of up to 15% SMS.	Awassi lambs	It can replace barley.	Aldoori et al., 2015
Pleurotus eryngii	Microbially fermented SMS 50%	Enhanced growth and carcass traits.	Hanwoo steers	After observing 12.6 months it can be concluded that it could be successfully replaced as part of conventional roughage.	Lee et al., 2017
Pleurotus eryngii	SMS (5, 10, 15 %) fermented with Bacillus subtilis	Egg production, egg mass, egg white, feed conversion, and viability were the same.	Laying hens	After 7 weeks yolk colour was more intense.	Kim et al., 2012

SMS did not improve the nutritional quality of agricultural by-products; it may not be considered ideal forage for ruminants in that context. Applying biological treatment can be effective in improving the digestion of straws and increasing digestibility for ruminant animals. Biological treatment has the potential to improve the nutritional composition of straws for ruminant animals. It can lead to an increase in crude protein and fat content while reducing the amount of crude fiber (Mahesh & Mohini, 2013; Abdel-Aziz et al., 2015). The high fibrinolytic activity of SMS from *A. bisporus* species is advantageous as it can significantly increase the degradation of forages for ruminants. This fibrinolytic activity is crucial in breaking down complex fibers in forages, making them more digestible and nutritionally available for ruminant animals during the digestive process (Kwak et al., 2009; Ayala et al., 2011).

Certain types of SMS have low nutrient composition and are deemed incompatible for use as ruminant feedstock; modifications may be necessary. Applying biological treatment is a viable strategy to enhance the nutrient composition and ruminal digestibility of SMS that may initially have lower nutritional value. The complex relationship among rumen microorganisms, conformation, and biological activity warrants further studies (Liu et al., 2015). Using SMS in combination with conventional roughage has the potential to improve forage quality, especially in Asian countries. To address this, conducting large-scale research would be practical and beneficial (Kim et al., 2015).

SMS for Fertilizer:

The nutrient content and generally non-toxic nature of SMS make it feasible for use as a bio-fertilizer, supporting plant growth. The nutrients present in SMS can contribute to soil fertility, promoting healthier and more robust plant development (Sendi et al., 2013). The main components of SMS that make it suitable for use as fertilizer include calcium, nitrogen, ash, and protein (Lou et al., 2017; Owaid et al., 2017). These components contribute to the nutrient content of SMS, providing valuable elements for plant growth and soil fertility. Numerous studies have demonstrated the feasibility of using SMS in horticulture applications, both alone and in combination with other materials (Nakatsuka et al., 2016; Lou et al., 2017). The attention to reusing SMSs for soil improvement is well-founded, given their richness in nitrogen (Lou et al., 2017). The ability of SMS to modify soil structure is noteworthy, as it can play a role in preventing the transport of pesticides or facilitating their dispersion. The utilization of SMS from *Lentinus edodes* as a replacement for mulch is promising, given its favourable physicochemical characteristics and biological activity in pesticide degradation (Gao et al., 2015). The richness of *Lentinus edodes* SMS in organic and essential plant nutrients enhances its utility for soil improvement and mulching. The results of a 42-day incubation of mushroom cultivation demonstrate a significant enhancement of mineral nitrogen in the soil (Lou et al., 2017). Phosphorus (P) is a major nutrient essential for plant growth. The application of SMS in improving soil structure can serve as an effective additive of phosphorus for soils (Zhu et al., 2012). The richness of SMS in phosphorus makes it a valuable addition to agricultural land. When applied, SMS contributes to enhancing soil organic matter and nutrient contents, particularly phosphorus (Lou et al., 2015).

SMS can serve as a bio-fertilizer for the cultivation of *Pleurotus spp*. (oyster mushrooms) and potentially other mushroom species (Owaid et al., 2017). Many studies have explored the use of SMS for growing crops, including pineapple, tomatoes, and lettuce (Adedokun and Orluchukwu et al., 2013; Lopes et al., 2013; Paredes et al., 2016). The addition of pig manure to SMS is a practical approach that can increase the nutritional content of nitrogen (N), phosphorus (P), and potassium (K) (Meng et al., 2018). This enhanced nutrient profile makes the combination suitable for use as fertilizers, providing a balanced mix of essential elements for plant growth (Zhu et al., 2013). The significant differences in yield were reviewed in plants cultivated on soil treated with SMS from *A. bisporus* and *Pleurotus spp*. The revision that soil treated with SMS can enhance plant yield compared to non-treated soil reinforces the positive impact of using SMS in agriculture (Alvarez-Martin et al., 2016). The example from Zhang et al. (2012), reporting higher yields of tomatoes and cucumbers in soil treated with SMS compared to non-treated soil, supports the notion that SMS application can positively impact crop productivity. The evidence indicating a positive effect of SMS on the growth of vegetables and its use as a replacement for mineral fertilizers is noteworthy. Additionally, the higher grain yield observed for maize treated with micronutrients from SMS, resulting in an 11.5% increase compared to non-treated ones, further supports the potential of SMS in improving crop yields. The finding that SMS led to a higher grain yield for maize when used as a source of micronutrients indicates its potential as a micronutrient fertilizer. The conversion of SMS into a micronutrient fertilizer through a bio-sorption process, leading to improvements in soil structure, quality, and sorption capacity, underscores the versatility and potential benefits of SMS in agriculture (Tuhy et al., 2015). Mixtures or improved agro-based SMS can serve as effective bio-fertilizers for various crops, enhancing their cultivation (Table 5).

Integrating SMS using new formulations and methodologies presents added advantages, including the potential to lower production costs and minimize the environmental impact of its over-growing accumulation. Further studies are crucial to explore new biological material drying methods and identify new types of biomass for the production of micronutrient fertilizer components. The strategy of exploring new biological material drying methods and diverse biomass sources is anticipated to lead to an increase in the portfolio of new micronutrient fertilizer products (Tuhy et al., 2015).

Table 5: Mixtures or Improved Agro-based SMS as Bio-Fertilizers for Different Crop Cultivations.

Types of mushroom	Mixture/improved substrates	Crops trials	Findings	Remarks	References
Agaricus bisporus	SMS + peat moss	*Brassica oleracea var. Alboglabra*	SMS can decrease the amount of peat moss for culture thus it is also cost-effective.	50% SMS and 50% peat moss should be used, SMS alone cannot work as a growing media	Sendi et al., 2013
Agaricus bisporus	SMS of Agaricus crop + SMS of *Pleurotus* crop	Lettuce	SMS improved soil fertility and	Mineral fertilizers also show the same results	Paredes et al., 2016

			nutritional contents		
Agaricus bisporus	Wheat straw	Italian grass	SMS increased the yield by up to 300%, and also enhanced the growth.	It can be used as a replacement for peat.	Paula et al., 2017
Agaricus bisporus	Bio-sorption of SMS	Maize	SMS increased the nutrient contents.	SMS shows better growth than NPK	Tuhy et al., 2015
Agaricus bisporus	SMS + Talc	*Trichoderma viride, rhizobium japonicum*	SMS was found to be a good carrier for shelf life and survival.	Talc gave maximum propagules.	Shitole et al., 2014
Agaricus subrufescens	Fresh SMS	Tomato crops	SMS increased the yielding capacity as well as the fruit size.	Yield was higher or equal as compared to other fertilizers.	Lopes et al., 2015
Hypsizygus marmoreus	SMS + cotton seed hull + wheat bran	*Pleurotus ostreatus*	25% SMS showed the best result.	Economically effective	Wang et al., 2015
Lentinula edodes	Wheat straw-based SMS	*Solanum lycopersicum*	SMS showed significant potential in germination, yield, growth, and biochem-ical	SMS potentially contributes to minimizing the carbon footprints of the mushroom	Kumar et al., 2022

			parameters.	production sector.	
Pleurotus ostreatus	Sawdust based SMS	Pineapple	SMS showed two times higher fruiting bodies than the control.	Performed better than control soil	Adedokon et al., 2013
Pleurotus ostreatus	Fresh SMS	-	SMS changed the soil structure and porosity.	SMS developed granular aggregates in the soil.	Nakatsu et al., 2016
Pleurotus ostreatus	Sawdust based SMS	Fluted pumpkin	SMS showed higher values of N, P, and K.	SMS improved the number of vines, vine length, and leaf structure.	Orluchukwu et al., 2016
Pleurotus sp.	SMS of Agaricus crop + SMS of Pleurotus crop	Lettuce	SMS improved soil fertility and nutritional contents	Mineral fertilizers also show the same results	Paredes et al., 2016
Pleurotus florida	Saw dust with paddy straw and tea	*Capsicum annum*	SMS alone resulted in a maximum increase of phosphorus in soil.	SMS can decrease the usage of chemical pesticides so, it is environment ally effective.	Ignatius et al., 2021
Volveriella volvacea,	Fresh SMS	*Capsicum annum*	SMS showed	SMS of Volveriella	Yang et al., 2019

Pleurotus ostreatus			higher growth and disease control.	showed greater results than SMS of Pleurotus.	

SMS for energy production:

Agro-industrial biomass, particularly lignocellulosic materials, is renewable, abundant, and represents a unique natural resource for bioenergy production. Its use in bio-energy processes contributes to sustainable energy practices, utilizing organic materials derived from agricultural processes to generate power or produce bio-fuels (Rezania et al., 2017). The utilization of SMS for energy production not only offers a sustainable management solution but also helps 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) (Finney et al., 2009). According to the literature, the application of SMS in energy production emerges as a promising alternative for mushroom producers. This approach not only helps minimize SMS production on-site but also promotes the sustainable growth of mushrooms. The use of SMS in bio-ethanol production can mitigate environmental issues arising from the mushroom industry (Kapu et al., 2012; Ryden et al., 2017). The lower lignin content in SMS, resulting from the degradation process during mushroom production, is advantageous for energy production (Phan & Sabaratnam, 2012). The example you provided, highlighting the efficient combustion of SMS in pellet form with a combination of coal tailing (up to 91.7% efficiency), underscores the practical advantages of using SMS in energy production (Finney et al., 2009). The highly degradable nature of SMS is advantageous, and the co-digestion of SMS with wheat straw has proven to be efficient in enhancing methane production (Lin et al., 2014). Hydrogen production from SMS using *Clostridium thermocellum* for lignin degradation showcases the versatility of SMS in bio-energy applications. The ability to harness hydrogen through microbial processes not only provides an alternative energy source but also addresses the challenge of lignin, which is often less accessible in traditional energy production methods (Lin et al., 2016). As reported by Wu et al., SMS contains a high yield of reducing sugar, indicating its potential as a carbon source (Wu et al., 2013). The usage of SMS in energy production holds significant potential due to its various favourable characteristics, such as high degradability, reduced lignin content, and the presence of reducing sugars (Table 6).

Table 6: Application of SMS in energy production.

SMS type	Findings	Energy	References
SMS	The concentration of ethanol produced and the substrate concentration.	Ethanol	Asada et al., 2011
Sorghum-based SMS	The yield of 63.9 g/kg dry matter means that for every kilogram of dry matter in the substrate, 63.9 grams of ethanol is produced.		Ryden et al., 2017
SMS and kelp seaweed	A process involving co-pyrolysis of sewage sludge (SMS) with 10% kelp seaweed. The presence of oxygen-containing groups in biochar can influence its reactivity and surface properties. These groups might include carboxyl, hydroxyl, and carbonyl functional groups. They can affect the biochar's ability to adsorb substances and play a role in its overall chemical reactivity.	Bio-char	Sewu et al., 2017
SMS with pig manure and rice straw	The biochar derived from sewage sludge (SMS) is rich in nutrients such as phosphorus (P), potassium (K), sodium (Na), and nitrogen (N). The nutrient content in biochar can have significant implications for its potential use as a soil amendment or fertilizer.		Chang et al., 2017
SMS-based biochar	The biochar derived from sewage sludge (SMS-biochar) has been observed to reduce 43% of total nitrogen (TN) and 66% of chemical oxygen demand (COD). These results suggest that biochar has the potential to be an effective treatment for wastewater or other environments with high levels of nitrogen and organic pollutants.		Lou et al., 2017
Oil shale semi-coke SMS	The bio-oil produced from the co-processing of sewage sludge (SMS) and shale semicoke has high carbon and hydrogen content, along with lower oxygen content.	Bio-oil	Jiang et al., 2017
SMS with chemical vapour deposition of SiO_2	The mixture (presumably the product of co-processing sewage sludge and shale semicoke) has a high oil fraction yield and contains toluene and xylene.		Zhang et al., 2017

SMS	In the context of producing bio-crude (bio-oil or liquid hydrocarbons from biomass), having an effective hydrogen-to-carbon (H/C) ratio above 1 is considered favourable for the quality of the product.	Biocrude	Jasiunas et al., 2017
SMS with *Clostridium thermocellum*	The addition of sewage sludge (SMS) has led to an accumulation of 28% more, specifically 5.06 g/L, of reducing sugars. Reducing sugars typically include monosaccharides and some disaccharides that can reduce certain chemicals, such as Fehling's solution.	Hydrogen	Hu & Zhu, 2017
SMS	There has been an improvement in sugar yield and a reduction in lignin content, and as a result, the maximum amount of butanol produced was 30.21 g/L.	Butanol	Zhu et al., 2016
Co-digestion of SMS and dairy manure	Sewage sludge (SMS) is a suitable feedstock for biogas production, and the high degradability of SMS has a positive influence on anaerobic digestion.	Methane	LUo et al., 2018
Spent mushroom compost and wheat straw	The maximum production (perhaps of biogas or another product) was achieved at a carbon-to-nitrogen (C/N) ratio of 30 and a temperature of 55 °C, with a specific production rate of 44.1001 ml/g.	Biogas	Najafi & Ardabili, 2018

Several important factors need consideration for energy production using SMS: 1. the type of biomass directly influences the yield of energy production. Different biomass sources may have varied compositions affecting their suitability for specific energy production processes; 2. The choice of mushroom species can impact the availability of lignocellulosic parts in the biomass and subsequently influence the sugar ratio. Understanding these variations is crucial for optimizing energy production; 3. Determining the optimum ratio of biomass to SMS is essential for enhancing production rates. Achieving the right balance in the mixture is key to maximizing energy yield; and 4. Co-digestion of SMS with suitable lignocellulosic biomass can be a strategic approach to increase the overall yield of energy production. This synergistic combination enhances the efficiency of the energy generation process (Hanafi et al., 2018). Considering and optimizing these factors contributes to a more efficient and effective utilization of SMS in energy production processes. While the utilization of SMS in energy production offers significant benefits, it’s important to acknowledge that the production yield may be impacted by the generation of certain by-products.

SMS for wastewater treatment:

Several studies have reported that SMS is used as an effective material for treating various pollutants from wastewater (Xu et al., 2012; Song et al., 2014; Garcla-Delgado et al., 2017). SMS proves to be a promising carbon source for nitrogen removal from wastewater due to its efficient characteristics. The addition of SMS has been shown to enhance nitrogen removal significantly, with reported increases from 46.9% to 87.8% (Yang et al., 2017). As discovered by Karas et al. (2016), the fresh mushroom substrate of *P. ostreatus* demonstrated efficiency in removing ortho-phenylphenol and imazalil from wastewater generated in citrus fruit-packaging plants. The use of immobilized SMS from *Pleurotus ostreatus* for the removal of Cd(II) from synthetic wastewater demonstrates the potential of SMS in adsorbing heavy metals (Jin et al., 2018). The study finding that the bio-sorption capacity of immobilized SMS from *Pleurotus ostreatus* for Cd(II) removal is dependent on pH value, initial concentration of Cd(II), and contact temperature in a batch system is significant. The observed maximum adsorption capacity of 100 mg/g, by the Langmuir isotherm model, provides valuable insights into the factors influencing the efficiency of Cd(II) removal using immobilized SMS. The development of SMS from *A. bisporus* as a strategy to improve volatile fatty acids (VFAs) bio-production from waste-activated sludge is noteworthy. This approach not only enhances the efficiency of VFA production but also has the potential to reduce operational costs (Zang et al., 2017).

The effectiveness of oyster mushroom (*P. ostreatus*) in reducing heavy metal and PAH contents in soil compared to the control *M. maximus* grass highlights the potential of certain mushroom species in remediation processes (Yan & Wang, 2013; Zhou et al., 2014; Toptas et al., 2014; Asemoloye et al., 2017). The recent work by Nakajima et al., where active enzymes were extracted from spent mushroom compost, including cellulases, β-glucosidase, dextranase, amylase, and laccase, highlights the potential for repurposing mushroom by-products. The finding that *Pleurotus sp.* exhibited the highest decolorizing capacity among the tested fungi underscores the enzymatic capabilities of mushroom-derived materials (Nakajima et al., 2018). While SMS (spent mushroom substrate) has various beneficial applications, there are challenges associated with its use for the treatment of different types of wastewater. Considering the characteristics of SMS is crucial, and the origin of the mushroom plays a significant role in enhancing adsorption capacity. While SMS-derived adsorbents can be effective for certain pollutants in water, their performance might be limited in high ranges of pollution. The assumption is reasonable; the application of SMS-based adsorbents may face limitations in industrial and refinery wastewater treatment due to the specific characteristics of these effluents. Applying Sewage Sludge (SMS) as a casing layer in mushroom cultivation involves using treated sewage sludge as a top layer covering the substrate to create an environment suitable for mushroom fruiting (Figure 6).

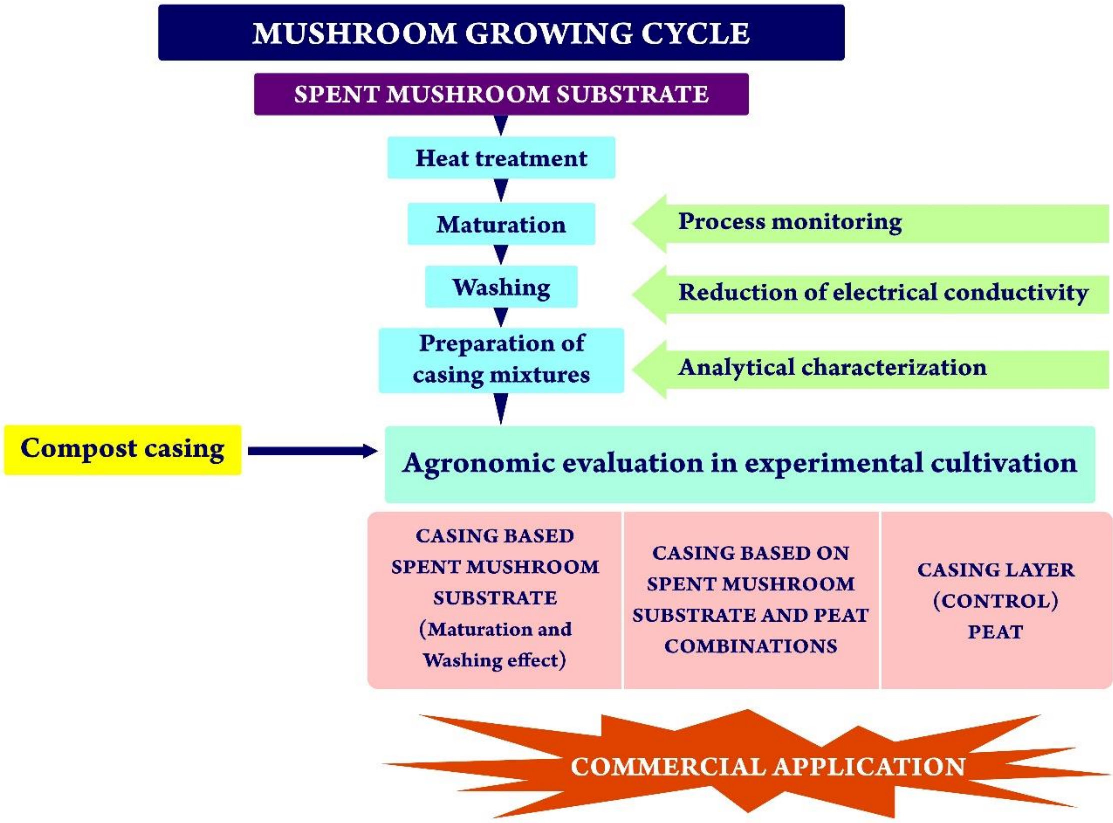

Figure 6. Application of SMS as a casing layer in mushroom cultivation.

Other applications of SMS:

The disposal of spent mushroom substrate (SMS) poses a significant challenge for mushroom-producing countries, as highlighted by Medina et al. One of the major concerns is finding environmentally friendly ways to manage and dispose of SMS to prevent environmental pollution (Medina et al., 2009). The issue of generating a substantial amount of spent mushroom substrate (SMS) in the mushroom industry, approximately 20% for each 1 kg of mushroom beds, presents a significant challenge (Stamets, 2011). The versatile application of spent mushroom substrate (SMS) extends beyond ruminant feedstock, fertilizers, energy production, and wastewater treatment. It also holds potential as a feed additive for aquaculture-farmed fish (Van Doan et al., 2017). The use of spent mushroom substrate (SMS) in the cultivation of fungi through solid-state fermentation for the production of enzymes such as xylanase, amylase, cellulose, and β-glucosidase are an interesting application (Grujic et al., 2015). This demonstrates the potential of SMS as a substrate for fostering fungal growth and enzyme production, adding another dimension to its utility in biotechnological processes. The study conducted by Liu et al., suggesting the use of spent mushroom substrate (SMS) as an antioxidant for the prevention of diabetes, highlights the potential health-related applications of SMS (Liu et al., 2017; Saha et al., 2022). Circular economy maximizes the value of spent mushroom substrate by transforming it into valuable resources like organic fertilizer or livestock feed, mitigating waste and promoting sustainable resource use (Saha, 2023). The other applications of spent mushroom substrate (SMS) are diverse.

Conclusions:

A diverse array of mushroom species, including *Pleurotus spp.*, *F. velutipes* and *V. volvacea*, showcase versatility in cultivation. These mushrooms thrive when cultivated with various agro-residues such as paddy, rice straw, and grass plants. The leftover material from mushroom cultivation, known as Spent Mushroom Substrate (SMS), is a valuable resource rich in nutrients. It contains organic matter, essential minerals, and residual mycelium, making it an excellent choice as a fertilizer. When applied to soil, SMS can enhance soil fertility, improve its structure, and contribute to the overall nutrient content. Spent Mushroom Substrate (SMS) demonstrates the ability to absorb a wide range of organic and inorganic compounds, as well as heavy metals, cost-effectively. The nutritional quality of Spent Mushroom Substrate (SMS) is influenced by the specific mushroom species cultivated on the substrates. Different mushroom species contribute varying amounts of nutrients to the substrate during cultivation. The observation that the growth of *Pleurotus djamor* on maize stover did not enhance the nutritional quality of Spent Mushroom Substrate (SMS) suggests its incompatibility for use as ruminant feedstock. Agro-based Spent Mushroom Substrate (SMS) holds promise for sustainable applications, serving as an eco-friendly alternative in various fields. Its potential lies in agriculture, where it can enhance soil fertility and structure. Additionally, SMS can be utilized in bioremediation, contributing to environmental cleanup efforts. However, considerations should address proper disposal methods, potential contaminants, and optimizing application rates to avoid ecological imbalances. In conclusion, while SMS presents environmentally sustainable opportunities, careful management and research are essential to fully realize its benefits while minimizing potential drawbacks.

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