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Spent mushroom substrate (SMS) as a sustainable soil amendment and biofertilizer: A review of opportunities and challenges in agricultural and horticultural systems

Ida Quisth[1,‡], Isabella Ulfsparre[1,‡], Bettina Müller[1], Volkmar Passoth[1], Svein Øivind Solberg[2], Carlos Martín[2,3], Luis A. Romero-Soto[2], Mari Pent[4] and Hesam Mousavi[2]

[1] Department of Molecular Sciences, Swedish University of Agricultural Sciences, Uppsala BioCentrum,
Box 7015, SE 75007 Uppsala, Sweden

[2] Faculty of Applied Ecology, Agricultural Sciences, and Biotechnology, University of Inland Norway, 2418 Elverum, Norway

[3] Department of Chemistry, Umeå University, SE-901 87 Umeå, Sweden

[4] Institute of Ecology and Earth Sciences, University of Tartu, 51005 Tartu, Estonia

[‡] These authors contributed equally to this work.

e-mail: hesam.mousavi@inn.no

Spent mushroom substrate (SMS), a byproduct of mushroom cultivation, has gained increasing attention as a sustainable soil amendment in agricultural and horticultural systems. SMS provides a promising alternative to peat-based substrates and synthetic fertilizers, supporting circular bioeconomy principles and sustainable farming practices. This is particularly relevant in boreal regions, where soils are typically acidic, nutrient-poor, and subject to short growing season conditions, presenting both opportunities and challenges for organic inputs. This review synthesizes current research on the agronomic and environmental implications of SMS use in agriculture and horticulture, including its effects on seed germination, plant growth, crop yield, root development, soil structure, and disease suppression. From an environmental perspective, the use of SMS contributes to waste reduction by repurposing organic residues and replacing peat, a non-renewable resource with significant ecological costs. However, several hurdles remain, including high salinity, inconsistent composition, nutrient imbalances, and complex compounds difficult for plants to access, which can impede plant performance. While prior studies have explored SMS in isolated settings, a comprehensive evaluation across systems is lacking. This review addresses that gap by assessing current evidence, identifying limitations, and outlining future research needs to optimize the use of SMS and scale its adoption in sustainable farming.

Key words: sustainable agriculture, peat alternative, organic waste recovery, circular bioeconomy, soil health, environmental safety

Introduction

Spent mushroom substrate (SMS) is the residual biomass generated after ending the mushroom cultivation cycle in lignocellulose-based substrates (Martín et al. 2023b). Once the mushrooms are harvested, a substantial quantity of SMS remains. Although the SMS still contains a part of the carbohydrates and lignin contained in the initial substrate (Klausen et al. 2025), it is depleted of the nutrients needed to support an additional mushroom production cycle (Kousar et al. 2024). SMS typically consists of partially decomposed lignocellulosic biomass, fungal mycelium remnants, and a small amount of non-utilized nutrients. It is rich in organic compounds, including proteins, polysaccharides, lipids, and phenolic compounds—many of which are beneficial for plant growth and soil health (Velusami et al. 2021, He et al. 2024). For each kilogram of fresh mushrooms produced, up to 5 kg of SMS is generated, totaling over 60 million tons of SMS worldwide in 2018 (Zhu et al. 2018, Meshram et al. 2024), and this amount is projected to reach approximately 104 million tons by 2026 (Atallah et al. 2021).

Due to its high organic matter content and presence of essential macro- and micronutrients, SMS has gained attention as a sustainable input in both agricultural and horticultural systems. Studies have shown that SMS from various mushroom species can enhance plant growth, act as an organic fertilizer, improve seedling development, and serve as an effective soil amendment (Velusami et al. 2021, Alves et al. 2022). Additionally, SMS harbors diverse microbial communities that not only support plant health but may also suppress soilborne pathogens such as nematodes and fungi. Its potential in bioremediation has also been explored, particularly in its capacity to remediate pollutants and contaminants from soils (Malik et al. 2021).

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SMS can be used in its raw form or processed into spent mushroom compost, a more stable, nutrient-rich product. When incorporated into peat-based growing media or soil in varying proportions, SMS has been shown to improve plant yield, root development, and growth, depending on crop type (Khalil et al. 2024). Moreover, it has been associated with enhanced soil physical properties, including better water retention, increased aggregate stability, and improved filtration capacity (Courtney and Mullen 2009, Priadi and Saskiawan 2018)

Environmental concerns about the use of peat—a non-renewable resource—have accelerated interest in alternatives such as SMS. Peat, while valued for its physicochemical properties, contributes significantly to greenhouse gas (GHG) emissions and the degradation of wetlands. Several countries have already implemented restrictions or bans on peat use (Gao et al. 2015). Consequently, SMS is being considered a more sustainable alternative, as research indicates it could effectively replace at least parts of growing media (Hernández et al. 2021, Oliveira Vieira et al. 2022).

Therefore, integrating SMS into horticultural and agricultural systems provides dual benefits: enhancing crop productivity and promoting circularity by diverting organic waste from landfills. Its valorization supports more resilient, eco-friendly food systems and contributes to global efforts to reduce the environmental impact of farming (Zied et al. 2020).

Objectives and scope of review

The purpose of this review is to critically assess the emerging use of SMS in agriculture and horticulture, focusing on its agronomic benefits, functionality as a biofertilizer, soil amendment, and peat substitute, and its environmental implications.

Firstly, the review aims to evaluate the potential of SMS as a biofertilizer and soil amendment by analyzing reported data on its nutrient composition, organic matter content, and effects on soil fertility. Secondly, it seeks to explore the agronomic benefits of SMS by assessing its impact on soil properties, crop productivity, and long-term soil health. This includes investigating improvements in soil structure, nutrient retention, and microbial activity, as well as their influence on plant growth and yield. Finally, the review will explore the environmental implications of SMS use and highlight the advantages and limitations of SMS, compared to traditional biofertilizers and soil amendments, in sustainable farming practices. Collectively, through a thorough analysis of the existing literature, this review aims to provide an understanding of SMS's viability as a valuable resource in modern farming systems, along with suggestions to guide further development and application.

Methodology

Systematic literature review

This review employs a systematic literature review approach to provide a comprehensive and unbiased assessment of existing research on the use of SMS. The approach involves selecting and analyzing relevant studies on the use of SMS as a soil amendment, peat substitute, and biofertilizer in agricultural and horticultural settings, along with their environmental implications.

Search strategy

A structured search was conducted in the Web of Science and Scopus databases to identify peer-reviewed, high-quality research articles published between 2009 and March 2025, written in English, and available as open access. The primary search terms included: “Spent Mushroom Substrate,” “biofertilizer,” “soil amendment,” “peat substitute,” “growing media,” “horticulture,” “agriculture,” and “environment.” Each keyword was supplemented with relevant free-text variants and Boolean operators to capture different word combinations. The whole search strategy, including exact search strings and combinations, is provided in the Appendix (Tables 1 and 2).

In addition to database searches, a manual review of reference lists and citations was conducted to identify further relevant studies. Where access was restricted, article titles or DOIs were used to locate full texts via institutional repositories or third-party sources. In some cases, EndNote was used to retrieve full-text PDFs directly. Studies were included if they investigated the use of SMS in agriculture or horticulture and explicitly focused on plant growth, soil properties, peat substitution, or environmental effects. Although review articles were not explicitly excluded, the emphasis was on original research, and review articles were given lower priority during the selection process.

Data extraction and analysis

From the selected studies, data were extracted on SMS use in agricultural and horticultural settings, including crop type, soil type, application methods, SMS-to-soil ratios, and measured outcomes such as plant growth, yield, or soil improvement. Environmental implications, limitations, and methodological characteristics were also recorded.

Key findings from each study were tabulated and grouped by thematic areas (e.g., crop type, application rate, observed effect, and method of application). A cross-comparison was then performed to identify recurring trends and patterns, such as how different SMS proportions influence crop performance or soil health. To ensure reliability, all included studies were reviewed critically, and extracted data were double-checked to reduce the risk of misinterpretation or omission.

SMS as a soil amendment in agriculture

A growing body of research has investigated the effects of SMS as a soil amendment in agriculture. This section synthesizes current knowledge on how SMS influences crop productivity, soil properties, microbial activity, and long-term agronomic performance. Table 1 consolidates the agronomic impacts of SMS on crop yields, soil health, and long-term fertility across diverse agricultural contexts.

Table 1. Integrated summary of spent mushroom substrate (SMS) applications as a bio-based soil amendment, fertilizer, and peat substitute in agriculture, horticulture, and environmental management

Aspect / Category	Key Findings	Representative References
Nutrient Content & Fertility	SMS is rich in macronutrients (N, P, K, Ca, Mg) and beneficial microbial biomass; composting enhances nutrient availability and stability. Some micronutrients (e.g., Fe, Zn, Mn) may be lacking.	Medina et al. 2009; Postinguel et al. 2025; Domínguez-Gutiérrez et al. 2022; Ravlikovsky et al. 2024; Alves et al. 2022
Crop Productivity	Increases growth, biomass, and yield in cereals, legumes, vegetables, and ornamentals; improves germination and seedling vigor; performance varies by SMS type, dose, and processing.	He et al. 2024; Elsakhawy et al. 2020a, b; Amarasinghe and Jayaweera 2022; Roy et al. 2015
Nutrient Uptake & Efficiency	Increases uptake of P, K, S, nitrate; improves protein content and nutrient cycling; may replace synthetic topdressings.	Domínguez-Gutiérrez et al. 2022; Ngan & Riddech 2021; Wiśniewska-Kadżajan and Malinowska 2022
Soil Physical Properties	Improves structure, porosity, aeration, water retention, root penetration, and reduces bulk density; enhances soil temperature regulation and aggregation.	Ma et al. 2025; Nakatsuka et al. 2016; Kumar and Chugh 2022; Marín-Benito et al. 2016
Soil Chemical Properties	Boosts SOC, CEC, P, and K availability, pH buffering; composting stabilizes pH and reduces EC; nutrient cycling is improved.	Pan et al. 2023; Igual et al. 2024; Mahato et al. 2024; Gupta et al. 2024
Soil Biological Properties	Enhances microbial biomass, respiration, enzymatic activity, and diversity; promotes beneficial microbes (*Trichoderma, Pseudomonas*); supports pollutant degradation.	Martín et al. 2023b; Kwiatkowska et al. 2024; Paula et al. 2020; Prasad et al. 2023
Disease Suppression & Stress Resilience	SMS enhances rhizosphere microbiota and suppresses pathogens (e.g., *Fusarium*), effective in tomato, lettuce, sesame, cucumber, and chili. Improves plant tolerance to drought and salinity; increases shoot/root biomass and physiological resilience when combined with fertilization.	Wang et al. 2020; Mahato et al. 2024; Kumar and Chugh 2022; Hernández et al. 2021; Postinguel et al. 2025
Environmental Benefits	Substitutes for peat and synthetic fertilizers; reduces GHG emissions and environmental degradation; enhances ecosystem resilience, water retention, and erosion control.	Meng et al. 2018; Zakaria et al. 2023; Othman et al. 2020; Roy et al. 2015
Circular Economy & Waste Valorization	Converts agro-waste into valuable input; reduces open dumping, transport emissions, and landfill use; integrates into circular agriculture.	Martín et al. 2023a; Singh et al. 2021; Thygesen et al. 2021; Kousar et al. 2024
Carbon Sequestration	SMS contains slowly decomposing lignocellulosic matter; composting facilitates humification and long-term SOC accumulation; boosts microbial C stabilization.	Singh et al. 2021; Leong et al. 2022; Afsar et al. 2024; Khalil et al. 2024
Long-Term Soil Health	Sustains fertility through slow nutrient release and organic matter buildup; enhances microbial networks and structural stability over time.	Ma et al. 2025; Lou et al. 2017; Paula et al. 2020; Grimm and Wösten 2018
Peat Replacement Comparison	Compared to peat, SMS has higher macronutrient levels and microbial activity but less uniformity and lower organic matter; suitable when mixed with compost or leached.	Medina et al. 2009; Gao et al. 2015; Hernández et al. 2021; Roy et al. 2015
Best Use Practices	Compost or leach SMS before use; blend with peat or compost; enrich with microbes/nutrients; match SMS properties to crop needs; monitor EC/pH regularly.	Prasad et al. 2021; Amarasinghe and Jayaweera 2022; Kahn et al. 2012

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SMS effect on agricultural productivity

Several studies have demonstrated that SMS can enhance crop productivity through various mechanisms. However, outcomes depend heavily on the quality of SMS, the application method, and the environmental context in which it is used. For instance, Courtney and Mullen (2009) reported a 50% increase in barley (*Hordeum vulgare*) yield following SMS application, a result comparable to that achieved with inorganic fertilizers. Their field experiment assessed different rates of SMS, aeration compost, and synthetic fertilizer on barley, revealing that SMS significantly improved soil organic carbon (SOC), available nutrients, and cation levels without raising heavy metal concentrations to concerning levels. The strongest correlations between increased soil nutrient content and barley yield were observed in plots with higher SMS application rates, up to 100 t ha^{-1}, indicating SMS's capacity to improve crop yields.

Similarly, Wiśniewska-Kadżajan and Malinowska (2022) studied the combined use of SMS and synthetic N in grass production (*Festulolium braunii*). They observed increased protein content, biomass formation, and digestibility, with the most effective treatment involving 15 t ha^{-1} of SMS combined with 68 kg ha^{-1} of synthetic N, demonstrating SMS's potential to replace synthetic N inputs partially.

In maize (*Zea mays*), SMS use was associated with improved germination and seedling vigor. In their pot study, Alves et al. 2022 demonstrated that incorporating spent *Agaricus subrufescens* substrate—especially when combined with synthetic fertilization at sowing—led to significant increases in germination rates and pace, as well as other key successive growth parameters, such as shoot height, stem diameter, fresh and dry biomass, and leaf area index. The SMS treatment increased the concentrations of P, K, and S in the biomass and increased soil K, suggesting it could reduce the need for synthetic fertilizers at the topdressing stage. Further, Prasad et al. (2023) documented a 44.5% increase in sesame yields when SMS was used in conjunction with beneficial microbes.

Similarly, Elsakhawy et al. (2020a, b) observed improved agronomic traits and yields in both rice (*Oryza sativa*) and faba bean (*Vicia faba* L.). In faba bean, SMS also suppressed *Orobanche crenata* (broomrape), a parasitic plant that reduces productivity. He et al. (2024) reported that incorporating SMS into soil during rice seedling production enhanced root development, thereby improving water retention, soil porosity, and nutrient availability. These improvements supported increased P uptake, photosynthesis, and shoot growth. SMS-treated seedlings also exhibited higher lateral root numbers, root volume, and surface area, contributing to elevated water-use efficiency.

Moreover, Domínguez-Gutiérrez et al. (2022) demonstrated that vermicomposted SMS increases nitrate, K, P, and micronutrient levels, while enhancing cation exchange capacity (CEC). In *Hibiscus sabdariffa* (Roselle), SMS-amended treatments increased chlorophyll content and biomass, indicating improved nutrient uptake (Ngan and Riddech 2021). A review by Baptista et al. (2023) concluded that the nutrient profile of SMS, especially when co-composted with manure, can match or even surpass that of conventional fertilizers across a wide range of crops.

SMS effect on soil

SMS application enhances soil physical, chemical, and biological properties, thereby improving overall soil functionality and health, although the magnitude of effects varies with treatment, method, and SMS origin.

Physical properties

Owing to its fibrous organic content, SMS improves soil structure, porosity, aeration, water-holding capacity, and root penetration. These effects, linked to greater aggregation and lower bulk density, also enhance temperature regulation (Marín-Benito et al. 2016, Ma et al. 2025). Nakatsuka et al. (2016) reported the development of granular microstructures and spongy aggregates in SMS-treated soils, providing greater physical stability.

Kumar and Chugh (2022) also found improved organic matter content and moisture retention in SMS-amended soils. However, environmental factors can complicate these benefits. For example, in hot, arid climates, SMS may form a surface crust that inhibits germination and moisture penetration (Kahn et al. 2012). Composting and vermicomposting processes help mitigate these effects by enhancing texture and reducing compaction (Domínguez-Gutiérrez et al. 2022).

Chemical properties

SMS contains organic matter but also macro and micronutrients (Mahato et al. 2024, Ma et al. 2025), and SMS has been shown to improve SOC, P, and K availability (Igual et al. 2024). These changes improve nutrient retention and availability (Marín-Benito et al. 2016, Domínguez-Gutiérrez et al. 2022). Although fresh SMS can have high EC and alkaline pH, raising salinity concerns, composting is a proven strategy to stabilize pH, reduce EC, and decrease volatile or phytotoxic compounds. This process also enhances the nutrient profile, reduces potential toxicity, and creates a safer, more consistent organic fertilizer (Medina et al. 2009, Ultra Jr. et al. 2018, Pan et al. 2023, Wang et al. 2024). SMS also enhances buffering capacity, supporting pH balance in the long term (Gupta et al. 2024).

Soil fertility, microbial activity, and overall soil health

SMS sustains soil fertility by enriching organic matter and releasing nutrients gradually, while stimulating microbial biomass, respiration, enzymatic activity, and diversity (Grimm and Wösten 2018, Paula et al. 2020, Martín et al. 2023b, Nie et al. 2024, Ma et al. 2025). Residual fungal mycelia and bioactive compounds further enhance microbial colonization and long-term soil health. Incorporating beneficial organisms such as *Trichoderma harzianum* and *Pseudomonas fluorescens* amplifies these effects by promoting root development and suppressing soilborne pathogens (Kumar and Chugh 2022, Prasad et al. 2023, Mahato et al. 2024).

Beyond fertility enhancement, SMS contributes to soil remediation by supporting microbial communities that degrade pollutants and immobilize heavy metals, thereby reducing phytotoxicity and environmental risk (Omoni et al. 2020, Malik et al. 2021, Amarasinghe and Jayaweera 2022, Pan et al. 2023, Gupta et al. 2024). SMS also improves nutrient cycling efficiency by stabilizing organic matter and enhancing the mineralization of N, P, and K (Lou et al. 2017, Baptista et al. 2023). Vermicomposting increases humic substances and nutrient availability, while composting reduces gaseous N losses and boosts overall fertility (Grimm and Wösten 2018, Domínguez-Gutiérrez et al. 2022).

Finally, SMS indirectly supports soil fertility by improving plant physiological traits such as chlorophyll content and water retention (Elsakhawy et al. 2020b, Kumar and Chugh 2022) and by promoting beneficial microorganisms—including ligninolytic fungi, actinomycetes, and nutrient-solubilizing rhizobacteria—that enhance soil resilience and nutrient turnover (Ngan and Riddech 2021, Gupta et al. 2024).

Long-term agronomic implications

SMS has been recognized for its potential as a biofertilizer, organic amendment, and key input in sustainable agriculture. Though not all studies provide long-term data, those that do suggest enduring improvements to soil properties and fertility. For instance, Ma et al. (2025) concluded that repeated SMS application improves SOC, microbial activity, and system stability—key indicators of long-term soil health. Lou et al. (2017) reported that SMS releases N gradually, reducing dependency on synthetic inputs. However, Kwiatkowska et al. (2024) suggested that the benefits may diminish if the application is discontinued or not integrated with other strategies.

While most studies do not directly measure long-term crop yields, indirect data suggest positive trends. Paula et al. (2020) found that SMS outperformed synthetic fertilizers over 14 weeks, likely due to improved microbial colonization. Some forms of SMS even improve over time as decomposition advances. In addition to its agronomic benefits, SMS also facilitates bioremediation. Marín-Benito et al. (2016) and Pan et al. (2023) found that SMS reduces cadmium uptake in crops, improving food safety.

Thus, by being reused across mushroom cultivation, composting, animal feed, and fertilization, SMS contributes to the concept of circular agriculture. It closes nutrient loops, reduces waste, and supports sustainable production systems (Martín et al. 2023a, Mahato et al. 2024, Mwangi et al. 2024).

Limitations and challenges

While SMS presents numerous agronomic and environmental advantages, several limitations hinder its widespread adoption. Key challenges include high EC, variable pH, inconsistent nutrient composition, potential chemical residues, and compatibility issues with certain crops. The key limitations and challenges associated with the SMS application, along with potential mitigation strategies, are summarized in Table 2.

One of the primary concerns is the elevated EC of SMS, due to high concentrations of ions such as K^+, Na^+, Cl^-, and nitrite. High EC levels can induce osmotic stress in plants, inhibit water uptake, and cause nutrient imbalances (Medina et al. 2009, Postinguel et al. 2025). Salinity is particularly detrimental to salt-sensitive crops and young seedlings, which are more vulnerable due to their underdeveloped root systems and limited capacity for water uptake (Lethin et al. 2022, Mousavi et al. 2022). For example, strawberries are susceptible to salt stress, which can damage photosynthetic pigments such as chlorophyll and carotenoids, thereby reducing yield.

Additionally, residual organic compounds in SMS may hinder seed germination and initial root growth (Prasad et al. 2021, Velusami et al. 2021, Kwiatkowska and Joniec 2022). Although these issues are significant, mitigation strategies such as leaching or blending SMS with other substrates can help reduce salinity. However, these can raise costs and may not be feasible for all growers (Roy et al. 2015, Paula et al. 2017).

Nutrient imbalances also pose a concern. SMS often lacks essential micronutrients, particularly Fe, Zn, and Mn, which are critical for plant growth and enzymatic functions. Iron deficiency, for instance, can limit root elongation and nutrient uptake (Postinguel et al. 2025). Additionally, the high levels of K commonly found in SMS may interfere with Ca uptake, potentially leading to physiological disorders in plants. This emphasizes regular nutrient monitoring and targeted supplementation when required (Zhai et al. 2009, Velusami et al. 2021, Alves et al. 2022).

Another important challenge relates to N availability. Fresh SMS often contains a large proportion of organic N bound in recalcitrant lignocellulosic fractions, making it only partially available to plants in the short term (Kahn et al. 2012). Its fertilizer benefit is therefore strongly dependent on composting or vermicomposting processes that mineralize organic N into plant-available forms. Even after such treatments, nitrogen release can be slow and uneven, and some batches with high C:N ratios may still induce temporary N immobilization, reducing short-term availability (Hackett 2015).

Additional N losses can occur through ammonia volatilization during storage or surface application, and nitrate leaching after mineralization, particularly in coarse soils, further decreasing N-use efficiency (Wiśniewska-Kadżajan and Malinowska 2022). While composting improves N availability and reduces the risk of immobilization, it requires additional time, labor, and infrastructure, increasing management costs for farmers (Roy et al. 2015). These challenges add to the broader issue of uneven nutrient content and physical structure, making consistent and practical use of SMS as a fertilizer more complex for end-users.

Another limitation is the potential presence of residual agrochemicals. SMS may contain traces of pesticides used during mushroom cultivation. These compounds can adversely affect soil microbial communities, pose phytotoxic risks to plants, and even contaminate surrounding soil and water bodies (Postemsky et al. 2016, Paula et al. 2017, Kwiatkowska and Joniec 2022). As a result, conducting soil toxicity assessments is essential to ensure the safe application of SMS in horticultural systems.

The physical characteristics of SMS also present challenges. Its properties vary considerably depending on the mushroom species, initial substrate, and composting methods used. This inconsistency makes it difficult to standardize SMS as a commercial growing medium, as batch-to-batch differences can affect plant performance (Prasad et al. 2021, Velusami et al. 2021, Khalil et al. 2024). Moreover, improper storage can cause spoilage, contamination, and compaction, reducing aeration and drainage and complicating the use of SMS for crops with specific needs. However, mixing SMS with porous materials enhances the structure and improves performance (Zied et al. 2020).

Moisture retention is another double-edged characteristic. SMS often retains excessive moisture, which can create anaerobic conditions in the root zone. This may encourage harmful microbial activity, promote the growth of fungi and bacteria, and lead to denitrification or waterlogging (Roy et al. 2015, Mousavi et al. 2023). Therefore, maintaining an appropriate balance between drainage and water retention is crucial to preserving soil health and crop productivity (Medina et al. 2009, Zied et al. 2020).

Although SMS has demonstrated suppressive effects against several soilborne pathogens, it may also harbor risks. Certain beneficial fungi, such as *Trichoderma* species, could become opportunistic pathogens in specific horticultural settings (Hernández et al. 2021). Incompletely decomposed SMS may release phytotoxic volatile organic compounds, which can negatively affect plant growth (Owaid et al. 2017, He et al. 2024). Moreover, improper disposal of SMS can contribute to GHG emissions—including methane and CO_2—further impacting the environment (Wang et al. 2024). As such, the responsible handling and treatment of SMS are essential for minimizing environmental harm.

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Finally, a major obstacle to wider SMS use is the lack of standardized guidelines and regulations. This gap hinders large-scale adoption, especially in commercial horticulture. Developing clear standards and protocols is essential for promoting safe, effective, and region-specific SMS applications (Kousar et al. 2024).

Table 2. Summary of the main limitations and challenges associated with the use of Spent Mushroom Substrate (SMS) in agricultural and horticultural systems, including their potential impacts on crop performance and soil health, along with suggested mitigation strategies and key references

Limitation / Challenge	Description	Potential Mitigation / Notes	References
High Electrical Conductivity (EC) and variable pH	Excess salts (K^+, Na^+, Cl^-, nitrite) can cause osmotic stress, inhibit water uptake, and reduce growth, especially in salt-sensitive crops. Also, an Inconsistent pH can affect nutrient availability and crop performance	Leaching, composting, or vermicomposting, blending with other substrates; Adjust pH via blending or liming	Medina et al. 2009; Postinguel et al. 2025; Lethin et al. 2022
Nutrient Imbalances	Deficiency of micronutrients (Fe, Zn, Mn), high K affecting Ca uptake	Targeted supplementation, regular nutrient monitoring	Alves et al. 2022; Zhai et al. 2009
Nitrogen Availability	Organic N often bound in lignocellulose, slow mineralization; risk of temporary immobilization	Composting or vermicomposting, reapplication	Kahn et al. 2012; Hackett, 2015; Roy et al. 2015
Residual Agrochemicals	Traces of pesticides may affect soil microbes, plants, or water	Soil toxicity testing, responsible sourcing, Leaching, composting, or vermicomposting, blending with other substrates	Kwiatkowska and Joniec, 2022; Postemsky et al. 2016
Physical Variability	Batch-to-batch differences in texture, structure, and porosity; storage issues	Blend with porous materials, proper storage	Prasad et al. 2021; Zied et al. 2020
Moisture Retention	Excess water can create anaerobic conditions, promote harmful microbes	Adjust substrate mix and drainage	Medina et al. 2009
Potential Phytotoxicity / Opportunistic Pathogens	Incompletely decomposed SMS may release toxic compounds; beneficial fungi may act as pathogens	Ensure proper composting and monitoring	He et al. 2024; Hernández et al. 2021
Environmental Impact	Improper disposal may generate GHG emissions	Proper treatment and reuse	Wang et al. 2024
Lack of Standardization and Guidelines	No uniform protocols limiting large-scale adoption	Development of standards and regulations	Kousar et al. 2024

SMS as a soil amendment in horticulture

Spent mushroom substrate (SMS) has been extensively studied for its potential to enhance plant growth, yield, and quality in horticultural systems. SMS includes key macronutrients that play vital roles in plant development (Medina et al. 2009). Research has demonstrated that incorporating SMS into soil increases microbial activity, SOC, and overall organic matter—factors that are fundamental for healthy plant growth (Hernández et al. 2021). When combined with other organic materials, SMS further improves soil structure and water retention, promoting root development and nutrient uptake. These combined effects can lead to significant gains in plant productivity (Oliveira Vieira et al. 2022). Key findings on the use of SMS in horticultural systems—including its effects on nutrient availability, crop productivity, peat replacement, and disease suppression—are summarized in Table 1.

SMS effect on horticultural productivity

Several studies have demonstrated that SMS can significantly enhance crop productivity, though outcomes depend on SMS quality, application method, and environmental conditions. SMS can be considered a biofertilizer in horticultural systems (Paula et al. 2017). Vegetable studies reported yield increases linked to improved root zone conditions and improved soil structure (Martín et al. 2023b). When combined with peat, SMS has also been shown to improve seed germination, early growth, disease resistance, and final seedling weights in a variety of crops, including lettuce (*Lactuca sativa*), cucumber (*Cucumis sativus*), tomato (*Solanum lycopersicum*), and strawberry (*Fragaria × ananassa*) (Mwangi et al. 2024).

SMS has further promoted the growth of sweet pepper (*Capsicum annuum*), enhancing plant height, branching, and biomass formation (Roy et al 2015). Treatments involving oyster (*Pleurotus ostreatus*) SMS leachate, weathered oyster SMS, and leachate from button mushroom (*Agaricus bisporus*) compost all yielded better than the control. The best results were seen with the oyster mushroom leachate, followed by weathered oyster SMS and button mushroom compost. Consistent with this, another study evaluated SMS as a partial substitute for peat in red baby leaf lettuce production, using three treatments: SMS from *A. bisporus* (Ab), *P. ostreatus* (Po), and a 70/30% Ab and Po mixture (AbPo), each mixed with peat at a 1:4 ratio. All SMS treatments outperformed peat alone, with yield increases of up to 2.5-fold under non-infested conditions and up to 7-fold (3 to 7-fold) under *Pythium irregulare*-infestation. This implies that the remarkable yield response was primarily associated with the suppression of *P. irregulare* disease pressure. The AbPo mixture showed the most potent effect, reducing disease incidence by 50%, compared to 38% and 15% for Ab and Po alone, respectively (Hernández et al. 2021). These results confirm that SMS can be a sustainable and effective alternative to traditional peat-based substrates.

In accordance with these, other studies indicated that applications of SMS compost nearly doubled pineapple (*Ananas comosus*) fruit yield compared to control treatments in Nigeria (Orluchukwu and Adedokun 2014). Similarly, research on root vegetables revealed that radish (*Raphanus sativus*) yield increased in spring but declined in fall with high SMS application rates—likely due to salt buildup or phytotoxic effects under hot, dry conditions in Oklahoma (Kahn et al. 2012). These results emphasize the importance of optimizing seasonality, compost maturity, and dosage. This is further corroborated by Amarasinghe and Jayaweera (2022), who demonstrated that radish germination and root development were improved with N-enriched and microbially inoculated SMS.

Further evidence comes from eucalyptus (*Eucalyptus* spp.) production under water-deficit conditions in Brazil. A study showed that combining SMS with synthetic fertilizers increased shoot weight, collar diameter, and seedling height, while also improving root dry matter and overall plant robustness (Postinguel et al. 2025). These results reinforce the suitability of SMS as a peat substitute, particularly in environments prone to stress.

The pathogen-suppressive properties of SMS are attributed to its microbial communities, including endophytes and plant growth-promoting rhizobacteria. These microbes enhance disease resistance by modulating the rhizosphere. For instance, SMS has been shown to suppress *Fusarium* wilt in cucumbers by reshaping root-associated microbial communities (Wang et al. 2020). Similarly, SMS enriched with beneficial microbes improved seedling survival and nutrient uptake in tomato, chili (*Capsicum annuum L.*), and sesame (*Sesamum indicum*), by reducing pathogen pressure and enhancing rhizosphere conditions (Kumar and Chugh 2022, Mahato et al. 2024). Additionally, SMS can be integrated into co-cultivation systems to optimize resource use. A study demonstrated that tomato production could be successfully combined with mushroom farming, providing a dual-use system that lowers production costs while facilitating the benefits of SMS (Oliveira Vieira et al. 2022).

Nutrient content and peat replacement

Peat is widely used worldwide as a horticultural substrate due to its favorable physical and chemical properties, including high organic carbon content, good aeration, high water-holding capacity, and nutrient retention. Moreover, peat's acidic pH (typically ranging from 3.5 to 4.5) and low electrical conductivity (EC) make it particularly suitable for salt-sensitive crops (Hernández et al. 2021).

Peat's high organic carbon levels contribute to better nutrient retention and improved soil structure (Gao et al. 2015). Peat also contains trace micronutrients such as zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn), which support overall plant health (Postinguel et al. 2025). In contrast, while SMS is lower in organic matter than peat, it is richer in nutrients and exhibits higher microbial activity (Medina et al. 2009). Its pH ranges from slightly acidic to alkaline (5.1 to 8.9), and its EC is higher than that of peat. SMS also contains more macronutrients, though typically fewer micronutrients. This variability—due to differences in SMS origin, type, and processing—impacts its performance with salt-sensitive and pH-sensitive crops. However, such variability also enables substrate customization (Meng et al. 2018, Ravlikovsky et al. 2024).

Nonetheless, SMS can sometimes lack essential micronutrients, such as Fe, which are critical for root development and photosynthesis (Kwiatkowska and Joniec 2022). Still, SMS may contain other micronutrients at levels like peat, depending on the feedstock composition, cultivation conditions, processing, and storage techniques (Roy et al. 2015). Hence, using SMS as a peat alternative offers several benefits: SMS provides nutrients comparable to peat with slow-release benefits (Medina et al. 2009, Roy et al. 2015) and improves soil structure, aeration, and water retention. While high pH and EC may stress sensitive crops, leaching can reduce salinity without causing significant nutrient or microbial losses (Prasad et al. 2021).

Environmental considerations of SMS use

The use of SMS offers several environmental benefits, despite some limitations. A comprehensive overview of the environmental benefits, sustainability implications, and limitations of SMS use is presented in Table 1 and 2.

Environmental and sustainability implications of SMS use

Replacing peat with SMS provides multiple environmental and agronomic benefits by reducing reliance on non-renewable resources, synthetic fertilizers, and agricultural waste. Peatlands, which have accumulated large carbon stocks over millennia, are critical ecosystems for climate regulation and biodiversity. However, peat extraction is energy-intensive, releases stored carbon, and causes habitat destruction, threatening rare species and ecosystem balance (Paula et al. 2017, Meng et al. 2018, Zakaria et al. 2023).

SMS, often discarded through dumping, burning, or landfilling, represents a significant opportunity for resource recovery. Mushroom cultivation produces 2.5–5.0 kg of SMS per kg of mushrooms (Sendi et al. 2013, Postinguel et al. 2025). Repurposing this byproduct as a peat alternative diminishes ecological damage from peat mining, lowers GHG emissions, and mitigates environmental risks (Priadi et al. 2018, Kousar et al. 2024, Ravlikovsky et al. 2024). Due to its high organic matter, nutrients, and residual fungal biomass, SMS enriches soils, supports carbon sequestration, enhances microbial activity, and improves overall soil health (Roy et al. 2015, Mohd Hanafi et al. 2018, Othman et al. 2020). It further contributes to water retention, erosion control, remediation of contaminated soils, and resilience of farming systems. Moreover, SMS promotes beneficial rhizosphere microbes, reduces chemical pesticide reliance, and enhances productivity and agroecosystem resilience (Leong et al. 2022).

In line with circular economy principles, SMS transforms waste into a valuable input, reducing transport-related emissions when used locally in place of imported peat (Singh et al. 2021, Thygesen et al. 2021, Afsar et al. 2024). Many countries have already restricted peat use for environmental reasons, creating strong demand for viable substitutes such as SMS (Velusami et al. 2021). Altogether, SMS functions as a renewable, multifunctional, and eco-friendly amendment that protects peatlands, improves soil conditions, reduces environmental impacts, and advances climate action, soil restoration, and sustainable farming (Phan and Sabaratnam 2012, Martín et al. 2023a, Ravlikovsky et al. 2024).

Carbon sequestration

Carbon sequestration is a crucial component of sustainable land management, and SMS plays a significant role in this process. Rich in lignocellulosic polymers—including lignin, cellulose, hemicelluloses—and fungal biomass, SMS decomposes slowly, contributing to long-term accumulation of SOC. As SMS components break down, they are transformed into humic substances through microbial and composting processes, which improve soil structure, nutrient retention, and fertility (Singh et al. 2021, Leong et al. 2022). Composting SMS further stabilizes organic matter, promotes humification, and reduces CO_2 emissions compared to untreated waste. For instance, partially decomposed oyster mushroom SMS increases enzymatic activity, facilitating the breakdown of complex C molecules into stable residues (Afsar et al. 2024).

Beyond its chemical composition, SMS promotes microbial growth, thereby influencing soil C dynamics. It boosts microbial biomass and activity, enhances bacterial populations that process organic C, and promotes the formation of soil aggregates. These bioprocesses convert organic inputs into stable forms of soil C, supporting nutrient cycling and long-term carbon storage. As a result, incorporating SMS into soil management systems not only improves soil health but also supports climate resilience by enhancing microbial stabilization, sustaining soil carbon pools, and aligning with broader goals for carbon-neutral farming (Singh et al. 2021, Leong et al. 2022, Khalil et al. 2024).

Synthesis of findings

As global agriculture shifts toward sustainability, finding alternatives to peat —a carbon-rich, non-renewable material —has become crucial. Spent mushroom substrate (SMS), a by-product of mushroom cultivation, offers a renewable substitute that supports circular economy and zero-waste principles.

Benefits of SMS as a soil amendment

In farming, SMS improves fertility, soil structure, and microbial activity. Physically, it improves porosity, aeration, and water retention (Nakatsuka et al. 2016, Grimm and Wösten 2018). Chemically, it supplies macro- and micronutrients, increases CEC, and buffers pH (Domínguez-Gutiérrez et al. 2022, Martín et al. 2023b). Biologically, it stimulates microbial biomass, enzymatic activity, and respiration, improving nutrient cycling (Paula et al. 2020, Ma et al. 2025), with consistent increases in dehydrogenase and β-glucosidase activity (Kwiatkowska et al. 2024). SMS boosts yield in crops, often matching or outperforming synthetic fertilizers, particularly when combined with manure or compost (Baptista et al. 2023). It also raises organic matter, improves N retention and aggregate stability, and reduces nutrient leaching and heavy metal uptake (Marín-Benito et al. 2016, Pan et al. 2023). Its use reinforces circular economy principles (Martín et al. 2023a, Mwangi et al. 2024).

Limitations of SMS as a soil amendment

Fresh or poorly composted SMS may contain undecomposed lignocellulose and salts, leading to N immobilization, phytotoxicity, or poor germination (Kahn et al. 2012, Amarasinghe and Jayaweera 2022). High pH and EC levels pose additional risks; leaching, composting, or vermicomposting can stabilize organic matter and reduce salt levels (Ultra Jr. et al. 2018, Domínguez-Gutiérrez et al. 2022). SMS effects are most potent in the first years, especially for microbial activity and nutrient availability, and decline without reapplication or integration into fertility strategies (Kwiatkowska et al. 2024). Thus, SMS is best applied within an integrated nutrient management framework.

Benefits of SMS as a peat substitute

SMS improves plant growth, yield, germination, and soil health by providing high organic matter, beneficial microbes, and a balanced nutrient profile, thereby enhancing soil structure, microbial activity, and root development (Medina et al. 2009, Hernández et al. 2021). SMS also suppresses pathogens through shifts in the rhizosphere microbiome and pathogen competition (Roy et al. 2015, Meng et al. 2018, Hernández et al. 2021). Environmentally, peat extraction drives GHG emissions, wetland loss, and biodiversity decline, while SMS reduces landfill waste and emissions linked to peat mining and fertilizer use (Huang et al. 2022, Zakaria et al. 2023, Postinguel et al. 2025).

Limitations of SMS as a peat substitute

Fresh SMS often has high EC from soluble salts, stressing salt-sensitive crops like pepper and strawberry; pre-leaching or blending mitigates this but raises costs and labor (Medina et al. 2009, Paula et al. 2017). Nutrient imbalances, particularly micronutrient deficiencies in SMS, require attention (Zhai et al. 2009, Mohd Hanafi et al. 2018). Composition also varies by mushroom species, substrate, and composting, complicating standardization and regulation (Velusami et al. 2021, Wang et al. 2024). The lack of quality protocols and usage guidelines limits the broader adoption of SMS (Medina et al. 2009, Kousar et al. 2024).

Knowledge gaps

Despite growing interest in using SMS in horticultural and agricultural systems, several knowledge gaps remain to be elucidated to enable its broader adoption. While many short-term studies report benefits, such as improved soil structure, enhanced water retention, increased microbial activity, and higher crop yields, the long-term effects of SMS on soil health, plant performance, and nutrient cycling remain insufficiently explored. Multi-year trials are particularly scarce, making it difficult to assess the sustainability of these benefits across different agroecological conditions. Some evidence even suggests a decline in positive effects, such as microbial activity and nutrient availability, by the third year without reapplication. This underscores the need for extended field studies to evaluate the persistence, variability, and potential risks of SMS use over time.

Furthermore, interactions between SMS-derived microbial communities and plant roots have received limited attention. It is unclear whether such interactions could lead to undesirable shifts in the rhizosphere dynamics or long-term impacts on plant health. The variability in SMS composition—driven by differences in mushroom species, substrates, and storage conditions—also presents challenges. Tailored formulations for specific crop types remain underdeveloped, underscoring the need for targeted research to optimize SMS use across diverse horticultural settings.

Concerns also persist regarding the potential for salt accumulation, nutrient imbalances, or the accumulation of trace contaminants, such as heavy metals, particularly when used continuously or repeatedly. Despite growing interest, research into optimal reapplication rates and timing is limited. SMS decomposition and nutrient release rates vary significantly with compost maturity and environmental conditions, such as temperature and moisture. Finally, while SMS holds potential in circular agriculture, its economic feasibility and role in sustainable farming systems remain poorly explored.

Practical implications

SMS offers several benefits for farming, including improving soil structure and microbial diversity, and reducing nutrient leaching and heavy metal uptake. From a policy standpoint, SMS facilitates the goals of the circular economy and waste reduction. Support mechanisms such as subsidies, certification schemes, and decentralized composting programs could encourage its broader use. Commercially, it offers opportunities for mushroom producers and composting companies to generate value-added products, including organic fertilizers and customized growing media. Given its low cost, widespread availability, and environmental benefits, SMS can meaningfully contribute to more resilient and sustainable agri-food systems.

However, while SMS is produced in large volumes globally, its application in open-field agriculture faces practical constraints due to the high rates typically required (20–100 t ha^{-1}). Such bulk volumes increase transport, handling, and spreading costs, limiting the feasibility of large-scale adoption. To improve scalability, several strategies are worth consideration, including co-composting SMS with other organic wastes to increase nutrient density, pelletizing or drying to reduce bulk and transport costs, and establishing decentralized composting and recycling networks near mushroom farms. These approaches can enhance logistics, reduce environmental footprints, and make SMS a more viable amendment in extensive field systems.

Recommendations for future research

To realize the full potential of SMS, further research must address key gaps:

Standardization and Regulation: The variability of SMS due to differences in mushroom species, cultivation substrates, microbial community found in SMS, and composting processes presents a challenge for consistency. Developing a standardized classification system and regulatory guidelines would support the commercial scaling of this approach.

Blending and Formulation: Research should focus on how SMS can be blended with other materials, such as synthetic fertilizers or co-composted substrates, to develop flexible and crop-specific formulations that enhance plant performance and nutrient efficiency.

Long-Term Trials: Multi-year field studies are crucial for evaluating the long-term persistence of SMS effects across multiple growing seasons, crop rotations, and climatic zones. This includes monitoring for yield sustainability, soil health indicators, and ecological impacts.

Risk Assessment and Reapplication Strategies: Further studies are necessary to establish safe and effective reapplication schedules and to monitor potential risks, including salinity, nutrient imbalance, and heavy metal accumulation.

Economic and Environmental Evaluation: Life-cycle assessments and techno-economic analyses should be conducted to quantify the costs, benefits, and practical scalability of SMS use across various farming systems, including open-field agriculture, where high application rates currently pose logistical and economic challenges.

By addressing these research needs, SMS can transition from an underutilized bioresource into a mainstream input for sustainable agriculture and horticulture.

Conclusion

This review synthesizes current research on agronomic performance and environmental implications of using Spent Mushroom Substrate as a soil amendment and biofertilizer. The findings consistently support SMS as a renewable and effective alternative to both synthetic fertilizers and non-renewable peat. Rich in organic matter and nutrients, SMS improves soil structure, porosity, water retention, pH regulation, and nutrient availability, while enhancing microbial activity and disease suppression. It supports nutrient cycling, serves as a carrier for beneficial microbes, and helps degrade agrochemical residues. Compared to peat, SMS is a more sustainable, locally available alternative that supports circular economy principles by reducing waste and conserving natural resources. However, variability in composition, risks of phytotoxicity, and the lack of regulatory standards remain challenges. Future research should emphasize long-term field trials, standardization of processing, and crop-specific guidelines. Overall, SMS presents a promising strategy for improving soil health, boosting productivity, and advancing sustainable agriculture. With continued research and supportive policy, it can play a central role in regenerative and circular farming systems.

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Appendix 1

Table 1. Complete final search including search terms, filters, and the number of hits from the database Scopus.

Database: Scopus	Search Term	Limitations (filters, limits, refine)	Amount of Hits
# 1	TOPIC: (“Spent Mushroom Substrate”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	55 620
# 2	TOPIC: (“Spent Mushroom Substrate as biofertilizer” OR “Spent Mushroom Substrate for soil amendment”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	6
# 3	TOPIC: (“Utilisation of SMS” OR “SMS in agriculture” OR “SMS in horticulture”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	190
# 4	TOPIC: (“Spent Mushroom Substrate” OR “Biofertilizer” OR “Soil Amendment”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	33 774
# 5	TOPIC: (“SMS in agriculture” OR “SMS in horticulture”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	28
# 6	TOPIC: (“Spent Mushroom Substrate” OR “Peat Substitute” OR “Peat”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	133 061
# 7	TOPIC: (“Spent Mushroom Substrate” OR “Growing Media”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	9 451
# 8	TOPIC: (“Spent Mushroom Substrate” OR “SMS and Environment”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	980

Table 2. Complete final search including search terms, filters, and the number of hits from the database Web of Science.

Database: Web of Science	Search Term	Limitations (filters, limits, refine)	Amount of Hits
# 1	TOPIC: (“Spent Mushroom Substrate”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	17 280
# 2	TOPIC: (“Spent Mushroom Substrate” AND “Biofertilizer*” OR “Soil amendment” OR Soil*)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	760 929
# 3	TOPIC: (“Spent Mushroom Substrate” AND “Utilization in agriculture” OR “Utilization in horticulture”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	814
# 4	TOPIC: (“Spent Mushroom Substrate” AND “Biofertilizer” OR “Soil Amendment”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	10 349
# 5	TOPIC: (“Spent Mushroom Substrate” AND Agriculture* OR Horticulture*)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	255 977
# 6	TOPIC: (“Spent Mushroom Substrate” AND “Peat Substitute” OR “Peat”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	21 000
# 7	TOPIC: (“Spent Mushroom Substrate” AND “Growing Media”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	2 727
# 8	TOPIC: (“Spent Mushroom Substrate” AND Environment”)	Refined by: Languages (ENGLISH) and publication years: (AFTER 2009)	715