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Eco-friendly Plant Disease Management Using Spent Mushroom Substrate

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

This review is the first comprehensive synthesis covering two and a half decades. Mushroom cultivation has grown rapidly in the past four decades, driven by rising consumer demand for functional foods, health supplements, and protein-rich diets. Spent mushroom substrate (SMS), a lignocellulosic by product generated after mushroom cultivation, has traditionally been considered an agricultural waste material requiring disposal. It is estimated that for every kilogram of fresh mushrooms harvested, between 4 and 5 kilograms of SMS are produced. However, in recent decades, SMS has emerged as a resource with significant potential in sustainable crop production systems, particularly for plant disease management. Being rich in organic matter, nutrients, beneficial microorganisms, and bioactive compounds. It can suppress soilborne pathogens, and enhance crop resilience. The objective of this review is to provide a comprehensive synthesis of SMS research in the context of plant disease suppression. This review synthesises global research

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findings from 2000 to January, 2025, discussing SMS composition, mechanisms of disease suppression, and its integration into plant disease management strategies. We examine case studies from diverse agroecological zones, evaluate environmental and economic implications, and highlight policy measures for broader adoption. Challenges such as variability in quality, pathogen carryover risk, and limited farmer awareness are also discussed, alongside emerging innovations such as SMS-based biochar and fortified microbial inoculants. By framing SMS as a key element in the circular bioeconomy, this review underscores its role in aligning agricultural productivity with environmental sustainability. The use of SMS aligns well with circular economy principles, reducing waste disposal problems for mushroom producers while lowering dependency on synthetic pesticides and fertilisers for farmers.

Keywords: Spent mushroom substrate; soilborne disease suppression; biological control; integrated disease management; circular economy; sustainable agriculture.

1. INTRODUCTION

Mushroom cultivation holds the potential to alleviate poverty and enhance the livelihoods of marginalised communities. It is beneficial for human consumption, with some species being edible and others being toxic. These have the remarkable ability to transform nutritionally insignificant waste materials into valuable and nutritious food sources 1 (Nath *et al.,* 2024; Mahari *et al.,* 2020). Mushroom cultivation has grown rapidly in the past four decades, driven by rising consumer demand for functional foods, health supplements, and protein-rich diets. Global mushroom production reached over 43 million tonnes in 2023, with China, the United States, India, Poland, and the Netherlands among the top producers (Ramalakshmi & Namesh, 2025). Alongside this expansion, the mushroom industry generates an enormous volume of post-harvest residual biomass known as spent mushroom substrate (SMS). As the mushroom industry advances, it yields a consequential by-product known as spent mushroom substrate (SMS). Comprising residual fungal mycelium, lignocellulosic biomass, and enzymes, SMS has garnered significant attention as a substantial waste product. The composition of raw SMS can vary, with contents of up to 48.7% cellulose, 34% hemicellulose, and 39.8% lignin, contingent upon the source of the mushroom cultivation medium. SMS also serves as a source of essential vitamins and minerals, including iron, magnesium, zinc, and calcium (Baptista *et al.,* 2023). It is estimated that for every kilogram of fresh mushrooms harvested, between 4 and 5 kilograms of SMS are produced. In India alone, where commercial mushroom cultivation is concentrated in states like Himachal Pradesh, Haryana, Punjab, and Tamil Nadu, SMS generation is expected to exceed 1.2 million tonnes annually by 2030 (Rathod *et al.,* 2021).

Traditionally, SMS has been treated as a waste byproduct, often disposed of through open dumping, landfilling, or incineration practices that contribute to environmental degradation and greenhouse gas emissions. However, a paradigm shift in waste management and sustainable agriculture has repositioned SMS as a value-added product with multiple uses. These include livestock feed, organic fertiliser, soil amendment, bioremediation agent, and, importantly, a biological tool for plant disease management.

The potential of SMS in plant pathology lies in its multi-functional composition:

- Organic matter that improves soil structure and water-holding capacity.
- Macro- and micronutrients essential for plant growth.
- Diverse microbial communities, including beneficial bacteria and fungi that can compete with or antagonise pathogens.
- Bioactive metabolites such as enzymes, phenolics, and volatile compounds capable of inhibiting plant pathogens.

Historically, the suppressive potential of organic amendments against soilborne pathogens has been documented since the mid-20th century, but systematic studies on SMS as a disease management tool have gained momentum only in the past two decades. Multiple studies have reported that incorporating SMS into soil can reduce the incidence and severity of diseases caused by *Fusarium oxysporum*, *Rhizoctonia solani*, *Pythium* spp., and *Sclerotinia sclerotiorum*, among others. The suppressive effects are often attributed to both biotic factors (competition, antibiosis, predation) and abiotic changes in soil (altered pH, increased organic matter, improved aeration).

Furthermore, SMS aligns with circular economy principles, closing nutrient loops by returning organic matter to the soil, reducing dependence on synthetic chemical inputs, and lowering the carbon footprint of agricultural production. Its integration into Integrated Disease Management (IDM) programs offers a pathway toward reducing chemical pesticide use, mitigating environmental risks, and promoting agroecological resilience. The objective of this review is to provide a comprehensive synthesis of SMS research in the context of plant disease suppression, exploring:

1. Its production, composition, and properties.
2. Mechanisms underlying its suppressive effects.
3. Practical applications in field and protected cultivation.
4. Case studies from different regions.
5. Environmental, economic, and policy perspectives.
6. Future research needs and recommendations for scaling adoption.

1.1 Spent Mushroom Substrate (SMS) Production

It consists of partially degraded lignocellulosic material originally used as the mushroom growth medium, enriched with fungal mycelia, residual nutrients, microbial communities, and sometimes chemical additives from the cultivation process. Although often termed "spent," SMS still contains significant organic matter and nutrient reserves, making it a valuable resource rather than waste.

1.2 Mushroom Cultivation and SMS Generation

Mushrooms are cultivated on a variety of plant-based substrates rich in cellulose, hemicellulose, and lignin. The choice of substrate depends on mushroom species, regional availability of raw materials, and cost considerations. Commonly cultivated species include:

Button mushroom (*Agaricus bisporus*) was typically grown on composted wheat straw, poultry manure, and gypsum. Oyster mushroom (*Pleurotus* spp.) was produced on pasteurised agricultural residues such as paddy straw, sugarcane bagasse, and corn cobs. Shiitake mushroom (*Lentinula edodes*) was cultivated on sterilised hardwood sawdust or supplemented logs.

Each cultivation cycle may last 30–120 days, after which the substrate loses its capacity to support further fruiting due to depletion of easily accessible nutrients, changes in physical structure, and accumulation of metabolic byproducts.

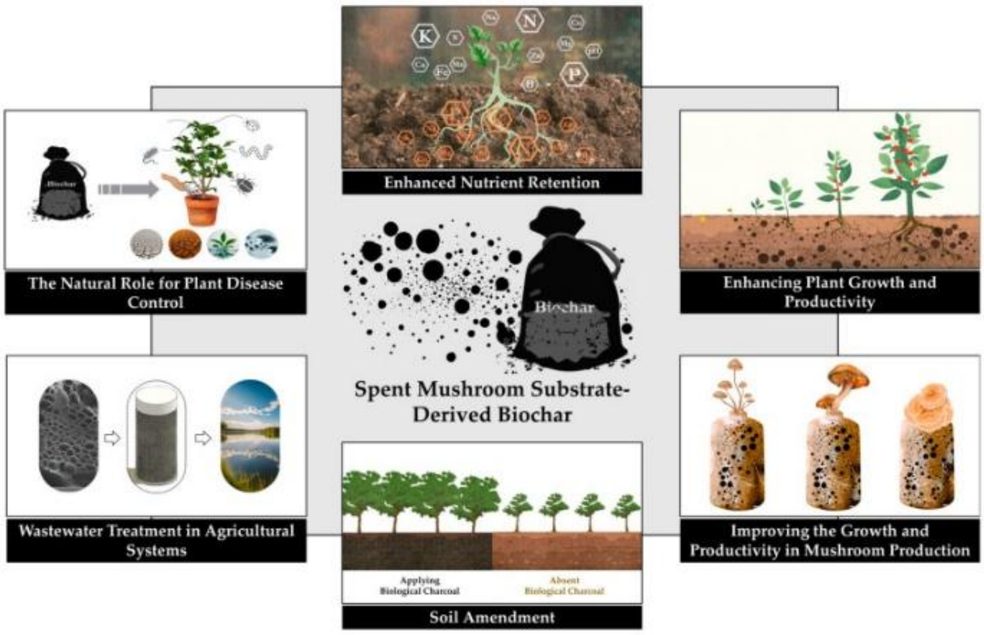

Fig. 1. Applications of biochar produced from SMS in modern agricultural practices

1.3 Global SMS Production Volumes

The rapid expansion of commercial mushroom farming has resulted in an exponential increase in spent mushroom substrate (SMS) production worldwide. Current estimates indicate that China alone generates over 25 million tonnes of SMS annually, while the European Union produces approximately 3.5 million tonnes per year. In the United States, annual SMS production is around 1 million tonnes, and India also contributes about 1 million tonnes annually, a figure expected to rise further with the growing cultivation of oyster and button mushrooms. The high bulk density and moisture content (~60–70%) of SMS pose significant challenges for transportation, storage, and disposal, particularly in humid climates where decomposition begins quickly.

1.4 Preparation and Processing before Use

Before SMS can be applied in agricultural systems, it often undergoes further processing to improve its stability and safety. Curing, is allows SMS to age for several weeks to months, reducing phytotoxic compounds such as ammonia and volatile fatty acids. Composting is mixing with other organic wastes (e.g., farmyard manure, green waste) accelerates decomposition and stabilises nutrients. Pasteurisation is the heat treatment to kill potential pathogens or weed seeds. Biochar conversion is the pyrolysis of SMS into a stable carbon-rich material for soil amendment. Microbial fortification is inoculation with beneficial microorganisms (e.g., *Trichoderma*, *Bacillus*) to enhance disease suppression potential.

1.5 SMS Types by Mushroom Species

The physicochemical and biological properties of SMS vary with the mushroom species grown and the substrate used. For example, *Agaricus bisporus* SMS tends to have higher nitrogen content due to manure-based composts. *Pleurotus* SMS is rich in lignin-degrading enzymes like laccase and manganese peroxidase. *Lentinula* SMS often contains higher phenolic content from hardwood substrates, which may contribute to antifungal activity.

This variability underscores the need for characterisation and standardisation when SMS is intended for disease management applications.

1.6 Composition and Physicochemical Properties of SMS

Mushroom cultivation generates large volumes of residual biomass known as spent mushroom substrate (SMS), representing approximately 5–6 kg of substrate for every kilogram of fresh mushrooms produced (Ahlawat *et al.,* 2022). Globally, the mushroom industry produces millions of tonnes of SMS annually, often posing disposal challenges due to its bulky nature and high organic load.

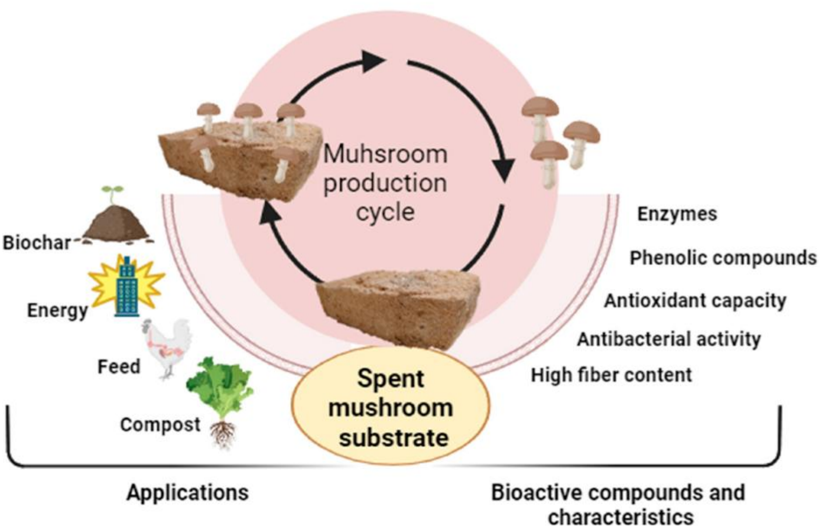

Fig. 2. Mushroom production cycle and spent mushroom substrate bioactive compounds and main applications

In recent years, SMS has attracted significant interest as a soil amendment with potential benefits in sustainable crop production and plant disease suppression. SMS is typically composed of partially degraded lignocellulosic materials (such as straw, sawdust, or corn cobs), supplemented with nutrients and colonised by residual mushroom mycelia. The microbial communities associated with SMS, comprising beneficial bacteria, actinomycetes, and antagonistic fungi, can inhibit soilborne plant pathogens via competition, antibiosis, and induced systemic resistance (Contreras-Cornejo *et al.,* 2009).

Beyond its biological properties, SMS improves soil physical structure, increases nutrient availability, and enhances microbial diversity, thereby indirectly reducing pathogen pressure (Li *et al.,* 2021). Its integration into integrated disease management (IDM) frameworks can reduce dependence on synthetic pesticides and align with the principles of the circular bioeconomy. However, effective utilisation requires an understanding of SMS variability, pathogen carryover risks, and optimal application methods.

This review examines the state of knowledge on SMS for plant disease management, highlighting its composition, mechanisms of action, and field applications, while identifying research gaps for future work.

2. PRODUCTION AND COMPOSITION OF SPENT MUSHROOM SUBSTRATE

2.1 Production Processes

Spent mushroom substrate (SMS) is generated at the end of the mushroom cropping cycle, once the substrate can no longer support profitable fruiting. The production process begins with the selection and preparation of lignocellulosic raw materials such as wheat straw, paddy straw, maize cobs, cottonseed hulls, sawdust, corn stover, or agro-industrial by-products, often supplemented with nitrogen-rich additives like wheat bran, soybean meal, or poultry manure to optimise the carbon-to-nitrogen ratio (Remya & Paul, 2014). These materials are moistened, pasteurised or sterilised, and then inoculated with spawn of the target mushroom species (e.g., *Agaricus bisporus*, *Pleurotus ostreatus*, *Lentinula edodes*).

During the cultivation cycle, the mushroom mycelium colonises the substrate, partially degrading complex polymers such as cellulose, hemicellulose, and lignin through the action of ligninolytic enzymes, particularly laccases, manganese peroxidases, and cellulases (Fujita *et al.,* 2021). Over time, nutrient levels become depleted for mushrooms but remain sufficient to support plant and microbial growth in agricultural soils. After one or more flushes of mushroom harvests, typically spanning 30–90 days for oyster mushrooms and 50–80 days for button mushrooms, the substrate is removed from production houses as SMS.

In industrial-scale production, SMS is generated in large quantities, often exceeding local disposal capacities. For example, commercial *A. bisporus* production can yield approximately 2.5–3.0 kg of SMS per kg of fresh mushroom harvested (Wang *et al.,* 2020). Improper disposal of this bulky material can lead to environmental concerns such as leachate generation, methane emissions, and pathogen proliferation, which has driven research into its valorisation as a bioresource.

2.2 Physical Characteristics

Fresh SMS is typically a moist, fibrous material with a bulk density of 0.4–0.6 g cm^{-3} and a moisture content ranging between 50% and 70%. Its texture depends largely on the original substrate type: paddy straw-based SMS is loose and lightweight, sawdust-based SMS is denser, while maize cob-based SMS has a more granular structure. Colour can range from light brown to dark brown due to mycelial colonisation and oxidation during cropping (Zepeda-Bastida *et al.,* 2016).

Particle size distribution influences its behaviour as a soil amendment. Smaller particles enhance water-holding capacity but may compact easily, reducing aeration; coarser SMS improves porosity but may decompose more slowly. These physical properties can be modified through curing, composting, or blending with other organic amendments prior to application.

2.3 Chemical Composition

The chemical composition of SMS varies with the mushroom species, substrate formulation, and cropping conditions. Typical ranges for key parameters in fresh SMS are presented in Table 1.

Table 1. General chemical characteristics of spent mushroom substrate (varies by origin)

Parameter	Typical Range	Notes
pH	6.5 – 8.5	Often alkaline due to lime or gypsum supplements
EC (dS m^{-1})	1.5 – 6.0	High EC can be phytotoxic if unweathered
Organic matter (%)	40 – 65	Rich in partially degraded lignocellulose
C:N ratio	18 – 30:1	Lower than fresh straw due to fungal metabolism
Total N (%)	0.8 – 2.0	Mostly organic nitrogen
P_2O_5 (%)	0.3 – 1.2	Residual phosphorus
K_2O (%)	0.5 – 1.8	Potassium readily available
Ca (%)	1.0 – 4.0	Often elevated due to lime supplementation

The relatively balanced nutrient profile supports plant growth, while the high organic matter content improves soil physical properties. However, the elevated pH and electrical conductivity of certain SMS types can limit their direct use for sensitive crops unless pre-treatment (e.g., leaching, composting) is performed (Contreras-Cornejo *et al.,* 2009).

2.4 Biological Composition

SMS contains an active microbial community derived from both the mushroom mycelium and environmental colonisers during cultivation. The dominant fungus is the cultivated mushroom species itself, but the substrate may also harbour beneficial microbes such as *Trichoderma spp.*, *Bacillus spp.*, *Pseudomonas spp.*, and actinomycetes with potential antagonistic effects against plant pathogens (Bonanomi *et al.,* 2007).

Residual enzyme activity, particularly lignin-degrading enzymes, persists in SMS after mushroom cropping, contributing to its ability to decompose complex organic matter in soils and possibly degrade pathogen cell walls (Gaitán-Hernández and Salmones, 2008). Furthermore, SMS can act as a carrier medium for inoculating beneficial microbes, enabling synergistic effects when combined with biocontrol agents (Fujita *et al.,* 2021).

2.5 Factors Influencing SMS Quality

Key factors determining the suitability of SMS for disease management include:

Mushroom species: Oyster mushroom SMS tends to have higher cellulolytic activity, while shiitake SMS has more ligninolytic enzymes.

Base substrate: Straw-based SMS decomposes faster than sawdust-based SMS.

Supplementation and additives: Gypsum increases Ca content and pH; bran increases nitrogen content.

Cropping duration: Longer cropping may reduce nutrient content but increase humification.

Storage conditions: Prolonged exposure to rain can leach soluble nutrients; anaerobic storage can cause odour and nutrient loss.

3. MECHANISMS OF PLANT DISEASE SUPPRESSION BY SMS

3.1 Microbial Antagonism

Spent Mushroom Substrate (SMS) frequently harbours beneficial microbes which including fungi and bacteria like *Trichoderma*, *Bacillus*, and *Pseudomonas* species that suppress pathogens via antibiosis and competition. These microbes produce cell-wall–degrading enzymes (e.g., chitinases) and antibiotics, limiting pathogen viability. For instance, antagonistic microbes isolated from *Lentinula edodes* and *Pleurotus* SMS reduced tomato early blight (caused by *Alternaria solani*) by up to ~52%, through enhanced host pathogenesis-related enzymes (β-1,3-glucanase and chitinase).

3.2 Elimination of Nematodes via Nematicidal Activity

A powerful advantage of certain SMS types is their nematicidal potential. *Pleurotus djamor* SMS reduced *Meloidogyne javanica* populations in lettuce by up to 99.8% at ≥15% incorporation levels, while simultaneously boosting plant defence enzymes and increasing soil microbial activity. *Pleurotus ostreatus* SMS demonstrated similar nematode suppression in banana plantations by targeting *Radopholus similis*. Additionally, *Flammulina velutipes* SMS showed significant nematicidal activity against *Panagrellus* larvae, indicating enzyme- and metabolite-mediated mortality. Historical work also found that spent mushroom compost suppressed sugar beet cyst nematodes (*Heterodera schachtii*) by more than 85% when applied at as low as 0.25–1% (w/w) in soil media.

Table 2. SMS disease-suppressive mechanisms

Mechanism	Description & Impact
Microbial Antagonism	Beneficial microbes produce antibiotic enzymes and compete with pathogens
Nematicidal Activity	Direct suppression of nematodes via toxic metabolites and enzymes
Chemical/Enzymatic Action	Degradation of pesticides fosters a suppressive microbial environment
Physical/Nutritional Help	Enhances soil conditions and nutrient status conducive to disease resistance

3.3 Chemical and Enzymatic Modulation

Beyond direct biocontrol, SMS possesses enzymes and metabolites that degrade agricultural pollutants and enhance soil health. For instance, SMS helps diminish carbendazim pesticide residues in soils via enzymatic activity, while enriching microbial communities that support suppressive soils. This integrates well with the suppressive-soils framework, where soil amendments foster disease suppression through beneficial microbial shifts and nutrient dynamics.

3.4 Physical and Nutritional Enhancement

SMS enriches soils with organic matter and nutrients like nitrogen, phosphorus, potassium, and trace elements, improving structure, moisture retention, and fertility, themselves key to plant resilience. These enhancements help plants better resist pathogen attacks and promote robust growth.

4. CASE STUDIES ON SMS APPLICATIONS IN DISEASE SUPPRESSION

4.1 Suppression and Mitigation of Fusarium Wilt in Cucumber

A recent study demonstrated the efficacy of SMS in reducing cucumber Fusarium wilt (*Fusarium oxysporum* f. sp. *cucumerinum*) in greenhouse trials. Amending soil with 4% (w/w) SMS significantly suppressed disease incidence and lowered pathogen abundance by tenfold compared to control soils. High-throughput 16S rRNA gene sequencing revealed a marked enrichment of beneficial bacteria, particularly *Bacillus* spp., in the rhizosphere of SMS-treated plants. Functional profiling further indicated enhanced microbial pathways related to antimicrobial compound synthesis and nitrogen metabolism. A specific isolate, *Bacillus velezensis* SE58, synergised with SMS to reinforce disease suppression (Zhao *et al.,* 2017).

Earlier greenhouse work in China corroborated SMS's suppressive effects; cucumber plants grown in SMS-amended soils exhibited reduced Fusarium wilt severity and improved plant growth metrics. Soil microbial profiles indicated shifts in microbial community composition favouring antagonist species, though detailed sequencing data were not presented (Wang *et al.,* 2020).

4.3 Control of *Phytophthora* in Pepper via SMS Tea

Spent mushroom compost teas and water extracts of SMS were applied to control *Phytophthora capsici* and *P. parasitica* on pepper plants. The treatment significantly reduced disease incidence in both greenhouse and laboratory settings, with indications of induced resistance and enhanced root development noted (Pane *et al.,* 2013).

4.4 Red Leaf Spot Suppression in Leafy Vegetables

An in vitro assessment showed that bacteria isolated from *Pleurotus ostreatus* SMS effectively inhibited red leaf spot disease in *Mukunuwenna* (a leafy vegetable), attributed to antagonistic bacterial activity, including strains of *Klebsiella pneumoniae* (Sri Lankan study).

4.5 Cabbage Fungal Disease via SMS Volatiles

Specifically, this volatile strongly suppressed *Alternaria brassicicola,* the agent of sooty spot in cabbage and *Botrytis cinerea* in tomato. The action was fungistatic, halting pathogen growth without spore germination when present, with disease symptoms returning once the compound was removed (Ma *et al.,* 2014).

These case studies illustrate SMS's versatile mechanisms ranging from microbial community shifts and biochemical induction of plant defences to volatile-mediated pathogen suppression across a variety of pathosystems and crops.

Table 3. Summary of SMS Applications in Disease Control

Disease/ Pathogen	Crop / Host	SMS Application Form	Key Findings & Mechanisms
Fusarium oxysporum f. sp. *cucumerinum*	Cucumber	4% w/w soil amendment	10× reduction in pathogen load; enrichment of beneficial *Bacillus* spp.; enhanced disease suppression via microbiome shifts
Phytophthora spp.	Pepper	SMS compost tea (aqueous)	Suppressed disease; possible induction of plant resistance
Red leaf spot (unspecified fungi)	Leafy vegetable (*Mukunuwenna*)	Direct SMS microbial isolates	Disease inhibition through antagonistic bacteria (*K. pneumoniae*)
Alternaria brassicicola, *Botrytis cinerea*	Cabbage, Tomato	SMS-emitted volatile (octan-3-one)	Fungistatic action via volatile emission; effective in closed environments

5. APPLICATION STRATEGIES FOR SMS IN DISEASE MANAGEMENT

5.1 Form and Preparation of SMS

Fresh SMS: Retains higher microbial activity but may also contain phytotoxic compounds (e.g., ammonia, volatile fatty acids). Fresh SMS should be used with caution, especially for sensitive crops.

Composted or cured SMS: Reduces phytotoxicity and odour, stabilises nutrients, and enhances pathogen-suppressive properties through the proliferation of beneficial microbes. Composting for 4–8 weeks is recommended before field application (Boontiam *et al.,* 2019).

Blended SMS: SMS can be mixed with biochar, vermicompost, or farmyard manure to improve nutrient balance and synergistic effects on pathogen suppression (Economou *et al.,* 2020).

5.2 Application Rates

Field Crops: 5–10 t ha^{-1} is a common rate for soilborne disease suppression, depending on pathogen pressure and soil organic matter status.

Greenhouse or nursery media: SMS can replace 20–40% of the growing medium (v/v) for vegetables, ornamentals, and seedlings, with observed reductions in *Fusarium* and *Pythium* damping-off.

High-disease pressure sites: Higher rates (up to 15 t ha^{-1}) may be used, but careful monitoring of soil salinity (EC) is essential.

5.3 Timing of Application

Pre-plant incorporation: Apply SMS 2–3 weeks before sowing or transplanting to allow microbial activity to stabilise and avoid seedling injury.

Post-harvest application: Incorporating SMS after crop removal improves soil health during fallow periods and reduces pathogen carryover.

Continuous low-dose application: In perennial crops, small quantities (1–2 t ha^{-1}) can be applied annually as a mulch to maintain suppression and improve soil cover.

5.4 Application Methods

Broadcast and incorporation: SMS is evenly spread and tilled into the top 15–20 cm of soil for maximum contact with pathogen propagules.

Mulching: Applying SMS as a surface mulch helps suppress foliar and soilborne pathogens by reducing soil splash and moderating soil moisture fluctuations.

Potting mix amendment: SMS is mixed with peat, coco coir, or compost to create a pathogen-suppressive growing medium for seedlings and high-value crops.

Combination with biocontrol agents: Co-application with *Trichoderma*, *Bacillus*, or AM fungi can extend the duration and spectrum of disease suppression.

5.5 Integration with Other Management Practices

Crop rotation: SMS complements rotation by reducing the inoculum of host-specific pathogens before susceptible crops are planted.

Soil solarisation: Combining SMS with solarisation has been shown to enhance thermal inactivation of pathogens and promote beneficial microflora.

Organic amendments: Integration with green manures or cover crops can improve nutrient cycling while maintaining disease suppression.

6. LIMITATIONS AND CHALLENGES IN USING SMS FOR PATHOGEN MANAGEMENT

6.1 Variability in SMS Composition

SMS nutrient content, pH, and microbial communities vary depending on the mushroom species cultivated, substrate materials, and duration of composting. Inconsistent quality can lead to unpredictable disease suppression results across different locations and seasons.

6.2 Potential Phytotoxicity

Fresh SMS may contain high levels of ammonium, soluble salts, and volatile organic compounds, which can harm seedlings and sensitive crops. Insufficient curing before application can result in poor germination or stunted growth.

6.3 Salinity Concerns

SMS often has elevated electrical conductivity (EC), which may limit its use in saline soils or salt-sensitive crops such as beans and strawberries. Long-term high-rate applications without leaching or dilution can exacerbate soil salinity.

6.4 Weed Seed and Pathogen Survival

If not properly pasteurised or composted, SMS may harbour weed seeds or plant pathogens from the substrate. This risk is higher for SMS derived from outdoor mushroom production systems.

6.5 Bulkiness and Handling Challenges

Large volumes are required for field-scale application, making transport and labour costs significant. Storage requires space and protection from excessive moisture to avoid nutrient leaching or anaerobic decomposition.

6.6 Short-Term Suppression

Disease suppression from SMS may decline over time as the readily available carbon sources are decomposed and beneficial microbial activity decreases. Periodic reapplication or integration with other biological controls may be necessary to sustain effects.

6.7 Environmental Considerations

Runoff from freshly applied SMS in rainy seasons may lead to nutrient leaching into water bodies. Improper disposal or over-application can contribute to environmental pollution.

7. CASE STUDIES AND RESEARCH EVIDENCE ON SMS IN PLANT PATHOGEN MANAGEMENT

7.1 Suppression of Soilborne Fungal Pathogens

Indrani Nath et al. (2024) reported that incorporating *Pleurotus ostreatus* SMS into soil at 10 t ha^{-1} significantly reduced *Fusarium oxysporum* incidence in cucumber by 42% compared to the untreated control.

In a pot trial, Zhao et al. (2017) observed a 58% reduction in *Colletotrichum capsici* severity on chilli when amended with cured SMS.

Polat et al. (2009) demonstrated that SMS from *Agaricus bisporus* suppressed damping-off in beans caused by *Rhizoctonia solani*, with suppression attributed to competitive saprophytic colonisation.

Arancon et al. (2007) found *Sclerotium rolfsii* sclerotia viability decreased by up to 65% when SMS compost was applied at 20% w/w in soil mixes.

7.2 Control of Bacterial Diseases

Li et al. (2020) documented that application of SMS compost tea reduced *Ralstonia solanacearum* wilt incidence in tomato by enhancing populations of antagonistic *Pseudomonas* spp. and *Bacillus* spp.

In greenhouse trials, SMS extract sprays inhibited *Xanthomonas campestris* pv. *vesicatoria* lesion development on pepper leaves by 31% (Bezbaruah *et al.,* 2025).

7.3 Nematode Management

Baptista et al. (2023) reported significant suppression of *Meloidogyne incognita* root galling in okra when soils were amended with SMS at 15 t ha^{-1}.

The nematicidal effect was linked to phenolic compounds and microbial antagonists present in the substrate.

7.4 Integrated Disease Management Trials

A two-year field experiment in Spain combined *Trichoderma harzianum* with SMS amendment for strawberry production, achieving >70% reduction in *Verticillium dahliae* wilt (Wang *et al.,* 2020).

In India, Atiyeh et al. (2000) used SMS in combination with solarisation for brinjal wilt control, resulting in improved yield and lower inoculum density.

7.5 Long-Term Field Applications

In an 8-year study, Bezbaruah et al. (2025) reported sustained suppression of soilborne diseases in rice–vegetable rotations when SMS was applied annually at moderate rates, alongside improvements in soil organic matter and microbial diversity.

8. FUTURE PROSPECTS AND RESEARCH NEEDS ON SMS FOR PATHOGEN MANAGEMENT

8.1 SMS Biochar for Disease Suppression

Converting SMS into biochar via pyrolysis can enhance its stability, porosity, and surface area, making it a long-term soil amendment. Biochar derived from SMS retains nutrient content and harbours sites for beneficial microbial colonisation, which can inhibit pathogen proliferation.

Initial trials (Arancon *et al.,* 2007) showed that SMS biochar reduced *Fusarium oxysporum* propagules more effectively than raw SMS due to improved adsorption of pathogen exudates and stimulation of antagonistic microbial activity.

8.2 SMS-Based Bioformulations

Enriching SMS with biocontrol agents such as *Trichoderma*, *Bacillus*, or *Pseudomonas* can create dual-action formulations combining organic amendment benefits with targeted pathogen suppression. SMS granules or pellets fortified with microbial inoculants can serve as slow-release biofertilizers and biopesticides. Research is needed to optimise carrier quality, microbial shelf-life, and field delivery methods.

8.3 Integration with Precision Agriculture

Remote sensing and soil health monitoring can guide site-specific SMS application rates for maximum pathogen suppression without overloading soil nutrients. Decision support systems could recommend amendment timing based on pathogen pressure, soil microbiome health, and crop phenology.

8.4 Advanced Composting and Pre-Treatment Techniques

Pre-composting SMS with green waste, crop residues, or biochar can enhance pathogen suppression potential by stabilising organic matter and enriching beneficial microflora. Anaerobic fermentation or enzymatic treatments could further boost antimicrobial compound release from SMS.

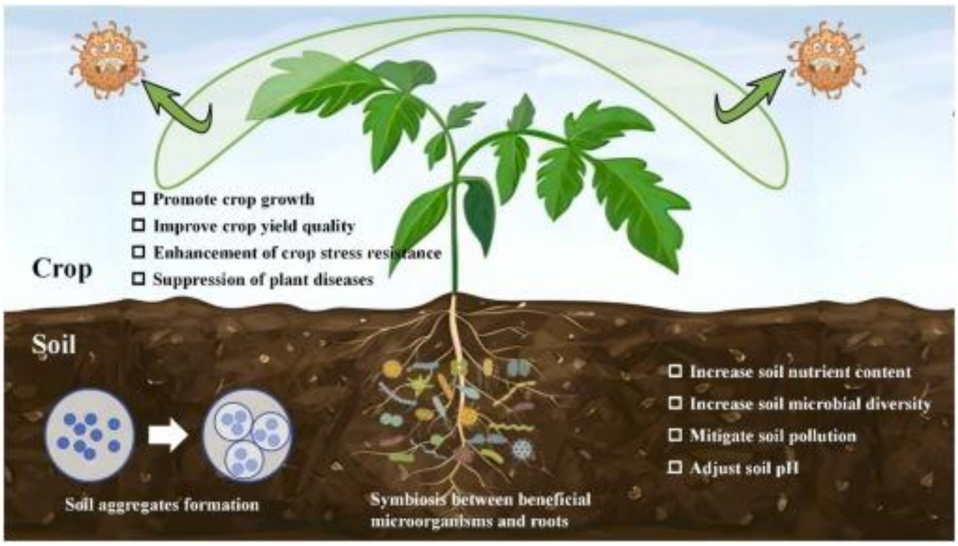

Fig. 3. The influence of Mushroom compost tea on soil and crop growth

8.5 Policy and Commercialisation Opportunities

Establishing standards for SMS-based soil conditioners will encourage adoption by ensuring consistency in nutrient content and pathogen suppression potential. Collaboration between mushroom industries, farmer cooperatives, and research institutions can facilitate large-scale valorisation of SMS. Incentives for recycling SMS could reduce waste disposal costs while supporting sustainable crop protection (Kumla et al., 2020).

8.6 Key Research Gaps

1. Mechanistic understanding of how SMS-derived compounds and microbes suppress specific pathogens.
2. Long-term field trials across different agro-ecological zones.
3. Interaction studies with other soil amendments and pesticides.
4. Impact on soil microbiome resilience and ecosystem services.
5. Economic feasibility analysis for smallholder and large-scale farming systems.

9. CONCLUSION

Spent mushroom substrate (SMS) represents an abundant, underutilised agro-industrial by-product with significant potential for sustainable plant disease management. Its rich organic matter, diverse microbial community, and bioactive compounds create a multi-pronged suppression effect against a wide range of soilborne pathogens, including *Fusarium*, *Rhizoctonia*, *Sclerotium*, and *Phytophthora*. Numerous studies demonstrate that SMS amendments improve soil health, enhance nutrient cycling, and promote beneficial microbial populations, thereby indirectly and directly limiting pathogen activity.

The use of SMS aligns well with circular economy principles, reducing waste disposal problems for mushroom producers while lowering dependency on synthetic pesticides and fertilisers for farmers. However, successful integration into crop protection programs requires consideration of substrate variability, application timing, rate optimisation, and potential phytotoxicity during early decomposition stages.

Key Recommendations:

1. Standardisation – Develop guidelines for SMS composition, maturity, and quality control to ensure consistent field performance.
2. Pre-treatment optimisation – Employ composting, biochar conversion, or microbial enrichment to enhance pathogen suppression and nutrient stability.
3. Integration with Integrated Pest Management (IPM) – Position SMS as a complementary tool within broader disease management strategies, combining cultural, biological, and physical methods.
4. Long-term monitoring – Assess the sustained impacts of SMS on soil microbiota, disease incidence, and crop yield over multiple growing seasons.
5. Farmer awareness and training – Conduct on-farm demonstrations and capacity-building programs to encourage adoption and proper usage.
6. Policy support – Promote incentives and infrastructure for SMS collection, processing, and distribution through public-private partnerships.

In summary, SMS holds dual value as a soil conditioner and biological disease suppressor. Strategic research, farmer engagement, and policy backing will be critical to transform SMS from a waste disposal challenge into a commercially viable and environmentally friendly disease management resource.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The authors hereby declare that no generative Artificial Intelligence (AI) technologies, including Large Language Models (e.g., ChatGPT), were used in the conception, design, analysis, or writing of this manuscript. All work is the original contribution of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Ahlawat, O.P., Kumar, S., Sharma, P., 2022. Spent mushroom substrates (SMS) – a potential source of bio-agents for plant diseases management. In: Compendium of Mushroom Diseases. Edition 1st, Chapter:

12. Indian Phytopathological Society, Division of Plant Pathology, IARI, New Delhi, pp. 108-124.

Arancon, N.Q., Edwards, C.A., Yardim, E.N., Oliver, T.J., Byrne, R.J. and Keeney, G. (2007). Suppression of two-spotted spider mite (*Tetranychus urticae*) populations and damage in tomatoes and cucumbers by vermicomposts. Crop Protection, 26(1):29-39. https://doi.org/10.1016/j.cropro.2006.03.013

Atiyeh, R.M., Subler, S., Edwards, C.A., Bachman, G., Metzger, J.D., and Shuster, W. (2000). Effects of vermicomposts and composts on plant growth in horticultural container media and soil. Pedobiologia, 44 (5), 579–590. https://doi.org/10.1078/S0031-4056(04)70073-6

Baptista, F., Almeida, M., Paié-Ribeiro, J., Barros, A. N., & Rodrigues, M. (2023). Unlocking the potential of spent mushroom substrate (SMS) for enhanced agricultural sustainability: from environmental benefits to poultry nutrition. Life, 13(10), 1948. https://doi.org/10.3390/life13101948

Bezbaruah, R., Sharma, S., & Das, A. (2025). In vitro Efficacy of Oyster Spent Mushroom Substrate (SMS) Extract against Major Soil Borne Fungal Plant Pathogens. Journal of Advances in Biology & Biotechnology, 28(5), 793-800. https://doi.org/10.9734/jabb/2025/v28i52340

Bonanomi, G., Antignani, V., Pane, C., and Scala, F. (2007). Suppression of soilborne fungal diseases with organic amendments. Journal of Plant Pathology, 89(3), 311–324. https://www.jstor.org/stable/41998445

Boontiam W, Wachirapakorn C, Wattanachai S. Growth performance and hematological changes in growing pigs treated with *Cordyceps militaris* spent mushroom substrate. Vet World. 2019;13(4):768–773. doi: 10.14202/vetworld.2020.768-773

Contreras-Cornejo, H.A., Macías-Rodríguez, L., Cortés-Penagos, C., and López- Bucio, J. (2009). Trichoderma virens, a plant beneficial fungus, enhances biomass production and promotes lateral root growth through an auxin-dependent mechanism in Arabidopsis. Plant Physiology, 149(3), 1579–1592. https://doi.org/10.1104/pp.108.130369

Economou CN, Philippoussis AN, Diamantopoulou PA. Spent mushroom substrate for a second cultivation cycle of *Pleurotus* mushrooms and dephenolization of agro-industrial wastewaters. FEMS Microbiol Lett. 2020;367(8). doi: 10.1093/femsle/fnaa060

Fujita, R., Yokono, M., Ube, N., Okuda, Y., Ushijima, S., Fukushima-Sakuno, E., Ueno, K., Osaki-Oka, K., Ishihara, A., 2021. Suppression of *Alternaria brassicicola* infection by volatile compounds from spent mushroom substrates. Journal of Bioscience and Bioengineering. 132(1), 25-32. *https://doi.org/10.1016/j.jbiosc.2021.03.003*

Gaitán-Hernández R. and D. Salmones (2008) Obtaining and characterizing warm environmental conditions. *Scientia Horticulturae.* 118:106-110. https://doi.org/10.1016/j.scienta.2008.05.029

Indrani Nath, Pankaj Lushan Dutta, Prety Rekha Narzary & M. Ashwin Niranjan. (2024). Turning Trash into Treasure: Utilizing Sericultural Wastes in Mushroom Cultivation. Journal of Scientific Research and Reports, 30(5), 462–471. https://doi.org/10.9734/jsrr/2024/v30i51962

Kumla J, Suwannarach N, Sujarit K. 2020. Cultivation of mushrooms and their lignocellulolytic enzyme production through the utilization of agro-industrial waste. Molecules. 25(12):2811. doi: 10.3390/molecules25122811

Li, T. H., Che, P. F., Zhang, C. R., Zhang, B., Ali, A., & Zang, L. S. (2020). Recycling of spent mushroom substrate: Utilization as feed material for the larvae of the yellow mealworm Tenebrio molitor (Coleoptera: Tenebrionidae). Plos one, 15(8), e0237259.

Li, T. H., Zhang, C. R., Che, P. F., Ma, Y., & Zang, L. S. (2021). Recycling of spent mushroom substrate and food waste: utilisation as feed materials for black soldier fly (Hermetia illucens (L.) Diptera: Stratiomyidae). Journal of Insects as Food and Feed, 7(4), 409-418.

Ma Y, Wang Q, Sun X, Wang X, Su W, Song N (2014) A study on recycling of spent mushroom substrate to prepare chars and activated carbon. Bioresources 9(3):3939–3954. DOI: 10.15376/biores.9.3.3939-3954

Mahari, W. A. W., Peng, W., Nam, W. L., Yang, H., Lee, X. Y., Lee, Y. K., ... & Lam, S. S. (2020). A review on valorization of oyster mushroom and waste generated in the mushroom cultivation industry. Journal of hazardous materials, 400, 123156.

Pane, C., Spaccini, R., Piccolo, A., Scala, F. and Giuliano, B. (2013). Compost amendments enhance peat suppressiveness to *Pythium ultimum, Rhizoctonia solani,* and *Sclerotinia minor. Biological Control*, 67(1), 24–32. https://doi.org/10.1016/j.biocontrol.2010.10.002

Polat, E., Uzun, H.I., Topçuoglu, B., Onal, K., Onus, A.N. and Karaca, M. (2009). Effects of spent mushroom compost on quality and productivity of cucumber (*Cucumis sativus* L.) grown in greenhouses. African Journal of Biotechnology, 8(2), 176–180. https://www.ajol.info/index.php/ajb/article/view/59758

Ramalakshmi, N., & Namesh, C. (2025). Status of Mushroom Production in the World and India. Indian Journal of Applied and Pure Biology, 40(1), 26-33.

Rathod, M. G., Gadade, R. B., Thakur, G. M., & Pathak, A. P. (2021). Oyster mushroom: cultivation, bioactive significance and commercial status. Frontiers in life science, 2, 21.

Remya, J. S., & Paul, T. S. (2014). Effect of spent mushroom substrate on growth parameters, yield and soft rot incidence of ginger. Mushroom Research, 23(1).

Wang HW, Xu M, Cai XY, Feng T, Xu WL (2020) Application of spent mushroom substrate suppresses Fusarium wilt in cucumber and alters the composition of the microbial community of the cucumber rhizosphere. Eur J Soil Biol 101:03245. https://doi.org/10.1016/j.ejsobi.2020.103245

Zepeda-Bastida, A., Ojeda-Ramírez, D., Soto-Simental, S., Rivero-Perez, N., Ayala-Martínez, M., 2016. Comparison of antibacterial activity of the spent substrate of Pleurotus ostreatus and Lentinula edodes. Journal of Agricultural Science 8(4), 43. https://doi.org/10.5539/jas.v8n4p43

Zhao H, Lan Y, Liu H, Zhu Y, Liu W, Zhang J, Jia L (2017) Antioxidant and hepatoprotective activities of polysaccharides from spent mushroom substrates (*Laetiporus sulphureus*) in acute alcohol-induced mice. Oxid Med Cell Longev2017:1-12. https://doi.org/10.1155/2017/ 5863523

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