Can edible mushrooms boost soil health in banana organic systems?

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Abstract

Manipulation of the rhizosphere can improve soil health; and foster sustainable management of pests and diseases. Biological inputs such as spent substrates from edible mushrooms (e.g., *Pleurotus ostreatus*) gardens offer sustainable alternatives on that direction. This work presents a meta-analysis of major trends in knowledge generation on edible mushroom use in agriculture, especially to benefit the crop rhizosphere. It further delves into a detailed synthesis of the effects of spent mushroom wastes (SMW) on the physical, chemical, and biological properties of the soil rhizosphere and agroecosystems. The review concludes by providing an outlook on how SMW can potentially support the management of key soil health challenges in organic banana production systems.

Keywords: biofertilizer, biological properties, biotic constraint, meta-analysis, mushroom, organic banana, spent mushroom waste

INTRODUCTION

The increasing global demand for safe and healthy foods produced using environmentally sound approaches has catapulted the importance of organic farming. Soil health, considered as the continued capacity of soils to function as a vital living ecosystem to sustain plants, animals, and humans (Karlen et al., 2003; Kibblewhite et al., 2008) is an integral component of this. Healthy soils provide regulating and supporting ecosystem functions such as nutrient cycling, water infiltration and retention, gas exchange, pest and disease suppression, biodiversity, and storage of carbon, many of which highly impact agricultural productivity (Lal, 2016; Barrios, 2007; Drinkwater et al., 2017).

Management of soil health has over the past few decades received an increased attention in the context of sustainable agriculture. For organic systems, this requires the elimination or reduction of the indiscriminate use of agrochemicals for the management of biotic constraints and meeting plant nutrient needs. Soil management strategies that promote soil health include increasing crop diversity, crop rotations, avoiding mechanical soil disturbance, and adding organic amendments (Kibblewhite et al., 2008; Moebius-Clune et al., 2016). These measures can be applied in combination, depending on the context of the farming systems. The use of organic amendments (manures, bio-pesticides, and biofertilizers) is constrained by challenges related to access, availability, and the tedious and often complex methods of preparation (Ghanghas et al., 2021). Spent wastes of edible mushrooms (SMW) and their composts (SMC) offer an opportunity for bridging some of the demand for soil organic amendments in organic banana systems.

Edible mushroom production has increased over the past two decades (FAO, 2022), resulting in large quantities of waste. Mushrooms are macrofungal species with members falling within the phylum *Basidiomycota* and phylum *Ascomycota* (Cao et al., 2021). About 67% of the 3000 known edible fungal spp. are consumed by humans (Li et al., 2021). Nearly 100 spp. are cultivated with about 30 spp. commercially cultivated for food (Chang, 1999; Li et al., 2021). Global mushroom consumption from 1993 to 2013 increased from 1 to 4.7 kg fresh

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weight person^{-1} year^{-1} (Royse et al., 2017). Mushrooms are also an important source of pharmaceutical products (Li et al., 2021).

In 2020, global mushroom trade reached USD 54.6 billion, with production exceeding 40 million t, a 300% increase from the year 2001 (IMARC Group, 2021; FAO, 2022). Rajavat et al. (2022) predict a growth in mushroom trade of over USD 87 billion by 2025. For each kg of mushroom, about 5 kg of SMW is produced (Prabu et al., 2014). Thus, about 200 million t of SMW was produced in 2020. This SMW poses a challenge of disposal due to its negative environmental impacts (Jasińska, 2018). However, SMS and their composts contain large amounts of mineral nutrients, lignocellulolytic enzymes and microbial biomass, making them suitable for agricultural use (Catal and Peksen, 2020). SMW have been reported to improve soil physical, biological and chemical parameters (Marin et al., 2014); and to suppress soil borne pests and diseases (Suárez-Estrella et al., 2012; Marin et al., 2014; Adedeji and Aduramigba, 2016; Ocimati et al., 2021). This review conducts a meta-analysis of publications to determine the major trends on the benefit of SMW in the rhizosphere through improvement of soil physical, chemical, and biological properties. The review concludes by providing an outlook on how SMW can potentially support the management of key soil health constraints in organic banana production systems.

METHODSOLOGY FOR THE META-ANALYSIS

A literature search was conducted in four available electronic databases: AGRIS, CAB Abstracts, SciVerse Scopus, and ProQuest. These are major comprehensive databases for research in agricultural and life sciences. Databases were searched from their first entries up to June 2022 using two search strings, one for each category (spent mushroom substrate, edible mushrooms) and while combining them with the Boolean operator “AND” to obtain the intersection. Due to limited resources for translation, publication in languages other than English were excluded. Duplicates were identified using queries targeting identical digital object identifiers, titles, authors, or first 50 characters of the abstract. Articles without an abstract or articles clearly indexed either as review, editorial, or errata were excluded. The articles were then screened to remove those not related to the theme of the study.

The contents of the papers were first coded into broad themes of biology and genetics, functional food, industrial applications, environmental applications, and agricultural applications. Papers on agricultural applications of edible mushrooms were further synthesised in to use as animal feeds, biofertilizers and biocontrol of pests and diseases.

The review then delved into agricultural uses of SMW as biocontrol agents and biofertilizer. Biofertilizer aspects included mushroom waste effects on soil physical, chemical and biological properties whereas the biocontrol aspects included mushroom effects on pathogenic fungi, bacteria, nematodes, and soil microbial diversity. The mechanisms of pest and disease suppression were also elucidated. The data were summarized and synthesised using MS excel and visualizations were performed using R version 4.2.1 (R Core Team, 2022).

REVIEW FINDINGS

A total of 1,851 publications were obtained from the period 1936 to 2022. Limited publications (121 publications) on edible mushrooms were observed between 1936 and 1996, with a predominant focus on the biology of the fungi. The period between 1985 and 2022 saw a proliferation in publications with additional subjects including the application of the fungi in agriculture, environment, functional foods, and industrial use (Figure 1A). This proliferation could be attributed to the increased consumption of mushrooms and the increased digitalization of data.

The highest number of publications (35%) focused on the biology and genetics of the fungi. Mushroom use in agriculture (23%) and environment (17%) also ranked highly. Thirteen and 12% of the publications, respectively, focused on functional foods and industrial use of mushrooms. On average, approximately between 7 and 17 publications have been published annually on each of the five themes above over the period 1985 to 2022 (Figure 1B).

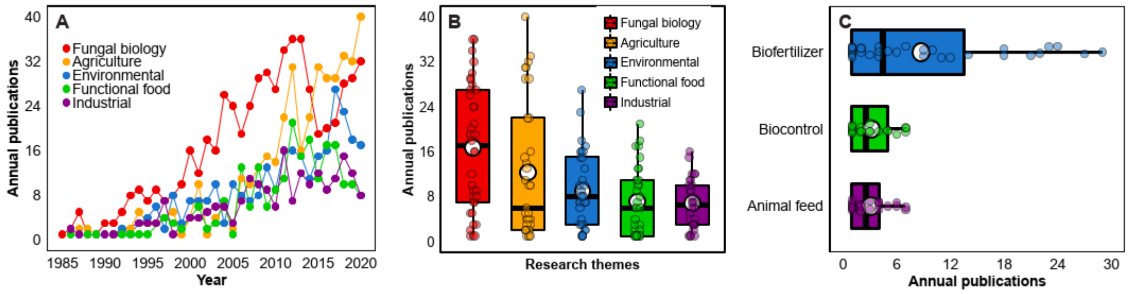

Figure 1. Major research themes on mushroom and spent mushroom substrate (SMS). Elaboration of research articles from AGRIS, CAB Abstracts, and ProQuest databases published (n=1,730) between 1985 and 2022 on mushroom and SMS. Boxplots show the upper and lower quartile, median (bold horizontal bar), mean (white circle), and whiskers (vertical lines). Each point corresponds to the cumulative number of articles related to the corresponding research theme per year.

Out of 427 publications that focused on agricultural application of mushrooms or their wastes, 69, 16 and 15%, respectively, focused on mushroom or SMS use as biofertilizers, animal feed and biocontrol agents. On average, 5 manuscripts have been published annually on spent mushroom waste (SMW) use as biofertilizer between the period 1985 and 2022, while their use as animal feed and biocontrol averaged at 3 publications per annum (Figure 1C). These findings suggest that SMS use in the field of agriculture is still new and/or underdeveloped.

Interaction of edible mushrooms and their wastes with biotic constraints of various crops

In the field of biocontrol, the meta-analysis revealed a diverse genus of edible mushrooms to be suppressive (Figure 2A) to different biotic constraints. *Pleurotus* and *Lentinula* were the most prevalent genera, while *P. ostreatus* was the most prevalent mushroom species reported in publications. SMS use in the management of fungal pathogens (58%) dominated the publications on biotic constraints (Figure 2B). Publications on SMW use in the management of bacterial pathogens (16%) and nematodes (12%) were also common. Other publications on biotic factors covered SMW use for mycotoxin degradation (9%), insect pest control (4%), and control of parasitic weeds (2%) (Figure 2A). Table 1 summarizes some of the pathogens and pests that have been reported to be suppressed by SMW in the form of SMS, SMC and extracts/teas.

Table 1. Examples of different mushroom species and their mechanisms of suppressing different target organisms.

Mushroom spp.	Mechanism(s) of suppression	Target organism	Citation
Pleurotus pulmonarius	- Nematicidal metabolites: S-coriolic acid, linoleic acid, p-anisaldehyde, p-anisyl alcohol, 1-(4-methoxyphenyl)-1,2-propanediol, and 2-hydroxy-(4'-methoxy)-propiophenone - Predation	Nematodes (*C. elegans*)	Stadler et al., 1994
Hericium coralloides	- Repellent and nematicidal compounds: linoleic acid, oleic acid, and palmitic acid	Nematodes (*C. elegans*)	Stadler et al., 1994
Pleurotus ostreatus	- Nematicidal compound - trans-2-decenoic acid, a derivative of linoleic acid	Nematodes (*Panagrellus redivivus*)	Kwok et al., 1992

Table 1. Continued.

Mushroom spp.	Mechanism(s) of suppression	Target organism	Citation
P. ostreatus	- Nematicidal activity of proteases - Predation - 95% reduction in nematodes	Nematode (*Panagrellus* sp.)	Genier et al., 2015
P. sajor-caju	- Nematicidal activity on all nematodes - Predation - 80-86% reduction in nematode egg masses, galling and population	Root-knot nematodes, (*Meloidogyne incognita*)	Mostafa et al., 2019
P. ostreatus	- Antifungal activity of a peptide Pleurostrin	*F. oxysporum*, *Physalospora piricola, Mycosphaerella arachidicola*	Chu et al., 2005
Lactarius rufus	- Antifungal activity of sesquiterpene, Rufuslactone	*Alternaria alternata*, *A. brassicae*, *Botrytis cinerea*, *F. graminearum*	Luo et al., 2005;
SMS	- Inhibition by metabolites - Plant growth promotion - Reduced disease severity	*Phytophthora capsici* and *P. parasitica*	Marin et al., 2014
P. ostreatus (SMS and SMS extract)	- Antifungal compounds - 44-69% inhibition of the disease	Basal rot disease (*F. oxysporum* f. sp. *cepae*)	Istifadah, 2018
P. ostreatus	- Antifungal compounds - Promotion of beneficial microbes - Plant growth promotion - In vitro inhibition - Reduced disease severity in pots	*F. oxysporum* f. sp *musacearum* (race 1)	Ocimati et al., 2021
Lentinula edodes, *Grifola frondosa*, *H. erinaceus*, *Hypsizygus marmoreus*	- Antibacterial activity of metabolites in culture filtrates	*Ralstonia solanacearum* in tomato	Kwak et al., 2015
H. erinaceus	- Antibacterial activity of water, *n*-butanol, and ethyl acetate extracts. - Induced expressions of plant defence genes encoding β-1,3-glucanase (GluA) and pathogenesis-related protein-1a (PR-1a)-associated with systemic acquired resistance - Plant growth promotion - 85% suppression of *R. solanacearum*	Phytopathogenic bacteria: *Pectobacterium carotovorum* subsp. *carotovorum*, *Xanthomonas oryzae* pv. *oryzae*, *X. campestris* pv. *campestris*, *X. axonopodis* pv. *vesicatoria*, *X. axonopodis* pv. *citiri*, and *X. axonopodis* pv. *glycine*, *Agrobacterium tumefaciens*, *R. solanacearum*	Kwak et al., 2015
P. eryngii	- Enhanced plant defence factors - Plant growth promotion - 70% disease suppression	*R. solanacearum*	Kwak et al., 2016

A diverse range of mechanism of suppression of plant pathogens and pests by SMW have been proposed in literature (Table 1; Figure 2C). Suppression through secondary metabolites or enzymes (33% of publications), was the predominantly reported mechanism of suppression by SMW (Figure 2C). Modulation of plant defence responses (16%), promotion of secondary metabolites (13%) and plant growth promotion are other highly reported mechanisms. Other mechanisms of pest and disease suppression in publications included, modification of the soil environment, predation, mycotoxin degradation, and competition for resources (Figure 2C).

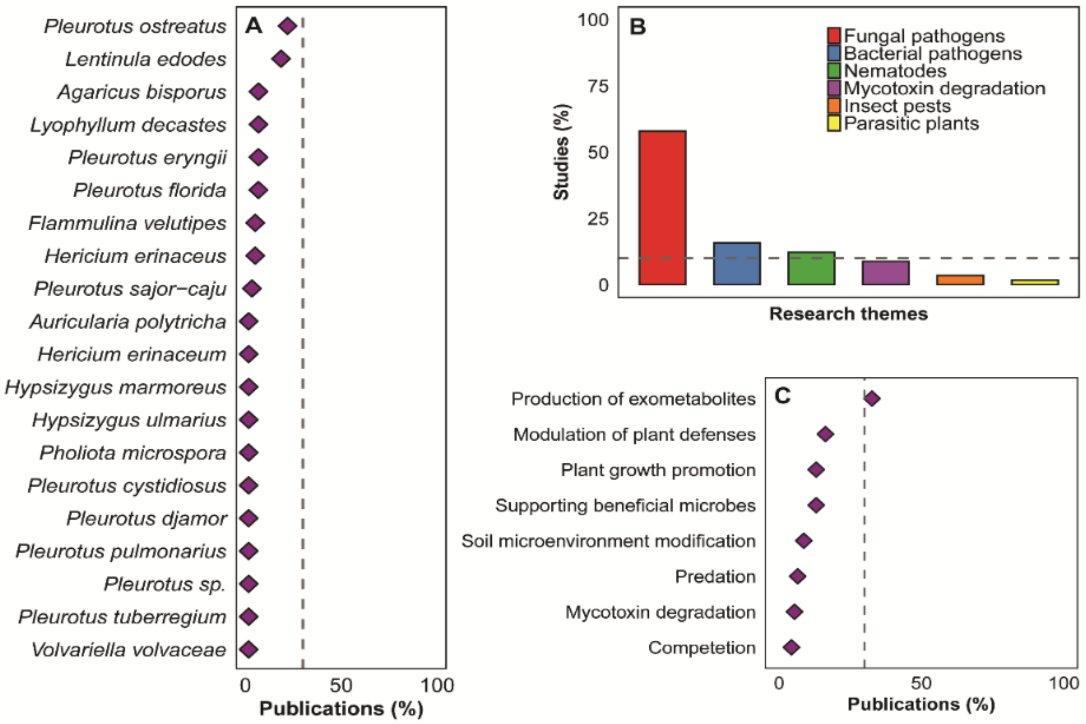

Figure 2. Proportion (%) of publications reporting on different A) mushroom species with pest and disease suppressive effects, B) biotic constraints of crops suppressed by spent mushroom wastes, and C) mechanisms of crop pest and disease suppression. The publications (48) cover the period between 1985 and 2022.

Application of spent mushroom substrates as biofertilizers

Use of SMW of different edible mushroom spp. as biofertilizers have been reported in literature, with *A. bisporus* and *P. ostreatus,* predominating (Figure 3A). Publications on SMW use as biofertilizers covered different biological, physical, and chemical soil properties (Figure 3B). Themes on SMW use as biofertilizers covered SMW effects on crop growth attributes (vigor, yield, and nutritional quality), soil nitrogen, soil organic matter (SOM), phosphorus, soil pH and potassium (Figure 3B). Edible mushrooms are grown on agricultural by-products and lignocellulosic wastes such as coffee husks, corn cobs, rice husks and cotton seeds (Sánchez, 2010). SMW thus contain diverse and high levels of SOM, macro- and micro-nutrients, and are suitable for improving soil pH, SOM and soil nutrient levels. For example, soil pH, SOM, total N, total P, total K, total Ca and Mg levels in SMS varying respectively from 6.0 to 8.25, 407-740 g kg^{-1}, 17-28 g kg^{-1}, 7-38 g kg^{-1}, 11-34 g kg^{-1}, 3-101 g kg^{-1}, and 0.6-39 g kg^{-1} have been reported (Jordan et al., 2008; Paredes et al., 2016). Unlike inorganic fertilizers, SMW have a slow mineralization and release nutrients slowly, making them a suitable source for these nutrients. The SMW can be used immediately after mushrooms harvesting or after composting/ vermicomposting to homogenize and stabilize it (Marín-Benito et al., 2016).

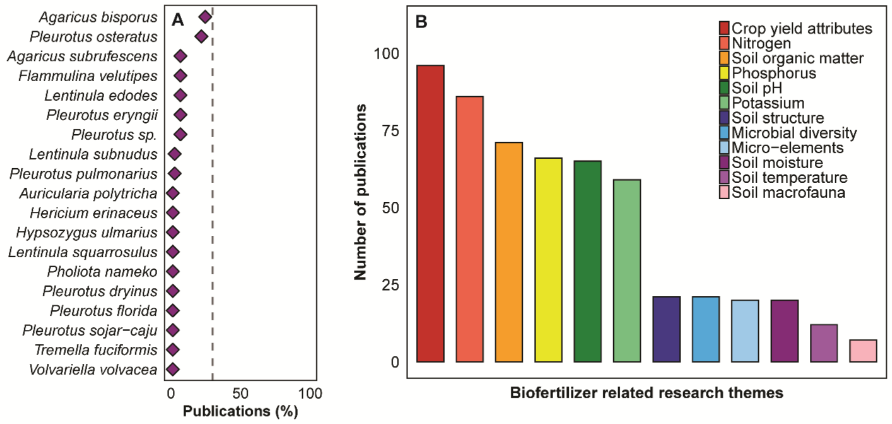

Figure 3. Publications showing A) different mushroom species evaluated for their effects as biofertilizer, and B) different study themes related to SMW use as biofertilizer. The publications (255) cover the period between 1985 and 2022.

Other themes in literature included SMW effects on soil structure, microbial diversity, micro elements, soil moisture, temperature, soil macrofauna and degradation of pollutants. Table 2 summarizes some of the benefits of using SMW as biofertilizers in different crop species.

Table 2. Summary of findings on the biofertilizer related benefits arising from the use of spent edible mushroom waste from some sampled publications.

Benefits in the soil rhizosphere	Citation
Improvement of crop growth (high vigor), and yield attributes	Kadiri and Mustapha, 2010
Improvement of soil organic carbon and matter	Li et al., 2020; Becher et al., 2021
Enhanced soil nitrogen, phosphorus, and potassium	Lou et al., 2017; Ma et al., 2021
Regulation and maintenance of soil pH in range of agricultural production	Majchrowska-Safaryan et al., 2020; Lipiec et al., 2021
Has a low bulk density which helps maintain a good soil structure, thus a higher and balanced air porosity	Courtney et al., 2009; Lipiec et al., 2021
Increased availability of micro-nutrients (e.g., iron, zinc)	Medina et al., 2009; Jonathan et al., 2011
Increased microbial biomass and functional diversity	Li et al., 2020; Frąc et al., 2021
Regulates soil moisture and temperature	Ma et al., 2021

POTENTIAL APPLICATIONS OF MUSHROOM WASTES TO ADDRESS SOIL HEALTH CHALLENGES WITHIN ORGANIC BANANA PRODUCTION SYSTEMS

Soil health management is a core challenge for organic production systems due to the heavy reliance on inorganic chemicals for improving soil nutrient availability, and managing weeds, pests, and diseases. Key soil health challenges in banana systems include the banana parasitic nematodes; soil borne pathogens, mainly *Fusarium oxysporum* f. sp. *cubense* (Foc) and low soil fertility (Dita et al., 2020; Blomme et al., 2020).

Plant parasitic nematodes (PPN) affect banana production globally. The most important banana nematode species include *Radopholus similis, Pratylenchus* spp., *Meloidogyne* spp., and *Helicotylenchus multicinctus* (Gaidashova et al., 2009; Lara Posadas et al., 2016). These PPN damage plant roots affecting their ability to take up water and nutrients from the soil reducing plant vigour and yield. Plants with heavily damaged roots become vulnerable to toppling. The damaged roots also become entry points for soil borne pathogens such as Foc. Yield losses of up to 51% have been reported for East African highland banana cultivars due to nematode damage (Speijer and Kajumba, 2000). The management of PPN is challenging due to their rapid population build-up and the presence of multiple alternative host plants (Atolani and Fabiyi, 2020). Use of nematicides, though effective, has potential negative environmental and health effects (Gowen, 1997) and are prohibited for organic systems. The above findings show SMW to have nematicidal effects on different nematode spp. in other crops (Table 1). Thus, SMW could potentially be beneficial for the management of banana nematodes.

Fusarium wilt caused by Foc is the main soil borne threat to banana production. Foc that is mainly spread through the infected planting materials and contaminated soil and water, has significantly impacted the banana industry and livelihoods of smallholder farmers (Ploetz, 2015; Dita et al., 2020). Banana production is especially threatened by the more recent outbreaks and spread of the Foc TR4 strain that has caused yield losses of up to 100% in Cavendish banana that currently dominates the banana export market (Dita et al., 2020). Foc has a long survival/residence time in soil and can survive on alternative hosts making fields unsuitable for susceptible banana cultivars for decades (Dita et al., 2020), thus complicating its management. This study shows (Table 1) SMW to suppress fungal pathogens including the genus *Fusarium*. Ocimati et al. (2021) also showed SMS of *P. ostreatus* to suppress Foc in-vitro and under screenhouse conditions using both sterile and naturally infested field soils. Assessing the potential of SMW of a wider range of edible mushroom species to suppress *Foc* (including Foc TR4) under field conditions is recommended. In addition, studies to elucidate the mechanisms of Foc suppression by SMW are also needed.

Wastes from different species of edible mushrooms have been shown to suppress a diverse range of bacterial pathogens (Table 1). In banana, important bacterial pathogens include *Xanthomonas vasicola* pv. *musacearum* (Xvm), *Ralstonia solanacearum* and *R. syzygii* subsp. *celebesensis* (Blomme et al., 2017). Though the rhizosphere is not a major route for Xvm spread, it is important for *Ralstonia* spp. Existing literature already shows the suppression of *Xanthomonas* spp. and *Ralstonia* spp. by SMW in other crop species. The integration of SMS as part of the current cultural control packages could potentially help in reducing or eliminating soil inoculum, thus in turn limiting the entry of these bacterial pathogens through wounds on roots or the corms.

Low soil moisture content and deficiency in soil nutrients, especially potassium (K) and nitrogen (N) have been reported as major yield limiting factors for the banana crop (Nyombi et al., 2010; Taulya, 2013). Deficiency in soil nutrients also affects the ability of the plants to withstand harsh environmental conditions, and pests and diseases. Soil K is for example, crucial for the uptake of soil water (Taulya, 2013) while K also enhances plant resistance to pests and diseases (Wang et al., 2013). Strategies for ensuring a balanced soil nutrient composition to meet crop nutrient needs is thus crucial for a sound soil health status. Studies above show SMW to improve soil structure, soil pH, levels of macro- and micro-elements that could be crucial for improving the performance of the banana crop in organic systems.

These findings reveal a huge potential for the improvement of soil health and management of key biotic and abiotic constraints of organic banana production systems using of SMW. In a cyclic farming, the residues from banana and other crops could be used as substrates for growing mushrooms and the resultant SMW subsequently returned to these fields to improve the soil health and key pests and diseases. Studies to explore the highlighted benefits above on organic banana systems is recommended. Exploration of other models for delivering the services provided SMW where it is not feasible to access SMW is also recommended.

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