International Journal of Statistics and Applied Mathematics

ISSN: 2456-1452
Maths 2023; SP-8(6): 275-281

https://www.mathsjournal.com
Received: 05-09-2023
Accepted: 07-10-2023

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Microbial magic: A review on harnessing the potential of mushroom metabolites for plant disease management

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Abstract
Plant diseases pose a significant threat to global food security, prompting the continuous exploration of innovative solutions for their management. In recent years, the utilization of mushroom metabolites has emerged as a promising option in this pursuit. Mushroom metabolites are basically secondary metabolites which are structurally diverse and can be unique to specific plant species or microbial strains. Their chemical diversity makes them valuable for pharmaceutical, agricultural, and industrial applications. Mushroom metabolites are rich sources of bioactive compounds with diverse chemical structures. The integration of these bioactive compounds into agricultural practices has the potential to reduce the ecological footprint of agriculture while ensuring crop health and productivity. These compounds exhibit a wide range of bioactivities, including antimicrobial, antiviral, and antioxidant properties. Their potential in suppressing plant pathogens and enhancing host plant resistance is a subject of increasing research interest. Various mushroom species, such as *Agaricus*, *Ganoderma*, *Lentinus edodes*, *Schizophyllum commune*, *Trametes versicolor* have been explored for their metabolites' disease control potential. This review delves into the multifaceted role of mushroom metabolites in plant disease management, offering a comprehensive overview of their mechanisms and applications. This review explores the modes of action of mushroom metabolites, including direct antimicrobial effects, induction of plant systemic resistance, and modulation of the plant microbiome. It also discusses the practical applications of mushroom metabolites in disease management, including their use in biopesticides, bio stimulants, and as biofertilizers. Furthermore, the challenges and prospects of integrating mushroom metabolites into sustainable agriculture are highlighted.

Keywords: Mushroom metabolite, secondary metabolites, antimicrobial, antioxidant, bio stimulants

Introduction
A mushroom is a macroscopic fungus known for its unique fruiting bodies, which can be found either underground (hypogeous) or above the ground (epigeous). These fruiting bodies are typically substantial in size, easily visible without the need for magnification, and can be harvested by hand (Chang and Miles, 1992) [9]. Mushrooms typically exhibit a classic umbrella-like structure, consisting of a cap (pileus) and a stem (stipe). Some species also feature a cup-like structure called a volva, like *Volvariella volvacea*, while others have only a ring known as an annulus, as seen in *Agaricus campestris*. Some other possess both a volva and an annulus, such as *Amanita muscaria*. There are some other categories mushroom such as earth stars (Geastrum), the stink horns (phalloides), and puff balls (Lycoperdon). Mushroom cultivation serves a dual purpose by not only providing a valuable source of protein-rich and nutritious food but also playing a role in the development of potent medicinal products (Chang and Wasser, 2012) [11]. They exhibit versatility in their utility, serving as a valuable resource for nutrition, tonics, pharmaceuticals, cosmeceuticals, and as natural agents for biocontrol in safeguarding plants. Their multifaceted properties encompass insecticidal, fungicidal, bactericidal, herbicidal, nematocidal, antiphytoviral, antitumor, and immunomodulating activities activities (Gargano *et al*., 2017) [16]. Mushrooms are abundant sources of polysaccharides, peptides, polyphenols, and various other compounds that are known for their positive impacts on human health.

As a result, mushrooms have gained considerable recognition as valuable resources for functional foods and are being explored for their potential in drug development and nutritional applications (Alves *et al*., 2012) [2].

Metabolites, by definition, are the intermediates and end products of metabolic processes, typically produced in relatively small quantities. During the growth phase of cells, primary metabolites are continuously generated. These primary metabolites play integral roles in fundamental metabolic processes like respiration and photosynthesis. In contrast, secondary metabolites, when cultivated in artificial settings, are not directly associated with the growth and survival of the organisms. They often share biosynthetic pathways with primary metabolites but serve additional functions, including defense, competition, and interactions with other species. These secondary metabolites are by products of primary metabolic pathways and, unlike primary metabolites, are not essential for sustaining cellular life. Interestingly, secondary metabolites are frequently produced during the non-growth phases of cells. Secondary metabolites are typically biosynthesized after the phase of active growth. These compounds have drawn substantial interest owing to their potential medical, industrial, and agricultural relevance. Furthermore, the economic importance of generating lipids, vitamins, polysaccharides, and intermediary components involved in the synthesis of essential cellular constituents such as amino acids and nucleotides remains pronounced in contemporary industrial sectors (Bano, 1976; Gupta, 1989; Sohi; 1988) [49, 17, 40].

There are various bioactive compounds found in cultured broth, mycelium, and fruiting bodies such as volatile oils, flavonoids, alkaloids, ascorbic and organic acids, fats, polysaccharides, tocopherols, glycosides, minerals, proteins, carotenoids, terpenoids, lectins, enzymes, phenolics, and folates (Venturella *et al*., 2021) [41].

Extraction of mushroom metabolite

The meticulous selection and preparation of mushroom samples is the first step towards the successful extraction and isolation of desired chemicals.

Identification, selection, and collection of mushroom samples

Materials related to mushroom selection, collection, and identification have a direct impact on the accuracy of phytochemical studies. Any carelessness at this stage of an investigation might reduce the scientific value and further outcome of the research when searching for a particular compound or metabolite from mushroom of our choice. Secondary metabolites are very specific and differ even within the members of same species, hence careful measures must be taken to extract them (Cantley, 1997) [7].

Drying, Grinding and Extraction Process

After successful collection of mushrooms, they must be dried at temperatures below 30 °C in order to avoid deterioration of any heat sensitive compound present in sample. Direct contact with sun light should be avoided as direct exposure to ultraviolet rays are harmful for mushroom metabolites extraction. For research purposes, it is advisable to promptly extract the necessary material using organic solvents like ethanol to inactivate any enzymes in the material. If you have a small amount of fungal material, you can crush it using a mortar and pestle or an electric grinder. When dealing with larger quantities, it is more efficient to use industrial-scale grinding equipment for milling. Effective grinding reduces the amount of solvent needed for extraction and enhances the extraction process's effectiveness. Harvested mycelium must be taken, dried and powdered in mortar and pestle. Powdered mycelium mixed with 50% (v/v) ethanol (100 mg/ml). After that it is centrifuged, through which deproteinization occurs.The culture filtrate is passed through DEAE cellulose, Sephadex G200 column. Finally, purified metabolite is collected. Numerous researchers have extensively documented the application of conventional extraction methods for obtaining valuable extracts that are abundant in secondary metabolites from various types of mushrooms (Ruthes *et al*., 2015; Kaewnarin *et al*., 2016; Boonsong *et al*., 2016) [34, 11, 5].

Mushrooms with potential secondary metabolites

***Ganoderma lucidum* (Lingzhi or Reishi): Latin - *lucidus* means "shiny" or "brilliant".**

Ganoderma lucidum (Curtis) P. Karst. is a medicinal mushroom known for its intriguing chemical makeup, which contributes to its qualities as a nutraceutical with pharmacological advantages. These properties can be harnessed for various purposes, including immune regulation, cholesterol reduction, and as a complementary approach in managing conditions like cancer, high blood pressure, sleep disturbances, loss of appetite, vertigo, and chronic hepatitis, among other health issues (Zhao *et al*., 2016) [51]. Ganoderma, often referred to as the "mushroom of immortality," is typically found on trees such as oaks, hazels, beech, apple, and willow. It contains an organic form of Germanium, obtained from its spores, which includes triterpenes and polysaccharides. Germanium is used to address heart and blood vessel conditions like high blood pressure, high cholesterol, and heart disease. It is also used for eye conditions such as glaucoma and cataracts, as well as liver conditions like hepatitis and cirrhosis. Reishi contains more than 100 oxygenated triterpenes, many of which have a significant impact on the activity of natural killer (NK) cells. The primary polysaccharides found in Reishi are -1,3; -1,6-D-glucans and ganoderan, with glucose as a major sugar component. These compounds are known for their strong antiangiogenic effects and their ability to enhance the immune system. Additionally, Reishi has been the subject of research examining its potential in preventing or combating colorectal cancer, with some studies indicating that a one-year treatment with Reishi led to a reduction in both the number and size of tumors in the colon (Baby *et al*., 2015) [4].

Metabolites of *Ganoderma* sp.

Ganoderma contains a range of metabolites, including ganoderic acids, aldehydes, alcohols, esters, glycosides, lactones, ketones, lucidenic acids, pentacyclic triterpenes, hydroquinones, steroids, and alkaloids. Among these, triterpenoids are the primary active components found in Ganoderma spores, and they exhibit various beneficial properties for medicinal purposes. These triterpene compounds are synthesized through the mevalonate pathway and originate from lanosterol, with examples including ganoderic acids, ganodermic acid, ganodermic alcohols, lucidones, and lucinedic acids. In addition to these, three novel lanostane-type triterpenoids containing farnesyl hydroquinone segments were discovered in the fruiting body of Ganoderma sinense and named ganosinensins A-C (1-3). Alongside these newly identified compounds, three known lanostane triterpenes, ganodermanontriol, ganoderiol A, and ganoderiol D, were also isolated. Ganoderma lucidum polysaccharide (GLP) consists of a core structure formed by D-glucopyranosyl residues linked together through β-(1→3) bonds. This core structure has side branches composed of mono-, di-, and oligosaccharide chains attached to the C-6 position of the glucosyl residues in the main chain (Baby *et al*., 2015) [4].

Role of Ganoderma lucidum polysaccharide in plant disease management

Ganoderma lucidum, commonly known as the lingzhi or reishi mushroom, is a fungus that has been used in traditional medicine for centuries, particularly in East Asia. It is known for containing bioactive compounds, including polysaccharides, which have been studied for their potential health benefits (Chang *et al*., 2015; Li *et al*., 2015) [10, 25].

When seeds undergo treatment with Ganoderma Lucidum Polysaccharide(GLP), they exhibit control over soil-borne diseases by around 35%, as observed in both greenhouse and field experiments. Prior studies have shown that while (GLP) biological elicitors might not directly act as fungicides, they can still effectively manage plant diseases by triggering the plant's disease resistance mechanisms. When plants are stimulated by these biological agents, they tend to alter various factors such as callose deposition, the production of defense enzymes, fortification of the plant cell wall involving phenylpropanoid compounds, and the accumulation of pathogenesis-related (PR) proteins. This activation serves as protection against pests and diseases. Some reports suggest that seaweed polysaccharides like ulvans, alginates, fucans, laminarin, and carrageenans, along with their derived smaller sugar molecules, can initiate an initial oxidative response and activate signaling pathways related to salicylic acid (SA), jasmonic acid (JA), and/or ethylene in land-based plants. The activation of these pathways results in an increase in the expression of PR proteins, known for their antifungal and antibacterial properties, and triggers the upregulation of defense enzymes involved in the synthesis of compounds like PPCs, terpenes, terpenoids, and alkaloids, which possess antimicrobial traits (Walters *et al*., 2013; Thakur *et al*., 2013; Aziz *et al*., 2003; Vera *et al*., 2011) [44, 39, 3, 42].

By prompting resistance in plants, it simplifies the management of pathogens, consequently lowering the necessity for chemical fungicides and reducing their frequency of application. GLP enhances plant well-being and is utilized alongside fungicides to enhance the efficacy of disease prevention (Oostendorp *et al*., 2001) [30].

Shiitake Mushroom - *Lentinula edodes*

The Shiitake mushroom (*Lentinus edodes*) stands as the second most substantial edible fungus, showing notable expansion in both production and utilization in recent years (Salwan *et al*., 2021) [33]. Shiitake mushroom flourishes specifically on decaying wood from a variety of deciduous trees such as Shii (*Castanopis cuspidate*), chinquapin, chestnut, oak, and maple. *Lentinula edodes* holds the distinction of being the primary medicinal macrofungus to venture into the domain of contemporary biotechnology and is regarded as the planet's second most sought-after edible mushroom within the global market, primarily for its promising potential in therapeutic applications (Ahn *et al.*, 2017) [1]. The organoleptic attributes of Shiitake mushrooms have sparked a resurgence in their global consumption and production in recent times (Youn, 2004) [47]. This mushroom is renowned for its combined medicinal and edible uses and has been classified as a "functional food". This mushroom has a rich history in oriental traditions, historically utilized for addressing various health concerns such as tumors, flu, heart diseases, high blood pressure, obesity, sexual dysfunction, aging-related issues, diabetes, liver conditions, respiratory ailments, as well as fatigue and weakness. Recognized as one of the most prized medicinal mushrooms, it carries significant value in traditional medicine. The protein composition of *L. edodes* encompasses 18 amino acids, including all essential amino acids in proportions akin to an optimal human nutritional profile. Additionally, this mushroom boasts significant levels of vital vitamins such as C, B1, B2, B12, niacin, and notably, the highest concentration of vitamin D among plant-based sources (Breene, 1990; Vetter, 1995) [6, 43].

Metabolites of *Lentinula edodes*

It serves as the origin of two extensively researched and widely accepted polysaccharide remedies: LEM, which is a protein-bound polysaccharide specifically obtained from the mycelium, and lentinan, a branched -β-D-glucan extracted from both the mycelium and the fruiting body (Suzuki *et al*., 1990; Chihara *et al*., 1969) [36, 12].

Both elements function as immune system boosters and have displayed anti-cancer properties. Moreover, *L. edodes* possesses additional compounds that hinder blood clotting, lower cholesterol levels, and demonstrate antibacterial and antiviral effects (Suzuki and Ohshima, 1976; Yang *et al*., 2002) [37, 47]. It provides a substantial supply of carbohydrates, proteins, and indispensable amino acids, maintaining low fat content while featuring a high concentration of polyunsaturated fatty acids. Moreover, it encompasses a diverse spectrum of vitamins and minerals. Furthermore, the polysaccharides derived from *L. edodes*, known for their immune-modulating and anticancer properties, are utilized in clinical applications as supplements to traditional chemotherapy. Shiitake mushrooms contain dietary fiber composed of both water-soluble elements like β-glucan and protein, as well as water-insoluble substances only extractable with salts, acids, and alkalis. These substances include polyuronides (acidic polysaccharides), hemicellulose, β-glucan with varied sugar chains, lignin, and chitin, which serve as constituents of the cell wall. Aroma components in these mushrooms comprise alcohols, ketones, sulfides, alkanes, fatty acids, and similar compounds (Mizuno *et al*., 1995) [28].

Role of Ganoderma lucidum polysaccharide in plant disease management

The antibacterial efficacy of *L. edodes* against *Bacillus subtilis* was appraised through the examination of cell-free filtrates acquired from growth in 14 diverse culture media (Hassegawa *et al*., 2005) [18]. Lenthionine, a sulfur-containing peptide sourced from shiitake, displays antibacterial and antifungal properties (Yasumoto *et al*., 1971) [48]. Furthermore, a derivative of lenthionine, bis[(methylsulfonyl)methyl] disulfide, showcases robust inhibitory effects against *Staphylococcus aureus*, *Bacillus subtilis*, and *Escherichia coli* (Hatvani, 2001) [19]. Additionally, extracts obtained from dried shiitake mushrooms using chloroform and ethyl acetate exhibit bactericidal activity against both actively proliferating and dormant forms of Streptococcus mutans and Prevotella intermedia (Hirasawa *et al*., 2001) [20].

A novel protein designated lentin with potent antifungal activity was isolated from the fruiting bodies of the *L. edodes*.

Lentin, which had a molecular mass of 27.5 kDa, inhibited mycelial growth in a variety of fungal species including *Physalospora piricola*, *Botrytis cinerea* and *Mycosphaerella arachidicola*. Lentin also exerted an inhibitory activity on HIV-1 reverse transcriptase and proliferation of leukemia cells (Ngai and Ng, 2003) [29].

To evaluate the efficacy of LNT, it was employed as a seed treatment to manage sharp eyespot disease in wheat. The treatment significantly enhanced wheat growth. Using 8 grams per 100 kilograms of seeds across various wheat cultivars, such as Jimai 22, Shannong 23, and Luyuan 502, seed germination rates improved notably, reaching 54%, 52%, and 51% from an initial 50%. Post-germination, treated wheat displayed considerable enhancements in both height and root activity compared to untreated controls, with effects scaling relative to the dosage. LNT proved effective in suppressing sharp eyespot development in wheat, notably reducing disease progression by 33.7%, 31.9%, and 30.4% at different intervals post-germination in the highly susceptible Jimai 22 cultivar. Additionally, LNT boosted specific enzyme activities, reduced detrimental content, increased chlorophyll levels, and improved root vigor in wheat, with the most evident effects observed at the 7-day mark post germination. The application of LNT induced the transcription of genes associated with alternative oxidase (AOX) and β-1,3-glucanase (GLU), as well as genes linked to the salicylic acid signaling pathway and sharp eyespot resistance. Notably, a direct relationship between the dosage and the transcription of the AOX gene was observed, hinting at its potential as a key target gene (Zhang *et al*., 2017) [50].

LNT exhibits inhibition against viral infections caused by both naked and enveloped viruses, although its control over TMV is limited. The antiviral activity of polysaccharides is increased through sulfated modification. Alongside its antimicrobial and antibacterial properties, LNT also demonstrates the ability to hinder viral infections from various types of viruses, primarily operating during the initial phases of viral infection. As the exploration of the biological potential of polysaccharides grows, the focus on molecular modification and structural enhancement of these compounds becomes a crucial area of research. Various methods, including sulfation, oxydo-reduce-hydrolysis, and enzyme-based reduction, are employed for polysaccharide modification (Wang *et al*., 2013) [45].

Split-gill mushroom: *Schizophyllum commune*

Schizophyllum commune Fr., belonging to the Schizophyllaceae family, is a prevalent edible mushroom found naturally on decaying wood, particularly during rainy seasons. The term "Schizophyllum" denotes "split gill," hence this mushroom is commonly called split gill mushroom. This fungus, causing white rot, thrives on wood decay and stands apart from other gilled fungi. Elias Magnus Fries gave Split Gill mushroom its current scientific name in 1815. It survive dehydration and rehydration and causes white rot (it consumes mainly the lignin within timber (Zhong *et al*., 2015). This mushroom is recognizable by its dense white hairs, lacking stalks, and possessing pale yellow to brownish continually branching gills, leading to its name "split gill." The fruiting body is small and fan-shaped, producing white spores. Its life cycle is fully developed within a span of 10 days (Imtiaj *et al*., 2008) [21].

The Split Gill fungus commonly grows as a fixed bracket structure. However, it often forms circular fan shapes attached at the center on the undersides of branches. This small white bracket-like fungus displays radial gill-like folds beneath the cap, each having a central split, hence the name "Split Gill." These splits represent an adaptive feature allowing it to adjust to varying environments. *S. commune* is found globally, thriving on every continent except Antarctica, establishing itself as one of the most prevalent mushroom species. The term "commune" in its species name denotes "common" or "widespread." Significant genetic diversity occurs within and between populations due to extensive spore dispersal over long distances and genetic changes through drift (James *et al*., 1999; Chang and miles, 2004) [22, 8].

Metabolites of *Schizophyllum commune*

The mushroom harbors exopolysaccharides like schizophyllan and sizofiran. Schizophyllan, a non-ionic, water-soluble homoglucan, consists of a β-(1→3)-linked backbone with occasional β-(1→6)-linked glucose side chains, occurring roughly every third residue. This compound contains elements known for their antitumor and antiviral properties. Beyond essential nutrients like protein, fiber, and minerals, analysis of S. commune samples reveals the production of at least three distinguishable biopolymers in an aqueous culture medium-a 24 kDa hydrophobin, a 17 kDa protein, and schizophyllan (Martin *et al*., 1999) [27]. The immunomodulatory effects of compounds like schizophyllan and other (1→3)-β-D-glucans (scleroglucan and lentinan) are influenced by their branching structures, molecular weight, and their specific triple helix conformations. Greater branching often correlates with heightened activity, and the impact in relation to size demonstrates a reasonably foreseeable pattern. Comparatively, structures with higher complexity trigger increased activation of monocytes, leading to cytokine production, particularly within the molecular weight range of below 60×10^4 g/mol or above 110×10^4 g/mol (Falch *et al*., 2000) [15]. Notably, the observed anti-tumor effects manifest exclusively in compounds with a molecular weight surpassing 50,000 (Tabata *et al*., 1988) [38].

Role of *Schizophyllum commune* metabolite in plant disease management

Numerous compounds sourced from the mycelial culture or the mushroom of *S. commune* have been extracted and examined for their potential beneficial effects. Sizofiran, an antitumor polysaccharide derived from the culture medium of *S. commune*, demonstrated effectiveness as an immune-therapeutic treatment for cervical carcinoma (Shittu *et al*., 2005) [35]. Recently, *S. commune* showed a decrease in the emergence of adult tobacco cutworms, pointing to the genotoxic and cytotoxic impact of the fungus and hinting at its potential as an insecticidal agent (Kaur *et al*., 2018) [24].

A study was conducted by Dutta *et al*., 2019 [14] to study the control of anthracnose and gray mold in pepper plants using culture extract of white-rot fungus containing active compound schizostatin. Mixing schizostatin, obtained from the split gill fungus culture filtrate, into PDA media required a minimum of 50 µg/mL to impede the growth of *B. cinerea*, while 10 µg/mL exhibited inhibitory effects against *Colletotrichum gloeosporioides*. At 150 µg/mL, the compound significantly suppressed the growth of *C. gloeosporioides* by 92.4% and B. cinerea by 87.3%. The LC50, representing the concentration causing 50% inhibition, was approximately 40.0 µg/mL for *C. gloeosporioides* and 95.0 µg/mL for *B. cinerea*. Metabolites from *S. commune* showcased antifungal properties, with scleraldehyde displaying antibacterial activity.

Further, a study was conducted by Park and colleagues in 2020 [31] to analyse the *in vivo* efficacy of co -treatment with tebuconazole and schizostatin against gray mold. A suspension containing *Botrytis cinerea* conidia (106 conidia/ml) was used for the inoculation process. Tebuconazole and schizostatin were administered one day before the inoculation. Four days after treatment, the extent of necrotic lesions was measured. Sole treatment with schizostatin at varying concentrations, even at the highest concentration of 2.5 µg/ml, did not exhibit significant control effects. Tebuconazole treatments at concentrations of 1, 5, and 10 µg/ml showed no substantial variation in lesion area compared to the untreated control. However, the treatment with 20 µg/ml tebuconazole displayed noticeable efficacy in controlling lesions. Nonetheless, a combination treatment involving 5 µg/ml tebuconazole and 0.4 µg/ml schizostatin demonstrated a significant reduction in lesion area compared to untreated leaves. Treatments combining 5 µg/ml tebuconazole with higher doses of schizostatin (1 or 2.5 µg/ml) resulted in further reductions in lesion area, comparable to the effects seen with the singular treatment using 20 µg/ml tebuconazole.

Caterpillar Fungus- *Cordyceps* sp.

Cordyceps sinensis, an ascomycetous entomopathogenic fungus, parasitically grows on *Hepialis armoricanus*. The name "Cordyceps" originates from Latin, combining "cord" for "club" and "ceps" for "head." This fungus, historically considered a remedy in ancient Chinese and Tibetan medicinal practices, is an annual Ascomycetes fungus closely resembling mushrooms. Typically found growing on immature larvae about 6 inches below ground, it extensively consumes its host, ultimately mummifying it as it nears maturity. Upon maturation, the stroma swells and produces perithecia, with an average weight ranging from 300–500 mg. *Cordyceps sinensis* demonstrates broad pharmacological effects, particularly in hepatic, renal, and cardiovascular diseases, and is also associated with increased sexual potency.

Secondary metabolites from *Cordyceps* spp.

Cephalosporolides are beta-lactam antimicrobials used to manage a wide range of infections from gram-positive and gram-negative bacteria. Cephalosporins are useful against skin infection, resistant bacteria, meningitis, and other infections. Cordypyridones is antimalarial in action. Cordyformamides acts as a softener for paper and fiber. It also has anti-metastatic effects of ergosterol peroxide from the entomopathogenic fungus *Ophiocordyceps gracilioides* on 4T1 breast cancer cells. Because cordycepin is similar to adenosine, some enzymes cannot discriminate between the two. It can therefore participate in certain biochemical reactions (for example, 3-dA can trigger the premature termination of mRNA synthesis).

Role of *Schizophyllum commune* metabolite in plant disease management

In a pot experiment, extracts derived from the entomopathogenic fungus *Ophiocordyceps sobolifera* were tested for their ability to suppress chili anthracnose fungi of the *Colletotrichum spp*. Among the extracts, mycelial extract treatments provide the best reduction in disease severity. Interestingly, two bioactive constituents, adenosine and cordytropolone, from the mycelial extract, inhibited growth of the fungal pathogens. Moreover, these bioactive compounds had a synergistic effect against the fungal pathogens in a pot experiment. These results confirmed the disease suppressive activity of the mycelial extract (Jaihan *et al*., 2018).

Conclusion

Secondary metabolites from mushroom exhibit notable potential in curtailing the growth of plant pathogens, presenting a promising avenue for developing sustainable agricultural disease control methods. For instance, lentinan, sourced from Shiitake mushrooms, demonstrates promise in combatting TMV, particularly with augmented antiviral properties via sulfated modification. Schizostatin serves as a fungicide synergist, enabling reduced concentrations of commercial fungicides. Ganoderma lucidum polysaccharide (GLP) showcases fungistatic attributes. Exploring bioactive compounds from wood-decay fungi could open new research avenues in biological protection. Utilizing natural preparations may effectively impede soil fungi development and mitigate the adverse impact of environmental xenobiotic pollution.

Current challenges and future prospects

At present, challenges persist in fully harnessing the potential of secondary metabolites from mushrooms for plant disease management. Factors include optimizing extraction methods for maximal yield and efficacy, understanding the mechanisms of action of these compounds on various pathogens, and enhancing their stability for practical application in agricultural settings. Future prospects lie in advancing research to comprehensively unravel the biochemical pathways and interactions of these metabolites with plant pathogens. Additionally, the development of efficient delivery systems and formulations that ensure their sustained efficacy in diverse environmental conditions is crucial. The exploration of novel compounds and their synergistic interactions could pave the way for more effective and sustainable plant disease management strategies. Integrating these secondary metabolites into holistic crop protection plans, alongside sustainable agricultural practices, holds promise for the future of disease management in agriculture.

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