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Bacteriostatic and Virostatic Activities of Mushrooms: A Mini-review

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Abstract

In this study, we discuss the various bacteriostatic and antiviral effects of mushrooms and their potential mechanisms of action. During this research, we included both Chinese and international studies. Mushrooms and their active constituents, such as fatty acids, polysaccharides and proteins, were found to exert significant antibacterial and antiviral effects. These antimicrobial mechanisms appear to be similar to those of penicillin, which prevents bacterial growth by inhibiting bacterial cell wall synthesis. In contrast, the antiviral effects likely result from non-specific enhancement of immune function and regulation and increase of cellular repair. However, at present, research on the effective ingredients and relevant mechanisms of action of mushrooms is lacking. Thus, further research is warranted.

Key words – active ingredients – antibacterial – antiviral – fungus – mechanism

Introduction

Fungi are nucleated, sporogenic and chloroplast-free eukaryotes. Mushrooms are a specific type of fungi, some of which are known to be both delicious and nutrient-rich (Reis et al. 2012). The class *Basidiomycetes* encompasses many mushrooms that are considered delicacies. These mushrooms have high nutritional and functional value, and many are also recognized as nutraceutical foods. These mushrooms are of considerable value due to their organoleptic merit, potential medicinal properties and economic significance (Elena et al. 2015). Moreover, mushrooms contain a wide variety of amino acids, minerals, proteins and vitamins, and can thus benefit our health (Wang et al. 2014). They have been described as an "appetizing" food source that "are beneficial to the stomach, dissolve phlegm and help regulate the body" (Friedman 2016). In traditional Chinese medicine, it is believed that mushrooms can promote gut health, dissipate phlegm and treat vomiting and diarrhea (De Silva et al. 2012, Reis et al. 2017, Wasser 2017). Modern medical studies have reported that mushrooms can effectively inhibit the growth of *Escherichia coli*, *Salmonella typhi* and *Staphylococcus aureus* and exert bacteriostatic and anti-inflammatory effects (Muszynska et al. 2018). For example, mushrooms have been found to exert a curative effect against Vesicular stomatitis virus Latin. Thus, mushrooms are anti-bacterial and anti-viral and thus have high medical value (Wasser 2010). In this review, we will summarize the various bacteriostatic and virostatic activities of fungi and discuss their potential mechanisms of action.

Bacteriostatic and antiviral effects of mushrooms

Mushrooms can enhance digestion and support liver function (Martel et al. 2017). In recent

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years, studies have reported that mushrooms possess lipotropic, antithrombotic, antibacterial and antiviral activities.

As an edible and medicinal fungus, *Agaricus blazei* Murill (AbM) is recognized as being both savory and nutritious, containing various nutritional and biologically active substances. Aqueous AbM extract has been reported to have antibacterial and antifungal properties, particularly against *E. coli* and *S. aureus*. It has also been found to display a strong inhibitory effect on molds. Moreover, aqueous or alcohol AbM extracts and AbM polysaccharides have been found to exert inhibitory effect on herpesviruses and poliovirus (Ye & Lin 2001, Wang et al. 2008). *Lentinus edodes*, commonly known as the shiitake mushroom, is a fungus of the basidiomycetes family that has a mild and sweet taste and is believed to aid digestion. The medicinal properties and functions of *L. edodes* have been reported by pharmacists. Lentinan, a polysaccharide produced by *L. edodes*, is a biologically active substance that possesses antibacterial, antitumor and antiviral properties. It can effectively inhibit the growth of microorganisms including adenovirus, *Bacillus subtilis*, *E. coli*, herpes simplex virus, influenza virus, respiratory syncytial virus, *Salmonella typhimurium*, *S. aureus* and *S. haemolyticus*. Additionally, it has been reported to delay the onset of pathological cellular changes and has no toxic side effects (Zhang et al. 2006, 2007, Zou et al. 2007, Hou & Zhang 2015, Tang et al. 2018). *Amanita verna* (AV) inhibits the pathogens responsible for poplar canker disease, such as *Cytospora chrysosperma* (Ji et al. 2012). *Russula* is a large mycorrhizal fungus that is nutritious and has been reported to have beneficial effects on the circulatory system. According to recent findings, some fungi display strong antibacterial activity against *B. subtilis*, *E. coli* and *Pseudomonas aeruginosa* (Chen et al. 2008). *Pleurotus eryngii* is a rare edible fungus that has both dietotherapuetic and medicinal properties. Both the liquid fermentation broth and bran extract of *P. eryngii* have been reported to inhibit the growth of three common pathogenic bacteria: *E. coli*, *S. enteritidis* and *S. aureus*, among which *S. aureus* experiences the most significant inhibitory effects (Dong et al. 2019). *Inonotus hispidus* (Bull.) P. Karst. has been used in traditional medicine to treat cancer, diabetes and dyspepsia. Numerous studies have confirmed the antimicrobial, antioxidative, antiproliferative, antiviral, anti-cytotoxic biological and immunomodulatory activities of extracts derived from this species. Moreover, it has been found to be effective against gram-positive bacteria (*Bacillus cereus*), gram-negative bacteria (*P. aeruginosa*) and fungi (*Candida albicans*) when analyzed using the agar diffusion method (Angelini et al. 2019). *Hypsizygus tessulatus*, commonly known as the Shimeji mushroom, contains glucans, niacin and vitamins B and D. Previously, the mushroom was named *Hypsizygus marmoreus* and was reported to contain a wide range of biologically active compounds that potentially have a variety of medicinal applications. Currently, studies are examining the antibacterial and antifungal activities of its extract (Chowdhury et al. 2015). Triterpenoids obtained from *Ganoderma* spp. such as applanoxidic acid G, ganodermadiol and lucidadiol, have also displayed antiviral activity in vitro against infuenza virus type A, while ganodermadiol also inhibited the proliferation of herpes simplex virus (HSV) type 1. Eleven fungal species including *Daedaleopsis confragosa*, *Datronia mollis*, *Laricifomes officinalis*, *Ischnoderma benzoinum*, *Trametes betulina*, and *Trametes gibbosa*, have been reported to produce effective antiviral compounds. *Agrocybe salicacola* produces agrocybone, a sesquiterpene with weak antiviral activity against respiratory syncytial virus (Dasgupta & Acharya 2019, Suwannarach et al. 2020).

Additionally, several studies have shown that AbM, *Agrocybe aegerita*, *Coprinus comatus* and fungi of the *Lentinus* and *Pleurotus* genera produced strong bacteriostatic and antiviral effects against *B. subtilis*, coxsackie group B virus, *E. coli*, and *S. aureus* (Liu et al. 2003, Gui 2004, Dai et al. 2007, Lin et al. 2014) (Table 1). These findings further support the hypothesis that mushrooms can exert both bacteriostatic and antiviral effects.

Active ingredients in mushrooms

Different species of mushroom contain different active ingredients. The strength of an active ingredient is proportional to its concentration. The same active ingredient may exert several different effects, some of which may depend on the combined activity of multiple substances.

Polysaccharides produced by AbM have an inhibitory effect on poliovirus (PV-1) (Wang et al. 2008). Compounds derived from the esterification of sesquiterpene alcohols produced by *Lactarius trivialis* can reduce HSV titers of herpes simplex virus (Gui 2004). Lentinan inhibits the coxsackie virus, HSV and influenza virus, with these inhibitory effects being proportional to the lentinan concentration (Zhang et al. 2006, 2007, Zou et al. 2007). Additionally, sulfated lentinan has a significantly enhanced inhibitory effect on the infection of cells by infectious bursal disease virus, infectious bronchitis virus and Newcastle disease virus (Tang et al. 2018).

Polysaccharides produced by *Agaricus crocopeplus* Berk. & Broome, *L. edodes* and *Pholiota nameko* (T. Ito) S. Ito & S. Imai are effective against *E. coli* and *S. aureus* (Liu 2009). Furthermore, the acidic polysaccharides found in *Agaricus bisporus* are effective against *Fusobacterium nucleatum, Porphyromonas gingivalis* and *Prevotella intermedia* (Wei et al. 2007). Lastly, an acidic polysaccharide fraction obtained from the edible mushroom *Pleurotus eous* (Berk.) Sacc. was found to exert an inhibitory effect on *B. subtilis, E. coli*, *Klebsiella pneumoniae* and *S. aureus* (Gunasekaran et al. 2021). L-amino acid oxidases (LAOs) obtained from the fruiting bodies of *Amanita phalloides* (*Ap*LAO) and *Infundibulicybe geotropa* (*Cg*LAO) possess antibacterial properties against *Agrobacterium tumefaciens*, *Dickeya chrysanthemi*, *Enterobacter* spp., *E. coli*, *Lactococcus lactis, Pectobacterium atrosepticum, Pectobacterium carotovorum, Ralstonia mannitolilytica*, *Ralstonia solanacearum* and *Xanthomonas arboricola* (Jerica et al. 2020). Additionally, a novel antibacterial protein with a molecular mass of 44 kDa was isolated from dried fruiting bodies of the wild mushroom *Clitocyb sinopica* (Fr.) Gill. It was determined that this protein possesses potent antibacterial activity against *Agr. rhizogenes*, *Agr. tumefaciens*, *Agr. vitis*, *X. oryzae* and *X. malvacearum* (Zhang et al. 2016). In one study, researchers induced the expression of members of two putative antibacterial peptide and protein families in *Coprinopsis cinerea*, cysteine-stabilized xp-defensins (Csxp-defensins) and GH24-type lysozymes, and purified the proteins; their analysis confirmed the antibacterial properties of these proteins against *B. subtilis and E. coli* (Kombrink et al. 2019). Psathyrelloic acid, a novel monocyclic diterpenoid isolated from *Psathyrella candolleana* cultures, has displayed effectiveness against *S. aureus* (Liu et al. 2019). Benzoic (4-OH-benzoic, protocatechuic, syringic and vanillic) and cinnamic (caffeic, ferulic and *p*-coumaric) acid derivatives obtained from 31 Polish's mushrooms displayed obvious antibacterial effects against *B. subtilis, E. coli, K. pneumoniae, Micrococcus luteus, P. aeruginosa, Proteus mirabilis, S. aureus* and *S. epidermidis* (Nowacka et al. 2017).

Fatty acids extracted from *A. bisporus* have displayed a significant inhibitory effect against gram-positive bacteria, while proteins from this species can inhibit methicillin resistant *S. aureus* and *S. aureus* (Tehrani et al. 2012, Zheng et al. 2016). Furthermore, polysaccharides produced by *A. aegerita* have an inhibitory effect against *B. subtilis, E. coli* and *S. aureus* (Xin et al. 2011). *Amanita virgineoides bas* and *Am. rufoferruginea hongo* alcohol extracts have been reported to exert an inhibitory effect on mycelial growth of *Fusarium graminearum, Pestalotia theae* and *Septogloeum mori* (Tang et al. 2015). Fermentation filtrate extracts from *Am. muscaria*, *Am. squama* and *Lactarius velutipes* have a significant inhibitory effect on the mycelial growth and spore germination of *Cytospora chrysosperm* and *Sphaeropsis sapinea*, but this effect varies with different extraction methods (Song & Ji 2005, Qi & Song 2006). High-performance liquid chromatography and electron spray ionization-mass spectrum methods are commonly used to separate and identify α-amamanotoxin (α-AMA), β-manotoxin (β-AMA) and dihydroxy phalloidin (PHD) from *Am. pallidorosea* P. Zhang & Zhu L. Yang, which are known to have an inhibitory effect on *C. albicans* (Wang et al. 2011). *Hericium erinaceus* polysaccharide can inhibit the growth of *E. coli* (Chen et al. 2012). Similarly, *Tricholoma matsutake* polysaccharide exerts a significant concentration-dependent antibacterial effect on *S. aureus* (Hu & Liu 2006). Gallic acid produced by *Cyclosporium* has a strong inhibitory effect on *B. cereus*, *B. subtilis*, *C. albicans*, *E. coli*, *Salmonella paratyphi* and *S. aureus*, and a weaker inhibitory effect on *M. luteus* (Wang et al. 2019). Furthermore, *L. edodes* coumarin, disulfide derivatives, methionine and thionine can inhibit *C. albicans, P. intermedia* and *S. mutans* (Hirasawa et al. 1999, Hatvani 2001).

Table 1 Summary of bacteriostatic and virostatic activities of mushrooms

Mushroom	Pathogenic bacterium	Effective constituent	References
Amanita fritillaria	*Fusarium graminearum* (24.86%[a]), *Pestalotiopsis theae* (7.62%[a]), *Septogleum mori* (24.58%[a])	Ethanol extract	Tang et al. (2015)
Amanita hemibapha	*Fusarium graminearum* (22.7%[a]), *Pestalotiopsis theae* (7.62%[a]), *Septogleum mori* (22.5%[a])	Ethanol extract	Tang et al. (2015)
Amanita manginiana	*Fusarium graminearum* (22.16%[a]), *Pestalotiopsis theae* (6.73%[a]), *Septogleum mori* (20.83%[a])	Ethanol extract	Tang et al. (2015)
Amanita rufoferruginea	*Fusarium graminearum* (65.95%[a]), *Pestalotiopsis theae* (77.58%[a]), *Septogleum mori* (85.00%[a])	Ethanol extract	Tang et al. (2015)
Agaricus bisporus	*Bacillus cereus* (59.52[c], 10.75[b]), *Enterococcus faecalis* (> 20[c]), *Escherichia coli* (59.52[c]), methicillin resistant *Staphylococcus aureus* (10[c]), methicillin sensitive *Staphylococcus aureus* (10[c]), *Pseudomonas aeruginosa* (59.52[c], > 20[c]), *Salmonella typhimurium* (59.52[c], 10.75[b]), *Staphylococcus aureus* (59.52[c], > 20[c])	Ethanol extract, methanol extracts	Taofiq et al. (2016), Fogarasi et al. (2020), Melinda et al. (2020)
Agaricus blazei	*Aspergillus niger* (5%[c]), *Bacillus subtilis* (1.25%[c]), *Escherichia coli* (2.5%[c]), human herpes virus (47%[a]), influenza virus, polio virus (58.6%[a]), *Penicillium citrinum* (2.5%[c]), *Proteus* (2.5%[c]), *Pseudomonas aeruginosa*, *Saccharomyces cerevisiae* (10%[c]), *Staphylococcus aureus* (1.25%[c]), *Western equine encephalitis*	Water extract, ethanol extract, polysaccharide	Ye & Lin (2001), Hetland et al. (2021)
Agaricus crocopeplus	*Escherichia coli* (2.5[c]), *Salmonella* (2.5[c]), *Staphylococcus aureus* (5[c])	Water extract	Liu (2009)
Agaricus gennadii	*Bacillus cereus* (8.01 [b]), *Bacillus subtilis* (7.93[b]), *Candida albicans* (7.62[b]), *Escherichia coli* (7.05[b]), *Micrococcus luteus* (6.38[b]), *Salmonella paratyphi B* (9.21[b]), *Staphylococcus aureus* (9.02[b])	Gallic acid	Wang et al. (2019)
Agaricus sp.	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Agaricus xanthodermus	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Amanita muscaria	*Cytospora chrysosperm* (92.42%[a])	Fermentation filtrate extract	Song & Ji (2005), Qi & Song (2006)
Amanita pallidorosea	*Candida albicans* (10.16%[a], 6.89%[a], 11.1%[a], 8.37%[a])	Ethanol extract, *α*-AMA, *β*-AMA, PHD	Wang et al. (2011)
Amanita phalloides	*Agrobacterium tumefaciens*, *Dickeya chrysanthemi*, *Enterobacter* sp., *Escherichia coli*, *Lactococcus lactis*, *Pectobacterium atrosepticum*, *Pectobacterium carotovorum*, *Ralstonia mannitolilytica*, *Ralstonia solanacearum*, *Xanthomonas arboricola*	L-amino acid oxidases	Jerica et al. (2020)
Amanita sp.	*Cytosporium chrysosporium* (68.27%[a])	Ethanol extract	Ji et al. (2012)
Amanita virgineoides Bas	*Fusarium graminearum* schw. (87.03%[a]), *Pestalotiopsis theae* (Sawada) Steyaert (83.86%[a]), *Septogleum mori* Bri et Cav (72.50%[a])	Ethanol extract	Tang et al. (2015)
Amanita virosa	*Cytospora chrysosperm* (92.42%[a]), *Sphaeropsis sapinea* (12.41%[a])	Fermentation filtrate extract	Song & Ji (2005), Qi & Song (2006)
Boletinus paluster	*Agrobacterium tumefaciens* (15[b]), *Xanthomonas oryzae* (7.5[b]), *Xanthomonas oryzae* (11[b]), *Xanthomonas campestris* (5.5[b])	Water extract	Zheng et al. (2010)
Boletus edulis	*Bacillus cereus* (12.04[b], 28.34[c]), *Escherichia coli* (28.34[c]), *Pseudomonas aeruginosa* (11.98[b], 28.34[c]), *Salmonella typhimurium* (13.49[c]), *Staphylococcus aureus* (28.34[c])	Methanolic extracts	(Fogarasi et al. (2020), Melinda et al. (2020)
Cantharellus cibarius	*Bacillus cereus* (59.52[c]), *Escherichia coli* (59.52[c]), *Pseudomonas aeruginosa* (59.52[c]), *Salmonella typhimurium* (59.52[c]), *Staphylococcus aureus* (59.52[c])	Methanolic extracts	Liu et al. (2003), Melinda et al. (2020)
Clitocybe rivulosa	*Sphaeropsis sapinea* (45.92%[a])	Fermentation filtrate extract	Qi & Song (2006)

Table 1 Continued.

Types of Fungus	Pathogenic Bacterium	Effective constituent	References
Clitocybe sinopica	*Agrobacterium rhizogenes*, *Agrobacterium tumefaciens* (16^{b}), *Agrobacterium vitis*, *Xanthomonas oryzae* (8.5^{b}), *Xanthomonas oryzae* (10.5^{b})	Water extract, protein	Zheng et al. (2010)
Coprinellus disseminatus	*Staphylococcus aureus*	water extract	Mariselvi & Ninganna (2018)
Coprinopsis cinerea	*Bacillus subtilis*, *Escherichia coli*	Cysteine stabilized *αβ*-defensins, GH24-type lysozymes	(Kombrink et al. 2019)
Coprinus comatus	*Bacillus licheniformis* (6^{b}), *Bacillus subtilis* (3.0^{b}), *Escherichia coli* (3.5^{b}), *Staphylococcus aureus* (4.5^{b})	Water extract	Zou et al. (2012), Sadi et al. (2015)
Phallus impudicus (=*Dictyophora indusiata* (Vent.ex Pers) Fisch)	*Escherichia coli* (12.5^{c}), *Listeria monocytogenes* (25^{c}), *Salmonella enteritidis* (25^{c}), *Staphylococcus aureus* (25^{c}), *Vibrio parahaemolyticus* (12.5^{c})	Alcohol extract	Zheng et al. (2013)
Flammulina velutipes	*Aerobic bacillus* (36.3%[a]), *Bacillus subtilis* (20.4%[a]), *Escherichia coli* (28.6%[a]), *Saccharomyces cerevisiae* (37.5%[a]), *Staphylococcus aureus* (57.2%[a]), *Waxy bacillus* (42.0%[a])	Ester extract	Li et al. (2007)
Fomitopsis pinicola	*Aspergillus fumigates* (*3.2*^{c}), *Bacillus subtilis* (0.8^{c}), *Candida albicans* (3.2^{c}), *Escherichia coli* (1.6^{c}), *Klebsiella pneumoniae* (12.8^{c}), *Penicillium chrysogenum* (3.2^{c}), *Proteus vulgaris* (0.8^{c}), *Pseudomonas aeruginosa* (1.6^{c}), *Saccharomyces cerevisiae* (1.6^{c}), *Staphylococcus aureus* (1.6^{c})	Ethyl acetate extract	Pala et al. (2019)
Ganoderma sp.	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Grifola frondosa	Enterovirus, *Pseudomonas* sp., *Streptococcus pneumoniae*	Protein, polysaccharide, water extracts	Hetland et al. (2021)
Hericium erinaceus	Dengue virus, *Escherichia coli* (7.0^{c}), *Helicobacter pylori*, Muscovy duck reovirus, *Streptococcus mutans*, *Streptococcus pneumoniae*	Polysaccharide	Chen et al. (2012), Hetland et al. (2021)
Hymenagaricus sp.	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Hypsizigus tessulatus	*Bacillus subtilis* (8^{c}), *Candida albicans* (6^{c}), *Escherichia coli* (7^{c}), *Klebsiella pneumoniae* (6^{c}), *Pseudomonas aeruginosa* (9^{c}), *Saccharomyces cerevisiae* (5^{c}), *Salmonella typhi* (7^{c}), *Staphylococcus aureus* (7^{c})	Methanolic extracts	Chowdhury et al. (2015)
Infundibulicybe geotropa	*Agrobacterium tumefaciens*, *Dickeya chrysanthemi*, *Enterobacter* sp., *Escherichia coli*, *Lactococcus lactis*, *Pectobacterium atrosepticum*, *Pectobacterium carotovorum*, *Ralstonia mannitolilytica*, *Ralstonia solanacearum*, *Xanthomonas arboricola*	L-amino acid oxidases	Jerica et al. (2020)
Inonotus andersonii	*Propionibacterium acnes* (0.2^{c}), *Staphylococcus aureus* (0.2^{c})	Ethanol extract	Tamrakar et al. (2017)
Inonotus clemensiae	*Propionibacterium acnes* (0.1^{c}), *Staphylococcus aureus* (0.1^{c})	Ethanol extract	Tamrakar et al. (2017)
Inonotus cuticularis	*Staphylococcus aureus* (0.2^{c})	Ethanol extract	Tamrakar et al. (2017)
Inonotus hispidus	*Aspergillus fumigates* (6.4^{c}), *Bacillus subtilis* (3.2^{c}, 0.32^{c}), *Candida albicans* (6.4^{c}), *Escherichia coli* (3.2^{c}), *Enterococcus faecalis* (0.64^{c}), *Klebsiella pneumoniae* (6.4^{c}), *Penicillium chrysogenum* (6.4^{c}), *Proteus vulgaris* (3.2^{c}), *Pseudomonas aeruginosa* (3.2^{c},2.03^{c}), *Saccharomyces cerevisiae* (3.2^{c}), Salmonella typhi (2.03^{c}), *Staphylococcus aureus* (3.2^{c}, 1.01^{c}), *Penicillium chrysogenum* (6.4^{c})	Ethyl acetate extract, methanol extracts	Angelini et al. (2019), Pala et al. (2019)

Table 1 Continued.

Types of Fungus	Pathogenic Bacterium	Effective constituent	References
Inonotus obliguus	*Cytospora chrysosperm* (65[c]), *Botryosphaeria laricina* (60[c])	Ethanol extract, polysaccharide	Zheng et al. (2010)
Lactarius piperatus	*Bacillus cereus* (56.68[c]), *Escherichia coli* (26.99[c]), *Pseudomonas aeruginosa* (56.68[c]), *Salmonella typhimurium* (26.99[c]), *Staphylococcus aureus* (56.68[c])	Methanol extracts	Melinda et al. (2020)
Lactarius uvidus	*Agrobacterium tumefaciens* (8.5[b]), *Xanthomonas campestris* (4.5[b]), *Xanthomonas oryzae* (5.5[b])	Water extract	Zhang et al. (2019)
Lactarius vellereus	*Alternaria alternata* (92.71%[a]), *Cytospora chrysosperm* (92.42%[a]), *Sphaeropsis sapinea* (58.89%[a])	Fermentation filtrate extract	Song & Ji (2005), Qi & Song (2006), Ji et al. (2008)
Lentinus edodes	Adeno virus (91%[a]), *Agrobacterium tumefaciens* (7[b]), *Bacillus subtilis* (2.5[b], 40[c]), *Bacillus typhi* (2.5[c]), *Candida albicans* (40[c]), coxsackie virus (91.1%[a]), echo virus (73%[a]), *Enterococcus faecalis* (5[c]), *Escherichia coli* (0.625[c], > 20[c]), *Hemolytic streptococcus* (1.25[c]), herpes simplex virus (89.4%[a]), influenza virus (95.6%[a]), methicillin resistant *Staphylococcus aureus* (2.5[c]), methicillin sensitive *Staphylococcus aureus* (2.5[c]), *Pasteurella multocida* (10[c]), *Pseudomonas aeruginosa* (> 20[c]), respiratory syncytial virus (82%[a]), rota virus (85%[a]), *Saccharomyces cerevisiae* (80[c]), *Salmonella paratyphi A* (5[c]), *Salmonella typhimurium* (10[c]), *Shigella dysenteriae* (2.5[c]), *Staphylococcus aureus* (2.5[c]), *Trichophyton rubrum* (160[c]), *Xanthomonas campestris* (6[b]), *Xanthomonas oryzae* (5[b])	Ethanol extract, polysaccharide, water extract	Zhang et al. (2006, 2007), Zou et al. (2007), Liu (2009), Zheng et al. (2010), Wang & Wang (2011), Hou & Zhang (2015), Taofiq et al. (2016)
Lentinus tigrinus	*Agrobacterium tumefaciens* (8[b]), *Aspergillus fumigates*, *Bacillus licheniformis* (8[b]), *Bacillus subtilis* (6[b], 3.2[c]), *Candida albicans*, *Escherichia coli* (6[b], 6.4[c]), *Klebsiella pneumoniae* (12.8[c]), *Penicillium chrysogenum*, *Proteus vulgaris* (6.4c), *Pseudomonas aeruginosa* (6.4[c]), *Saccharomyces cerevisiae*, *Staphylococcus aureus* (6[b], 6.4[c])	Ethyl acetate extract, N-Hexane extract	Sadi et al. (2015), Pala et al. (2019)
Lepiota cbypolaria	*Cytospora chrysosperm* (92.42%[a]), *Sphaeropsis sapinea* (37.96%[a])	Fermentation filtrate extract	Song & Ji (2005), Qi & Song (2006)
Lepiota cristata	*Sphaeropsis sapinea* (38.15%[a])	Fermentation filtrate extract	Qi & Song (2006)
Lepista sordida	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Leucopaxillus giganteus	*Agrobacterium tumefaciens* (12[b]), *Bacillus subtilis* (2[b]), *Xanthomonas campestris* (6.5 mm[b]), *Xanthomonas oryzae* (9[b]), *Xanthomonas oryzae* (14[b])	Water extract	Zheng et al. (2010)
Lyophyllum sp.	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Lysurus mokusin	*Botrytis cinerea* (88.76%[a])	Ethanol extract	Zhang et al. (2019)
Melanoleuca cognata	*Agrobacterium tumefaciens* (14[b]), *Xanthomonas campestris* (6.5[b]), *Xanthomonas oryzae* (10[b]), *Xanthomonas oryzae* pv. *oryzicola* (Fang et al.) Swing et al. (15[b])	Water extract	Zheng et al. (2010)
Microporus spp. (Kakamega forest)	*Candida albicans* (1.33[c]), *Candida parapsilosis* (1.33[c]), *Escherichia coli* (1.67[c]), *Klebsiella pneumoniae* (1.00[c]), methicillin resistant *Staphylococcus aureus* (1.00[c]), *Pseudomonas aeruginosa* (1.33[c]), *Staphylococcus aureus* (0.67[c])	Hot water extracts	Gebreselema et al. (2019)
Omphalotus olivascens	*Pseudomonas aeruginosa*, *Staphylococcus aureus*	Water extract	Mariselvi & Ninganna (2018)
Phlebopus portentosus	*Pseudomonas aeruginosa*	Water extract	Mariselvi & Ninganna (2018)

Table 1 Continued.

Types of Fungus	Pathogenic Bacterium	Effective constituent	References
Pholiota nameko	*Escherichia coli* (2.5[c]), *Salmonella* (2.5[c]), *Staphylococcus aureus* (5[c])	Water extract	Liu (2009)
Pleurotus eryngii	*Escherichia coli* (14.38[b]), *Fusarium graminearum* (87.45%[a]), *Fusarium oxysporum* (92.78%[a]), *Salmonella enteritidis* (9.31[b]), *Staphylococcus aureus* (21.74[b])	Fermentation broth, polysaccharides	Hou et al. (2016), Dong et al. (2019)
Pleurotus florida	*Bacillus subtilis* (13.8[b]), *Escherichia coli* (17.9[b]), *Pseudomonas aeruginosa* (16.2[b]), *Salmonella typhi* (15.5[b]), *Streptococcus faecalis* (14.6[b])	Methanol extract	Gashaw et al. (2020)
Pleurotus ostreatus	*Bacillus subtilis* (13.6[b], 59.52[c]), *Enterococcus faecalis* (10[c]), *Escherichia coli* (19.5[b], 59.52[c], > 20[c]), methicillin resistant *Staphylococcus aureus* (2.5[c]), methicillin sensitive *Staphylococcus aureus* (2.5[c]), *Mycobacterial strains* (15[c]), *Pseudomonas aeruginosa* (16.4[b], 59.52[c]), *Salmonella typhi* (16.9[b]), *Streptococcus faecalis* (14.8[b], 59.52[c], > 20[c])	Ethanol extract, methanol extract	Taofiq et al. (2016), Gashaw et al. (2020), Melinda et al. (2020)
Pleurotus eous	*Bacillus subtilis* (8.1[b]), *Escherichia coli* (11.1[b]), *Klebsiella pneumonia* (10.2[b]), *Staphylococcus aureus* (12.3[b])	Acidic polysaccharide	Gunasekaran et al. (2021)
Psathyrella candolleana	*Staphylococcus aureus* (0.016[c])	Psathyrelloic acid	Liu et al. (2019)
Ramaria ephemeroderma	*Sphaeropsis sapinea* (63.89%[a])	Fermentation filtrate extract	Qi & Song (2006)
Rhizopogon luteolus	*Agrobacterium tumefaciens* (6[b]), *Bacillus licheniformis* (6[b]), *Bacillus subtilis* (13[b])	Chloroform extract	Sadi et al. (2015)
Russula sp.	*Aspergillus niger*, *Aspergillus oryzae*, *Bacillus subtilis*, *Escherichia coli*, *Saccharomyces Carlsbrgensis*, *Staphylococcus aureus*	Ethanol extract, water extract,	Chen et al. (2008)
Termitomyces sp.	*Pseudomonas aeruginosa*	Water extract	Mariselvi & Ninganna (2018)
Trametes spp. (Kakamega forest)	*Candida albicans* (0.83[c]), *Candida parapsilosis* (0.67[c]), *Escherichia coli* (0.83[c]), *Klebsiella pneumoniae* (0.67[c]), methicillin resistant *Staphylococcus aureus* (0.83[c]), *Pseudomonas aeruginosa* (1.00[c]), *Staphylococcus aureus* (0.50[c])	Hot water extracts	Gebreselema et al. (2019)
Trametes spp. (Arabuko-Sokoke forest)	*Candida albicans* (0.83[c]), *Candida parapsilosis* (0.83[c]), *Escherichia coli* (0.83[c]), *Klebsiella pneumoniae* (0.83[c]), methicillin resistant *Staphylococcus aureus* (0.83[c]), *Pseudomonas aeruginosa* (0.83[c]), *Staphylococcus aureus* (0.67[c])	Hot water extracts	Gebreselema et al. (2019)
Tricholoma sp.	*Staphylococcus aureus* (31[b])	Polysaccharide	Hu & Liu (2006)
Tricholoma fracticum	*Agrobacterium tumefaciens* (6[b]), *Bacillus licheniformis* (6[b]), *Bacillus subtilis* (6[b]), *Staphylococcus aureus* (9[b])	Acetone extract	Sadi et al. (2015)
Xylobolus princeps	*Staphylococcus aureus* (0.4[c])	Ethanol extract	Tamrakar et al. (2017)

a, inhibition rate; b, inhibition zone (mm); c, minimal inhibitory concentration (mg/mL).
IC_{50} is not listed here because it is not the primary indicator of antimicrobial efficacy.

In summary, polysaccharides are the main active compound produced by mushrooms that are capable of inhibiting the proliferation of bacteria and viruses. Additionally, antibiotics, fatty acids, gallic acid, methionine, proteins, sulfides and toxins produced by mushrooms can exert antibacterial and antiviral effects (Tab 1). However, most studies to date have focused on the antibacterial and antiviral effects of mixed extracts, rather than specific components. Therefore, such active ingredients warrant further investigation.

Antibacterial and antiviral mechanism of mushrooms

Antibiotics can kill bacteria via several different mechanisms. For example, they can inhibit

bacterial cell wall synthesis, resulting in the rupture and death of bacterial cells (Yan & Bassler 2019). Such antibiotics include penicillin and cephalosporins (Mishra & Kasik 1970). The growth and reproduction of bacteria also require specific osmotic pressure and pH. Some antibiotics can alter cell membrane of permeability, creating an imbalance in the osmotic pressure across the cell. Both polymyxin and Brevibacterium act in this way (Yu et al. 2015). Other antibiotics interfere with synthesis, including aminoglycosides and fosfomycin (Cai et al. 2009).

Viruses parasitize the host and depend on host cells for replication and proliferation. Antiviral drugs generally interfere with specific aspects of the viral replication cycle, such as virus adsorption, entry into cells, biosynthesis and release, and enhance host antiviral capabilities (Graci & Cameron 2006). Amantadine and maraviroc (Wang & Lu 2008) are penetration and shelling inhibitors, while saquinavir is a protein inhibitor.

Lentinus edodes (Berk.) Sing polysaccharide (Zhang et al. 2006, Zou et al. 2007) is known to be an enhancer and regulator of biological reaction enhancer and regulator. It can not only enhance humoral and cellular immunity nonspecifically but also exert immunomodulatory effects. Therefore, the antiviral mechanism of lentinan may lie in its ability to boost the immunity of infected cells, enhance the cell membrane stability, inhibit cytopathic effects and promote cellular repair (Zhang et al. 2007). AbM is rich in β-glucan, sterols and other components that can regulate cellular and humoral immunity. It can activate immune cells and improve immune function (Wang et al. 2008). Experiments have confirmed that *A. aegerita* polysaccharide exerts similar antibacterial activities to amoxicillin, and they both exhibit similar inhibitory effects on bacteria, but not mold. Penicillin, the main component of amoxicillin, is a β-lactam antibiotic that inhibits the synthesis of the bacterial cell wall by binding to bacterial cell membrane proteins that participate in the synthesis of peptidoglycan (Xin et al. 2011). It remains unclear whether the antibacterial mechanism of *A. aegerita* polysaccharide is similar to that of penicillin, and further research is thus warranted.

The antiviral mechanisms leveraged by mushrooms most likely relies on the ability of the active compounds to reduce or block viral adsorption and inhibit the replication of the virus in the host cell (Wang et al. 2008). Additionally, antiviral effects can be produced through improving the immunity of infected cells, enhancing the stability of cell membranes, inhibiting the development of cellular pathologies and promoting cell repair (Wang & Wang 2011). The antibacterial mechanisms of mushrooms are mainly related to their ability to inhibit mycelial growth, spore germination and bacterial protein synthesis (Ji et al. 2008). Polysaccharides produced by mushrooms can inhibit cell adhesion by forming a protective layer on the surface of cells or adhering to the surface of pathogens themselves. This ultimately prevents interactions between the pathogens and the surface of healthy cells to inhibit bacterial infection (Ji et al. 2008, Hou et al. 2016, Dong et al. 2019). Furthermore, polysaccharides can inhibit bacterial growth by inhibiting bacterial defense enzymes and infection-related cell wall-degrading enzymes, or by destroying the bacterial cell membrane (Zhang et al. 2019). Additionally, the mushroom mycelium and the pathogenic bacteria can become enmeshed. Mycelial cell protoplasm containing pathogenic bacteria has been reported to become concentrated at the junction of two mycelial hyphae. Thus, the mycelium is likely acting in a beneficial manner to promote bacterial outflow. Additionally, shrinkage and breakage eventually disintegrate the pathogenic fungal hyphae to achieve an antibacterial effect (Zhang et al. 2014).

Conclusion

According to the studies discussed in this review, mushrooms can exert both bacteriostatic and antiviral effects. However, current research on the effects of mushrooms is limited. The wide repertoire of edible mushrooms has not yet been fully explored, and their active ingredients have not yet been fully characterized. Additionally, the mechanisms associated with the bacteriostatic and antiviral effects of mushrooms remain unclear. Therefore, further studies are warranted to clarify the effective components and the underlying mechanisms associated with the bacteriostatic and antiviral effects of mushrooms.

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