Chapter 2
Bioactives from Mushroom and Their Application

Carmen Sánchez

1 Introduction

This chapter describes the variety and biomedical potential of mushrooms as well as their bioactive compounds. It starts with a description of the structure, growth, and composition of mushroom fungi. A description of polyssacharides (e.g., β-glucan) and polysaccharide–protein complexes was found in different mushrooms, and their potential medical uses are mentioned. In addition, the immunomodulatory bioactivity of β-glucans is illustrated in this section. Terpene compounds as the largest group of anti-inflammatory compounds in mushrooms are addressed. The importance of phenolic compounds acting as free radical inhibitors, peroxide decomposers, metal inactivators, or oxygen scavengers in biological systems is described. Bioactive proteins and peptides, including lectins, which have no enzymatic activity, as well as those bioactive proteins possessing enzymatic activity such as fungal immunomodulatory proteins, ribosome-inactivating proteins, and laccases, are addressed. Finally, other compounds are able to reduce oxidative stress in the endoplasmic reticulum, demonstrating its potential effect in neurodegenerative diseases, and others showing antidepressant properties are also mentioned.

2 Mushroom: Structure, Growth, and Composition

Mushrooms are a very large and diversified group of macrofungi belonging to basidiomycetesand ascomycetes, which have two phases of growth: the reproductive phase (fruit bodies) and the vegetative phase (mycelia). These organisms are

C. Sánchez (✉)
Laboratory of Biotechnology, Research Centre for Biological Sciences, Universidad Autónoma de Tlaxcala, Ixtacuixtla, Tlaxcala CP. 90062, Mexico
e-mail: sanher6@hotmail.com

M. Puri (ed.), *Food Bioactives*, DOI 10.1007/978-3-319-51639-4_2

epigeous (grow above the earth) with the umbrella-shaped fruiting body, where spores are produced (in lamellae, structures on the underside of the pileus). The fungal spores for these two groups are located in a special structure called basidium (for basidiomycetes) or ascus (for ascomycetes). In the fungal growth, after spore germination (or inoculation of in vitro-grown mycelia), the substrate is invaded by microscopic filaments called hyphae. The cells in a hypha are separated by a cross-wall called septum. Hyphae continually grow and branch to form a network of hyphae or mycelia (mycelial growth). Mycelial growth is generally coupled with increased enzyme production and respiration. Hyphae absorb digestive products, penetrating the substrate to some extent. The fungal cell wall can be formed by mannoproteins, β-D-glucans, and chitin (Fig. 1). From the ecological point of view, mushroom fungi can be saprotrophs, parasites, and mycorrhiza. There are only few parasitic mushrooms. Most of the cultivated mushrooms are saprotrophs. Mycorrhizal mushrooms have a symbiotic relationship with some vegetation, mainly trees, having a relationship of mutual benefit. Saprotrophs are able to obtain nutrients from dead organic material, and parasites obtain their food from living animals and plants, causing harm to the host (Cheung 2008). Mushrooms have been eaten and appreciated for their exquisite flavor, economic and ecological values, and medicinal properties for many years. In general, mushrooms contain 90% water and 10% dry matter (Sánchez 2010). They have a chemical composition, which is attractive from the nutritional point of view (Dundar et al. 2008). Their nutritional value can be compared to those of eggs, milk, and meat (Oei 2003). Mushrooms contain vitamins (thiamine, riboflavin, ascorbic acid, ergosterol, and niacin) as well as an abundance of essential amino acids. They also have proteins, fats, ash, glycosides, volatile oils, tocopherols, phenolic compounds, flavonoids, carotenoids, folates, organic acids, etc. (Sánchez 2004; Patel and Goyal 2012). The total energetic value of mushroom caps is between 250 and 350 cal/kg of fresh mushrooms (Sánchez 2010). Mushrooms can be considered as functional food which provides health benefits in addition to nutritional value (Rathee et al. 2012). They have been collected in several countries for hundreds of years, and technological improvements have made possible their cultivation worldwide.

3 Bioactive Compounds in Mushroom

There has been an increasing interest in mushrooms as a source of biologically active compounds which provide to humans medicinal or health benefits such as the prevention and treatment of diseases (Rathee et al. 2012). Bioactive compounds can be found in mushroom as cell wall components such as polysaccharides (e.g., β-glucans) and proteins or as secondary metabolites such as phenolic compounds, terpenes, and steroids. The concentration and efficacy of the bioactive compounds are varied and depend on the type of mushroom, substrate, fruiting conditions (if cultivated), stage of development, age of the fresh mushroom, storage conditions, and cooking procedures (Guillamón et al. 2010). Many studies have reported that

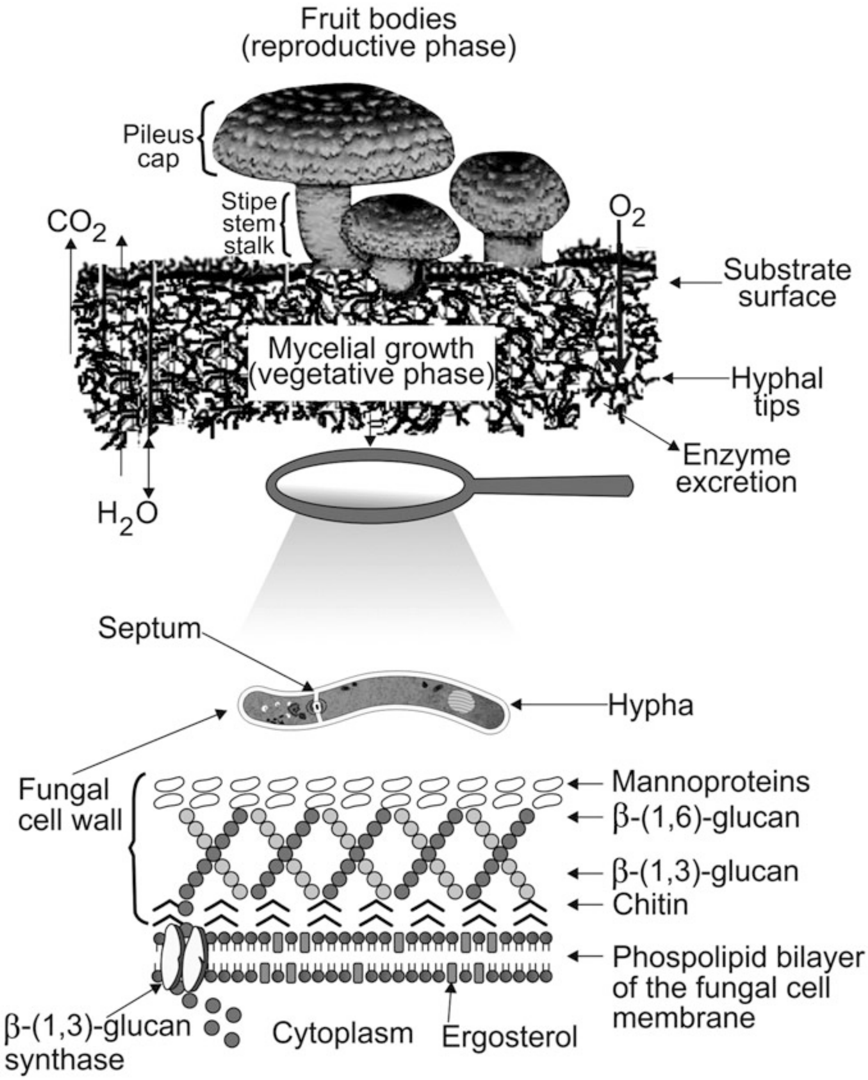

Fig. 1 Schematic representation of mushroom phases of growth and fungal cell wall composition

the medicinal properties of mushrooms include anti-inflammatory, antioxidant, immunomodulatory, anticarcinogenic, antiviral, antibacterial, antifungal, hepato-protective, antineurodegenerative, antidiabetic, antiangiogenic, and hypoglycemic, among others (Badalyan 2012; Elsayed et al. 2014; Xu and Beelman 2015). Mushrooms' bioactive compounds on the basis of their chemical structure can be polysaccharides, phenolic compounds, terpenes and terpenoids, phenols, peptides, proteins, etc. (Table 1).

Table 1 Biologically active compounds from mushrooms and their medical applications

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Agaricus bisporus	Champignon, Button mushroom, White mushroom,	B/E	Pyrogallol hydroxybenzoic acid derivatives Flavonoids	Anti-inflammatory	Moro et al., 2012; Ndunguts et al., 2015
Agaricus macrosporus	Macro mushroom	B/E	Agaricoglycerides	Anti-inflammatory	Han and Cui, 2012
Agaricus subrufescens (= *Agaricus blazei*, *Agaricus brasiliensis*, *Agaricus rufotegulis*)	Almond mushroom, God's mushroom, Mushroom of life, Royal sun *Agaricus*	B/E	Glycoprotein, β-(1, 3)-glucan, with β-(1,6)-glucan branch	Immunomodulatory	Firenzuoli et al., 2007; Lima, 2008
			Protein fractions and polysaccharides fractions	Immunomodulatory	Jeurink et al., 2008
Agrocybe cylindracea (= *Pholiota aegerita*)	Poplar mushroom	B/E	β-Glucans	Anti-oxidant	Rathee et al., 2012; Zhang et al., 2003 Gupta et al., 2014 Ngai et al., 2005
			Agrocybin (peptide)	Hypoglycemic Anti-fungal	
Albatrellus ovinus (= *Polyporus ovinus*)	Forest lamb mushroom, sheep polypore	B/E	Grifolin and grifolin derivatives	Anti-inflammatory Anti-oxidant	Nukata et al., 2002
Albatrellus caeruleoporus	Blue albatrellus	B/E	Phenolic compound Grifolinones A, B	Anti-inflammatory	Nukata et al., 2002 Quang et al., 2006
Antrodia camphorata (=*Taiwanofungus camphoratus*)	Stout camphor fungus	B/NE	Glycoprotein ACA	Immunomodulatory	Sheu et al., 2009
			Diterpenes	Neuroprotective	Chen et al., 2006

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Auricularia auricula	Jew´s ear, wood ear, jelly ear	B/E	Glucan	Hyperglycemia, Immunomodulatory Anti-tumor Anti-inflammatory	Zhang et al., 2007
Boletus edulis	Cep, penny bun, king bolete	B/E	Polysaccharides	Anti-inflammatory	Moro et al., 2012
Boletus spp	Gelam mushroom	B/E	2,4,6-trimethylacetophenone imine, glutamyl tryptophan, azatadine, lithocholic acid glycine conjugate	Anti-oxidant	Yuswan et al., 2015
Cantharellus cibarius	Chanterelle, golden chanterelle, girolle	B/E	Pyrogallol	Anti-inflammatory	Moro et al., 2012; Dugler et al., 2004
			Flavonoids Polysaccharides	Anti-microbian	Palacios et al., 2011
			Caffeic acid, catechin	Anti-oxidant	
Calvatia gigantea	Giant puffball	B/E	Calvacin	Anti-tumor	Rathee et al., 2012
Caripia montagnei	Pod parachute	B/E	Polysaccharides (glucans)	Anti-inflammatory	Queiroz et al., 2010
Clitocybe maxima		B/NE	Laccase	Anti-tumor	Zhang et al., 2010b

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Coprinus comatus	Shaggy ink cap, lawyer's wig, shaggy mane	B/E	β - 1,3-glucan	Immunomodulatory	Chan et al., 2009
			Protein fractions and polysaccharides fractions	Immunomodulatory	Jeurink et al., 2008
Cordyceps militaris	Beldar-mazo, deer fungus, caterpillar fungus	A/E	Cordycepin	Anti-inflammatory, Anti- angiogenic Anti-cancer	Won et al., 2005; Kumar et al., 2010
			Cordymin	Anti-inflammatory	Das et al., 2010 Wong et al., 2011
Cordyceps sinensis	Summer grass, winter worn	A/E	Cordycepin,	Anti-oxidant	Holliday et al., 2004
			Ciclosporin	Immunosuppressive	Holliday, 2005
			Cordymin (peptide)	Anti-inflammatory	Wang et al., 2012; Qian et al., 2011
Cortinarius infractus	Sooty-olive Cortinarius, the bitter webcap	B/NE	6-hydroxyinfractine, infractopicrine	Anti-neurodegenerative	Brondz et al. 2007; Geissler et al., 2010
Craterellus cornucopioides	Black chanterelle, horn of plenty, black trumpet, trumpet of the dead.	B/E	Myricetin	Anti-oxidant	Palacios et al., 2011

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Craterellus tubaeformis	Yellow foot, winter mushroom, funnel chanterelle	B/E	Polysaccharides	Anti-inflammatory	Tsvetkova et al., 2006
Cyathus africanus	Bird's nest fungi	B/NE	Diterpenoid (neosarcodonin, cyathatriol, and 11-O-acetylcyathatriol)	Anti-inflammatory	Han et al., 2013
Daldinia concentrica	King Alfred's Cake, cramp balls, coal fungus	A/NE	1-(3,4,5-trimethoxyphenyl) ethanol, caruilignan C	Neuroprotective	Lee et al., 2002b
Dictyophora indusiata (=*Phallus indusiatus*)	Veiled lady mushroom, bamboo mushroom	B/E	Dictyophorine A and B	Anti-neurodegenerative	Kawagishi et al., 1997
			Dictyoquinazol A, B, and C	Neuroprotective	Lee at al., 2002a
Elaphomyces granulatus	False Truffle	A/NE	Syringaldehyde,	Anti-inflammatory	Wang and Marcone., 2011 Stanikunaite et al., 2009
			Syringic acid		
Flammulina velutipes	Golden needle mushroom Enoki	B/E	Peptidoglycan	Anti-inflammatory, antiviral	Yin et al., 2010
			Polysaccharides	Anti-inflammatory	Wu et al., 2010
			Flammulin (protein)	Anti-tumor	Chen et al., 2003; Chang et al., 2010
Fomitopsis pinicola	Red-belt conk	B/NE	Polysaccharides	Anti-inflammatory	Cheng et al., 2008

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Ganoderma lucidum	Reishi, lingzhi, mannentake	B/NE	Ganoderic acids, ganoderiol, ganodermanontriol,	Anti-tumor, anti-metastasis anti-HIV anti-viral	Xu et al., 2010, Walton, 2014; Xu and Zhong, 2012
			Ganoderan A and B	Hypoglycemic	El-Mekkawy et al., 1998
			Ganopoly	Hepatoprotective	Rai et al., 2005
			Triterpenes	Anti-inflammatory	Rathee et al., 2012 Gao et al., 2002; Dudhgaonkar et al., 2009. Akihisa et al., 2007; Iwatsuki et al. (2003) Akihisa et al. (2005) Kino et al., 1989 Wang and Ng (2006b) Du et al., 2007
			Lucidenic acids and ganoderic acids	Anti-inflammatory	
			Lanostane-type triterpenic acids	Anti-inflammatory	
			Ling zhi-8 (protein)	Immunomodulatory	
			Ganodermin (protein)	Antifungal	
			Se-containing protein	Anti-tumor	
Ganoderma microsporum	LingZhi (Chinese name)	B/NE	Protein GMI	Immunomodulatory	Lin et al., 2010

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Ganoderma pfeifferi	Paksulattakääpä (Finnish common name)	B/NE	Sesquiterpenoid hydroquinones (lucialdehyde D, ganoderone A, ganoderone C)	Anti-bacterial, anti-fungal, anti-viral	Niedermeyer et al., 2005
Geastrum saccatum	Rounded earthstar	B/NE	Polysaccharides (β-glucans)	Anti-inflammatory	Guerra-Dore et al., 2007
Ganoderma tsugae (= Polyporus tsugae)	Hemlock varnish shelf		Fip-gts (protein)	Immunomodulatory	Lin et al., 1997
Grifola Frondosa	Hen-of-the-woods, ram's head, sheep's head, maitake	B/E	Grifolan[1] (1-6-monoglucosyl-branched β-1,3-glucan) Proteoglycan, Heteroglycan, Galactomannan, Glucoxylan Mannogalactofucan Fucomannogalactan Agaricoglycerides	Immunomodulatory anti-tumor, Anti-viral, hepatoprotective	Yang, 2007; Kidd et al., 2000
				Anti-inflammatory	Han and Cui, 2012
			Low-molecular weight protein fraction	Anti-tumor	Kodama et al., 2002

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Hericium erinaceus	Lion's mane mushroom, bearded tooth, Satyr's Beard, pompom mushroom, bearded tooth fungus	B/E	Phenol-analogous compounds (hericenons C, D, E, F, G, H)	Anti-oxidant	Wang et al., 1996
			Hericenons Erinacines, hericerins, , resorcinols, steroids, mono-terpenes, diterpenes	Anti-biotic, anti-carcinogenic, anti-diabetic, anti-fatigue, anti-hypertensive, anti-hyperlipodemic,	Mizuno, 1999
			Heteroglycan peptide, β-1,3 branched-β-1,2-mannan	Hyperglycemia, Immunomodulatory anti-tumor Anti-senescence, cardioprotective, hepatoprotective, nephroprotective, neuroprotective, etc.	Lee et al., 2009; Friedman, 2015
			Lectin (glycoprotein)	Anti-tumor, Anti-virus	
			Hericenones (A-H), Erinacines (A-K, P-Q),	Anti- neurodegenerative	Li et al., 2010b
			Dilinoleoylphosphatidylethanolamine	Anti-neurodegenerative	Xu and Beelman, 2015; Phan et al., 2014 Nagai et al., 2006

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Hypsizygus marmoreus (=*Hypsizygus tessellatus*)	Brown Beech, buna - shimeji	B/E	Ergosterol, manitol,	Anti-oxidant, anti-inflammatory,	Yoshino et al., 2008
			Trehalose, methionine	Anti-allergic	Wong et al., 2008
			Marmorin	anti-tumor activity	Chowdhury et al., 2015
			Phenolic compounds flavonoids	Anti-bacterial, antifungal, anti-oxidant	
Inonotus obliquus	Chaga, clinker polypore, cinder conk, black mass	B/E	β-D-glucans	Anti-oxidant, stomach diseases, cancer	Rathee et al., 2012
			Mannogalactoglucan	Anti-tumor,	Wasser, 2010
			Sterols	Anti-inflammatory	Van et al., 2009; Park et al., 2005
			Triterpenes	Anti-inflammatory, anti-cancer	Ma et al., 2013
Lactarius deliciosus (= *L. flavidulus*)	Saffron milk cap, red pine mushroom	B/E	Pyrogallol, Flavonoids	Anti-inflammatory	Moro et al., 2012
			Polysaccharides	Anti-inflammatory	Fijimoto et al., 1993
Lactarius rufus	Rufous milk cap, red hot milk cap	B/E	Polysaccharides: (1,3), (1,6)β-D-glucans	Anti-inflammatory	Ruthes et al., 2013

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Lentinula edodes	Shiitake,	B/E	Lentinan, glucan, mannoglucan,	Immunomodulatory antitumor,	Sasaki and Takasuka, 1976; Israilides et al., 2008
			Fucomannogalactan	Anti-inflammatory	Attarat and Phermthai, 2015
			Lentin (protein)	Anti-fungal	Ngai and Ng, 2008
			Catechin (Phenolic compound)	Anti-oxidant	Chowdhury et al., 2015
			Phenolic compounds flavonoids	Anti-bacterial, antifungal, anti-oxidant	
Lentinula polychrous	NA	B/NE	Catechin	Anti-oxidant	Attarat and Phermthai, 2015
Lentinula squarrosulus	NA	B/NE	Catechin	Anti-oxidant	Attarat and Phermthai, 2015
Lenzites betulina	Gilled polypore, birch maze gill, multicolor gill, polypore	B/NE	Betulinan A	Anti-oxidant	Rathee et al., 2012
Lignosus rhinocerus	Tiger milk mushroom	B/NE	Polysaccharides-protein	Anti-cancer	Gupta et al., 2015
Lyophyllum decastes	Fried chicken mushroom	B/E	Polysaccharides: (1, 3) and (1,6)β-D-glucans	Anti-inflammatory	Ukawa et al., 2000

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Mycoleptodonoides aitchisonii	Bunaharitake	B/E	3-(hydroxymethyl)-4-methylfuran-2(5H)-one, (3R,4S,1'R)-3-(1'-hydroxy-ethyl)-4methyldihydrofuran-2(3H)-one, 5-hydroxy-4-(1-hydroxyethyl)-3-methylfuran-2(5H)-one, 5-phenylpentane-1,3,4-triol	Anti-neurodegenerative	Choi et al. 2009; Choi et al., 2014
Morchella esculenta	Common morel, Morel, Yellow morel, True morel, Morel mushroom, Sponge morel	A/E	Heteroglycan Galactomannan, β-1,3-D-glucan	Hyperglycemia, Anti-tumor	Cheung, 2008
Phellinus linteus	Black hoof mushroom	B/NE	Glucans	Anti-tumor	Kim and Iwahashi, 2015
			Acidic polysaccharides	Inmmunomodulatory	Hsieh et al., 2013; Wu et al., 2013
			Hispidin (polyphenol)	Anti-oxidant	Park et al., 2004
Pholiota adiposa	Fatty pholiota, pineapple pholiota, sticky pholiota	B/E	Lectin (glycoprotein)	Anti-tumor Anti-viral	Zhang et al., 2009
Pholiota nameko	Nameko, butters cotch mushroom	B/E	Polysaccharides	Anti-inflammatory	Li et al., 2008

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Pleurotus citrinopileatus	Golden oyster mushroom	B/E	Glycoprotein (PCP-3A)	Anti-tumor anti-cancer	Chen et al., 2009
Pleurotus eryngii	King trumpet mushroom, French horn mushroom, king oyster mushroom	B/E	laccase	Anti-viral	Wang and Ng, 2006a.
Pleurotus florida	White oyster	B/E	β-glucans	Anti-oxidant	Ganeshpurkar et al., 2015
Pleurotus ostreatus	Oyster mushroom	B/E	Pleuran (β-1, 3-glucan with galactose and mannose),	Immunomodulatory Anti-tumor,	El Enshasy et al., 2013b
			proteoglycan	hyperglycemia, anti-oxidant	Tong et al., 2009
			Laccase	Ani-viral	El Fakharany et al., 2010
			Pleurostrin (peptide)	Anti-fungal	Chu et al., 2005
Pleurotus pulmonarius	Indian Oyster, Italian oyster, phoenix mushroom, lung oyster	B/E	Polysaccharides β(1,3)-glucopyranosyl	Anti-inflammatory	Lavi et al., 2012
			Polysaccharides (1,3), (1,6)-linked β-glucan		Smirdele et al., 2008

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Psilocybe species (eg. P.cubensis, P. samuiensis, P. Mexicana)	Magic mushroom, shrooms	B/NE (hallucinogen)	Psilocybin (psilocin: 4-hydroxy-dimethyltryp-tamine)	Anti-depressant (Psychotherapy)	Mason-Dambrot, 2012; Kraehenmann, 2015; Grob et al., 2011; Carhart-Harris et al., 2012; Petri et al., 2014
Russula lepida (=*Russula rosea*)	Rosy russula	B/NE	Lectin (glycoprotein)	Anti-tumor	Zhang et al., 2010a
Schizophyllum commune	Split Gill	B/NE	Schizophyllan, 1,6- monoglucosyl branched β-1, 3- D-glucan	Immunomodulatory Anti-tumor	Bae et al., 2004; Hobbs, 2005
Sparassis crispa	Rooting cauliflower mushroom	B/E	β-Glucan	Immunomodulatory	Ohno et al., 2002; Takashi, 2013
Termitomyces albuminosus (=*Macrolepiota albuminosa*)	Termite mushroom	B/E	Termitomycesphins (cerebrosides)	Anti- neurodegenerative	Qi et al., 2000; Qu et al., 2012
			Termitomycamides (fatty acid amides	Anti- neurodegenerative	Choi et al., 2010
Trametes versicolor (=*Coriolus versicolor Polyporus versicolor*)	Wild turkey	B/E, unpalatable)	Krestin (PKS), (PSP)	Anti-metastatic	Wasser, 2002
			Coriolan (β-glucanprotein complex)	Hypoglycemic	Rathee at al., 2012

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Tremella aurantia alba	Golden ear	B/E	Heteroglycan	Immunomodulatory	Du et al., 2010
Tremella mesenterica	Yellow brain, golden jelly fungus, yellow trembler, witches butter	B/E	Glucurono-xylomannan polysaccharide	Hypoglycemic Immunomodulatory	Gupta et al., 2014
Tricholoma giganteum	Giant mushroom		Trichogin (protein)	Antifungal	Guo et al., 2005
Tricholoma mongolicum	NA	B/E	Laccase	Anti-viral, anti-tumor	Wang et al., 1996; Li et al., 2010a
Volvariella volvacea	Paddy straw mushroom, straw mushroom		Fip-vvo	Immunomodulatory	Hsu et al., 1997
Wolfiporia cocos (=Poria cocos)	Hoelen, poria, tuckahoe, China root,	B/NE	Dehydrotrametenolic acid	Hypoglycemic	Rathee et al., 2012
			Lanostane	Anti- inflammatory agents	Zheng and Yang, 2008a; 2008b

(continued)

Table 1 (continued)

Mushroom Scientific name	Common names	Phyllum or group/ Edibility	Bioactive compound	Bioactivity	Reference
Xylaria hypoxylon	Candlestick fungus, candle snuff fungus, carbon antlers, stag's horn fungus	A/NE	Lectin (glycoprotein)	Anti-mitogenic anti-tumor	Liu et al., 2006

B: Basidiomycota
A: Ascomycota
E: Edible
NE: Non-edible
NA: not avalaible

3.1 Polysaccharides

Polysaccharides are the major class of bioactive compounds found in mushroom and have been reported in most of the edible mushrooms. The general therapeutic effects of polysaccharides are antioxidant, antidiabetic, antimicrobial, anti-inflammatory, anticancer, and immunomodulators (Elsayed et al. 2014; Chan et al. 2009).

3.1.1 Glucans

Glucan polysaccharides differ in their primary structure (type of basic sugar, e.g., xylose, mannose, galactose, etc.), type of linkage (α or β), degree of branching, molecular weight, solubility, etc. Fungal glucans can be water soluble, soluble in alkali or insoluble. Some glucans are intracellular (serve as reserve material), others are secreted in the medium, and few are present in the cell wall (Ruiz-Herrera 2012). The insoluble fractions are usually structural components of the cell wall and cross-linked to other polysaccharides like chitin or to proteins (e.g., mannoproteins and glycoprotein). Soluble glucans correspond to 20–50% of the total glucans, and insoluble glucans correspond between 50 and 80% (He et al. 2012). The diversity of glucans results from at least eight different ways in which two glucose units can link. Formations of α- or β-bond are a result of the condensation reactions. The diversity of glucans is further increased due to the different length and branches of

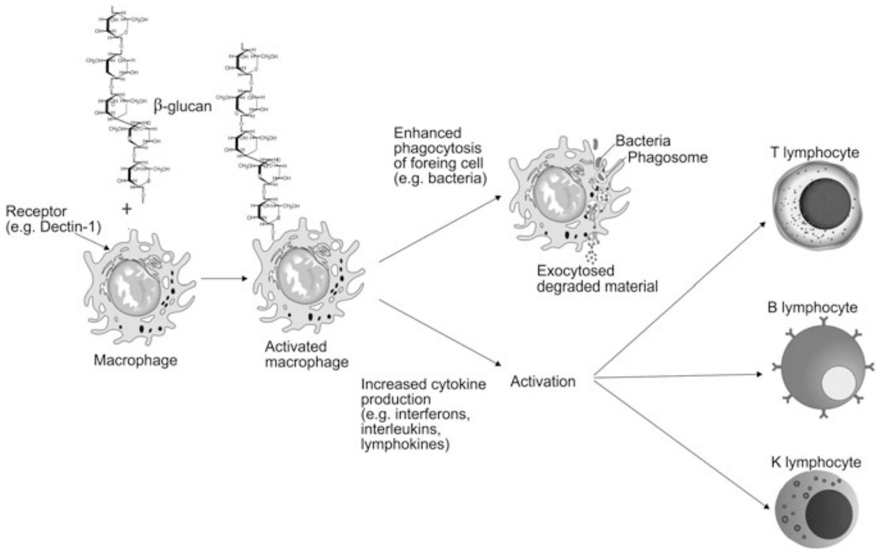

Fig. 2 Schematic illustration of the mechanism of immune activation by β-glucan from mushrooms

chains and substitutions on the sugar rings (Ren et al. 2012). β- and α-glucans can be present in fungal cell wall. Fruit body extracts of *Pleurotus pulmonarius* showed mixed α-linkages and β-anomeric carbon linkages, whereas polysaccharide from mycelial extracts had mainly α-glucan linkages (Lavi et al. 2010). α(1, 3)-glucan is present at levels of 9–46% of the cell wall in several basidiomycetes. It can be present in the cell wall of certain mushrooms such as *Agaricus bisporus* fruit bodies (Smiderle et al. 2010). β-glucan is one of the key components of several basidiomycete and ascomycete cell wall. It is a long-chain polysaccharide with β-D glucose as basic subunit linked to one another by 1-3 glycosidic chain with 1-6 glycosidic branches. β-glucans have been reported to have antimicrobial immune response, acting on several immune receptors such as dectin-1 (major β-glucan receptor), complement receptor (CR3), and TLR-2/6 (Toll-like receptor-2/6, receptor of the innate immune) (Chan et al. 2009). Therefore, β-glucans are able to enhance the immune system and prevent and treat several common diseases to promote health (Batbayar et al. 2012). In the innate immune system, β-glucan binds with macrophages that are responsible to detect intruders and coordinate the body defense system. Macrophages start out as monocytes (white blood cells), which leave the bloodstream and turn into macrophages. Macrophages are activated by β-glucan, enhancing their ability to identify and destroy intruders through phagocytosis. Macrophages also play an important role in activating the rest of the immune system (T lymphocyte, B lymphocyte, and NK cells) to destroy invaders. T lymphocytes (thymus-derived) have a receptor for antigen (T cell receptor) and are specialized cells trained to kill invaders. B lymphocytes (bone marrow-derived) make antibody, and their antigen receptor is the antibody on their surface. NK (natural killer) cells are T lymphocytes, which kill virus or bacterium-infected cells and tumor cells. In this way, the immune system protects the body from harmful invaders (Chan et al. 2009; Legentil et al. 2015) (Fig. 2). The bioactive glucans have been isolated from mushroom fruit bodies and from mycelia produced via submerged fermentation (Song et al. 2012; Queiroz et al. 2010; Guerra-Dore et al. 2007; Ruthes et al. 2013; Li et al. 2008). Several biologically active fungal β-glucans have been found in the fruiting bodies from mushrooms. Karácsonyi and Kuniak (1994) described the isolation of pleuran from *Pleurotus ostreatus* which is made of β(1,4)- or β(1,6)-branched for every fourth β(1,3)-glucan backbone (El Enshasy et al. 2013a). The bioactive glucan, lentinan from *Lentinula edodes,* is made of one β(1,6)-branched residue for every three β(1,3) glucose residues with molecular weight of 400–1000 kDa (Sasaki and Takasuka 1976). It showed immunomodulatory and antitumor activities (Firenzuoli et al. 2007). Schizophyllan is the active β-glucan from *Schizophyllum commune* which is formed by one β(1,6)-branched residue for every three β(1,3) glucose residues with molecular weight of 450 kDa (Bae et al. 2004). Maitake D-fraction was isolated from *Grifola frondosa*, which is made of mixture of β(1,6)-glucan main chain with β(1,4)-branched glucan and β(1,3)-glucan main chain with β(1,6)-branched glucan (Grifolan) (Kidd 2000). For example, *Agaricus subrufescens* extract is rich in β(1,3)-, β(1,4)-, and β(1,6)-glucans and induces the release of proinflammatory cytokines in human monocytes and human vein endothelial cells in vitro (Bernardshaw et al. 2005). Glucans such as (1,3)-glucopyranosyl from *Pleurotus pulmonarius* have been reported to exhibit anti-inflammatory properties (Lavi et al. 2012). Rathee et al. (2012) reported that ganoderan A and B, glucans from *Ganoderma lucidum* fruiting bodies, showed hypoglycemic effects. On the other hand, ganopoly, the polysaccharide-containing preparation of *G. lucidum*, exhibited hepatoprotective effects in patients with chronic hepatitis B (Gao et al. 2002). It has been suggested that glucans from *G. lucidum* had immunomodulating properties, as well as enhancement of lymphocyte proliferation and antibody production. These polysaccharides also showed both antigenotoxic and antitumor-promoting activities (Bao et al. 2001; Wasser 2002). The antioxidative and free radical scavenging effects of polysaccharides of *G. lucidum* have also been reported (Rathee et al. 2012). A β-glucan (β-1,3-linked glucose residues, which occasionally branches at O-6) isolated from the fruiting bodies of *P. ostreatus* has also been proven to exert antitumor activity against Hela tumor cell (Tong et al. 2009). Two mechanisms have been proposed to be responsible for the anticancer effect of β-glucan: (1) via direct cytotoxic effect and (2) indirectly through immunomodulatory action (Chan et al. 2009). *L. edodes* has shown anti-inflammatory activities. The active fraction was made of fucomanno-galactan with a main chain of (1,6)-linked α-D-galactopyranosyl units, partially substituted at O-2 (Carbonero et al. 2008). Additionally, glucans such as (1,3)-D-glucopyranosyl from *P. pulmonarius* have been reported to exhibit anti-inflammatory properties (Lavi et al. 2012). Wu et al. (2010) reported that polysaccharides of *Flammulina velutipes* are composed of three monosaccharides (glucose, mannose, and xylose) in a molar ratio of 3.5:0.8:1.4 and have been found to have anti-inflammatory activities (Wu et al. 2010). Polysaccharides extracted from mushrooms such as *Cantharellus tubaeformis* (Tsvetkova et al. 2006), *Lactarius flavidulus* (Fujimoto et al. 1993), *Lactarius rufus* (Ruthes et al. 2013), *Lyophyllum decastes* (Ukawa et al. 2000), *Pholiota nameko* (Li et al. 2008), *Geastrum saccatum* (Guerra-Dore et al. 2007), *Fomitopsis pinicola* (Cheng et al. 2008), *Craterellus tubaeformis* (Tsvetkova et al. 2006), *Auricularia auricula* (Zhang et al. 2007), and *Boletus edulis* (Moro et al. 2012) have also been reported ‘to exhibit anti-inflammatory properties.

3.1.2 Polysaccharide–Protein Complexes

Some polysaccharides have been identified as polysaccharide–protein complexes, which have been shown to possess immunomodulatory and antitumor activities. For example, polysaccharide-K (polysaccharide-Kureha; PSK) also known as krestin, protein bound with β(1,6) side chain, and β(1,3)-branched β(1,4) main chain glucan (94–100 kDa) were isolated from *Trametes versicolor*. Krestin showed antimeta-static activity (Fisher et al. 2002; Wasser 2002). Coriolan, a β-glucanprotein complex obtained from submerged grown *T. versicolor* biomass, exhibited hypo-glycemic effects and ameliorated the symptoms of diabetes (Rathee et al. 2012). Chatterjee et al. (2011) isolated calvacin from *Calvatia gigantea*. It is a moderately heat stable, nondiffusible, and basic mucoprotein, which showed antitumor activity. On the other hand, ethanolic extracts and a proteoglycan purified from *Phellinus linteus* showed anti-inflammatory properties (Kim et al. 2003, 2004).

3.2 Terpenes

Terpenes are the largest group of anti-inflammatory compounds in mushrooms. Several terpenes have been isolated from *G. lucidum*. These are nonpolar metabolites comprised of the following groups: (1) volatile mono and sesquiterpenes oils (C10 and C15), (2) less volatile diterpenes (C20), (3) involatile triterpenoids and sterols (C30), and (4) the carotenoid pigments (C40). Triterpene chemical structures are based on lanosterol. It is an important intermediate for their synthesis. Stereochemical rearrangement of this compound among triterpenoids results in their structural diversity (predominant pairs of C-3 stereoisomers) (Paliya et al. 2014). Akihisa et al. (2005) and Iwatsuki et al. (2003) isolated nine lucidenic acids and four ganoderic acids from fruit bodies of *G. lucidum*. On the other hand, several lanostane-type triterpenic acids were isolated by Akihisa et al. (2005) and terpenoids (triterpenes) were also isolated from Reishi mushroom (Dudhgaonkar et al. 2009). All those terpenes showed anti-inflammatory activity. Some triterpenes from *G. lucidum* (ganoderic acid C and derivatives) are able to inhibit the biosynthesis of cholesterol (Komoda et al. 1989). Other triterpenes (ganoderic acid F) of this mushroom contribute to atherosclerosis protection (Morigiwa et al. 1986). The antioxidative and free radical effects of triterpenoids from *G. lucidum* have also been shown (Rathee et al. 2012). El-Mekkawy et al. (1998) reported that different triterpenes from *G. lucidum* (i.e., ganoderiol, ganodermanontriol, and ganoderic acid) showed antiviral activity. Sterols and triterpenes (e.g., lucialdehyde D, ganoderone A, and ganoderone C) were isolated from the fruiting bodies of *Ganoderma pfeifferi.* Antifungal, antibacterial, and antiviral properties were found for some of such isolated compounds (Niedermeyer et al. 2005). Furthermore, different sterols with potent anti-inflammatory properties have been also isolated from *Inonotus obliquus* (Van et al. 2009; Park et al. 2005). Several triterpenes (trametenolic acid, ergosterol peroxide, 3*β*-hydroxy-8,24-dien-21-al, ergosterol, and inotodiol) were isolated from the sclerotia of *I. obliquus*, which had anti-inflammatory and anticancer activities (Ma et al. 2013). Han et al. (2013) isolated five novel cyathane diterpenes (identified as cyathins DH) and three diterpenes (neosarcodonin, cyathatriol, and 11-O-acetylcyathatriol) from *Cyathus Africans*, which showed potent anti-inflammatory properties. Chen et al. (2006) reported that several triterpenes (e.g., 19-hydroxylabda-8(17)-en-16,15olide, and 14-deoxy-11,12-didehydroandrographolide) isolated from *Antrodia camphorate* showed neuroprotective activity.

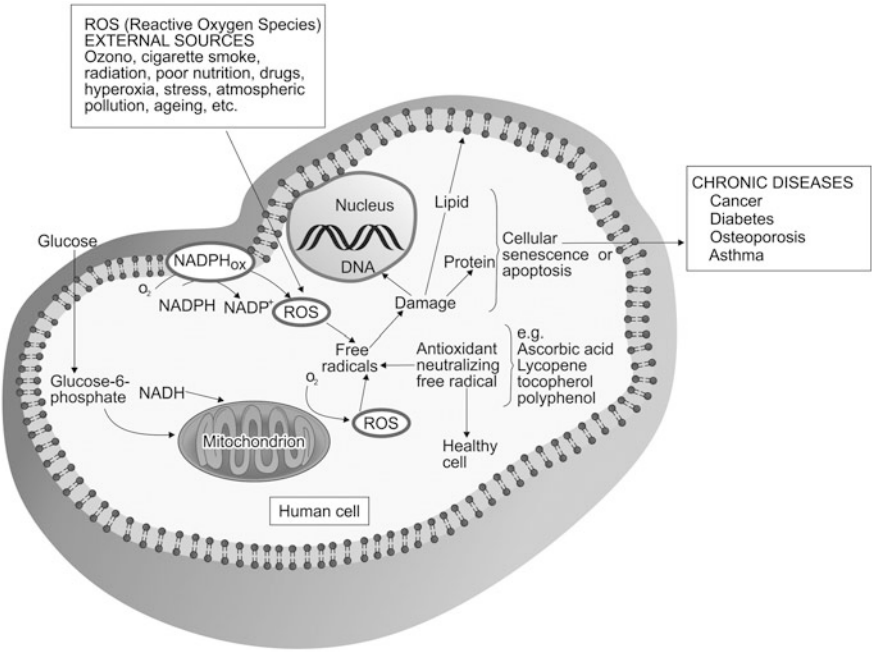

Fig. 3 Schematic representation of antioxidant activity, showing molecules neutralizing free radicals to prevent cellular and tissue damage

3.3 Phenolic Compounds

Phenolic compounds are aromatic hydroxylated compounds with one or more aromatic rings and one or more hydroxyl groups. They include phenolic acids, flavonoids, hydroxybenzoic acids, hydroxycinnamic acids, lignans, tannins, stilbenes, and oxidized polyphenols (Cote et al. 2010; D'Archivio et al. 2010). It has been reported that phenolic compounds exhibit antioxidant activity in biological systems, acting as free radical inhibitors, peroxide decomposers, metal inactivators, or oxygen scavengers (Dziezak 1986; Yagi 1970). Therefore, the key role played by antioxidants in the body is their ability to react with free radicals. A free radical is a chemical compound that contains one or more unpaired electrons. Reactive oxygen species (ROS) (i.e., superoxide, hydrogen peroxide, hydroxyl radical, hydroxyl ion, and nitric oxide) are reactive molecules and free radicals derived from molecular oxygen. These molecules can be produced either by external sources (e.g., cigarette smoke, ozone, and stress) or as by-products during the mitochondrial electron transport of aerobic respiration or by oxidoreductase enzymes and metal-catalyzed oxidation. Because they are reactive, radicals search out ways of pairing up their electron, so radicals often attack nearby chemical compounds. These chemical compounds may be involved in important enzyme reactions, may be components of cell walls (i.e., lipid and protein), or may be part of a DNA molecule. If their chemical structure is changed, their function in the cell may be lost and the result can be cellular senescence or apoptosis (chronic diseases in the body). ROS have the potential to cause several deleterious events, and neutralizing of free radicals or peroxide radicals by an antioxidant agent may avoid such damage in the cell (Fig. 3). There are a number of nonenzymatic small molecules that play a role as antioxidants. Glutathione may be the most important intracellular defense against the deleterious effects of ROS. It is a tripeptide (glutamyl-cysteinyl-glycine), which provides an exposed sulfhydryl group as target for attack. Ascorbic acid (vitamin C) and α-tocopherol (vitamin E), lycopene, and polyphenol are examples of molecules capable of reducing ROS (Held 2015) (Fig. 3). Palacios et al. (2011) studied the antioxidant activity of phenolic compounds in *Agaricus bisporus*, *Boletus edulis*, *Cantharellus cibarius, Craterellus cornucopioides, Calocybe gambosa, Hygrophorus marzuolus, and Lactarius deliciosus*, and *P. ostreatus. C. cibarius,* and *C. cornucopioides* exhibited the greatest antioxidant effect with respect to the other species. *C. cornucopioides* showed the highest myricetin amount, and *C. cibarius* presented greater amounts of caffeic acid and catechin. The phenolic molecule pyrogallol has been extracted from *A. bisporus*, *C. cibarius*, and *L. deliciosus* (Dugler et al. 2004; Witkowska et al. 2011), which have been found to exhibit anti-inflammatory activity. Grifolin and grifolin derivatives are farnesyl phenolic compounds which have been isolated from the edible mushroom *Albatrellus ovinus*, which showed anti-inflammatory properties (Nukata et al. 2002). It has been reported that phenol analogous compounds (hericenones C, D, E, F, G, H) isolated from *H. erinaceus* had antioxidant activity (Mizuno 1999) and antineurodegenerative properties (Xu and Beelman 2015). Human trials have been carried out using *H. erinaceus*. In this study, 30 subjects were randomized into two 15-person groups, one of which was given *H. erinaceus* (250 mg tablets containing 96% of this mushroom dry powder) and the other given a placebo. The tablets were taken for three times a day for 16 weeks. Those subjects whose took *H. erinaceus* power showed significantly increased scores on the cognitive function scale compared with the placebo group (Mori et al. 2009). On the other hand, Attarat and Phermthai (2015) reported that catechin, a major group of phenolic compounds, was isolated from *Lentinula squarrosulus*, *Lentinula polychrous,* and *L. edodes*, which exhibited antioxidant activity. Chowdhury et al. (2015) isolated phenolic compounds and flavonoids from *P. ostreatus*, *L. edodes,* and *Hypsizygus tessellatus*, which showed antioxidant, antifungal, and antibacterial properties. On the other hand, it has been suggested that an increased free radical generation and the consequent elevated oxidative stress in neural system cause neurodegenerative diseases. Mushrooms can potentially reduce the risk of neurodegenerative diseases attributing to the high antioxidative capacity of bioactive compounds such as vitamin D and polyphenols (Xu and Beelman 2015). It has been reported that hericenones (A-H) and erinacines (A-K & P-Q), from fruiting bodies and mycelia of *H. erinaceus*, respectively, induced nerve growth factor synthesis (both in vitro and in vivo) (Kawagishi et al. 2008; Phan et al. 2014). Dai et al. (2010) reported that hispidin, a class of polyphenols, is an important medicinal metabolite from

Phellinus spp. Hispidin was isolated from the culture broth of *P. linteus*, and it has been shown to be an efficient ROS scavenger (Park et al. 2004).

3.4 Peptides and Proteins

Mushrooms produce many bioactive proteins and peptides, primarily including lectins, which have not enzymatic activity. Mushrooms also produce bioactive proteins, which possess enzymatic activity such as fungal immunomodulatory proteins (FIPs), ribosome-inactivating proteins (RIPs), and laccases. Chu et al. (2005) isolated an antifungal peptide (pleurostrin) (7 kDa) from *P. ostreatus*, which exhibited antifungal activity. Wang et al. (2007) isolated a peptide (SU2) (4.5 kDa) from *Russula paludosa*, which showed antiviral properties. Ngai et al. (2005) isolated an antifungal peptide (agrocybin) (9 kDa) from fresh fruiting bodies of the mushroom *Agrocybe cylindracea*. Cordymin, a low molecular weight peptide (10,906 Da), has been purified from *Cordyceps sinensis* (a highly prized edible fungus found in the mountains of Sichuan, Yunnan, and Tibet) (Wang et al. 2012; Qian et al. 2011) and from *Cordyceps militaris* (Wong et al. 2011). This peptide showed anti-inflammatory activity. Lectins are nonimmune proteins or glycoproteins that bind specifically to fungal cell wall carbohydrates and have ability to cell agglutination. Liu et al. (2006) isolated a xylose-specific lectin (28.8 kDa) from fresh fruiting bodies of *Xylaria hypoxylon*. It showed potent antimitogenic and antitumor activities. It has been reported that lectins were isolated from *Pholiota adiposa* and from *H. erinaceum* (16 and 51 kDa, respectively), which exhibited antiviral and antitumor activities (Zhang et al. 2009; Lin et al. 2010). Zhang et al. (2010a) isolated a lectin (32 kDa) from *Russula lepida*, which exhibited antitumor activity. Ribosome-inactivating proteins (RIPs) are enzymes that inactivate ribosomes by eliminating adenosine residues from rRNA. It has been reported that a ribosome-inactivating protein (9 kDa) (marmorin) was isolated from *Hypsizigus marmoreus* and showed antitumor activity (Wong et al. 2008). On the other hand, laccases are phenol oxidases widely diffused in basidiomycete and ascomycete fungi. These fungi use laccases to degrade lignocellulosic substrates. However, laccases with antiviral activity have been isolated from *Pleurotus eryngii* (Wang and Ng 2006a) and from *P. ostreatus* (El Fakharany et al. 2010). Zhang et al. (2010b) purified a laccase from *Clitocybe maxima*, which also showed antitumor activity. Some proteins targeting immune cells known as fungal immunomodulatory proteins (FIPs) are a new group bioactive proteins also isolated from mushroom. Kino et al. (1989) isolated ling zhi-8 (LZ-8), an immunomodulatory protein from *G. lucidum*. FIPs have been isolated from the mushrooms *F. velutipes* (Fip-fve) (Ko et al. 1995), *Ganoderma tsugae* (Fip-gts) (Lin et al. 1997), and *Volvariella volvacea* (Fip-vvo) (Hsu et al. 1997). It has been reported the potential application of Fip-fve for tumor immunotherapy (Ding et al. 2009; Chang and Sheu 2006; Chang et al. 2010). A novel immunomodulatory glycoprotein ACA (27 kDa) was purified from *Antrodia camphorata* (Sheu et al. 2009). Lin et al. (2010) isolated an immunomodulatory protein GMI from *Ganoderma microsporum*, which showed antimetastasis activity. Du et al. (2007) purified a water-soluble Se-containing protein Se-GL-P (36 kDa) from the Se-enriched *G. lucidum*, which exhibited antitumor activity. The immunomodulatory activity of the isolated protein fractions and polysaccharide fractions from the mushrooms *A. blazei*, *C. comatus*, *F. velutipes*, *G. lucidum, G. frondosa*, *L. edodes*, *P. ostreatus,* and *V. volvacea* has been reported (Jeurink et al. 2008). Maiti et al. (2008) examined the antiproliferative and immunomodulatory activities of a protein fraction, named Cibacron blue affinity eluted protein (CBAEP), which was isolated from *Astraeus hygrometricus*, *Termitomyces clypeatus*, *Pleurotus florida*, *Calocybe indica,* and *V. volvacea*. A glycoprotein (PCP-3A) was purified from *Pleurotus citrinopileatus*, which showed antitumor activity (Chen et al. 2009). Kodama et al. (2002) isolated a low molecular weight protein fraction from *G. frondosa*, which showed antitumor activity. Ngai and Ng (2008) isolated a novel and potent antifungal protein lentin (27.5 kDa) from the fruiting bodies of *L. edodes*. Guo et al. (2005) also isolated an antifungal protein (trichogin) from *Tricholoma giganteum*. Wang and Ng (2006b) isolated an antifungal protein (15 kDa) (ganodermin) from *G. lucidum*. Zheng et al. (2010) isolated a novel antibacterial protein (44 kDa) from dried fruiting bodies of *Clitocybe sinopica*.

3.5 Other Compounds

Agaricoglycerides are fungal secondary metabolites that constitute esters of chlorinated 4-hydroxy benzoic acid and glycerol, which are produced in the culture of *G. frondosa* and *Agaricus macrosporus.* These compounds showed potent anti-inflammatory activity (Han and Cui 2012). Nagai et al. (2006) reported that dilinoleoylphosphatidylethanolamine isolated from fruiting bodies of *H. erinaceum* reduces oxidative stress in endoplasmic reticulum, demonstrating its potential effect in neurodegenerative diseases. It has been reported that termitomycesphins A, B, C, D, G, and H (cerebrosides) (Qi et al. 2000; Qu et al. 2012) and termitomycamide A, B, C, D, and E (fatty acid amides) were extracted and identified from dried fruiting bodies of *Termitomyces albuminosus* (Choi et al. 2010). These bioactive compounds also exhibited antineurodegenerative activity, since reduced endoplasmic reticulum stress-induced. Kawagishi et al. (1997) isolated dictyophorine A and B from *Dictyophora indusiata*, which can significantly improve the amount of nerve growth factor. Lee et al. (2002a) identified dictyoquinazol A, B, and C in *D. indusiata*, which showed neuroprotective properties. Choi et al. (2009, 2014) isolated 3-(hydroxymethyl)-4-methylfuran-2(5H)-one, (3R, 4S, 1’ R)-3-(1’-hydroxyethyl)-4methyldihydrofuran-2(3H)-one, 5-hydroxy-4-(1-hydroxyethyl)-3-methylfuran-2(5H)-one, and 5-phenylpentane-1,3,4-triol from *Mycoleptodonoides aitchisonii*, which also exhibited activity. It has been reported that Alzheimer’s disease pathogenesis includes microglial activation associated with neuroinflammation, increased level of acetyl cholinesterase (AChE) activity, and free radical generation

(Martorana et al. 2012). Brondz et al. (2007) isolated 6-hydroxyinfractine and infractopicrine (alkaloids infractine) from *Cortinarius infractus*, which showed AChE-inhibiting activity with nondetectable cytotoxicity (Geissler et al. 2010). Caruilignan C and 1-(3,4,5-trimethoxyphenyl) ethanol were isolated and purified from *Daldinia concentrica*, which showed neuroprotective activity (Lee et al. 2002b). On the other hand, it has been reported that psilocybin from the hallucinogen *Psilocybe* species showed antidepressant properties (Mason-Dambrot 2012; Kraehenmann 2015; Grob et al. 2011; Carhart-Harris et al. 2012; Petri et al. 2014). Psilocybin is a phosphate derivative of N,N-dimethyltryptamine that is present at concentrations of 0.1–1.5% in species of the *Psilocybe* genus. This compound is considered nonaddictive and rarely abused. In humans, psilocybin converts to psilocin, which is a pharmacologically active drug (Norchem 2011). The antioxidant metabolites, 2,4,6-trimethylacetophenone imine, glutamyl tryptophan, azatadine, and lithocholic acid glycine conjugate were isolated from *Boletus* spp, which exhibited antioxidant activity (Yuswan et al. 2015).

4 Future Trends

Mushrooms are functional food and are a source of biologically valuable components that offer great therapeutic potential for the prevention and control of several diseases. A large number of mushroom-derived bioactive compounds, both cellular components and secondary metabolites, have been isolated. Some studies about mushrooms' bioactivity were assayed using crude mushroom extracts or mixture of mushroom metabolites. These studies will require the isolation and identification of the bioactive compounds in order to determine the bioactive effect of each compound. Both the optimization of submerged culture conditions for mycelial growth and strain improvement by genetic manipulation are crucial in order to overproduce the desired compound. Further research and clinical trials have to be carried out to validate that mushrooms are source of bioactive molecules with medicinal application.

References

Akihisa T, Tagata M, Ukiya M et al (2005) Oxygenated lanostane-type triterpenoids from the fungus *Ganoderma lucidum*. J Nat Prod 68(4):559–563. doi:10.1021/np040230h

Akihisa T, Nakamura Y, Tagata M et al (2007) Anti-inflammatory and anti-tumor-promoting effects of triterpene acids and sterols from the fungus *Ganoderma lucidum*. Chem Biodiver 4 (2):224–231

Attarat J, Phermthai T (2015) Bioactive compounds in three edible *Lentinus* mushrooms. Walailak J Sci Technol 12(6):491–504. doi:10.14456/WJST.2015.80

Badalyan S (2012) Medicinal aspects of edible ectomycorrhizal mushrooms. DDM 34. Springer, Berlin, pp 317–334

Bae AH, Lee SW, Ikeda M et al (2004) Rod-like architecture and helicity of the poly(C)/schizophyllan complex observed by AFM and SEM. Carbohydr Res 339(2):251–258. doi:10.1016/j.carres.2003.09.032

Bao X, Liu C, Fang J et al (2001) Structural and immunological studies of a major polysaccharide from spores of *Ganoderma lucidum* (Fr.) Karst. Carbohydr Res 332:67–74

Batbayar S, Lee DH, Kim HW (2012) Immunomodulation of fungal β-glucan in host defense signaling by dectin-1. Biomol Ther 20(5):433–445. doi:10.4062/biomolther20.5.433

Bernardshaw S, Johnson E, Hetland G (2005) An extract of the mushroom *Agaricus blazei* Murill administered orally protects against systemic *Streptococcus pneumoniae* infection in mice. Scand J Immunol 62(4):393–398. doi:10.1111/j.1365-3083.2005.01667.x

Brondz I, Ekeberg D, Høiland K et al (2007) The real nature of the indole alkaloids in *Cortinarius infractus*: evaluation of artifact formation through solvent extraction method development. J Chromatogr A 1148(1):1–7. doi:10.1016/j.chroma.2007.02.074

Carbonero ER, Gracher AHP, Komura DL et al (2008) *Lentinus edodes* heterogalactan: antinociceptive and anti-inflammatory effects. Food Chem 111(3):531–537. doi:10.1016/j.foodchem.2008.04.015

Carhart-Harris R, Erritzoe D, Williams T et al (2012) Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin. Proc Natl Acad Sci USA 109:2138–2143

Chan GCF, Chan WK, Sze DMY (2009) The effects of β-glucan on human immune and cancer cells. J Hematol Oncol 2:25–35. doi:10.1186/1756-8722-2-25

Chang HH, Sheu F (2006) Anti-tumor mechanisms of orally administered a fungal immunomodulatory protein from *Flammulina velutipes* in mice. Nutr Immunol 6(20):A1057

Chang HH, Hsieh KY, Yeh CH et al (2010) Oral administration of an Enoki mushroom protein FVE activates innate and adaptive immunity and induces anti-tumor activity against murine hepatocellular carcinoma. Int Immunopharmacol 20:239–246. doi:10.1016/j.intimp.2009.10.017

Chatterjee S, Biswas G, Basu SK (2011) Antineoplastic effect of mushrooms: a review. Aust J Crop Sci 5(7):904–911

Chen C, Xue JG, Zhou KS et al (2003) Purification and characterization of flammulin, a basic protein with anti-tumor activities from *Flammulina velutipes*. J Chin Pharm Sci 12(2):60–65

Chen CC, Shiao YJ, Lin RD et al (2006) Neuroprotective diterpenes from the fruiting body of *Antrodia camphorata*. J Nat Prod 69:689–691

Chen JN, Wang YT, Wu JSB (2009) A glycoprotein extracted from golden oyster mushroom *Pleurotus citrinopileatus* exhibiting growth inhibitory effect against U937 leukemia cells. J Agric Food Chem 57(15):6706–6711. doi:10.1021/jf901284s

Cheng JJ, Lin CY, Lur HS et al (2008) Properties and biological functions of polysaccharides and ethanolic extracts isolated from medicinal fungus, *Fomitopsis pinicola*. Process Biochem 43(8):829–834. doi:10.1016/j.procbio.2008.03.005

Cheung PCK (2008) Mushrooms as functional food. Wiley, NJ, p 280

Choi JH, Horikawa M, Okumura H et al (2009) Endoplasmic reticulum (ER) stress protecting compounds from the mushroom *Mycoleptodonoides aitchisonii*. Tetrahedron 65(1):221–224. doi:10.1016/j.tet.2008.10.068

Choi JH, Maeda K, Nagai K et al (2010) Termitomycamides A to E, fatty acid amides isolated from the mushroom *Termitomyces titanicus*, suppress endoplasmic reticulum stress. Org Lett 12(21):5012–5015. doi:10.1021/ol102186p

Choi JH, Suzuki T, Okumura H et al (2014) Endoplasmic reticulum stress suppressive compounds from the edible mushroom *Mycoleptodonoides aitchisonii*. J Nat Prod 77(7):1729–1733. doi:10.1021/np500075m

Chowdhury MMH, Kubra K, Ahmed SR (2015) Screening of antimicrobial, antioxidant properties and bioactive compounds of some edible mushrooms cultivated in Bangladesh. Ann Clin Microbiol Antimicrob 14:8. doi:10.1186/s12941-015-0067-3

Chu KT, Xia LX, Ng TB (2005) Pleurostrin, an antifungal peptide from the oyster mushroom. Peptides 26(11):2098–2103

Cote J, Caillet S, Doyon G (2010) Bioactive compounds in cranberries and their biological properties. Crit Rev Food Sci Nutr 50(7):666–679. doi:10.1080/10408390903044107

D'Archivio M, Filesi C, Vari R et al (2010) Bioavailability of the polyphenols: status and controversies. Int J Mol Sci 11:1321–1342. doi:10.3390/ijms11041321

Dai YC, Zhou LW, Cui BK et al (2010) Current advances in *Phellinus sensu lato*: medicinal species, functions, metabolites and mechanisms. Appl Microbiol Biotechnol 87(5):1587–1593. doi:10.1007/s00253-010-2711-3

Das SK, Masuda M, Sakurai A et al (2010) Medicinal uses of the mushroom *Cordyceps militaris*: current state and prospects. Fitoterapia 81:961–968

Ding Y, Seow SV, Huang CH et al (2009) Coadministration of the fungal immunomodulatory protein FIP-Fve and a tumour-associated antigen enhanced antitumour immunity. Immunology 128(1):881–894

Du M, Zhao L, Li CR et al (2007) Purication and characterization of a novel fungi Se-containing protein from Se-enriched *Ganoderma Lucidum* mushroom and its Se-dependent radical scavenging activity. Eur Food Res Technol 224(5):659–665. doi:10.1007/s00217-006-0355-4

Du XJ, Zhang JS, Yang Y et al (2010) Purification, chemical modification and immunostimulating activity of polysaccharides from *Tremella aurantialba* fruit bodies. Univ-Sci B 11(6):437–442. doi:10.1631/jzus.B0900402

Dudhgaonkar S, Thyagarajan A, Sliva D (2009) Suppression of the inflammatory response by triterpenes isolated from the mushroom *G. lucidum*. Int Immunopharmacol 9(11):1272–1280. doi:10.1016/j.intimp.2009.07.011

Dugler B, Gonuz A, Gucin F (2004) Antimicrobial activity of the macrofungus *Cantharellus cibarius*. JBS 7(9):1535–1539

Dundar A, Acy H, Yildiz A (2008) Yield performance and nutritional contents of three oyster mushroom species cultivated on wheat stalk. Afr J Biotechy 7:3497–3501

Dziezak JD (1986) Antioxidants-The ultimate answer to oxidation. Food Techn 40(9):94

El Enshasy HA, Hatti-Kaul R (2013) Mushroom immunomodulators: unique molecules with unlimited applications. Trends Biotechnol 31(12):668–677. doi:10.1016/j.tibtech.2013.09.003

El Enshasy HA, Rajni HK (2013) Mushroom immunomodulators: unique molecules with unlimited applications. Trends Biotechnol 31(12):668–677. doi:10.1016/j.tibtech.2013.09.003

El Enshasy HE, Maftoun P, Malek RA (2013b) Pleuran: Immunomodulator polysaccharide from *Pleurotus ostreatus*, structure, production and application. Nova Science Publishers, New York, pp 153–172

El Fakharany EM, Haroun BM, Ng TB et al (2010) Oyster mushroom laccase inhibits hepatitis C virus entry into peripheral blood cells and hepatoma cells. Protein Pept Lett 17(8):1031–1039. doi:10.2174/092986610791498948

El-Mekkawy S, Meselhy MR, Nakamura N et al (1998) Anti-HIV-1 and anti-HIV-1 protease substances from *Ganoderma lucidum*. Phytochem 49(6):1651–1657. doi:10.1016/S0031-9422(98)00254-4

Elsayed EA, Enshasy HE, Wadaan MAM et al (2014) Mushrooms: a potential natural source of anti-inflammatory compounds for medical applications. Mediat Inflamm 1:1–15. doi:10.1155/2014/805841

Firenzuoli F, Gori L, Lombardo G (2007) The medicinal mushroom *Agaricus blazei* murrill: review of literature and pharmaco-toxicological problems. Evid Based Complement Altern Med 5(1):3–15. doi:10.1093/ecam/nem007

Fisher M, Yang LX et al (2002) Anticancer effects and mechanisms of polysaccharide-K (PSK): implications of cancer immunotherapy. Anticancer Res 22(3):1737–1754

Friedman M (2015) Chemistry, nutrition, and health-promoting properties of *Hericium erinaceus* (Lion's mane) mushroom fruiting bodies and mycelia and their bioactive compounds. J Agric Food Chem 63:7108–7123. doi:10.1021/acs.jafc.5b02914

Fujimoto H, Nakayama Y, Yamazaki M (1993) Identification of immunosuppressive components of a mushroom, *Lactarius flavidulus*. Chem Pharm Bull (Tokyo) 41(4):654–658

Ganeshpurkar A, Pardhi P, Bhadoriya SS et al (2015) Antioxidant potential of white oyster culinary-medicinal mushroom, *Pleurotus florida* (higher basidiomycetes). Int J Med Mushrooms 17(5):491–498. doi:10.1615/IntJMedMushrooms.v17.i5.90

Gao Y, Zhou S, Chen G et al (2002) A phase I/II study of a *Ganoderma lucidum* (Curt.:Fr.) P. Karst (LingZhi, Reishi mushroom) extract in patients with chronic hepatitis B. Int J Med Mushrooms 4(4):2321–2327. doi:10.1615/IntJMedMushr.v4.i4.50

Geissler T, Brandt W, Porzel A et al (2010) Acetylcholinesterase inhibitors from the toadstool *Cortinarius infractus*. Bioorg Med Chem 18(6):2173–2177. doi:10.1016/j.bmc.2010.01.074

Grob CS, Danforth AL, Chopra GS et al (2011) Pilot study of psilocybin treatment for anxiety in patients with advanced-stage cancer. Arch Gen Psychiatry 68:71–78. doi:10.1001/archgenpsychiatry.2010.116

Guerra-Dore CMP, Azevedo TCG, De Souza MCR et al (2007) Antiinflammatory, antioxidant and cytotoxic actions of *β*- glucan—rich extract from *Geastrum saccatum* mushroom. Int Immunopharmacol 7(9):1160–1169. doi:10.1016/j.intimp.2007.04.010

Guillamón S, García-Lafuente A, Lozano M et al (2010) Edible mushrooms: role in the prevention of cardiovascular diseases. Fitoterapia. 81(7):715–723. doi:10.1016/j.fitote.2010.06.005

Guo YX, Wang HX, Ng TB (2005) Isolation of trichogin, an antifungal protein from fresh fruiting bodies of the edible mushroom *Tricholoma giganteum*. Peptides 26(4):575–580

Gupta VK, Tuohy MG, O'Donovan A et al (2014) Biotechnology of bioactive compounds: sources and applications. Blackwell, London

Gupta VK, Mach RL, Sreenivasaprasad S (2015) Fungal biomolecules: sources, applications and recent developments. Wiley-Backwell, London

Han C, Cui B (2012) Pharmacological and pharmacokinetic studies with agaricoglycerides, extracted from *Grifola frondosa*, in animal models of pain and inflammation. Inflammation 35 (4):1269–1275. doi:10.1007/s10753-012-9438-5

Han J, Chen Y, Bao L et al (2013) Anti-inflammatory and cytotoxic cyathane diterpenoids from the medicinal fungus *Cyathus africanus*. Fitoterapia 84:22–31. doi:10.1016/j.fitote.2012.10.001

He J-Z, Ru Q-M, Dong D-D et al (2012) Chemical characteristics and antioxidant properties of crude water soluble polysaccharides from four common edible mushrooms. Molecules 17 (4):4373–4387. doi:10.3390/molecules17044373

Held P (2015) An introduction to reactive oxygen species: Measurement of ROS in cells. http://www.biotek.com/resources/articles/reactive-oxygen-species.html. Accessed 5 Nov 2015

Hobbs C (2005) The chemistry, nutritional value, immunopharmacology, and safety of the traditional food of medicinal plit-gill fungus *Schizophyllum commune*. Int J Med Mushrooms 7 (182):127–140. doi:10.1615/IntJMedMushr.v7.i12.130

Holliday J (2005) *Cordyceps*. In: Coates, Paul M. Encyclopaedia of dietary supplements 1. Marcel Dekker. pp. 4 of Cordyceps Chapter

Holliday J, Cleaver P, Lomis-Powers M et al (2004) Analysis of quality and techniques for hybridization of medicinal fungus *Cordyceps sinensis* (Berk.) Sacc. (ascomycetes). Int J Med Mushrooms 6(2):151–154. doi:10.1615/IntJMedMushr.v6.i2.60

Hsieh PW, Wu JB, Wu YC (2013) Chemistry and biology of *Phellinus linteus*. Biomed 3(3):106–113. doi:10.1016/j.biomed.2013.01.002

Hsu HC, Hsu CI, Lin RH et al (1997) Fip-vvo, a new fungal immunomodulatory protein isolated from *Vovariella volvacea*. Biochem J 323:557–565

Israilides C, Kletsas D, Arapoglou D (2008) *In vitro* cytostatic and immunomodulatory properties of the medicinal mushroom *Lentinula edodes*. Phytomed 15:512–519. doi:10.1016/j.phymed.2007.11.029

Iwatsuki K, Akihisa T, Tokuda H et al (2003) Lucidenic acids P and Q, methyl lucidenate P, and other triterpenoids from the fungus *Ganoderma lucidum* and their inhibitory effects on Epstein-Barr virus activation. J Nat Prod 66(12):1582–1585

Jeurink PV, Noguera CL, Savelkoul HFJ et al (2008) Immunomodulatory capacity of fungal proteins on the cytokine production of human peripheral blood mononuclear cells. Int Immunopharmacol 8(8):1124–1133. doi:10.1016/j.intimp.2008.04.004

Karácsonyi S, Kuniak L (1994) Polysaccharides of *Pleurotus ostreatus*: isolation and structure of pleuran, an alkali-insoluble β–D-glucan. Carbohydr Polym 24(2):107–111. doi:10.1016/0144-8617(94)90019-1

Kawagishi H, Ishiyama D, Mori H et al (1997) Dictyophorines A and B, two stimulators of NGF-synthesis from the mushroom *Dictyophora indusiata*. Phytochem 45(6):1203–1205. doi:10.1016/S0031-9422(97)00144-1

Kawagishi H, Zhuang C, Yunoki R (2008) Compounds for dementia from *Hericium erinaceum*. Drugs Future 33(2):149. doi:10.1358/dof.2008.033.02.1173290

Kidd PM (2000) The use of mushroom glucans and proteoglycans in cancer treatment. Altern Med Rev 5(1):4–27

Kim YK, Iwahashi H (2015) Properties of polysaccharides extracted from *Phellinus linteus* using high hydrostatic pressure processing and hot water treatment. J Food Process Eng 38(2):197–206. doi:10.1111/jfpe.12153

Kim GY, Kim SH, Hwang SY et al (2003) Oral administration of proteoglycan isolated from *Phellinus linteus* in the prevention and treatment of collagen-induced arthritis in mice. Biol Pharm Bull 26:823–831

Kim SH, Song YS, Kim SK et al (2004) Anti-inflammatory and related pharmacological activities of the n-BuOH subfraction of mushroom *Phellinus linteus*. J Ethnopharmacol 93:141–146

Kino K, Yamashita A, Yamaoka K et al (1989) Isolation and characterization of a new immunomodulatory protein, Ling Zhi-8 (LZ-8), from *Ganoderma lucidum*. J Biol Chem 264:472–478

Ko JL, Hsu CT, Lin RH et al (1995) A new fungal immunomodulatory protein, FIP-fve isolated from the edible mushroom, *Flammulina velutipes* and its complete amino acid sequence. Eur J Biochem 228:244–249

Kodama N, Komuta K, Nanba H (2002) Can maitake MDfraction aid cancer patients? Altern Med Rev 7:236–239

Komoda Y, Shimizu M, Sonoda Y et al (1989) Ganoderic acid and its derivatives as cholesterol synthesis inhibitors. Chem Pharm Bull 37:531–533

Kraehenmann R (2015) Psilocybin-induced decrease in amygdala reactivity correlates with enhanced positive mood in healthy volunteers. Biol Psychiatry 78(8):572–581. doi:10.1016/j.biopsych.2014.04.010

Kumar S, Mina M, Akihiko S et al (2010) Medicinal uses of the mushroom *Cordyceps militaris*: current state and prospects. Fitoterapia 81(8):961–968. doi:10.1016/j.fitote.2010.07.010

Lavi I, Levinson D, Peri I et al (2010) Chemical characterization, antiproliferative and antiadhesive properties of polysaccharides extracted from *Pleurotus pulmonarius* mycelium and fruiting bodies. Appl Microbiol Biotechnol 85(6):1977–1990. doi:10.1007/s00253-009-2296-x

Lavi I, Nimri L, Levinson D et al (2012) Glucans from the edible mushroom *Pleurotus pulmonarius* inhibit colitis-associated colon carcinogenesis in mice. J Gastroenterol 47(5):504–518. doi:10.1007/s00535-011-0514-7

Lee IK, Yun B, Kim Y et al (2002a) Two neuroprotective compounds from mushroom *Daldinia concentrica*. J Microbiol Biotechnol 12:692–694

Lee IK, Yun BS, Han G et al (2002b) Dictyoquinazols A, B, and C, new neuroprotective compounds from the mushroom *Dictyophora indusiata*. J Nat Prod 65(12):1769–1772. doi:10.1021/np020163w

Lee JS, Cho JC, Hong EK (2009) Study on macrophage activation and structure al characteristics of purified polysaccharides from the liquid culture broth of *Hericium erinaceus*. Carbohydr Polym 78(1):162–168. doi:10.1016/j.carbpol.2009.04.036

Legentil L, Paris F, Ballet C et al (2015) Molecular interactions of β-(1 → 3)-glucans with their receptors. Molecules 20(6):9745–9766. doi:10.3390/molecules20069745

Li H, Lu X, Zhang S (2008) Anti-inflammatory activity of polysaccharide *from Pholiota nameko*. Biochem 73(6):669–675. doi:10.1134/S0006297908060060

Li MA, Zhang GQ, Wang HX et al (2010a) Purification and characterization of a laccase from the edible wild mushroom *Tricholoma mongolicum*. J Microbiol Biotechnol 20(7):1069–1076. doi:10.4014/jmb.0912.12033

Li YR, Zhang GQ, Ng TB (2010b) A novel lectin with antiproliferative and HIV-1 reverse transcriptase inhibitory activities from dried fruiting bodies of the monkey head mushroom *Hericium erinaceus*. J Biomed Biotechnol 1–9. doi:10.1155/2010/716515

Lima LF, Habu S, Gern JC et al (2008) Production and characterization of the exopolysaccharides produced by *Agaricus brasiliensis* in submerged fermentation. Appl Biochem Biotechnol 151(2–3):283–294. doi:10.1007/s12010-008-8187-2

Lin WH, Huang CH, Hsu CI et al (1997) Dimerization of the N-terminal amphipathic α-helix domain of the fungal immunomodulatory protein from *Ganoderma tsugae* (Fip-gts) defined by a yeast two-hybrid system and site-directed mutagenesis. J Biol Chem 272:2044–2048

Lin CH, Sheu GT, Lin YW et al (2010) A new immunomodulatory protein from *Ganoderma microsporum* inhibits epidermal growth factor mediated migration and invasion in A549 lung cancer cells. Process Biochem 45(9):1537–1542. doi:10.1016/j.procbio.2010.06.006

Liu QH, Wang HX, Ng TB (2006) First report of a xylose-specific lectin with potent hemagglutinating, antiproliferative and anti-mitogenic activities from a wild ascomycete mushroom. Biochim Biophys Acta 1760(12):1914–1919. doi:10.1016/j.bbagen.2006.07.010

Ma L, Chen H, Dong P et al (2013) Anti-inflammatory and anticancer activities of extracts and compounds from the mushroom *Inonotus obliquus*. Food Chem 139(1–4):503–508. doi:10.1016/j.foodchem.2013.01.030

Maiti S, Bhutia SK, Mallick SK et al (2008) Antiproliferative and immunostimulatory protein fraction from edible mushrooms. Environ Toxicol Phar 26(2):187–191. doi:10.1016/j.etap.2008.03.009

Martorana A, Bulati M, Buffa S et al (2012) Immunosenescence, inflammation and Alzheimer's disease. Longev Healthspan 1:8. doi:10.1186/2046-2395-1-8

Mason-Dambrot S (2012) Your brain on 'shrooms: fMRI elucidates neural correlates of psilocybin psychedelic state. Med Xpress doi:10.1073/pnas.1119598109. Link: https://www.atlantisentertainment.net/mushroom-powders/361-cordyceps-mushroom-extract-powder. Accessed 4 Nov 2015

Mizuno T (1999) Bioactive substances in *Hericium erinaceus* (Bull.:Fr.) Pers. (Yamabushitake), and its medicinal utilization. Int J Med Mushrooms 1:105–119. doi:10.1615/IntJMedMushrooms.v1.i2.10

Mori K, Inatomi S, Ouchi K et al (2009) Improving effects of the mushroom *Yamabushitake (Hericium erinaceus)* on mild cognitive impairment: a double-blind placebo-controlled clinical trial. Phytother Res 23(3):367–372. doi:10.1002/ptr.2634

Morigiwa A, Kitabatake K, Fujimoto Y et al (1986) Angiotensin converting enzyme inhibitory triterpenes from *Ganoderma lucidum*. Chem Pharm Bull 34:3025–3028

Moro C, Palacios I, Lozano M et al (2012) Anti-inflammatory activity of methanolic extracts from edible mushrooms in LPS activated RAW 264.7 macrophages. Food Chem 130(2):350–355. doi:10.1016/j.foodchem.2011.07.049

Nagai K, Chiba A, Nishino T et al (2006) Dilinoleoyl-phosphatidylethanolamine from *Hericium erinaceum* protects against ER stress-dependent neuro-2a cell death via protein kinase C pathway. J Nutr Biochem 17:525–530. doi:10.1016/j.jnutbio.2005.09.007

Ndunguts V, Mereddy R, Sultanbawa Y (2015) Bioactive properties of mushroom (*Agaricus Bisporus*) stipe extracts. J Food Process Pres 1-9. doi:10.1111/jfpp.12467

Ngai PHK, Ng TB (2008) Lentin, a novel and potent antifungal protein from shitake mushroom with inhibitory effects on activity of human immunodeficiency virus-1 reverse transcriptase and proliferation of leukemia cells. Life Sci 73(26):3363–3374

Ngai PHK, Zhao Z, Ng TB (2005) Agrocybin, an antifungal peptide from the edible mushroom *Agrocybe cylindracea*. Peptides 26(2):191–196. doi:10.1016/j.peptides.2004.09.011

Niedermeyer TH, Lindequist U, Mentel R (2005) Antiviral terpenoid constituents of *Ganoderma pfeifferi*. J Nat Prod 68(12):1728–1731. doi:10.1021/np0501886

NORCHEM (2011) Urine drug test information sheet psilocybin (mushrooms). http://www.norchemlab.com/wp-content/uploads/2011/10/Psilocybin-facts.pdf. Accessed 2 Nov 2015

Nukata M, Hashimoto T, Yamamoto I et al (2002) Neogrifolin derivatives possessing anti-oxidative activity from the mushroom *Albatrellus ovinus*. Phytochem 59(7):731–737. doi:10.1016/S0031-9422(02)00050-X

Oei P (2003) Manual on mushroom cultivation: techniques species and opportunities for commercial application in developing countries. TOOL Publications, Amsterdam

Ohno N, HaradaT, Masuzawa S et al (2002) Antitumor activity and hematopoietic response of a β-glucan extracted from an edible and medicinal mushroom *Sparassis crispa* Wulf.:Fr. Aphyllophoromycetideae. Int. J. Med. Mushrooms 4(1):13–26. doi:10.1615/IntJMedMushr.v4.i1.20

Palacios I, Lozano M, Moro C et al (2011) Antioxidant properties of phenolic compounds occurring in edible mushrooms. Food Chem 128(3):674–678. doi:10.1016/j.foodchem.2011.03.085

Paliya BS, Verma S, Chaudhary HS (2014) Major bioactive metabolites of the medicinal mushroom: *Ganoderma lucidum*. Int J Pharm R 6(1):12–24

Park IH, Chung SK, Lee KB et al (2004) An antioxidant hispidin from the mycelial cultures of *Phellinus linteus*. Arch Pharmacal Res 27(6):615–618

Park YM, Won JH, Kim YH et al (2005) In vivo and in vitro anti-inflammatory and antinociceptive effects of themethanol extract of *Inonotus obliquus*. J Ethnopharmacol 101(1–3):120–128

Patel S, Goyal A (2012) Recent developments in mushrooms as anti-cancer therapeutics: a review. Biotech 2(1):1–15. doi:10.1007/s13205-011-0036-2

Petri G, Expert P, Turkheimer F et al (2014) Homological scaffolds of brain functional networks. J R Soc Interface 11:1–10. doi:10.1098/rsif.2014.0873

Phan CW, David P, Naidu M et al (2014) Therapeutic potential of culinary-medicinal mushrooms for the management of neurodegenerative diseases: diversity, metabolite, and mechanism. Crit Rev Biotechnol 35(3):355–568. doi:10.3109/07388551.2014.887649

Qi J, Ojika M, Sakagami Y (2000) Termitomycesphins A - D, novel neuritogenic cerebrosides from the edible Chinese mushroom *Termitomyces albuminosus*. Tetrahedron 56(32):5835–5841. doi:10.1016/S0040-4020(00)00548-2

Qian GM, Pan GF, Guo JY (2011) Anti-inflammatory and antinociceptive effects of cordymin, a peptide purified from the medicinal mushroom *Cordyceps sinensis*. Nat Prod Res 26(24):2358–2362. doi:10.1080/14786419.2012.658800

Qu Y, Sun K, Gao L et al (2012) Termitomycesphins G and H, additional cerebrosides from the edible Chinese mushroom *Termitomyces albuminosus*. Biosci Biotechnol Biochem 76(4):791–793. doi:10.1271/bbb.110918

Quang DN, Hashimoto T, Arakawaetal Y (2006) Grifolin derivatives from *Albatrellus caeruleo porus*, new inhibitors of nitric oxide production RAW264.7 cells. Bioorg Med Chem 14:164–168

Queiroz LS, Nascimento MS, Cruz AKM et al (2010) Glucans from the caripiamontagnei mushroom present anti-inflammatory activity. Int Immunopharm 10:34–42. doi:10.1016/j.intimp.2009.09.015

Rai M, Tidke G, Wasser SP (2005) Therapeutic potential of mushrooms. Nat Prod Radiance 4 (4):246–257

Rathee S, Rathee D, Rathee D et al (2012) Mushrooms as therapeutic agents. Braz J Pharmacog 22 (2):459–474

Ren L, Perera C, Hemar Y (2012) Antitumor activity of mushroom polysaccharides: a review. Food Funct 3(11):1118–1130. doi:10.1039/c2fo10279j

Ruiz-Herrera J (2012) Fungal cell wall: structure, synthesis, and assembly, 2nd edn. CRC Press, Taylor and Francis Group, Boa Raton, FL

Ruthes AC, Carbonero ER, Córdova MM et al (2013) Lactarius rufus (1 → 3), (1 → 6)-β-d-glucans: structure, antinociceptiveand anti-inflammatory effects. Carbohydr Polym 94: 129–136. doi:10.1016/j.carbpol.2013.01.026

Sánchez C (2004) Modern aspects of mushroom culture technology. Appl Microbiol Biotechnol 64(6):756–762

Sánchez C (2010) Cultivation of *Pleurotus ostreatus* and other edible mushrooms. Appl Microbiol Biotechnol 85(5):1321–1337. doi:10.1007/s00253-009-2343-7

Sasaki T, Takasuka N (1976) Further study of the structure of lentinan, an anti-tumor polysaccharide from *Lentinus edodes*. Carbohydr Res 47:99–104. doi:10.1016/S0008-6215(00)83552-1

Sheu F, Chien PJ, Hsieh KY et al (2009) Purification, cloning, and functional characterization of a novel immunomodulatory protein from *Antrodia camphorata* (Bitter Mushroom) that exhibits TLR2-dependent NF-kappa B activation and M1 polarization within murine macrophages. J Agric Food Chem 57(10):4130–4141

Smiderle FR, Sassaki GL, Van AJ et al (2010) High molecular weight glucan of the culinary medicinal mushroom *Agaricus bisporus* is an alpha-glucan that forms complexes with low molecular weight galactan. Molecules 15(8):5818–5830. doi:10.3390/molecules15085818

Smirdele FR, Olsen LM, Carbonero ER et al (2008) Anti- inflammatory and analgesic properties in rodent model (1 → 3), (1 → 6)-linked-glucan isolated from Pleurotus pulmonarius. Eur J Pharmacol 597(1–3):86–91. doi:10.1016/j.ejphar.2008.08.028

Song HH, Chae HS, Oh SR et al (2012) Anti-inflammatory and anti-allergic effect of *Agaricus blazei* extract in bone marrow-derived mast cells. Am J Chin Med 40(5):1073–1084. doi:10.1142/S0192415X12500796

Stanikunaite R, Khan SI, Trappe JM et al (2009) Cyclo- oxygenase-2 inhibitory and antioxidant compounds from the truffle *Elaphomyces granulatus*. Phytother Res 23(4):575–578. doi:10.1002/ptr.2698

Takashi K (2013) Natural products and biological activity of the pharmacologically active cauliflower mushroom *Sparassis crispa*. Bio Med Res Int 1–9. doi:10.1155/2013/982317

Tong H, Xia F, Feng K et al (2009) Structural characterization and in vitro antitumor activity of a novel polysaccharide isolated from the fruiting bodies of *Pleurotus ostreatus*. Bioresour Technol 100:1682–1686. doi:10.1016/j.biortech.2008.09.004

Tsvetkova I, Naydenski H, Petrova A et al (2006) Antibacterial activity of some Bulgarian higher basidiomycetes mushrooms. Int J Med Mushrooms 8(1):63–66. doi:10.1615/IntJMedMushr.v8.i1.80

Ukawa Y, Ito H, Hisamatsu M (2000) Antitumor effects of (1 → 3)-*β*-D-glucan and (1 → 6)-*β*-D-glucan purified from newly cultivated mushroom, Hatakeshimeji (*Lyophyllum decastes* Sing). J Biosci Bioeng 90(1):98–104. doi:10.1016/S1389-1723(00)80041-9

Van Q, Nayak BN, Reimer M et al (2009) Anti-inflammatory effect of *Inonotus obliquus*, *Polygala senega* L., and *Viburnum trilobum* in a cell screening assay. J Ethnopharmacol 125(3):487–493. doi:10.1016/j.jep.2009.06.026

Walton EL (2014) Buried treasure: unlocking the secrets of medicinal mushrooms. Biomed J 37:339–342. doi:10.4103/2319-4170.146538

Wang HX, Ng TB (2006a) Purification of a laccase from fruiting bodies of the mushroom *Pleurotus eryngii*. Appl Microbiol Biotechnol 69(5):521–525

Wang HX, Ng TB (2006b) Ganodermin, an antifungal protein from fruiting bodies of the medicinal mushroom *Ganoderma lucidum*. Peptides 27(1):27–30

Wang HX, Liu WK, Ng TB et al (1996) The immunomodulatory and antitumor activities of lectins from the mushroom *Tricholoma mongolicum*. Immunopharmacol 31(2–3):205–211. doi:10.1016/0162-3109(95)00049-6

Wang JB, Wang HX, Ng TB (2007) A peptide with HIV-1 reverse transcriptase inhibitory activity from the medicinal mushroom *Russula paludosa*. Peptides 28(3):560–565. doi:10.1016/j.peptides.2006.10.004

Wang J, Liu YM, Cao W et al (2012) Anti-inflammation and antioxidant effect of cordymin, a peptide purified from the medicinal mushroom *Cordyceps sinensis*, in middle cerebral artery occlusion-induced focal cerebral ischemia in rats. Metab Brain Dis 27(2):159–165. doi:10.1007/s11011-012-9282-1

Wasser SP (2002) Medical mushrooms as a source of antitumor and immunomodulating polysaccharides. App Microbiol Biotechnol 60(3):258–274. doi:10.1007/s00253-002-1076-7

Wasser SP (2010) Medicinal mushroom science: History, current status, future trends, and unsolved problems. Inter J Med Mush 1–16. doi:10.1615/IntJMedMushr.v12.i1.10
Witkowska MA, Zujko ME, Mironczuk-Chodakowska I (2011) Comparative study of wild edible mushrooms as sources of antioxidants. Int J Med Mushrooms 13(4):335–341. doi:10.1615/IntJMedMushr.v13.i4.30
Won S-Y, Park E-H (2005) Anti-inflammatory and related pharmacological activities of cultured mycelia and fruiting bodies of *Cordyceps militaris*. J Ethnopharmacol 96(3):555–561. doi:10.1016/j.jep.2004.10.009
Wong JH, Wang HX, Ng TB (2008) Marmorin, a new ribosome inactivating protein with antiproliferative and HIV-1 reverse transcriptase inhibitory activities from the mushroom *Hypsizigus marmoreus*. Appl Microbiol Biotechnol 81(4):669–674
Wong JH, Ng TB, Wang H et al (2011) Cordymin, an antifungal peptide from the medicinal fungus *Cordyceps militaris*. Phytomed 18(5):387–392. doi:10.1016/j.phymed.2010.07.010
Wu DM, Duan WQ, Liu Y et al (2010) Anti-inflammatory effect of the polysaccharides of golden needle mushroom in burned rats. J Biol Macromol 46(1):100–103. doi:10.1016/j.ijbiomac.2009.10.013
Wu S, Zhong J, Zhu J et al (2013) *Phellinus linteus* polysaccharides and their immunomodulatory properties in human monocytic cells. J Funct Food 5(2):679–688. doi:10.1016/j.jff.2013.01.011
Xu T, Beelman RB (2015) The bioactive compounds in medicinal mushrooms have potential protective effects against neurodegenerative diseases. Adv Food Technol Nutr Sci Open J 1(2):62–65. doi:10.17140/AFTNSOJ-1-110
Xu YN, Zhong JJ (2012) Impacts of calcium signal transduction on the fermentation production of antitumor ganoderic acids by medicinal mushroom *Ganoderma lucidum*. Biotechnol Adv 30:1301–1308. doi:10.1016/j.biotechadv.2011.10.001
Xu JW, Zhao W, Zhong JJ (2010) Biotechnological production and application of ganoderic acids. Appl Microbiol Biotechnol 87:457–466. doi:10.1007/s00253-010-2576-5
Yagi K (1970) A rapid method for evaluation of oxidation and antioxidants. Agric Biol Chem 34(1):142–145
Yang BK (2007) Chemical characteristics and immune-modulating activities of exo-bio polymers produced by *Grifola frondosa* during submerged fermentation process. Int J Biol Macromol 41(3):327–333. doi:10.1016/j.ijbiomac.2007.02.012
Yin H, Wang Y, Wang Y et al (2010) Purification, characterization and immunomodulating properties of polysaccharides isolated from *Flammulina velutipes* mycelium. Am J Chin Med 38(01):191–204. doi:10.1142/S0192415X10007750
Yoshino K, Nishimura M, Watanabe A et al (2008) Preventive effects of edible mushroom (*Hypsizigus marmoreus*) on mouse type IV allergy: Fluctuations of cytokine levels and antioxidant activities in mouse Sera. J Food Chem Toxic 3(3):21–27. doi:10.1111/j.1750-3841.2008.00664.x
Yuswan MHMY, Al-Obaidi JR, Rahayu A (2015) New bioactive molecules with potential antioxidant activity from various extracts of wild edible Gelam mushroom (*Boletus spp*.). Adv Biosci Biotechnol 6:320–329. doi:10.4236/abb.2015.64031
Zhang Mills GL, Nair MG (2003) Cyclooxygenase inhibitory and antioxidant compounds from the fruiting body of an edible mushroom, *Agrocybe aegerita*. Phytomed 10(5):386–390. doi:10.1078/0944-7113-00272
Zhang DW, Zhao L, Wu TX (2007) Optimization of *Auricularia Auricula* exopolysaccharide fermentation medium by orthogonal experiment design. J Guizhou Univ Technol (Nat Sci Ed) 36:40–43
Zhang GQ, Sun J, Wang HX (2009) A novel lectin with antiproliferative activity from the medicinal mushroom *Pholiota adiposa*. Acta Biochim Pol 56(3):415–421
Zhang G, Sun J, Wang H et al (2010a) First isolation and characterization of a novel lectin with potent antitumor activity from a *Russula* mushroom. Phytomedicine 17(10):775–781. doi:10.1016/j.phymed.2010.02.001

Zhang GQ, Wang YF, Zhang XQ et al (2010b) Purification and characterization of a novel laccase from the edible mushroom *Clitocybe maxima*. Process Biochem 45(5):627–633. doi:10.1016/j.procbio.2009.12.010

Zheng Y, Yang XW (2008a) Poriacosones A and B: two new lanostane triterpenoids from *Poria cocos*. J Asian Nat Prod Res 10:645–651

Zheng Y, Yang XW (2008b) Two new lanostane triterpenoids from *Poria cocos*. J Asian Nat Prod Res 10:323–328

Zheng SY, Liu QH, Zhang GQ et al (2010) Purification and characterization of an antibacterial protein from dried fruiting bodies of the wild mushroom *Clitocybe sinopica*. Acta Biochim Pol 57(1):43–48