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Mycochemicals in wild and cultivated mushrooms: nutrition and health

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Abstract The mushrooms have contributed to the development of active ingredients of fundamental importance in the field of pharmaceutical chemistry as well as of important tools in human and animal health, nutrition, and functional food. This review considers studies on the beneficial effects of medicinal mushrooms on the nutrition and health of humans and farm animals. An overview of the chemical structure and composition of mycochemicals is presented in this review with particular reference to phenolic compounds, triterpenoids and sterols, fatty acids and lipids, polysaccharides, proteins, peptides, and lectins. The nutritional value and chemical composition of wild and cultivated mushrooms in Italy is also the subject of this review which also deals with mushrooms as nutraceuticals and the use of mushrooms in functional foods. The nutraceutical benefits of UV irradiation of cultivated species of basidiomycetes to generate high amounts of vitamin D2 is also highlighted and the ability of the muhsrooms to inhibit glycation is analyzed. Finally, attention is paid to studies on bioactivities of some Italian wild and cultivated mushrooms with particular reference to species belonging to the genus *Pleurotus*. The review highlights the potential of medicinal mushrooms in the production of mycochemicals that represent a source of drugs, nutraceutical, and functional food.

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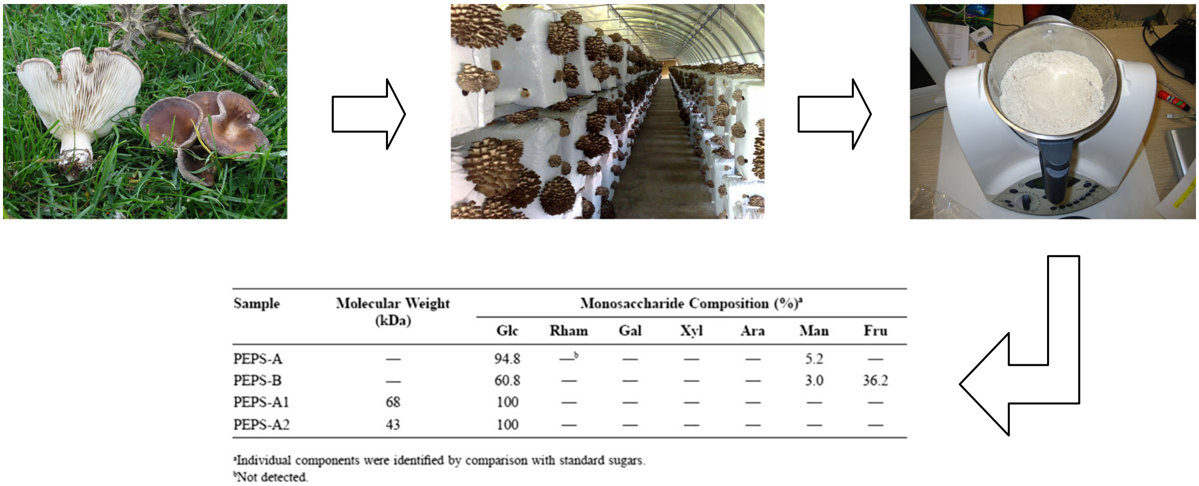
Graphic abstract



Sample	Molecular Weight (kDa)	Monosaccharide Composition (%)[a]						
		Glc	Rham	Gal	Xyl	Ara	Man	Fru
PEPS-A	—	94.8	—[b]	—	—	—	5.2	—
PEPS-B	—	60.8	—	—	—	—	3.0	36.2
PEPS-A1	68	100	—	—	—	—	—	—
PEPS-A2	43	100	—	—	—	—	—	—

[a]Individual components were identified by comparison with standard sugars.
[b]Not detected.

Keywords Fungal diversity · Cultivation · Mycochemicals · Chemical structures · Nutrition

Abbreviations

AGLs	Acidic glycosphingolipids
BEPF	*Boletus edulis* Polysaccharides
BRMs	Biological response modifiers
CBAEP	Cibacron blue affinity-purified protein
COSY	Correlation spectroscopy
FAB-MS	Fast atom bombardment
FAME	Fatty acid methyl esters
FIP	Immunomodulatory proteins
FT-IR	Fourier-transformed infrared spectroscopy
GC	Gas chromatography
GLC–MS	Gas-liquid chromatography–mass spectrometry
GLS	Glycosphingolipids
GSH	Glutathione peroxidase
HBA	Hydroxybenzoic acid
HCA	Hydroxycinnamic acid
HIV	Human immunodeficiency viruses
HMBC	Heteronuclear multiple bond coherence
HMG-CoA	β-Hydroxy β-methylglutaryl-CoA
HMQC	Heteronuclear multiple quantum coherence
HPLC–MS	Liquid chromatography–mass spectrometry
HS-ITEX/GC-MS	Head Space “In Tube Extraction” Technique and gas chromatography
IEC	Ion-exchange chromatography
iNKT	Invariant natural killer cell
LCB	Long-chain base
LDG-M	*Lactarius deliciosus* Polysaccharides
MHS-SPME	Multiple headspace-solid phase microextraction
MIC	Minimum inhibitory concentration
MM	Medicinal mushrooms
MUFA	Monounsatured fatty acid
NMR	Nuclear magnetic resonance
NOESY	Nuclear overhauser effect spectroscopy
OMW	Olive mill wastewaters
PELPS	*Pleurotus eryngii* var. *elaeoselini* polysaccharides
PEPE	*Pleurotus eryngii* Purified polysaccharides
PSK	Polysaccharide K
PSP	Polysaccharide peptide
PUFA	Polyunsaturated fatty acid
ROESY	Rotating-frame nuclear overhauser effect correlation spectroscopy
RVP	*Russula virescens* Polysaccharide
SEC	Size-exclusion chromatograpy
SFA	Saturated fatty acid
SPG	Schizophyllan
TLC	Thin layer chromatography
TOCSY	Total correlation spectroscopy

TPC	Total phenolic content
VOC	Volatile organic compounds

Introduction

Definition of mycochemicals

For millennia, mushrooms were well known as a nutritional and pharmaceutical resource especially in traditional oriental therapies, but after the discovery of Penicillin (Fleming 1929), they became a prominent source of natural antibiotics and other bioactive compounds.

The subject of mycochemistry, has developed as a distinct discipline that is concerned with the enormous variety of chemical substances, named "mycochemicals", elaborated and accumulated by mushrooms. It deals with the isolation and structure elucidation of the chemical structures of these substances, their biosynthesis, metabolism, turnover, their natural distribution, and their biological properties (Dewick 2009).

The mycochemicals play an important role in human and animals health, nutrition, and as functional food (Scheme 1).

Obviously, in all these applications, methods are needed for separation, and identification of the many different mycochemicals present in mushrooms. Thus, advances in our understanding of mycochemistry are directly related to the application of known techniques together with the continuing development of new analytical techniques to solve outstanding problems as they appear (Ruthes et al. 2015).

The characterization of mycochemicals is carried out using one or other, or a combination, of different chromatographic techniques that include thin layer chromatography (TLC), gas and/or liquid chromatography (CC, GC, HPLC). FT-IR, mass spectrometry and NMR experiments [1D ^{1}H, ^{13}C NMR and 2D NMR (H–H COSY, TOCSY, HMQC, HMBC and NOESY)] are useful in providing information for the mycochemical structural elucidation.

Beneficial effects of mushrooms on human and animals health and their nutrition

The use of mushrooms in Chinese folk medicine and the Eastern countries has been known for a long time while only in recent decades, especially in Europe, there has been interesting in studies on their effects on human health (Wasser 2014; Gründemann et al. 2020). Moreover, the consumer's attention is increasingly shifting to the role that adding mushrooms to the diet can promote health and prevent the risk of disease, thanks to the effects of bioactive compounds on the human body.

In Asian countries, mushrooms have always been a primary source of food and medicine, due to the benefits they bring to physical well-being in general and the preventive and curative effects on various diseases such as cancer, cardiovascular diseases,

Scheme 1 The role of mycochemicals. Partially modified from www.dreamstime.com

hypertension, neuropathies, etc. Numerous studies carried out in Asian countries, and more recently also in Europe, have demonstrated the multiple effects that the different chemical components of mushrooms have on the organism, not only humans but also animals. As reported by Fernandes et al. (2015) and Cheung (2013), dietary fiber of mushrooms helps to prevent constipation, hemorrhoids, colon diseases, diabetes, and cardiovascular diseases, improves intestinal tract function and insulin and cholesterol metabolism. It also strengthens the immune system and has anti-tumor activity. But the bioactive compounds in mushrooms are numerous and varied, as well as their possible uses. Wasser (2014) suggested medicinal mushroom drugs (MM drugs) in immunosuppressed patients.

The antitumor MM drugs, called biological response modifiers (BRMs), are used in different types of cancer and patients undergoing chemo- and radiotherapy, improving their quality of life as they reduce side effects and help overcome cancer growth. To date, several MM products have been developed for therapeutic and commercial purposes, especially from species widespread and used in the East. The most important polysaccharides which characterize mushroom extracts are Lentinan, isolated from *Lentinula edodes* (Berk.) Pegler, Schizopyllan (Sonifilan, Sizofiran, or SPG) from *Schizophyllum commune* Fr., Ganoderan from *Ganoderma lucidum* (Curtis) P. Karst., Krestin (PSK), and PSP (polysaccharide peptide) from *Trametes versicolor* (L.) Lloyd, Grifolan from *Grifola frondosa* (Dicks.) Gray, Befungin from *Inonotus obliquus* (Fr.) Pilát, and Imunoglukan P4H (pleuran) from *Pleurotus ostreatus* (Jacq.) P. Kumm. (Giavasis 2014; Wasser 2014).

The daily intake of MM as part of a healthy diet also produces beneficial effects. Food supplements such as fruit bodies powders and extracts; biomass or extracts from mycelium harvested from a submerged liquid culture in fermentation tanks or bioreactors; dried and pulverized preparations of the combined substrate, mycelium, and mushroom primordial; spores and their extracts; dried mushrooms in tablets or pills are available on the market (Wasser 2014; Reis et al. 2017).

Mushroom bioactive compounds have an enormous potential for use as performance-enhancing natural additives for livestock animals. A survey, carried out by Bonanno et al. (2019), reveals how the integration in the diet of dairy ewes of mushroom myceliated grains (a mixing of *L. edodes*, *Cordyceps* spp., *G. lucidum*, *P. ostreatus*) improves production both in terms of quantity, with a higher milk yield, and quality (less intense yellow colour of cheese, lower secondary lipid oxidation, greater oxidative stability and antioxidant content of the cheese). Bederska-Łojewska et al. (2017) showed how adding edible Basidiomycetes to feed improves the productive and physiological performance of broiler chickens and laying hen. Considerable benefits are also obtained from by-products of mushroom production, which are also rich in interesting bioactive compounds for the production of beneficial animal feed, fertilizers, cosmetics, and cosmeceuticals. (He et al. 2016; Taofiq et al. 2016; Antunes et al. 2020).

Mycochemicals structures and composition

Several mycochemicals are present in mushrooms with different chemical structures and composition such as phenolic compounds, terpenoids, lipids, polysaccharides and proteins, which are easily separated from other constituents by their high molecular weights.

Phenolic compounds

The term ’phenolic compounds’ includes a wide range of mycochemicals that are characterized by an aromatic ring bearing one or more hydroxyl groups. Phenolic substances are water-soluble since they most frequently occur in combination with sugar as glycosides, but also as esters and polymers. These compounds belong to different classes based on the number of phenol rings and of the functional groups linked to these moieties. Thus, a classification comprises simple phenols, phenolic acids, phenylpropanoids, flavonoids, flavonols, flavones, stilbenes, and lignans.

Phenolic acids are the main phenolic substances found in mushrooms (Ferreira et al. 2009); they are classified into two groups; hydroxybenzoic acid (HBA) and hydroxycinnamic acid (HCA). Hydroxybenzoic acid derivatives are in the bound form and are part of more complex structures as hydrolyzable tannins, lignins, sugars and organic acids. Hydroxycinnamic acid derivatives are also present mainly in the bound form, attached to cell-wall structural elements, such as lignin, cellulose, proteins or linked to organic acids, through ester bonds, such as quinic or tartaric acids (Manach et al. 2004). The most widespread are the HCAs, which are useful not only as providing the building blocks of lignin but also concerning disease resistance and growth regulation. Five HCAs are common, in fact almost ubiquitous in mushrooms: ferulic, sinapic, caffeic, and *p*-/*o*-coumaric acids. HCAs usually are present in mushrooms in combined form as esters; and they are obtained in best yield by mild alkaline hydrolysis, since with hot acid hydrolysis material is lost for the decarboxylation to the corresponding hydroxystirenes.

Caffeic acid occurs in mushrooms regularly as a quinic acid ester (3-*o*-caffeoylquinic, 4-*o*-caffeoylquinic, 5-*o*-caffeoylquinic). Besides, tannic and ellagic acids are observed (Ferreira et al. 2009). In mushrooms, the most prevalent HBAs derivatives are reported to be gallic, protocatechuic, gentisic, homogentisic, *p*-hydroxybenzoic, 5-sulphosalicylic, syringic, veratric, vanillic (Ferreira et al. 2009) (Table 1).

HBA and HCA compounds are derived biosynthetically from the shikimate pathway. L-phenylalanine and -tyrosine are the crucial amino acids and the building blocks in this pathway.

Flavonoids are another large group of naturally occurring phenolic compounds that are all structurally derived from the parent substance flavone consisting of two benzene rings (A and B) combined with a pyran one (C). Different classes of flavonoids are recognized, such as anthocyanidins, flavonols, flavones, isoflavones, flavanones, and flavonols (Manach et al. 2004). The flavonoids are present in nature as glycosides or aglycones.

It was reported that mushrooms do not synthesize flavonoids, however, the presence of flavonoids was found in various edible mushrooms, e.g. catechin, myricetin, chrysin, hesperetin, naringenin, naringin, formometin, biochanin, resveratrol, quercetin, pyrogallol, rutin, and kaempferol (Gil-Ramirez et al. 2016; Ferreira et al. 2009).

Phenolic acids and flavonoids identification and quantification from some selected mushrooms [*P. ostreatus*, *P. eryngii* (DC.) Quél., *Agaricus bisporus* (J.E. Lange) Imbach, *Cyclocybe aegerita* (V. Brig.) Vizzini, *Russula cyanoxantha* (Schaeff.) Fr., *R. virescens* (Schaeff.) Fr., *Macrolepiota procera* (Scop.) Singer, *Boletus edulis* Bull., *Lactarius deliciosus* (L.) Gray, *Coprinus comatus* (O.F. Müll.) Pers., *Tuber melanosporum* Vittad.] were done by high-performance liquid chromatography coupled with mass spectrometry (HPLC–MS) (Table 1). The compounds identification derives from their retention times, their UV–Vis absorption spectra and mass spectra data and also by comparison with available data (Fogarasi et al. 2018). 4-Hydroxybenzoic acid and 5-feruloylquinic acid were found to be the major compounds in *P. ostreatus* and *A. bisporus* with concentrations of 75.042 mg/100 g·fw and 35.040 mg/100 g·fw for *P. ostreatus* and 79.50 mg/100 g·fw and 71.01 mg/100 g·fw for *A. bisporus*, respectively. *B. edulis* extract is characterized by high concentrations of cinnamic acid 168.614 mg/100 g·fw and catechin 145.566 mg/100 g·fw (Fogarasi et al. 2018). Hasnat et al. (2014) reported content of phenolic compounds for *R. virescens* of 8.74 and 2.21 mg gallic acid/100 g·fw, and flavonoid compounds were 2.83 and 1.02 mg catechin/100 g·fw for the water and ethanol extracts, respectively.

Among phenolic acids, the major amount of protacatechuic acid was found in *M. procera* (5.19 mg/Kg DW) (Nowacka et al. 2014). Kalogeropoulos et al. evaluated the content of individual phenolic compounds for *L. deliciosus*; *p*-OH-benzoic acid (24.5 µg/100 g fw) and *p*-OH-phenylacetic acid (18.3 µg/100 g fw) were the more abundant among the hydroxyl-benzoic acids, *o*-coumaric acid (30.2 µg/100 g fw) among the hydroxycinnamic acids, and chrysin (16.5 µg/100 g fw) among the flavonoids.

As concerns *C. comatus*, among the phenolic compounds, the highest content was detected for quinic acid (14.6 mg/100 g dw) and quercetin (3.01 mg/100 g fw), where the lowest amount was detected for the isoflavonoids genistein (0.023 mg/100 g dw) and daidzein (0.061 mg/100 g dw) (Nowakowski et al. 2020). Besides, Comatin (4, 5-Dihydroxy-2-methoxy-benzaldehyde) isolated and identified from *C. comatus* has shown hypoglycaemic properties on alloxan-induced-diabetic rats (Ding et al. 2010) (Table1).

In the literature, it is common to find the total phenolic content (TPC) found in mushrooms methanolic extract by the Folin-Ciocalteu assay. However, this assay has some limitations since other readily oxidized compounds such as amino acids, ascorbic acid, and sugars could interfere overestimating the total phenolic content (Arbaayah and Umi 2013).

Phenolic compounds possess antioxidant properties to scavenge free radicals, to prevent lipid peroxidation, and to chelate ferrous ions (Kumar and Pandey 2013).

Table 1 Phenolic compounds of some selected mushrooms species

Mushroom species	Phenolic compounds	References
Pleurotus ostreatus	4-HBA, 2,4-dihydroxybenzoic acid, 4-hydroxy phenylacetic acid, pirocatechuic acid, protocatechuic acid, catechin, gallocatechin, *o*-coumaric acid, cinnamic acid, 5-feruloylquinic acid, 3,5-dicaffeoylquinic acid, chlorogenic acid, syringic acid, vanillic acid, caffeic acid, ferulic acid, 2,6-dimethoxyphenol	Sarma et al. (2018), Fogarasi et al. (2018), Koutrotsios et al. (2017) and Palacios et al. (2011)
Pleurotus eryngii	4-HBA, *p*-coumaric acid, cinnamic acid, protocatechuic acid, gallic acid, phenol	Souilem et al. (2017) and Reis et al. (2012)
Pleurotus cornucopiae	Gallic acid, protocatechuic acid, chlorogenic acid, vanillin, ferulic acid, naringin, naringenin, hesperitin, formononetin, biochanin-A	Nuhu et al. (2011)
Agaricus bisporus	4-HBA, 2,4-dihydroxybenzoic acid, 4-hydroxy phenylacetic acid, protocatechuic acid, catechin, gallocatechin, *p*-hydroxybenzaldehyde, *p*-aminophenol, catechol, coumaric acid, cinnamic acid, 4- and 5-feruloylquinic acid, 3,5-dicaffeoylquinic acid	Weijn et al. (2013), Fogarasi et al. (2018), Palacios et al. (2011)
Cyclocybe aegerita	Protocatechuic acid, 4-HBA, chlorogenic acid, gallic acid, caffeic acid, vanillic acid, *p*-coumaric acid, ferulic acid, sinapic acid, *t*-cinnamic acid, rutin, quercetin, kaempferol	Gasecka et al. (2016)
Russula cyanoxantha	Quercetin, quercetin-3-*o*-rutinoside, catechin, epicatechin	Butkhup et al. (2018)
Russula virescens	Catechin, ferulic acid, kaempferol, luteolin, vanillic acid, apigenin	Hasnat et al. (2014)
Macrolepiota procera	Protocatechuic acid	Nowacka et al. (2014)
Boletus edulis	4-HBA, 2,4-dihydroxybenzoic acid, gallic acid, 4-hydroxy phenylacetic acid, protocatechuic acid, caffeic acid, catechin, chlorogenic acid, gallocatechin, *p*-coumaric acid, sinapic acid, *o*-coumaric acid, cinnamic acid, 3,5-dicaffeoylquinic acid, gentisinic acid, homogentisinic acid, myricetin, protocatechuic acid	Fogarasi et al. (2018) and Palacios et al. (2011)
Lactarius deliciosus	4-HBA, 4-hydroxy phenylacetic acid, 3,4-dihydroxy phenylacetic acid, syringic acid, vanillic acid, caffeic acid, cinnamic acid, chlorogenic acid, ferulic acid, *o*-coumaric acid, *p*-coumaric acid, tyrosol, vanillin, chrysin, kaempferol, resveratrol, gallic acid, gentisinic acid, homogentisinic acid, myricetin, protocatechuic acid, pyrogallol	Kalogeropoulos et al. (2013) and Palacios et al. (2011)
Coprinus comatus	Flavones, flavonols, flavanones, flavanols, biflavonoids, isoflavonoids, hydroxybenzoic acids, hydroxycinnamic acids, coumarins, chlorogenic acids	Nowakowski et al. (2020) and Cayan et al. (2018)
	4,5-Dihydroxy-2-methoxy-benzaldehyde (comatin)	Ding et al. (2010)
Tuber melanosporum	Homogentisic acid, 4-HBA, 3,4-dihydroxybenzaldehyde	Villares et al. (2012)
	Flavonoids, phenols	Li et al. (2019)

Terpenoids

The general term ’terpenoid’ includes all such substances with a common biosynthetic origin. Terpenoids arise from the isoprene molecule $CH_2=C(CH_3)-CH=CH_2$ and their carbon skeletons originate from the union of two or more of these C5 units. Their classification is according to whether they contain two (C_{10}), three (C_{15}), four (C_{20}), six (C_{30}), or eight (C_{40}) such unit. Essential oils, volatile mono- and sesquiterpenes (C_{10} and C_{15}), including the less volatile diterpenes (C_{20}), the involatile triterpenoids and sterols (C_{30}), and the carotenoids pigments (C_{40}) are terpenoids. Each of these different classes of terpenoid is of importance in mushroom growth, metabolism, or ecology (Dewick 2009).

Chemically, terpenoids are generally lipid-soluble and are extracted from mushrooms with dichloromethane, light petroleum, or ether and can be separated by flash chromatography on silica gel or alumina using some solvents. Isomerism and the presence of different geometric conformations are common among terpenoids. It depends on the substitution around the cyclohexane ring, twisted in the so-called ‘chair’ form. The stereochemistry of the cyclic terpenoids is highly involved. During purification procedures, structural re-arrangement and isomerization may occur and lead to artifact formation.

Essential oils.

The mainly terpenoid essential oils include the volatile fraction responsible for the characteristic odor and scent found in many mushrooms. They are commercially important as the basis of skincare in cosmetics and flavorings in the food industry. Fogarasi et al. (2018) reported the presence of α-pinene, β-phellandrene, β-pinene, β-myrcene, and D-limonene in *A. bisporus* and *B. edulis* as main terpenoids. The in-tube extraction headspace coupled with gas chromatography-mass spectrometry (HS-ITEX/GC–MS) permits to obtain the volatile profile of selected mushrooms. The volatile constituents strongly influence the aroma profile of each mushroom variety.

Triterpenoids and sterols

Triterpenoids are compounds with a carbon skeleton based on six isoprene units. They biosynthetically derived from squalene, an acyclic C10 hydrocarbon. They have relatively complex cyclic structures, most being either alcohols, aldehydes, or carboxylic acids.

Sterols are triterpenes which are based on the cyclopentane perhydrophenantrene ring system. So, one example is ergosterol, ubiquitous in occurrence in mushrooms. Ergosterol is a component of the fungal cell membrane, which under the influence of UV irradiation is converted to vitamin D_2. Besides, ergosterol shows several healthy beneficial properties such as antihyperlipidemic, anti-inflammatory, antioxidant and the effect for inhibiting fungi and bacteria growth (Koutrotsios et al. 2017).

All types of triterpenoids are isolated by very similar procedures, based mainly on column chromatography, GLC and TLC. Identities are confirmed by melting point, rotation, FT-IR, GLC-MS, and NMR experiments.

Table 2 includes the triterpenoids and sterols found in some selected mushroom species.

Different *P. ostreatus* strains were evaluated for their sterol composition. In all mushroom samples analyzed ergosterol dominated, comprising 51.9–87.4% of sterols, followed by its metabolites ergosta-7-enol (12.7%), ergosta-5,7-dienol (7.6%), and ergosta-7,22-dienol (6%) (Koutrotsios et al. 2017). The ergosterol content in *P. eryngii* was reported as 20 mg/100 g dw, although a higher value was measured in commercial samples (Souilem et al. 2017). Kikuchi et al. (2017, 2018) reported the isolation and structure elucidation of ergostane type sterols and bisabolane-type sesquiterpenes from *P. eryngii* with aromatase and nitric oxide production inhibitory effects, respectively (Table 2).

Wang et al. (2013a) reported the identification of novel and rare perhydrobenzannulated 5,5-spiroketal sesquiterpenes, named pleurospiroketals A-E from the edible mushroom *P. cornucopiae* with inhibitory activity against nitric oxide production in lipopolysaccharide-activated macrophages with IC_{50} values between 6.8–20.8 µM.

From *M. procera* were isolated and identified 12 lanostane-type triterpenoids characterized by the presence of a rare ’1-en-1,11-epoxy’ moiety, namely lepiotaprocerins A-L. Lepiotaprocerins A-F showed significant inhibitions of nitric oxide (NO) production, while lepiotaprocerins G-L, showed cytotoxicity effects against different human cancer cell lines, and lepiotaprocerin I displayed antitubercular activity

Table 2 Triterpenoids of some selected mushrooms species

Mushrooms species	Triterpenoids	References
Pleurotus ostreatus	Ergosterol, ergosta-5,7-dienol, ergosta-7-enol, ergosta-7,22-dienol, oleanolic acid, ursolic acid	Sarma et al. (2018) and Koutrotsios et al. (2017)
Pleurotus eryngii	Ergosterol	Souilem et al. (2017)
	Ergostane-type sterols	Kikuchi et al. (2017)
	Strophasterols E and F	Kikuchi et al. (2019)
	Bisabolane-type sesquiterpenes	Kikuchi et al. (2018)
	Eryngiolide A, pentacyclic triterpenoids	Fu et al. (2016)
Pleurotus cornucopiae	Ergosterol, Ergosta-5,8,22-trien-3-ol, 5,6-Dihydro-ergosterol, Ergosta-7-enol, Ergosta-7,22-dienol, Ergosta-14,22-dien-3-ol, Campesterol	Parmar and Kumar (2015)
	Pleurospiroketals A-E, Perhydrobenzannulated 5,5-spiroketal sesquiterpenes	Wang et al. (2013a)
	Monoterpenoids, sesquiterpenoids	Wang et al. (2013b)
	Ergostane-type sterols	Lee et al. (2017)
Agaricus bisporus	Ergosterol	Alshammaaa (2017)
	Terpenoid spiro ketals	Grothe et al. (2013)
Cyclocybe aegerita	Bovistols A-C, Protoilludane Pasteurestin C	Surup et al. (2019)
Russula cyanoxantha	Ergosta-4,6,8(14),22-tetraen-3-one	Zhao et al. (2011)
Macrolepiota procera	Lanostane triterpenoids (Lepiotaprocerins A-L)	Chen et al. (2018)
Boletus edulis	Botryane sesquiterpenoids (Boledulins A-C)	Feng et al. (2011)
Lactarius deliciosus	Ergosterol, Ergosta-5,7-dienol, Ergosta-7-enol, Ergosta-7,22-dienol, Lanosterol, Lanosta-8,24-dienol, 4α-Methylzymosterol	Kalogeropoulos et al. (2013)
	Azulene-type sesquiterpenoids	Tala et al. (2017)
Coprinus comatus	Terpenoids	Dulay et al. (2015)
Tuber magnatum	Ergosterol, Ergosta-7,22-dienol, Ergosta-5,8-dien-3-ol, Brassicasterol, 5-Dihydroergosterol, Campe-sterol, 24(28)-Dehydroergosterol, Barrigenol R1, Fungisterol, Lanosterol, Dehydroepiandrosterone	Tejedor-Calvo et al. (2020) and Yeh et al. (2016)
Tuber melanosporum	Ergosterol, Ergosta-7,22-dienol, Brassicasterol, 5-Dihydroergosterol, Campesterol, 24(28)-Dehydroergosterol, Barrigenol R1, Fungisterol, Lanosterol, β-Sitosterol, Dehydroepiandrosterone	Tejedor-Calvo et al. (2020) and Yeh et al. (2016)
Tuber borchii	Ergosterol, Ergosta-7,22-dienol, Brassicasterol, Campesterol, 24(28)-Dehydroergosterol, Dehydroepiandrosterone	Tejedor-Calvo et al. (2020) and Yeh et al. (2016)

against *Mycobacterium tuberculosis* H37Ra with a MIC of 50 µg/mL (Chen et al. 2018).

Three non-isoprenoid botryane sesquiterpenoids, named boledulins A-C were isolated from the cultures of *B. edulis* Bull. with moderate inhibitory activity against five human cancer cell lines (Feng et al. 2011), while from the edible mushroom *L. deliciosus*, azulene-type sesquiterpenoids were characterized (Tala et al. 2017).

Many sterols such as campesterol, lanosterol, brassicasterol, β-sitosterol, ergosterol were analyzed in the fruiting bodies of different *Tuber* species

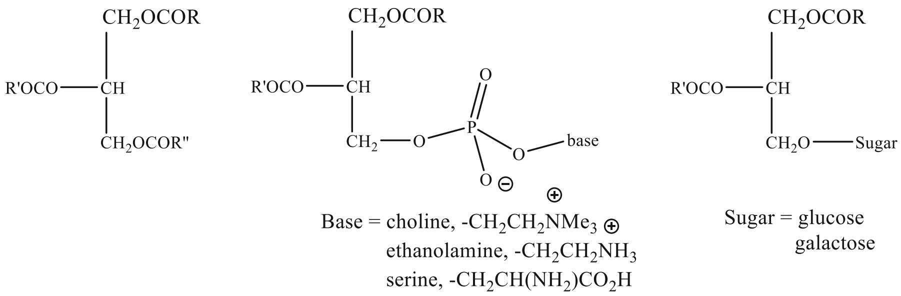


Fig. 1 Chemical structures of mushroom lipids

(R, R', R" = Hydrocarbon chains of different fatty acids)

(Table 2). The main sterols found in *Tuber magnatum* Picco and *T. melanosporum* fruiting bodies were ergosterol and brassicasterol, which amounted to 63.1–66.7% and 15.7–21.3% of the total sterols, respectively. Also the mycelia of *T. borchii* Vittad. are a rich source of ergosterol (90.3%). The complex composition profile of the truffle sterols might be taken as the fingerprint for the identification of the truffle species (Yeh et al. 2016).

Fatty acids and lipids

Mushrooms are an essential source of fatty acids that occur mainly in bound form, esterified to glycerol, as fats or lipids. They are crucial as membrane constituents in the mitochondria and chloroplasts and provide mushrooms with a storage form of energy. The content of total lipids ranges mostly from 1 to 4% of the dry weight. Besides, mushroom fats are rich in unsaturated fatty acids (PUFA) and particularly in linoleic acid (Koutrotsios et al. 2017).

Lipids are known by their distinct solubility properties and are extracted with alcohol, ether or dichloromethane from mushrooms.

The general structures for the three main classes of mushrooms lipids are reported in Fig. 1.

Structural variation within each class is due to the different fatty acid residues that may be present. The identification of lipids mainly requires the determination of their fatty acid components. Fatty acids are determined as methyl esters (FAMEs) after hot saponification of the sample, followed by reaction with BF_3/MeOH. The resulting FAMEs are analyzed by GC–MS by comparison with standard FAMEs and confirmed utilizing mass spectra library (Helrich 1990).

In some selected mushrooms species, the fatty acid composition is characterized by a prevalence of polyunsaturated linoleic acid (C18:2ω6), monounsaturated oleic acid (C18:1ω9), and saturated palmitic acid (C16:0) (Table 3). The fatty acids are divided into saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA). In particular, the ratio between the single components of PUFA is fundamental in preventing cardiovascular diseases. PUFAs are a family of so-called 'essential' fatty acids that are converted to tissue hormones useful to prevent blood clotting and hypertension (Pietrzak-Fiećko et al. 2016).

Koutrotsios et al. (2017) evaluated the fatty acid profile of different *P. ostreatus* strains, collected in Greece, including saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), ω3 and ω6 fatty acids. PUFA was the major fatty acid class detected; linoleic acid (C18:2ω6) dominated in all samples (56.8–80.5%) followed by oleic (C18:1ω9) and palmitic (C16:0) (6.3–19.5 and 7.5–12.1%, respectively) (Table 3).

Jing et al. (2012) reported a selective method where fatty acids from cultivated mushrooms *P. eryngii*, *C. aegerita* and *C. comatus* were derivatized with BAETS as the labeling reagent and identified by high-performance liquid chromatography with fluorescence detection and online mass spectrometry (HPLC-FLD-MS/MS).

Total fatty acids (TFAs) values for *P. eryngii*, *C. aegerita* and *C. comatus* (dw) were 42.60, 48.95, and 79.21 mg 10 g^{-1}, respectively, while UFA:SFA ratio were 3.23, 3.29, and 3.03, respectively. Linoleic (C18:2ω6) and oleic (C18:1ω9) acids were the main FA found and their content was between 27.17–49.34 mg 10 g^{-1} and 4.08–22.15 mg 10 g^{-1}, respectively.

Table 3 Fatty acids of some selected mushrooms species

Mushrooms species	Fatty acids	References
Pleurotus ostreatus	SFA, MUFA, PUFA, n − 6, n − 3	Koutrotsios et al. (2017) and Fogarasi et al. (2018)
Pleurotus eryngii	SFA (C10:0, C11:0, C12:0, C13:0, C14:0, C15:0, C16:0, C17:0, C18:0, C19:0, C20:0, C21:0, C22:0), MUFA (C16:1ω7, C16:1ω9, C18:1ω9), PUFA (C18:2ω6, C18:3ω3, C20:4ω6, C22:6ω3)	Jing et al. (2012) and Rodrigues et al. (2015)
Pleurotus cornucopiae	SFA (C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C24:0), MUFA (C16:1ω7, C16:1ω9, C18:1ω9), PUFA (C18:2ω6, C18:3ω3, C20:4ω6, C22:6ω3)	Rodrigues et al. (2015)
Agaricus bisporus	SFA, MUFA, PUFA, C16:1ω7, C16:0, C18:0, C18:1ω9, C18:2ω6, C20:0	Sande et al. (2019) and Fogarasi et al. (2018)
Cyclocybe aegerita	SFA (C10:0, C11:0, C12:0, C13:0, C14:0, C15:0, C16:0, C17:0, C18:0, C19:0, C20:0, C21:0, C22:0), MUFA (C16:1ω7, C16:1ω9, C18:1ω9), PUFA (C18:2ω6, C18:3ω3, C20:4ω6, C22:6ω3)	Jing et al. (2012)
Russula cyanoxantha	SFA (C6:0, C8:0, C10:0, C12:0, C13:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C21:0, C22:0, C23:0, C24:0), MUFA (C16:1, C18:1ω9, C20:1, C24:1), PUFA (C18:2ω6, C18:3ω3, C20:2, C20:3ω3, C20:5ω3)	Grangeia et al. (2011)
Russula virescens	SFA (C16:0, C18:0), MUFA (C18:1ω9), PUFA (C18:2ω6)	Leal et al. (2013)
Macrolepiota procera	SFA (C16:0, C18:0), MUFA (C18:1ω9), PUFA (C18:2ω6)	Yilmaz et al. (2013)
Boletus edulis	SFA (C6:0, C8:0, C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, C23:0, C24:0), MUFA (C16:1, C17:1, C18:1ω9, C20:1, C22:1ω9, C24:1), PUFA (C18:2ω6, C18:3ω3, C18:3ω6, C20:2, C20:4ω6, C20:3ω3 + C21:0, C20:5ω3)	Heleno et al. (2011) and Pietrzak-Fiećko et al. (2016)
Lactarius deliciosus	SFA (C10:0, C11:0, C12:0, C13:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C21:0, C23:0, C24:0), MUFA (C16:1ω9, C16:1ω7, C18:1ω9, C20:1ω9), PUFA (C18:2ω6, C18:3ω3, C20:2ω6, C20:3ω6, C20:4ω6 + C22:0, C20:3ω6, C20:5ω3, C22:2ω6)	Kalogeropoulos et al. (2013) and Ergönül et al. (2012)
Coprinus comatus	SFA (C10:0, C11:0, C12:0, C13:0, C14:0, C15:0, C16:0, C17:0, C18:0, C19:0, C20:0, C21:0, C22:0), MUFA (C16:1ω7, C16:1ω9, C18:1ω9), PUFA (C18:2ω6, C18:3ω3, C20:4ω6, C22:6ω3)	Jing et al. (2012) and Ergönül et al. (2012)
Tuber melanosporum	SFA (C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C21:0, C22:0, C23:0, C24:0), MUFA (C16:1, C17:1, C18:1ω9, C20:1ω9, C22:1ω9, C24:1ω9), PUFA (C18:2ω6, C20:2, C20:4ω6, C22:6ω3)	Jiang et al. (2018)

SFA saturated fatty acids, *MUFA* monounsaturated fatty acids, *PUFA* polyunsaturated fatty acids

Also for *P. cornucopiae* the linoleic acid (C18:2ω9) was the main FA, with a composition characterized by a higher content of mono (MUFA) and polyunsaturated FA (PUFA) than of saturated FA (SFA) (Rodrigues et al. 2015).

The lipids analyzed for *A. bisporus* showed a high content of unsaturated acids with linoleic acid (C18:2ω6) as the main constituent of fruiting bodies (33.3%) and stems (39.4%). The total saturated fatty acid (SFA) content was between 22.1 and 26.5% of total lipids, palmitic acid (C16:0) was the major SFA at about 14% followed by stearic acid (C18:0) at about 4%. Oleic acid (C18:1ω9) was the major monounsaturated fatty acid (MUFA) present at about 1.5% of total lipids (Sande et al. 2019).

As concerns *R. cyanoxantha* the major fatty acid found was linoleic acid (C18:2ω6) (43.65%) followed by oleic acid (C18:1ω9) (28.39%) and palmitic acid (C16:0) (12.95%) (Grangeia et al. 2011).

The fatty acid composition of different wild *Boletus* species collected in Portugal was reported by Heleno et al. (2011). (Table 3). The major fatty acid found in

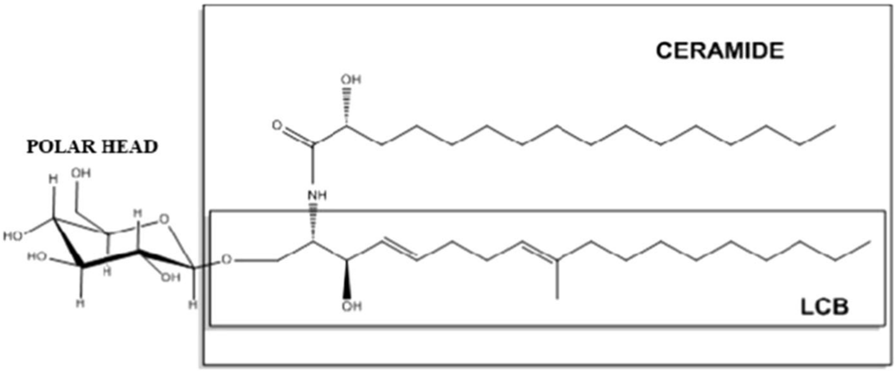


Fig. 2 Chemical structure of mushroom glycosphingolipids

B. *edulis* was oleic acid (C18:1ω9) (42.5%) followed by linoleic acid (C18:2ω6) (41.32%) and palmitic acid (C16:0) (9.57%). A very similar profile of fatty acid composition was reported for 33 samples of wild *B. edulis* in the form of caps and stems, collected from selected regions of Poland. The dominant fatty acids in all samples analyzed were C18:2ω6, C18:1ω9, and C16:0 (Pietrzak-Fiećko et al. 2016).

Kalogeropoulos et al. (2013) reported the fatty acid composition of wild *L. deliciosus* from Greece. The prevalent fatty acids were linoleic acid (C18:2ω6) (31.78%), followed by stearic acid (C18:0) (29.83%) and oleic acid (C18:1ω9) (21.82%) (Table 3).

Another class of lipids found in mushrooms is glycosphingolipids (GLSs) and the cerebrosides in particular. A polar head (usually a monosaccharide or a carbohydrate chain) and a fatty acyl group are linked to a long-chain aminoalcohol called a long-chain base (LCB). The fatty acyl chain is amide-linked to the LCB and together they make up the ceramide; the monosaccharide or oligosaccharide group is linked to the primary alcoholic function of the ceramide (Fig. 2).

GLSs are ubiquitous membrane constituents of mushrooms and are believed to possess a wide range of biological activities, including modulation of growth and regulation of differentiation. They are involved in membrane phenomena, such as cell–cell recognition, cell–cell adhesion, antigenic specificity, and other kinds of transmembrane signaling.

β-Glucosylceramide is by far the most common GLS from mushrooms. A peculiarity of glucosylceramides from mushrooms is the frequent occurrence of a di-unsaturated C_{18} sphingosine with a methyl branching at C-9. Structure determination was based on carbohydrate analysis, methylation analysis, chemical degradation, and extensive use of FAB-MS (Itonori et al. 2004). Three cerebrosides with different lengths of the fatty acid portion have been isolated and identified from *Pleurotus cornucopiae* (Paulet) Rolland (Lee et al. 2017). Furthermore, purified acidic glycosphingolipids (AGLs) from *P. eryngii* were reported to induce interleukin-2 (IL-2) release from invariant natural killer T (iNKT) cells inducing prolonged retention of IL-4 in serum in vitro and in vivo (Fu et al. 2016). So through iNKT cell activation AGLs isolated from *P. eryngii* might be involved in the maintenance of immunohomeostasis.

An important secondary metabolite from mushrooms is lovastatin, a polyketide employed as a cholesterol-lowering drug that inhibits (3*S*)-hydroxy-3-methylglutaryl-coenzyme A (HMG-CoA) reductase. This is a key enzyme in the synthesis of mevalonate, since it is the immediate precursor of cholesterol and lovastatin is the lead compound of all of the drugs classified as statins. Lovastatin was discovered from *Aspergillus terreus* and *Monascus ruber* in the 1970s and is a natural product in oyster mushrooms (Chen et al. 2012) (Fig. 3).

Polysaccharides

Mushrooms are a significative source of polysaccharides. The structural complexity of polysaccharides is ascribed to the linkage between two sugar units, through an ether linkage, in several different ways. The reducing end of one sugar (C1) can condense with any hydroxyl group of a second sugar (at C2, C3, C4, or C6) so that during polymerization some sugars may be substituted in two positions, leading to branched

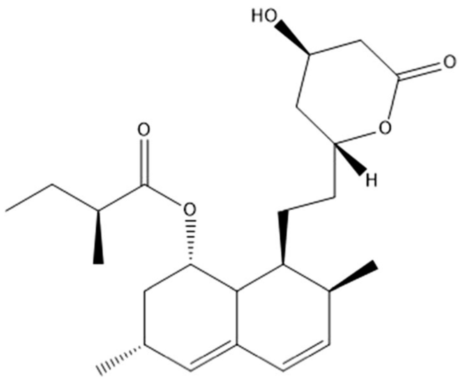


Fig. 3 Chemical structure of lovastatin

chains structures. Besides, the ether linkage can have either a α- or β-configuration, due to the stereochemistry of simple sugars, and both kinds of linkage can co-exist in some molecule.

Generally, the polysaccharides are present in the mushroom cell wall and include α-glucans and β-glucans. These macromolecules are composed of glucopyranose units linked with glycosidic bonds of the type (1 → 6)-β, (1 → 3)-β, or (1 → 3)-α. Mushrooms are characterized by different kinds of polysaccharides that include not only glucans but also heteroglycans and proteoglycan classes. Polysaccharides that include residues of only one type of monosaccharide unit are known as homoglycans, while residues of two or more types of monosaccharide molecules are categorized as heteroglycans (Kozarski et al. 2014).

As concerns, the extraction and purification procedures, usually the polysaccharides are isolated by successive hot-water extractions followed by ethanol precipitation. Chromatographic methods such as size-exclusion (SEC) and ion-exchange chromatography (IEC) are used as purification procedures of the crude polysaccharides, while chemical reactions of hydrolysis and derivatization together with NMR experiments are useful in providing information for their structural elucidation (Sun et al. 2010a).

Polysaccharides isolated and identified from mushrooms differ in their physical–chemical properties such as in their water solubility, molecular weight, size of the molecule, and structure (Table 4). Recently, polysaccharides isolated from mushrooms have attracted increasing attention for their wide spectrum of biological properties, such as antioxidative, antitumor, immunomodulation (BRMs), and anti-inflammatory effects (Selvamani et al. 2018). The major pharmaceutical properties of mushrooms, i.e. antitumor activities and immunity potentiation, are ascribed to β-glucans. Many fungal β-glucans stimulate both innate and adaptive immunity. They activate innate immune system components such as natural killer (NK) cells, neutrophils, macrophages, and cytokines. These cytokines, in turn activate adaptive immunity with the stimulation of B-cell for antibodies production and promotion of T-cell differentiation to T-helper cells, which mediate cell and humoral immunities (Oloke and Adebayo 2015).

Pleuran, a water soluble polysaccharide [β-(1,3/1,6)-D-Glucan], is the best-known β-glucan isolated from *P. ostreatus* with a molecular weight of 762 KD. It is composed of a backbone (1 → 3) linked β-D-glucose with a side chain of a β-(1 → 6) or β-(1 → 4)-D-glucosyl residue of ever fourth glucose unit. The compound exhibit anti-neoplastic properties against different cells, including breast cancer MCF-7, prostate cancer cells PC-3 and colorectal HT-29 cancer cells. It possesses also antiviral and anti-oxidative properties (Golak-Siwulska et al. 2018).

The purified polysaccharides PEPE-A1 and PEPE-A2 from *P. eryngii* are characterized by a β-(1 → 3)-glucan as the backbone accompanied by α-(1 → 6)-D-glucosyl residues side chains. They showed a strong inhibitory effect on lipid accumulation (Fu et al. 2016). Recently, a mannogalactan with the main chain of (1 → 6)-linked-α-D-galactopyranosyl and 3-O-methyl-α-D-galactopyranosyl residues, both partially substituted at OH-2 by β-D-Manp units was isolated from *P. eryngii* and tested against murine melanoma cells (Biscaia et al. 2017).

Zhang et al. (2014) isolated three subfractions of intracellular zinc polysaccharides (IZPS) from *P. cornucopiae*. All the subfractions have shown antioxidant activities in vitro and in vivo. They were found able to act as upregulatation of the superoxide dismutase, GSH peroxidase and catalase, and significantly decreased the contents of malondialdehyde and lipid peroxidation in vivo. PCPS from *P. cornucopiae* mushroom extract is a β-(1 → 6)-glucan possessing a proinflammatory effect on innate immune cells (Minato et al. 2017).

From *A. bisporus* a new heteropolysaccharide consisting of ribose, rhamnose, arabinose, xylose, mannose, glucose, and galactose with 1 → 2 and

Table 4 Polysaccharides of some selected mushrooms species

Mushrooms species	Polysaccharides	References
Pleurotus ostreatus	Pleuran [β-(1,3/1,6)-D-Glucan]	Selvamani et al. (2018)
	α-(1 → 3)-glucans	Golak-Siwulska et al. (2018)
	Mycelium polysaccharides 2 (POMP2), POPS-1	Sarma et al. (2018)
Pleurotus eryngii	PEPE-A1, PEPE-A2	Fu et al. (2016)
	Partially methylated mannogalactan	Biscaia et al. (2017)
Pleurotus cornucopiae	Intracellular zinc polysaccharides (IZPS)	Zhang et al. (2014)
	β-glucan (PCPS) [β-(1 → 6)-Glucan]	Minato et al. (2017)
Agaricus bisporus	β-glucan [β-(1 → 6)-Glucan], mannogalactan	Smiderle et al. (2011)
	Heteropolysaccharide ABP Ia	Liu et al. (2020a, b, c)
Cyclocybe aegerita	Fucogalactan (FG-*Aa*)	Motoshima et al. (2018)
	Ac-MPS, AI-MPS	Jing et al. (2018)
Russula cyanoxantha	β-glucan	Butkhup et al. (2018)
Russula virescens	(1 → 3)-β-D-glucan, RVP	Sun et al. (2010b)
	SRVPs	Li et al. (2020)
Macrolepiota procera	Polysaccharides	Nowak et al. (2018)
Boletus edulis	Polysaccharides (BEBP-1, BEBP-2 and BEBP-3)	Luo et al. (2012)
	Polysaccharids (BEPF30, BEPF60 and BEPF80)	Zhang et al. (2011)
Lactarius deliciosus	Polysaccharide (LDG-M)	Su et al. (2019)
	Polysaccharide (LDG-A)	Hou et al. (2019)
	Polysaccharide (LDG-B)	Hou et al. (2016)
	Polysaccharide (LDGO-A)	Ding et al. (2015)
Coprinus comatus	Modified polysaccharide (MPCC)	Zhao et al. (2019)
	Polysaccharide (CCPP-1)	Liu et al. (2013)
	Polysaccharide (CC30w-1)	Zhou et al. (2013)
Tuber magnatum	(1 → 3)-β-D-glucan	Tejedor-Calvo et al. (2020)
	(1 → 3)-β-D-glucan	Tejedor-Calvo et al. (2020)
Tuber melanosporum	Exo-polysaccharides (TP1, STP1, STP2)	Liu et al. (2020a, b, c)
Tuber borchii	(1 → 3)-β-D-glucan	Tejedor-Calvo et al. (2020)

1 → 4 glycosidic bonds and probably 1 → 3 glycosidic bonds was isolated and identified with high in vitro immunobiological activity (Liu et al. 2020a, b, c).

Motoshima et al. (2018) identified a fucogalactan from *C. aegerita* (FG-Aa) characterized by (1 → 6)-linked α-D-galactopyranosyl main chain, substituted at O-2 by non-reducing end units of α-L-Fucp, on the average of one to every second residue of the backbone. The obtained fucogalactan was evaluated against arginase from *Leishmania amazonensis*.

A water-insoluble (1 → 3)-β-D-Glucan was firstly isolated from the fresh fruiting bodies of *R. virescens*, and then the sulfated derivative was synthesized with sulfur trioxide-pyridine complex. The sulfated derivative exhibited enhanced anti-tumor activities against Sarcoma 180 tumor cell (Li et al. 2020). Besides, a water-soluble poaysaccharide (RVP) with anti-oxidant properties was isolated from the fruiting bodies of *R. virescens* consisting of (1 → 6)-linked-α-D-galactopyranosyl and (1 → 2,6)-linked-α-D-galactopyranosyl residues that terminated in a single non-reducing terminal (1 →)-α-D-mannopyranosyl residue at the O-2 position of each (1 → 2,6)-linked-α-D-galactopyranosyl residues along the backbone (Sun et al. 2010a). Also RVP was sulfated and in vitro activity test data indicated that the SRVPs showed better antioxidant, anticoagulant, antitumor and antibacterial activities compared with RVP.

Three crude polysaccharides (BEPF30, BEPF60, and BEPF80) were isolated from the fruiting bodies of *B. edulis* and investigated for their antioxidant activities. BEPF60 showed significant reducing power and chelating activity together with the highest inhibitory effects on hydroxyl and superoxide radicals (Zhang et al. 2011). Other crude water-soluble polysaccharides (BEBPs) were extracted from *B. edulis* and evaluated for their antioxidant activities. BEBP-3 showed a significant anti-oxidant activity (Luo et al. 2012).

Lactarius deliciosus is an important source of polysaccharides. Su et al. (2019) reported the structural characterization and immune regulation activity of a novel polysaccharide (LDG-M) from *L. deliciosus* Gray. LDG-M was composed of β-D-glucose and α-D-lyxose with ratio 2:1. The proposed structure of LDG-M was a backbone of 1,6-linked-β-D-glucose and 1,4,6-linked-β-D-glucose, with branches composed of one (1 → 4)-linked-α-D-lyxose residue (Table 4). The structural elucidation of LDG-A indicated a backbone of 1,6-disubstituted-α-L-mannopyranose with branches at O-2 mainly composed of a (2 → 3)-α-D-xylopyranose residue. LDG-A exhibited marked antitumor activities in vivo. A new heteropolysaccharide (LDG-B) with a backbone of (1,6)-linked-D-galactose and (1,2,6)-linked-D-galactose with branches composed of 4-linked-D-glucose and 6-linked-D-galactose residue was identified from *L. deliciosus*. Cell cycle test data showed that LDG-B could promote the proliferation of B cells and macrophage cells by affecting G0/G1, S and G2/M phases (Hou et al. 2016). Besides, also the structure elucidation and anti-tumor activity of water-soluble oligosaccharides (LDGO-A) were reported by Ding et al. (2015).

A modified polysaccharide named MPCC was obtained by snailase hydrolysis from *C. comatus* with antioxidant and hepatoprotective properties (Zhao et al. 2019). The structural investigation of CCPP-1 from *C. comatus* has shown that CCPP-1 was α-D-(1 → 4)-glucan with branches at C-6 consisting of non-reducing terminal approximately every fourteen residues. While the crude polysaccharide fractions CCPF showed significant hypoglycemic activity, CCPP-1 was not useful on reducing blood sugar (Liu et al. 2013).

As concerns *Tuber* fruiting bodies and fermentation system, the structure, the physicochemical and biological properties of the polysaccharides have not been thoroughly investigated. Tejedor-Calvo et al. (2020) reported a preliminary screening of the main bioactive compounds for *T. magnatum*, *T. melanosporum* and *T. borchii* by using pressurized liquid extractions (PLE). The polysaccharide composition of the obtained extracts was investigated by NMR analysis and their immunomodulatory activity tested in vitro with cell cultures. NMR investigation revealed that the extracted polysaccharides were β-(1 → 3)-glucans and a heteropolymer consisting of galactose and mannose.

Proteins, peptides and lectins

Other macromolecular mycochemicals isolated from mushrooms with high molecular weight are proteins, peptides, and lectins.

The proteins in mushrooms, as in other plants, are high molecular weight polymers of amino acids. The amino acids are arranged in a particular linear order and each protein has a specific amino acid sequence. Proteins are usually purified according to molecular weight so they are subjected to gel filtration on a column of Sephadex. Separation of proteins by gel electrophoresis is also partly determined by their molecular size since their mobility on the gel is closely related to their charge properties (Oloke and Adebayo 2015).

The composition of mushroom proteins seems to be of higher nutritional value concerning most plant proteins. Mushrooms proteins contain all nine essential amino acids required by humans and can be used as a substitute for meat (Kakon et al. 2012). High contents of proteins 38.9 and 36.9% were observed in *A. bisporus* and *B. edulis*, respectively (Nagy et al. 2017). Mushrooms are a rich source of proteins with several properties for biotechnological and medicinal applications. Immunomodulatory proteins (FIPs) are a group of fungal proteins able to alter the cytokine response (Oloke and Adebayo 2015). Proteins isolated from selected mushrooms exhibited antiviral, antitumor, antifungal, and antibacterial properties (Table 5). Moreover, the fruiting bodies and mycelium of several mushrooms are an abundant source of ergothioneine, an unusual sulfur-containing derivative of histidine, with antioxidant properties (Chen et al. 2012).

Table 5 Proteins, peptides and lectins of some selected mushrooms species

Mushrooms species	Proteins, peptides and lectins	References
Pleurotus ostreatus	Cibacron blue affinity purified protein (CBAEP)	Sarma et al. (2018)
	Pleurostrin	Erjavec et al. (2012)
	Dimeric lectin	Oloke and Adebayo (2015)
	Laccase	Golak-Siwulska et al. (2018)
	Concanavalin A	Sarma et al. (2018)
Pleurotus eryngii	Eryngin	Erjavec et al. (2012)@
	Laccase	Fu et al. (2016)
	Protease (Pleureryn)	Fu et al. (2016)
	PEP 1b	Hu et al. (2018)
Pleurotus cornucopiae	Oligopeptides	Golak-Siwulska et al. (2018)
	Laccase	Wu et al. (2014)
	Lectin (PCL-M)	Oguri (2020)
Agaricus bisporus	Lectin (ABL)	Verma et al. (2019)
	Protein FIIb-1	Verma et al. (2019)
Cyclocybe aegerita	Ribotoxin-like protein (Ageritin)	Citores et al. (2019)
	Lectin (AAL)	Liu et al. (2017)
	Lectin (AAL-2)	Ren et al. (2015)
Russula virescens	Laccase	Zhu et al. (2013)
	Feruloyl esterase (FAE)	Wang et al. (2014b)
Macrolepiota procera	β-Trefoil lectin (MpL)	Žurga et al. (2017)
Boletus edulis	β-Trefoil lectin (BeL)	Žurga et al. (2017)
Lactarius deliciosus	Laccase	Khaund and Joshi (2014)
Coprinus comatus	Protein Y3	Nowakowski et al. (2020)
	Laccases	Nowakowski et al. (2020)
Tuber borchii	Lectin (Cyanovirin-N)	Matei et al. (2011)

Many proteins are also enzymes, catalyzing particular steps in either primary or secondary metabolism, and possess health-promoting effects. Laccases were isolated from *P. ostreatus* and *P. cornucopiae* with antiviral effect against the hepatitis C virus and HIV-1 reverse transcriptase, respectively (Table 5). Lectins are another group of mycochemicals that include polysaccharide-protein and polysaccharide-peptide complexes. Lectins derived from mushrooms exhibit antiproliferative, immunomodulatory, antitumor, HIV-1 reverse transcriptase inhibiting, cell growth-regulating, and many more properties (Oloke and Adebayo 2015). Some proteins, peptides, and lectins isolated from various selected mushrooms are reported in Table 5.

From *P. ostreatus* a Cibacron blue affinity-purified protein (CBAEP) was isolated with potent antitumor, anticancer and immunomodulatory activity against Sarcoma-180, Dalton lymphoma (DL)-bearing mice, and B16FO melanoma tumor-bearing mice (Sarma et al. 2018).

Besides, pleurostrin and eryngin are two proteins isolated from *P. ostreatus* and *P. eryngii* mushrooms with antibacterial and antifungal properties (Erjavec et al. 2012). The laccase isolated from *P. ostreatus* exhibited an antiviral effect against the hepatitis C virus (Golak-Siwulska et al. 2018). A dimeric lectin, composed of subunits with a molecular weight of 40 and 41 KDa, isolated from fresh fruiting bodies of *P. ostreatus* exerted antitumor activity in mice bearing sarcoma S-180 and hepatoma H-22 (Table 5).

Fu et al. (2016) reported the isolation of a laccase from *P. eryngii* with antiviral activity against HIV. The laccase was active against HIV-1 growth with an IC_{50} of 2.2 μM by inhibiting HIV-1 reverse transcriptase. Also a protease named pleureryn, extracted from fresh fruiting bodies of *P. eryngii*, showed (23.1 ± 0.6)% and (91.4 ± 3.2)% inhibition of HIV-1 reverse transcriptase at 3 and 30 mM, respectively (Table 5).

Hu et al. (2018) reported the functional characterization of a *P. eryngii* protein (PEP 1b). PEP 1b is an immunomodulatory protein with 21.9 KDa able to induce the M1-polarization of the macrophage cell line RAW 264.7 cells through the activation of the TLR4-NF-κB and MAPK signal pathways.

Two types of angiotensin I-converting enzyme (ACE) inhibitory oligopeptides were obtained from the basidioma of *P. cornucopiae*. The amino acid sequences of the two purified oligopeptides were found to be RLPSEFDLSAFLRA and RLSGQTIEVTSEYLFRH. Besides, from the fermentation broth of *P. cornucopiae* was isolated a new laccase with a molecular mass of 67 KDa. It inhibited proliferation of the hepatoma cells HepG2, the breast cancer cells MCF-7, and the activity of HIV-I reverse transcriptase with IC50 values of 3.9, 7.6 and, 3.7 μM, respectively (Wu et al. 2014). Besides, a divalent cation-dependent GalNAc-specific lectin (PCL-M) was purified from the mycelia of *P. cornucopiae*. It is a multimeric glycoprotein composed of 40 KDa subunits linked by disulfide bonds (Oguri 2020).

A lectin, isolated from *A. bisporus* (ABL) showed antiproliferative effects on different cell types and might be useful for glaucoma. Besides, the fruiting bodies of *A. bisporus* are associated with a protein, named FIIb-1, characterized as tyrosinase (Verma et al. 2019).

Recently, a ribotoxin-like protein, named Ageritin was isolated from the basidiomycetes *C. aegerita*. Several biological activities are ascribed to Ageritin such as antibacterial, antiviral, endonuclease, nuclease, antifungal, and cytotoxicity to COLO 320, HeLa and, Raji cells by promoting apoptosis (Citores et al. 2019). The lectin (AAL), isolated from *C. aegerita* exhibited antitumor activity by inducing apoptosis (Liu et al. 2017), while lectin-2 (AAL-2) and its complexes with GlcNAc and GlcNAcβ1-3Gal β1-4GlcNAc revealed the structural features of specific recognition of non-reducing terminal N-acetylglucosamine (Ren et al. 2015).

A novel laccase was purified and characterized by *R. virescens*. Its N-terminal amino acid sequence was AIGPTAELVV and it was able to degrade various phenolic compounds and to decolorize several dyes (Zhu et al. 2013).

Žurga et al. (2017) isolated novel ricin B-like lectin with a β-trefoil fold from *M. procera*, designated as MpL with nematocidal activity indicating a function in protecting fruiting bodies against parasites. MpL was studied for potential delivery of peptidase protein inhibitors to lysosomes showing that it is a promising carrier of protein drugs to intracellular targets.

An antiviral protein Y3 isolated from *C. comatus* showed an inhibitory effect on the tobacco mosaic virus. Y3 has shown anticancer potential inducing caspase-dependent apoptosis in Jurkat cells of human T-cell leukemia. Besides, also laccases from mycelia of *C. comatus* have shown antiproliferative and antiviral properties (Nowakowski et al. 2020) (Table 5).

Nutritional value of mushrooms

The consumption of mushrooms as food has ancient origins. There is evidence of their inclusion in the diet, in fact, already in the civilizations of the Greeks and Romans, who considered them “the food of the Gods” (Valverde et al. 2015).

The enormous alimentary potential of mushrooms lies not only in their rich aroma and flavor, which make them an authentic delicacy but also in their high nutritional value so that they are considered functional foods (Barros et al. 2008; Tsai et al. 2009; Wani et al. 2010; Wang et al. 2014c; Kumar 2015; Corrêa et al. 2016; Rathore et al. 2017; Reis et al. 2017; Antunes et al., 2020). The fungal fruiting body is composed mostly of water, so the caloric intake provided by it is very low (about 350–400 kcal kg-1; Kalač 2012). Dry matter (DM) represents only 5–15%, with variable contents of carbohydrates and proteins, but also fibers and minerals, depending on the fungal species (Barros et al. 2008; Wani et al. 2010; Reis et al. 2012; Cheung

2013; Kalogeropoulos et al. 2013; Wang et al. 2014c; Heleno et al. 2015).

Of all the species of mushrooms cultivated or available in Italy, those belonging to the genus *Pleurotus* are among the most appreciated for their high nutritional value. Studies have shown that the content of *P. eryngii* carbohydrates, the main components of the fungal fruiting body, is very high (75.4%), even comparable to that of wheat grains and oat bran (Venturella et al. 2015; Carrasco-González et al. 2017). *C. aegerita* has an even higher content, around 84% (Petrović et al. 2015), in the wild *L. deliciosus* is 66.61 g/100 g dw, while that of *C. comatus*, *M. procera* and *B. edulis* is significantly lower (58.4%, 54.70% and 46.95%, respectively) (Tsai et al. 2007; Ayaz et al. 2011; Xu et al. 2019). Lower is also the carbohydrate content of *A. bisporus* (51.05%; Atila et al. 2017). Particular is the case of the wild mushrooms *R. cyanoxantha* and *R. virescens*, which, although belonging to the same genus, may show significantly different, and in any case rather low, carbohydrate contents (9.56 and 24.40%, respectively) (Srikram and Supapvanich 2016). Most of the fungal carbohydrates are not digestible and include dietary fiber, cell wall polysaccharides as chitin, ß-glucans and mannans, and oligosaccharides. Mushroom dietary fiber is composed by insoluble fiber: mostly chitin and ß-glucans, but also other structural polysaccharides such as hemicelluloses. Soluble fiber (mainly pectines) is generally less than 10% DM. *Pleurotus* genus has a high content of crude fiber (10.2%), as well as *C. comatus* (12.5%), and ß-glucans (25.9%); in particular, the highest amount of ß-glucans is found in *P. ostreatus* (up to 50%) (Tsai et al. 2007; Corrêa et al. 2016; Carrasco-Gonzalez et al. 2017; Bulam et al. 2019). This makes this genus one of the main and most interesting sources of ß-glucans, including pleuran, currently commercialized as a natural immunostimulant (Imunoglukan P4H®) due to its bioactivity (Carrasco-González et al. 2017; Reis et al. 2017; Golak-Siwulska et al. 2018; Bulam et al. 2019). On the contrary, the chitin level is significantly higher in *A. bisporus* than in *P. ostreatus* (Atila et al. 2017). Of the total free sugars, the most abundant is mannitol (80% ca, enough to be called "the mushroom sugar"), except in *C. aegerita* and *C. comatus*, where the dominant sugar is trehalose (12.49 g/100 g dw and 169.14 mg/g dw, respectively) (Tsai et al. 2007; Wani et al. 2010; Petrović et al. 2015; Atila et al. 2017).

Another important component of the fungal dry matter (19–35% DM) are proteins, which confer mushrooms a nutritional value comparable to some foods such as meat, eggs and, milk products (Barros et al. 2008; Kalač 2009; Wani et al. 2010; Wang et al. 2014c; Khatun et al. 2015; Corrêa et al. 2016; Rathore et al. 2017). In fact, not only these are highly digestible proteins (e.g. the digestibility of *Pleurotus* proteins is even higher than plants, that is 90%, hence only slightly below the meat and comparable with casein and eggs), but they also include all the essential amino acids usually found in animal proteins: tryptophan, isoleucine, valine, phenylalanine, leucine, threonine, lysine, histidine, methionine. There are, also, non-essential amino acids such as arginine, glutamic acid, aspartic acid, tyrosine, serine, aspargine, and many others (Tsai et al. 2009; Wani et al. 2010; Çağlarirmak 2011; Erjavec et al. 2012; Kakon et al. 2012; Kalač 2012; Kivrak et al. 2014; Wang et al. 2014c; Kumar 2015; Corrêa et al. 2016; Atila et al. 2017). Excellent protein content was found by Srikram and Supapvanich (2016) in *R. cyanoxantha* (49.20%, while it was 29.50% in *R. virescens*), by Ayaz et al. (2011) in *B. edulis* (32.50 g/100 g dw) and a good one by Xu et al. (2019) in *L. deliciosus* (17.19 g/100 g dw), rather low (4.22%), instead, in *M. procera*. Recent studies have shown as *P. ostreatus* (protein content 23%) meets the nutritional requirements for all essential amino acids, or even doubles or triples for some of them (Corrêa et al. 2016; Carrasco-González et al. 2017; Bulam et al. 2019), and that *A. bisporus* has significant amounts of numerous essential and non-essential amino acids, with an overall protein content of 29.14% (Kakon et al. 2012; Atila et al. 2017). Also relevant is the fact that mushrooms are the major food source of ergothioneine, especially *B. edulis*, and some species also of glutathione (mainly *C. aegerita* among the national mushrooms, followed by *B. edulis* and *P. ostreatus*), amino acid compounds that are important antioxidants (Kalaras et al. 2017). Interesting is also the content of γ-aminobutyric acid (GABA), a hypotensive agent, in *C. comatus*, as well as in *B. edulis* (Tsai et al. 2007). Therefore, mushrooms are a viable dietary alternative for vegetarians and vegans and also an ideal component of healthy food especially for child development.

One more advantage of mushrooms as nutrients is their low crude fat content (2–6% of DM), making them suitable for a low-calorie diet. Among the species of the genus *Pleurotus*, the lowest lipid levels are found in *P. nebrodensis* (Inzenga) Quél. (1.6%), while the highest in *P. eryngii* and *P. ostreatus* (3.5% and 3.4%, respectively) (Venturella et al. 2015; Carrasco-González et al. 2017; Sande et al. 2019). The crude fat content of *C. comatus* is 3.11% (Tsai et al. 2007), while lower are that of *B. edulis* and *M. procera* (2.85% and 2.40%, respectively) (Ayaz et al. 2011), whereas *L. deliciosus* show a slightly higher content (4.82 g /100 g dw) (Xu et al. 2019). A higher fat content was found in *R. virescens* (12.54%) and *R. cyanoxantha* (7.87%) (Srikram and Supapvanich 2016). Generally, in mushrooms, the unsaturated fatty acid prevail over the saturated ones. In *Pleurotus* spp., for example, monounsaturated fatty acids prevails over others, accounting for up to about 70% of the total, and their content is considerably higher than other species such as *A. bisporus* (Corrêa et al. 2016). In this species, the essential polyunsaturated linoleic acid is the most abundant, 5-folds more than in *P. ostreatus*, followed by palmitic, stearic, oleic acids, and others (Atila et al. 2017; Sande et al. 2019). As reported by Reis et al. (2012), however, the total content of monounsaturated fatty acids is higher in *P. eryngii* and *P. ostreatus*; in the latter, the oleic acid seems to be the prevailing monounsaturated fatty acid while linoleic acid is the major polyunsaturated one, whereas palmitic acid is the most abundant among the saturated ones (Corrêa et al. 2016). Also in *C. aegerita* linoleic acid is the most abundant (78.4%), followed by palmitic, oleic and, stearic acids (Petrović et al. 2015). In *L. deliciosus*, on the other hand, the prevalent fatty acid is palmitic, followed by stearic, oleic, and linoleic acid (Xu et al. 2019). Thus, mushrooms can play an important role in nutrition as a source of essential fatty acids for humans as linoleic and linolenic.

The content of primary vitamins such as riboflavin, niacin, thiamine, tocopherol, vitamin of D complex, and folates is noteworthy (La Guardia et al. 2005). Mushroom is, thus, the only non-animal-based food containing vitamin D. As regards niacin, a significantly high content (5.9 mg/kg) was found in *P. eryngii* var. *eryngii* (DC.) Quél., hence sufficient to satisfy 55–82% of the recommended dietary allowance (RDA) of nicotinic acid, and higher than that of other mushroom species such as *P. ostreatus* (4.95 mg), *A. bisporus* (3.8 mg) and *Boletus* spp. (0.8 mg); the riboflavin content (0.2 mg/kg) is similar for all these species, while the values of biotin are higher for *P. eryngii* (7.45 μg) (Venturella et al. 2015; Atila et al. 2017). A high vitamin B12 and riboflavin content has been reported for *P. nebrodensis* (La Guardia et al. 2005; Venturella et al. 2015). *B. edulis* is the mushroom species with significant ascorbic acid content (4.11 g/kg dw) as found by Ayaz et al. (2011). If compared with vegetables, mushrooms have riboflavin content significantly higher. The bioavailability of folates is good, content in ergosterol (a precursor of vitamin D2) is high. For this reason, mushrooms are particularly suitable for those who need to take ergocalciferol from foods of non-animal origin, such as vegetarians and vegans. Also of note is the vitamin C content in *Pleurotus* spp. (Kalač 2009, 2012; Çağlarirmak 2011; Feeney et al. 2014; Kumar 2015; Atila et al. 2017; Rathore et al. 2017; Papoutsis et al. 2020). Compared with vegetables, mushrooms have a higher or similar content of micro- and macro-elements, mostly K and P, followed by Ca, Mg, and Fe (La Guardia et al. 2005; Wani et al. 2010; Ayaz et al. 2011; Kakon et al. 2012; Kalač 2012; Wang et al. 2014c; Corrêa et al. 2016; Atila et al. 2017; Carrasco-González et al. 2017). Particularly interesting is the iron content of *P. ostreatus*, which overcomes that of pork and beef liver (23.3 and 4.9 mg Fe/100 g) (Carrasco-González et al. 2017). Thanks to the lower Na content that characterizes them, mushrooms are recommended for the prevention of hypertension and particularly for the diet of whose suffer from this medical condition (Vetter 2003; Kalač 2012; Rathore et al. 2017).

No less important is the characteristic and excellent aroma of edible mushrooms, which, together with the texture of their flesh, makes them a valid and delicious substitute for meat and an ideal enrichment for many dishes. Mushrooms are appreciated for their umami or savory flavor, deriving from non-volatile (taste) and volatile (smell) components, such as terpenes, aldehydes, lactones, free amino acids, aromatic alcohols, 5′-nucleotides, soluble sugars, ketones, octanes, and octenes (Kalač 2009, 2012; Tsai et al. 2009; Feeney et al. 2014; Wang et al. 2014c; Atila et al. 2017; Rathore et al. 2017).

Also in *Tuber* species, there is interesting nutrient composition, which changes qualitatively and quantitatively at various stages of maturation. Basically, their composition reflects that of the most commonly described fungi, with the exception of two characteristics: the absence of mannitol and the presence of melanins. As reported by Harki et al. (2005) and Lee et al. (2020), *T. melanosporum* and *T. magnatum*, two common species in Italy and among the most appreciated among truffles, are rich in proteins, K and P, sulfur amino acids and unsaturated fatty acids such as oleic and linoleic acid (more than 60% of total FA content). More specifically, the mature (stage VI) ascocarps of *T. melanosporum* contain 30.6% carbohydrates (lower than many species of basidiomycetes), 29.7% proteins, and 5.4% lipids, of which linoleic acid prevails (55.9%), followed by oleic and palmitic acid.

According to Patel et al. (2017) and Wang and Marcone (2011), truffles are reached in free (particularly the sulfur-containing cysteine and methionine) and essential amino acids (methionine, phenylalanine, valine, serine, isoleucine, and threonine), metals (Fe, Ca, K, P, Cu, Zn, and Mn), contain rhamnose, ergosterol (especially in *T. melanosporum*, 1.90 mg/g DM), as well as being rich in melanins (up to 15% dry weight). Also important are their volatile organic compounds such as aldehydes, alcohols, ketones, and organic acids (ascorbic acid), responsible for their typical umami and aroma.

Chemical composition of Italian wild mushrooms

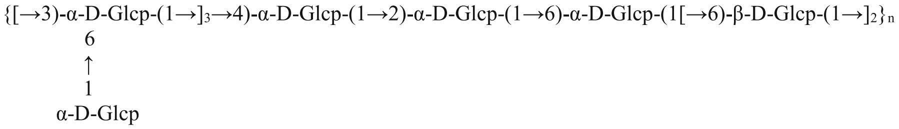
The consumption pattern from Europe shows a greater preference for wild mushrooms than for cultivated ones (Peintner et al. 2013). In Italy, gathering wild mushrooms is a common practice due to the favorable geographic conditions where the Alps, the Apennine mountains and the forests of southern Italy are ideal grounds for the growth of the most popular mushrooms. The knowledge of edible species is necessary since non-edible ones may have toxic effects. The peak season for mushroom gathering in most areas of Italy is from April to early November, with variations from region to region. Weather conditions are key factors for an abundant mushroom season, which requires a perfect combination of sun, rain, humidity, and warmth.

With the aim of evaluating the chemical composition of mushrooms widely consumed in Italy, different species have been examined to determine their proximate composition.

Pseudomonas eryngii var. *eryngii* the ’cardoncello’ mushroom, is a highly prized and widely distributed edible mushroom throughout Italy. Protein acidic extracts of Mediterranean culinary-medicinal Oyster mushrooms *P. eryngii* var. *eryngii*, *P. eryngii* var. *ferulae* (Lanzi) Sacc., *P. eryngii* var. *elaeoselini* Venturella, Zervakis & La Rocca and *P. nebrodensis* were tested for their in vitro growth inhibitory activity against *Staphylococcus aureus* ATCC 25,923, *Staphylococcus epidermidis* RP 62A, *Pseudomonas aeruginosa* ATCC 15,442 and *Escherichia coli* ATCC 10,536. All the *Pleurotus* species analyzed inhibited the tested microorganisms in varying degrees (Schillaci et al. 2013).

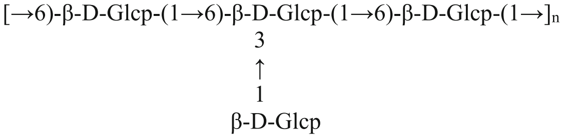
From the basidiomata of the edible mushroom *P. eryngii* var. *elaeoselini* three water-soluble glucans (PELPS-A1, PELPS-A2 and PELPS-A3) were obtained from the hot water extract by chromatography on DEAE-cellulose 32 and Sephadex G-100 column. Acid hydrolysis, periodate oxidation and NMR experiments (^{1}H-, ^{13}C-NMR, DQF-COSY, TOCSY, ROESY, HMQC and HMBC) were useful in providing information for their structural elucidation. Based on the data obtained, the structures of the repeating unit of the three isolated polysaccharides were established as follows:

(1) PELPS-A1:



$$\{[\rightarrow 3)\text{-}\underset{\substack{6\\ \uparrow\\ 1\\ \alpha\text{-D-Glc}p}}{\alpha\text{-D-Glc}p}\text{-}(1\rightarrow]_3\rightarrow 4)\text{-}\alpha\text{-D-Glc}p\text{-}(1\rightarrow 2)\text{-}\alpha\text{-D-Glc}p\text{-}(1\rightarrow 6)\text{-}\alpha\text{-D-Glc}p\text{-}(1[\rightarrow 6)\text{-}\beta\text{-D-Glc}p\text{-}(1\rightarrow]_2\}_n$$

(2) PELPS-A2:



$$[\rightarrow 6)\text{-}\beta\text{-D-Glc}p\text{-}(1\rightarrow 6)\text{-}\underset{\substack{3\\ \uparrow\\ 1\\ \beta\text{-D-Glc}p}}{\beta\text{-D-Glc}p}\text{-}(1\rightarrow 6)\text{-}\beta\text{-D-Glc}p\text{-}(1\rightarrow]_n$$

(3) PELPS-A3: $[\rightarrow 6)\text{-}\alpha\text{-D-Glc}p\text{-}(1\rightarrow 6)\text{-}\alpha\text{-D-Glc}p\text{-}(1\rightarrow 6)\text{-}\alpha\text{-D-Glc}p\text{-}(1\rightarrow]_n$

PELPS-A1 is a new polysaccharide, isolated and identified for the first time from *P. eryngii* var. *elaeoselini*. The crude extract of *P. eryngii* var. *elaeoselini* was tested for the antioxidant activity by DPPH and hydroxyl radical scavenging assays showing an SC_{50} of 1.4 mg/mL and SC_{50} of 5.7 mg/mL, respectively. In vitro, antioxidant tests showed that the three isolated polysaccharides exhibited moderate and similar hydroxyl radical scavenging activity (Cateni et al. 2020).

Costa et al. (2015) developed a headspace-solid-phase microextraction (HS-SPME) method coupled with GC–MS and GC-FID to evaluate the volatile profiles of ten wild mushroom species including *C. aegerita* and *L. deliciosus* collected in south Italy. The mushroom *C. aegerita* showed consistent amounts of ethanol (34%), isopropyl acetate (10%) and isopentanol (30%), while *L. deliciosus* presented not only an abundant fraction of 3-octanone but also consistent amounts of terpenoids, such as limonene (5%), linalool (8%), and dihydrocitronellol (4%).

C. aegerita, commonly known as Pioppino, an edible wild species of the Campania Region (southern Italy), was screened for its bio-chemical composition, nutritional values, and antioxidant effect. GC–MS analysis showed that the most abundant unsaturated acid in Pioppino was linoleic acid (C18:2; 0.618 g kg^{-1}), while palmitic acid (C16:0; 0.107 g kg^{-1}) was the major of saturated fatty acids.

The alcoholic extracts of three different samples of Pioppino were analyzed by liquid chromatography-high resolution mass spectrometry (LC-HRMS) in full scan mode (Landi et al. 2017a). Pioppino was mainly constituted of disaccharides, hexitol derivatives and malic acid. Other metabolites as saccharopine, agaritine, pentosylhexitol, ergothioneine, γ-glutaminyl-4-hydroxybenzene, pentosyl xanthosine, homogentisic acid, malic acid, pentos-2-ulose, fumaric acid, veratric acid, *p*-cumaric acid, *o*-cumaric acid, δ-tocopherol and, γ-tocopherol were identified by comparison of their relative retention times and MS/MS spectra with those of reference pure compounds.

Wild mushrooms [*Fistulina hepatica* (Schaeff.) With., *Infundibulicybe geotropa* (Bull.) Harmaja, *Laetiporus sulphureus* (Bull.) Murrill, *Macrolepiota procera* var. *procera* (Scop.) Singer and *Suillus granulatus* (L.) Roussel] collected in different forests of Sicily (southern Italy) were analyzed for the content of protein, fat, carbohydrate and, vitamins showing their importance from a nutritional point of view (Palazzolo et al. 2012).

A lectin was isolated from the wild mushroom *B. edulis* (porcini mushroom) collected in Italy. This protein is a dimer and each monomer folds as a β-trefoil domain. Its X-ray structure, the interaction with galactose, lactose, N-acetylgalactosamine, Galβ1-3GalNAc and, T-antigen disaccharide were studied together with its antiproliferative properties on human cancer cells (Bovi et al. 2013).

B. edulis is a culinary mushroom highly appreciated for its aroma, but fresh mushrooms are very perishable products with a limited shelf life of 1 to 3 days at room temperature. Thus, dehydration is one of the significant preservation methods used for the storage of mushrooms. The composition of volatile compounds of dried porcini mushroom during commercial shelf-life (up to 12 months) at the storage temperature of 20 °C and under stressed conditions at 37 °C was investigated using two mass spectrometry (MS)-based techniques.

66 volatile compounds were identified, 36 of which reported for the first time. Alcohols, aldehydes, ketones, and monoterpenes diminish during the storage while carboxylic acids, pyrazines, lactones and, amine increase. The storage temperature influences the final quality of the dried porcini (Aprea et al. 2015).

The mycochemical studies regarding truffles are mainly focused on the complex mixture of volatile organic compounds (VOCs) released from their ascomata that in addition to their biological value determine their economic value.

T. magnatum grows in some regions in Italy (Tuscany, Piedmont, Marche and, Umbria) and its volatile organic compounds were analyzed by PTR-TOF–MS experiments comparing samples from different regions of Italy and different seasons (Vita et al. 2015). The chemical composition of the aroma has led to the identification of 111 compounds divided into six different chemical classes as follows: hydrocarbons, aromatic hydrocarbons, phenols, sulfur compounds, terpenes, and other compounds. The VOCs profiles vary within the different seasonal and geographical productions.

A further study of the VOCs generated by *T. magnatum* fruiting bodies from different regions of Italy with different environmental conditions was reported by Vita et al. (2018). The white truffle's aroma is frequently correlated to sulfur-containing volatiles which can be used to trace the origin of truffle fruiting bodies. Dimethyl sulfide, dimethyl disulfide, bis (methylthio) methane were detected in all samples, dimethyl trisulfide in some samples while S-allyl-thiopropionate and 3-methylthio-propionaldehyde were found for the first time in the aroma. Aldehydes [e.g. (4*Z*)-decenal, (2*E*)-butenal, 4-methylpent-2-enal, 2-methylpent-2-enal], alcohols [e.g. 1-octen-3-ol, dodecanol, (4*Z*)-decen-1-ol], ketones [e.g. 3-octanone, 2-octanone, 6-methyl-5-hepten-2-one, 2-decanone, 2-undecanone], terpenes [e.g. limonene, α- and β-pinene, α-terpinene, eucalyptol, camphor], hydrocarbons and esters [e.g. (2*E*)-hexenyl-acetate, ethyl lactate, 3,5,5-trimethylhexyl-acetate, isobutyl pentanoate, 3-acetoxyoctane] were also detected.

Besides, since the quality of the fruiting bodies of *T. magnatum* varies significantly based on of the origin area due to the differences in environmental growth conditions, a proteomic analysis was reported for samples collected in different areas of Italy (Vita et al. 2017).

As concerns the black truffle *T. melanosporum* Vitt. the volatile organic compounds from samples collected in middle Italy and the variation induced by the storage temperature was reported (Bellesia et al. 1988). The major volatile compounds of *T. melanosporum* are butan-2,3-dione, 2- and 3-methylbutanal, 2- and 3-methylbutanol. The two aldehydes (2- and 3-methylbutanal) and two alcohols (2- and 3-methylbutanol) play an important role, while sulfur compounds are present at trace levels. On storage, all these compounds are lost, but at 0 °C, an increase of the 2- and 3-methyl butanal and of 2- and 3-methyl butanol occurs.

In many cases, *T. borchii* is illegally used as a substitute of the more appreciated *T. magnatum*. The composition of the volatile organic fraction of *T. borchii* was analyzed by gas–solid extraction and purge and trap injection in GC–MS, together with the variations during storage (Bellesia et al. 2001). In fresh samples the aroma mainly consists of a mixture of alcohols, the most important one is 1-octen-3-ol together with aldehydes and 2- and 3-methylthiophenes as sulfur compounds. Also for *T. borchii* the best preservation conditions seem to be at 0 °C, while comparing *T. borchii* with *T. magnatum*, the absence in the volatile fraction of dimethyldisulfide, dimethyltrisulfide and 2,4-dithiapentane seems to be the distinguishing feature.

D'Auria et al. (2012) reported a further study on volatile organic compounds of samples of *T. borchii* and *T. asa-foetida* Lesp., collected in woodlands of the Basilicata region (southern Italy). Solid-phase microextraction-gas chromatography–mass spectrometry analysis of the samples showed the presence of 2-methyl-1,3-butadiene as the significant component in both truffles. In *T. borchii* 3-methylbutanal, 3-methyl-1-butanol and tetradecane were present in low amounts.

Besides, a lectin named TBFL-1 was isolated and identified from *T. borchii*. The fruiting body that is able selectively to bind the exopolysaccharides produced by ascoma-associated *Rhizobium* spp. TBFL-1 is a 11.9-KDa phase-specific protein, it is a nonglycosylated polypeptide chain localized on the hyphal cell wall and is the main soluble protein in the fruiting body aqueous extract. Studies of the related gene *tbf-1* demonstrated the presence of an N-terminal signal peptide of 12 amino acids (Cerigini et al. 2008).

Chemical composition of Italian cultivated mushrooms

A study conducted on different mushroom strains cultivated in an Italian farm (Italmiko, Senise-Potenza, Italy) was carried out by solid-state 13C CPMAS NMR (Pizzoferrato et al. 2000). This technique can investigate the chemical composition in the solid-state of a food sample. This property was useful to study mushrooms of different species [*P. ostreatus*, *P. eryngii*, *Pleurotus pulmonarius* (Fr.) Quél. And *L. edodes*] to obtain the quantitative evaluation of the protein/polysaccharide ratio. The value of the protein/polysaccharide ratio has been correlated with the results obtained by chemical analysis and a good correlation (R2 = 0.93; R2 = 0.81) has been obtained. As concerns *P. ostreatus* the resonances are quite similar and only slight changes in the relative intensity can be observed. The *P. eryngii* samples analyzed show a similar pattern with a high content of polysaccharides and a low amount of proteins.

P. ostreatus, *P. eryngii* and *C. aegerita* were investigated for their β-1–3-glucan synthase activity and its induction by olive mill wastewaters (OMW) (Reverberi et al. 2004). In the control medium, although with different degrees, all fungal strains displayed β-1,3-glucan synthase activity. When the isolates grew on OMW an increase of about 12-fold was observed for *P. ostreatus*, while no differences were reported for *P. eryngii* and *C. aegerita*.

Two different polysaccharides (PEPS-A1 and PEPS-A2) were isolated from the cultivated edible mushroom, *P. eryngii* C-142-c strain. The chemical structures of the repeating unit of PEPS-A1 and PEPS-A2 were established based on acid hydrolysis, methylation analysis, and NMR experiments as follows:

(1) PEPS-A1 (α-glucan):

$$[\rightarrow 6) - \alpha - \mathrm{D} - \mathrm{Glcp} - (1 \rightarrow 6) - \alpha - \mathrm{D} - \mathrm{Glcp} - (1 \rightarrow 6) - \alpha - \mathrm{D} - \mathrm{Glcp} - (1 \rightarrow]_n$$

(2) PEPS-A2 (β-glucan):

$$[\rightarrow 6) - \beta - \mathrm{D} - \mathrm{Glcp} - (1 \rightarrow 6) - \beta - \mathrm{D} - \mathrm{Glcp} - (1 \rightarrow 6) - \beta - \mathrm{D} - \mathrm{Glcp} - (1 \rightarrow]_n$$

The antioxidant activity of PEPS-A1 and PEPS-A2 was evaluated by hydroxyl radical scavenging activity test showing SC_{50} values of 400 μg/mL and 122 μg/mL, respectively. Both polysaccharides affected cell viability after 48 and 72 h of treatment, inducing the death of 50% of HT-29 cells between 0.25 and 1 μg/mL and 0.5 and 1 μg/mL, respectively for PEPS-A1 and PEPS-A2 (Cateni et al. 2018).

Punelli et al. (2009) reported the molecular characterization and enzymatic activity of laccases in *P. eryngii* and *P. eryngii* var. *ferulae*. Using a PCR-based approach, four putative laccase genes (*lac1*, *lac2*, *lac3* and *lac5*-like gene) have been isolated and identified in both *P. eryngii* and *P. eryngii* var. *ferulae*.

Multiple headspace-solid phase microextraction (MHS-SPME) followed by gas chromatography/ mass spectrometry (GC–MS) and flame ionization detection (GC-FID) was applied to the identification and quantification of volatiles from the mushroom *A. bisporus* (Costa et al. 2013). 1-Octen-3-ol, 3-octanone, 3-octanol, 1-octen-3-one and benzaldehyde are key compounds of mushroom samples analyzed. Quantitative differences among the samples were observed, in particular for 1-octen-3-ol when fresh mushrooms were differently pre-treated (0.75 and 3.30 μg^{-1}, in chopped and homogenized samples, respectively). It seems that from 1-octen-3-ol breakdown other 8-carbon compounds are formed: 3-octanone (3.34 vs. 2.01 μg^{-1}) and 3-octanol (0.19 vs. 0.07 μg^{-1}) were found in high amount in chopped samples, balancing the reduced presence of 1-octen-3-ol.

Agaricus bisporus is the most cultivated mushroom in Italy. Samples of the cultivated species *A. bisporus* in Sicily (South Italy) were analyzed by the headspace-solid-phase microextraction (HS-SPME) method coupled with GC–MS and GC-FID to evaluate compositional changes occurring during storage (Costa et al. 2015). 51 compounds were identified, with high amounts of C8 compounds such as 3-octanone, 3-octanol and (2*E*)-octenol. Besides, compounds with the aromatic ring were determined at significative amounts, such as benzaldehyde and benzyl alcohol. In Italy, *A. bisporus*, when purchased in the supermarkets, is found in refrigerated counters. So, 10-day-old mushrooms, kept in the refrigerator were analyzed. After 10 days of storage, a reduction of about 3.5% of the volatile fraction was observed. Ethanol, (2*E*)-octenol and phenylacetaldehyde were not detected in the stored mushrooms. As concerns compounds with aromatic ring a drastic decrease was observed. The amount of terpenoids was constant, while a reduction of C8 compounds, 3-octanol and (2*E*)-octenol was observed.

Landi et al. (2017a) reported the nutritional value, chemical composition, and anti-radical properties of cultivated *A. bisporus* (J.E. Lange) Imbach purchased in Campania (South Italy). As concerns fatty acid composition analysis the most abundant unsaturated acids in Champignon were linoleic (C18:2; 0.858 g kg^{-1}) and γ-linolenic (C18:3; 0.243 g kg^{-1}), which represented 67% and 19% of the total, respectively. The prevalence of polyunsaturated fatty acids (PUFA) showed linoleic acid (C18:2) as the major fatty acid, while palmitic acid (C16:0) was the major of saturated fatty acids (SFA). The tentative identification of constituents from Champignon alcoholic extract by liquid chromatography—high-resolution mass spectrometry (LC-HRMS) showed the presence of mannitol, saccharopine, trehalose, agaritine, pentosylhexitol, ergothioneine, γ-glutaminyl-4-hydroxybenzene, malic acid, fumaric acid, ferulic acid, sinapic acid, and cinnamic acid.

Mycochemicals as nutraceuticals

Mushrooms are an excellent food not only from a culinary point of view, as unique sensory experiences, but also for well-being because of the many positive effects they have on the human body, helping it to maintain a good state of health and defend it against illness. This aspect is becoming increasingly important in a society more and more threatened by an unhealthy lifestyle, pollution, radiation and many other stress factors. Thereby in the last decades, the gaze on food has changed, and new concepts of it were developed. The term 'nutraceuticals' was first used by de Felice (1989) who, combining the words nutrition and pharmaceuticals, defined them as 'a food (or part of a food) that provides medical or health benefits, including the prevention and treatment of a disease'.

The term "mushroom nutraceuticals" refers to refined or partially refined extracts, single compounds or nutrients, or dried biomass obtained from either mushroom mycelium or fruiting body, usually included in dosed, concentrated, and purified form in different pharmaceutical formulations such as capsules, tablets, pills, etc., and consumed as a dietary supplement and has potential therapeutic applications (Reis et al. 2017). Nonetheless, being considered non-specific biologic therapies, nutraceuticals differ from pharmaceuticals in that they are not currently subject to medical prescription and their therapeutic properties are not recognised from a legal point of view. Since 2011, in fact, in EU the registration and marketing of 'botanical medicinal products' is no longer permitted and, therefore, despite their pharmacological properties, they can only be classified as food supplements, falling under EU Regulation no. 1924/2006 (Pirillo and Capatano 2014). Therefore, several aspects of their preparation and marketing remain still unresolved, such as standardization of the production chain, safety parameters, regulation, efficacy, and mechanism of action. Although the market does not have production standards, it is mainly developed in Asian countries; Western countries, on the other hand, are used to buy from the East finished products for resale or raw materials (powders and extracts not always of ascertained origin) and then make the final pipeline. In these areas, therefore, the potential for exploitation and investment is enormous.

Several recent studies have demonstrated the multiple nutraceutical properties of mushrooms by the presence of numerous bioactive molecules that give them antioxidant, antimicrobial, antitumor, immunomodulating, anti-hypercholesterolemia, anti-inflammatory, antiviral, radical scavenging, hypolipidemic, antithrombotic, hepatoprotective, anti-hypercholesterolemia, hypotensive, and anti-diabetic activities, antinociceptive and cardiovascular beneficial effects (Barros et al. 2008; Carrasco-González et al. 2017; Gargano et al. 2017; Rathore et al. 2017; Reis et al. 2017; Ma et al. 2018; Islam et al. 2019). These bioactive compounds, contained in different quantities depending on the fungal species and growing conditions, are the most varied, including polysaccharides and especially ß-glucans, dietary fibers, phenolics, peptides, terpenes, glycoproteins, ergosterols, alcohols, unsaturated fatty acids (UFA), lectins, tocopherols, ascorbic acid, carotenoids and others

(Barros et al. 2008; Rathore et al. 2017; Reis et al. 2017; Ma et al. 2018; Islam et al. 2019).

As for the genus *Pleurotus*, many species belonging to it have shown activity against various chronic diseases in various studies, thus with a wide spectrum for potential biotechnological applications. They possess numerous bioactive compounds such as polysaccharides, lipopolysaccharides, proteins, peptides, glycoproteins, nucleosides, triterpenoids, lectins, lipids, and their derivatives (Patel et al. 2012; Talkad et al. 2015; Golak-Siwulska et al. 2018). Fruiting bodies possess higher concentration of antioxidants than other commercial mushrooms (Talkad et al. 2015); the AOX properties of different kinds of *Pleurotus* extracts efficiently contrast reducing the occurrence of age-associated disorders like stroke, Parkinson's disease, atherosclerosis, diabetes, cancer, and cirrhosis (Patel et al. 2012); they help also to reduce the severity of inflammatory skin disease and regulate hyperpigmentation disorders (Taofiq et al. 2016).

Pleuran is the polysaccharide isolated from *Pleurotus* spp. A variety of properties such as immunomodulatory, antitumor, AOX, antiviral and antimicrobial, and anti-inflammatory. It was also found that by including 100 mg of Imunoglukan in the diet of elite athletes, the suppressed immune system responses induced by short-term high-intensity exercise decreased (Bobovčák et al. 2010).

Studies have remarked also on the importance of proteins isolated from *P. ostreatus* and *P. eryngii* (pleurostrin and eryngin) as an effective antifungal and antibacterial agents (Carrasco-González et al. 2017). Many bioactive compounds of *Pleurotus* spp. and their properties are reported in Table 6.

A. bisporus is also of increasing importance thanks to the innumerable medicinal properties of its bioactive extracts and compounds, which make it suitable against many human diseases such as coronary heart diseases, diabetes mellitus, bacterial and fungal infections, disorders of the human immune system, and cancers (Öztürk et al. 2011; Atila et al. 2017). Even the Canadian Cancer Society recommends its consumption because of its beneficial effects against various diseases (Atila et al. 2017). The high dietary fiber and antioxidant content of this mushroom, including vitamins C, D, and B12, as well as folate and polyphenols have positive effects on diabetes and cardiovascular diseases (Atila et al. 2017).

Moreover, the prebiotics contained in the fruiting bodies has a positive influence on gut health. A study conducted by Hess et al. (2018) has shown that, compared to meat, the consumption of mushroom may impact laxation in healthy adults. It is demonstrated by the increase in stool weight and presence of undigested mushrooms in stool and by the different fecal microbiota composition, with a greater abundance of Bacteroidetes and lower presence of Firmicutes.

In vivo tests on mice have shown analgesic and antipyretic properties comparable to that of the common drug diclofenac (Bose et al. 2019). As reported by Ismaya et al. (2020), recently a new molecule from *A. bisporus* has been discovered; is a mannose-binding protein (Abmb) that might be employed as a drug carrier for oral administration due to its capability to permeate a dialysis bag made of fresh jejunum ex vivo, that doesn't suffer alterations in a bioconjugation with a drug model, and to its resistance to the harsh gastrointestinal tract (Ismaya et al. 2020). Some activities and compounds of *A. bisporus* are reported in Table 7.

Other mushrooms already mentioned, which can be found spontaneous or cultivated in Italy, are still less studied compared to the previous ones. This is also due to the fact that their consumption is often smaller in quantitative terms or less widespread. Some of the studies carried out to date are reported in Table 7. They reveal the enormous therapeutic potential of these mushrooms, as well as the benefits that their more frequent inclusion in the diet would bring to the individual's state of health.

As far as truffles are concerned, most of the studies carried out refer to the culinary aspect, analyzing their composition and focusing mainly on the volatile components responsible for their particular aroma and flavor.

In recent years, studies on the therapeutic potential of this type of food are increasing.

It has been seen, in fact, as *Tuber* spp. have numerous bioactive compounds, with properties ranging from anti-tumor to anti-inflammatory, antioxidant, hepatoprotective, anti-cholesterolemic, and even antidepressant. In Table 7 some bioactivities of this genus are reported.

A more recent topic concerns the nutraceutical benefits of UV irradiation of cultivated *A. bisporus* and *P. ostreatus* to generate high amounts of vitamin D2 and to maintain the ability of the fungus to inhibit

Table 6 Bioactivities of *Pleurotus* spp

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
Anti-oxidative	Lectins	*P. ostreatus*	Activation of Toll-like receptor 6 signal pathway of dendritic cells	Ma et al. (2018)
	Polysaccharides	*Pleurotus* spp.	Improved activity after polysaccharides sulphonation,	Li and Shah (2016)
		P. ostreatus	Increase of the activity of SOD and consequent inactivation of superoxide radicals;	Islam et al. (2019)
			Increase of CAT activity by upregulating gene expression and consequent prevention of the cells from hydrogen peroxide toxicity;	Islam et al. (2019)
			Reduction of GPx activity and increase of GR, GST and APx activity	Islam et al. (2019)
		P. eryngii *P. ostreatus*	Activation of SOD, CAT and GPx and decreasing ALT in mice with CCI_4-induced liver injury;	Carrasco-González et al. (2017)
			Inhibition of lipid peroxidation on porcine brain homogenates	Carrasco-González et al. (2017)
		P. eryngii	Inhibition of cell viability in colorectal adenocarcinoma cell line (HT29)	Cateni et al. (2018)
	Phenols	*P. ostreatus*	Inhibition of the growth of HL-60 cells by inducing apoptosis	Patel et al. (2012) and Vanamu (2012)
	Flavonoids, ß-carotene, ascorbic acid	*P. ostreatus*	Inhibition of the growth of HL-60 cells by inducing apoptosis;	Patel et al. (2012) and Vanamu (2012)
			Reduction of ascorbate radicals	Islam et al. (2019)
	α-tocopherol (Vitamin E)	*P. ostreatus*	Prevention of lipid peroxidation in cell membranes	Islam et al. (2019)
	Glutathione	*Pleurotus* spp.	Prevention of GSH oxidation and assurance of the safety of its redox enzymes	Islam et al. (2019)
	Statins (lovastatin)	*P. ostreatus*	Inhibition of the plasma and hepatic lipid peroxidation and increase of the hepatic catalase activity in high-cholesterol fed rabbits	Jeon et al. (2001)

Table 6 continued

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
Immunomodulatory	Polysaccharides	*Pleurotus* spp.	Macrophage stimulation	Corrêa et al. (2016)
		P. ostreatus	In children with RRTIs, pleuran (Imunoglukan P4H®) increases immunoglobulin isotypes, slows down the decline of T-cytotoxic lymphocytes, and e increases the NK cell number	
		P. nebrodensis	PN-S evaluated in RAW264.7 macrophage; improved phagocytosis of macrophages, enhanced production of f interleukin-6 (IL-6), nitric oxide (NO), interferon gamma (INF-γ), and tumor necrosis factor-a (TNF-α) in the macrophages, with up-regulation of mRNA expressions of interleukin6 (IL-6), inducible nitric oxide synthase (iNOS), interferon gamma (INF-γ) and tumor necrosis factor-α (TNF-α)	Corrêa et al. (2016)
		P. ostreatus	Immunomodulatory activity against infectious bursal disease (IBD) in broilers;	Islam et al. (2019)
			Decrease of the toxicity of cyclophosphamide in mice	Islam et al. (2019)
	Triterpenoids (i.e. ergosterol) and steroids	*Pleurotus* spp.	Not specified	Gargano et al. (2017)
Anti-inflammatory	Polysaccharides (ß-glucans)	*P. ostreatus*	Synergistic effect with methotrexate in arthritis induced rats	Carrasco-González et al. (2017)
	Aqueous extract	*P. ostreatus*	Inhibition of DNA-binding activity of AP-1 and NF-kB in RAW264.7 cell line and suppression of the secretion of TNF and IL-6 in a mice model;	Carrasco-González et al. (2017) and Patel et al. (2012)
			Reduction of NO and TNF-a production in murine macrophage cell line RAW264.7	Carrasco-González et al. (2017)
	Pleuran	*P. eryngii*	Suppression of inflammation in delayed type (type IV hypersensitive) allergy response in mice	Patel et al. (2012); Talkad et al. (2015)
	Phenols (ethanolic extract)	*P. eryngii*	Suppression of induced dermatitis and decrease of serum level of IgE and TARC as well as expression of cytokines related with inflammation (TNF-a, INF-g, IL-4, IL-5 and IL-13) and severe skin lesions in mice	Carrasco-González et al. (2017) and Ma et al. (2018)

Table 6 continued

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
Antihypercholesterolemic	Statins (Lovastatin)	*P. ostreatus*	Inhibition of 3-hydroxy-3-methylglutaryl coenzyme A (HMG CoA) reductase that catalyzes the conversion of HMGCoA to mevalonic acid in the cholesterol synthesis pathway; pleiotropic actions in the cardiovascular, immune and nervous systems;	Talkad et al. (2015)
			Inhibition of the plasma and hepatic lipid peroxidation and increase of the hepatic catalase activity in high-cholesterol fed rabbits;	Jeon et al. (2001)
			Acceleration of HDL, reducetion of production of VLDL, LDL, cholesterol; reduction of cholesterol absorption and of HMG-CoA reductase activity in the liver;	Patel et al. (2012)
			Positively affect the coagulation system and fibrinolysis	Golak-Sivulska et al. (2018)
	Flavons (Chrysin)	*P. ostreatus*	Decrease in mean blood/serum levels of glucose, lipid profile parameters, and hepatic marker enzymes and a concomitant increase in enzymatic and nonenzymatic antioxidant parameters in hypercholesterolemic rats	Anandhi et al. (2013)
Anti-cancer and anti-tumor	Cold-water extract	*P. eryngii* var. *ferulae* *P. nebrodensis*	On human colon cancer cells: inhinition of viability of HCT116 cells; promotion of apoptosis; increase of *Bax*-to-*Bcl-2* messenger RNA ratio; inhibition of cell migration and effect on homotypic and heterotypic cell–cell adhesion; negative influence on protein tyrosine and phosphorilation levels of extracellular signal-regulated kinase 1/2	Fontana et al. (2014)
	Methanolic extract	*P. ostreatus*	In breast cancer: suppression of different cell lines proliferation (MCF-7, MDA-MB-231);	Chaturvedi et al. (2018)
			Induction of expression of tumor suppressor p53 and cyclin-dependent kinase inhibitor p21	Carrasco-González et al. (2017)

Table 6 continued

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
	Polysaccharides	*P. eryngii*	In mice with renal cancer: increase of relative thymus and spleen lymphocytes proliferation by elevated activity of NK cells and CTL in spleen; increase of serum concentration level of TNF-α and IL-2;	Chaturvedi et al. (2018)
			Inhibition of tumor growth and increased relative thymus and spleen indices	Zhang et al. (2016)
		P. ostreatus	Inhibition the development of Ehrlich Tumor (ET) and Sarcoma 180 (S-180)	Carrasco-González et al. (2017)
		P. nebrodensis	Apoptosis induction by reduction of mitochondrial membrane potential and changes in migration cell rate	Carrasco-González et al. (2017)
		P. ostreatus	Cytotoxic activity towards HeLa cell lines	Golak-Sivulska et al. (2018)
		P. citrinopileatus Singer	Cytotoxic activity to cervical cancer cells (and no to normal cells)	Golak-Sivulska et al. (2018)
		Pleurotus spp.	Thymus-dependent immune mechanism, which involves the activation of cytotoxic macrophages, monocytes, neutrophiles, natural killer cells, dendritic cells, and chemical messengers (cytokines, such as interleukins, interferons., and colonystimulating factors) which triggers the complementary and acute phase responses	Rathore et al. (2017)
	Pleuran (ß-glucan)	*P. ostreatus*	Anti-neoplastic properties against different cells, including breast cancer MCF-7, prostate cancer cells PC-3 and colorectal HT-29 cancer cells	Golak-Sivulska et al. (2018)
	Proteins	*P. ostreatus*	Therapeutic effect towards the colorectal cancer cell line SW 480 and monocytic leukaemia THP-1 by inducing their apoptosis	Golak-Sivulska et al. (2018)
	Proteins (hemolysin)	*P. nebrodensis*	Strong growth inhibition (IC50 < 40 mg/mL) against five cancer cell lines (Lu-04, Bre-04, HepG2, L929 and HeLa) and apoptosis induction in L929 and HeLa cell lines	Carrasco-González et al. (2017)

Table 6 continued

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
	Lectins	*P. ostreatus*	Reduction of tumor burden in Sarcoma S180 (88.4%) and hepatoma H-22 (75.4%) inoculated mice and increase of the survival time	Carrasco-González et al. (2017)
	Ethanolic extract	*P. eryngii* var. *ferulae*	Inhibition of growth and proliferation of stomach (BGC 823) and melanoma (B16F10) cancer cells;	Carrasco-González et al. (2017)
			Induction of cell cycle arrest in G0/G1 of stomach and melanoma cancer cell lines;	Carrasco-González et al. (2017)
			Delay and reduction of melanoma tumor growth in a murine model	Carrasco-González et al. (2017)
	Laccase	*P. cornucopiae*	Inhibition of proliferation of the hepatoma cells HepG2, the breast cancer cells MCF-7	Wu et al. (2014)
	Monoterpenes and sesquiterpenoids (Pleurospiroketal)	*P. cornucopiae*	Cytotoxicity against cancer line	Rathore et al. (2017)
	Triterpens	*P. eryngii*	Inhibitory activity against breast cancer MCF-7 cell lines in vitro	Zhang et al. (2016)
Antihypertensive	Aqueous extract	*Pleurotus* spp.	High angiotensin l-converting enzyme (ACE) inhibition	Carrasco-González et al. (2017)
	Hot water extract D-mannitol Oligopeptides	*P. cornucopiae*	ACE inhibition in vitro and antihypertensive effect on spontaneously hypertensive rats	Carrasco-González et al. (2017)
	Not specified	*P. ostreatus*	Pressure lowering activity	Patel et al. (2012)
Antiviral, antimicrobial	Nebrodeolysin	*P. nebrodensis*	Inhibition of the viral cytopathic effect of HIV-1	Carrasco-González et al. (2017)
	Laccase	*P. ostreatus*	Antiviral effects against hepatitis C	Golak-Sivulska et al. (2018)
	Ubiquitin-like protein	*P. ostreatus*	Antiviral effects against HIV-1 viruses	Carrasco-González et al. (2017)
	Lectin	*P. citrinopileatus*	Potent effect against HIV-1 reverse transcriptase activity	Carrasco-González et al. (2017)
	Water-soluble sulfonated polysaccharides	*P. eryngii*	Inhibition in growth of pathogenic *Escherichia coli*, *Staphylococcus aureus* and *Listeria monocytogenes*	Carrasco-González et al. (2017)
	Nanoparticles synthesized through mixing queous extract with silver nitrate	*P. cornucopiae*	Remarkable antifungal effects	Carrasco-González et al. (2017)
	Nanoparticles synthesized through mixing a silver solution with aqueous extract	*P. ostreatus*	Inhibition in Gramnegative bacteria growth	Carrasco-González et al. (2017)

Table 6 continued

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
	Aqueous extract	*P. ostreatus*	Inhibition in replication of Herpes simplex virus type 1 in vitro	Carrasco-González et al. (2017)
	Polysaccharides	*Pleurotus* spp.	Activation of the microbial autolytic system of eight strains: seven autolyzing strains with intensity values ranging from 2.7% in *Candida* sp. to 36.1% in *Saccharomyces cerevisiae*, while autolysis was of 1.8% in one non-autolyzing strain (*Bacillus cereus*)	Corrêa et al. (2016)
	Methanolic extract	*Pleurotus* spp.	Inhibition in growth of *Bacillus megaterium*, *S. aureus*, *E. coli*, *Klebsiella pneumoniae*, *C. albicans*, *C. glabrata*, species of *Trichophyton* and *Epidermophyton*	Patel et al. (2012)
	Ether and acetone extract	*P. ostreatus*	Effective against *B. subtilis*, *E. coli* and *S. cerevisiae*	Patel et al. (2012)
	Ethanolic extract	*P. ostreatus*	Inhibition in growth of Gram positive bacteria (*Listeria innocua*, *B. cereus*, *Staphylococcus aureus*), Gram negative bacteria (*E. coli*, *Pseudomonas aeruginosa*), and yeast (*Candida albicans*, *Candida* sp.)	Vanamu (2012)
	Ribonucleases	*P. ostreatus*	Potentiality to neutralize HIV through degradation of viral genetic material	Patel et al. (2012)
	Protein (hemolysin)	*P. nebrodensis*	Anti-HIV-1 activity in CEM cell culture	Patel et al. (2012)
Hyperglycemic	Guanide	*Pleurotus* spp.	Anti-hypoglycemic effect	Patel et al. (2012)
	Polysaccharides	*P. citrinopileatus*	Elevation of the activity of glutathion peroxidase	Patel et al. (2012)
Hepatoprotective	Polysaccharopeptides	*P. ostreatus*	Alleviation of thioacetamide-induced alterations, inflammation, steatosis, necrosis and fibrosis	Patel et al. (2012)
	Hot-water extract	*P. ostreatus*	Less leakage of alkaline phosphatase, less pronounced increase in hepatic malondialdehyde concentration, less notable reduction in hepatic total protein, RNA and DNA contents; in contrast, increase in hepatic superoxide dismutase, glutathione peroxidase and glutathione reductase activities	Patel et al. (2012)

Table 6 continued

Activity	Bioactive compound or extract	*Pleurotus* species	Mechanisms of action	References
Anti-Ageing	Aqueous, methanolic, and acetonic extracts	*Pleurotus* spp.	Anti-tyrosinase, anti-hyaluronidase, anti-collagenase and anti-elastase activity	Taofiq et al. (2016)
	Mushroom powder	*P. ostreatus* and *P. eryngii*	Significant bifidogenic effect and strong lactogenic effect, respectively	Mitsou et al. (2020)
	Extracts	*P. ostreatus*	Lowered levels of malondialdehyde, a polyunsaturated lipid and an electrophilic mutagen, on administration of mushroom extract to aged rats, and subsequent reaction with deoxyadenosine and deoxyguanosine in DNA, forming a DNA adduct	Patel et al. (2012)

glycation of a target protein (Gallotti and Lavelli 2020). Besides polysaccharides from cultivated *Rubroboletus sinicus* (W.F. Chiu) Kuan Zhao & Zhu L. Yang showed high inhibitory effects on glycation (Liping et al. 2016). A medium-molecular-weight fraction obtained by sclerotia of *Lignosus rhinocerus* (Cooke) Ryvarden contain bioactive compounds which exhibit potent anti-glycation activity and is eligible for preventing diabetic complications by Advanced Glycation End Products (AGE) (Yap et al. 2018).

Mycochemicals in functional foods

As mentioned, today's concept of food is changing, becoming more complex. "Functional food" namely conventional food is consumed as part of the daily diet.

This type of food positively affects one or more physiological functions of the human body is proven; therefore, in addition to the nutritional intake, they contribute to maintaining the state of wellness, improving health, and reducing the risk of disease.

This concept is flanked by that of "food supplements" which, compared to the previous ones, constitute a concentrated source of nutrients or substances with nutritional and/or physiological effect; they are marketed in various dose forms, including tablets, capsules, gummies, and powders, as well as drinks and energy bars and aim to provide nutrients to fulfil the nutritional requirement of an individual.

Mushrooms are functional food, because of their nutritional features: they are hypocaloric and a good source of high-quality dietary fiber. Their carbohydrate content as glycogen (and not of starch) is low.

They also have significative digestible proteins and all the essential amino acids required by an adult and often deficient in plants, as well as various vitamins and mineral elements in content often at higher levels than vegetables.

Therefore, in addition to taking a leading role in diseases such as hypertension, cholesterol, obesity, etc.) and they provide an efficient alternative in areas with widespread malnutrition.

Mushrooms show potential for obtaining fortified foods, improving nutrition, and adding health benefits.

Although knowledge about the therapeutic properties of mushrooms is now quite extensive, their incorporation into foods to produce fortified foods is not so widespread today. However, various research has been undertaken in recent years in this direction, demonstrating how the addition of extracts or compounds of medicinal mushrooms, such as *Pleurotus* spp., into processed food, increases their sensory, nutritional, functional, or nutraceutical features

Table 7 Bioactivities of some Italian wild and cultivated mushrooms

Mushrooms species	Bioactive compound or extract	Activity and mechanisms		References
Agaricus bisporus	Polysaccharides	Scavenging activity, metal chelating activity, reducing power; anti-hypoxic activity		Li et al. (2015)
	Lectin (ABL)	Anticancer	Inhibition of proliferation of cancerous human epithelial colon cells (HT29) in vitro	Ismaya et al. (2020)
			Inhibition of MCF-7 (breast cancer cells) and Caco-2 cancer cell proliferation in vitro	
		Antineoplastic	Suppressed proliferation of retinal pigment epithelium (RPE) cells, and subsequent lowering of proliferative vitreoretinopathy;	Ismaya et al. (2020)
			Slows down proliferation of human ocular fibroblast and reduces collagen lattice contraction in vitro	
		Antiviral	Strong inhibition against human immunodeficiency virus type-1 (HIV-1) reverse transcriptase (IC50 of 8 μM) in vitro;	Ismaya et al. (2020)
	Mannose-binding protein (Abmb)	Anticancer	Inhibits proliferation of MCF-7 breast cancer cells at 12.5 μM and arrests growth at lower concentrations in vitro	Ismaya et al. (2020)
	Methanolic and aqueous extracts	Anti-inflammatory, analgesic, antipyretic, antioxidative and antimicrobial (in mice and/or in vitro)		Bose et al. (2019)
	Polysaccharide	Immunostimulatory and antitumor bioactivity in vivo and in vitro		Atila et al. (2017)
	Fruiting body extracts	Immunostimulating	On activated human peripheral blood mononuclear cells (PBMCs) and induced synthesis of interferon gamma (IFN-γ)	Atila et al. (2017)
		Antitumor	Inhibition on cell proliferation of HL-60 leukemia cells and other leukemia human cell lines via the induction of apoptosis;	Atila et al. (2017)
			Suppression of aromatase activity, inhibition on breast cancer cell proliferation, and decrease in mammary tumor formation in vivo	Atila et al. (2017)
	UFA	Antitumor	Inhibition on aromatase activity	Atila et al. (2017)
	Arginine	Antitumor	Delay of tumor growth and metastasis	Atila et al. (2017)
	Lovastatin	Antitumor	Anti-cancer effects in the triple-negative breast cancer cell line MDA-MB-231	Atila et al. (2017)
		Antihyperlipidemic	Reduction of cholesterol level in serum and/or liver	Atila et al. (2017)
	Sterols	Antihyperlipidemic	Reduction in cholesterol absorption and thereby lowered plasma cholesterol and LDL cholesterol	Atila et al. (2017)
	Fruiting body extracts	Antidiabetic	Decreased severity of streptozotocin-induced diabetes in rat	Atila et al. (2017)
	α-glucans	Antidiabetic	Lowered producing lipopolysaccharide-induced TNFa	Atila et al. (2017)
	Polysaccharides and phenolics	Scavenging of superoxide, hydroxyl and DPPH radicals and hydrogen peroxide, enhancement of the activities of antioxidant enzymes in sera, liver, and heart of mice		Zhang et al. (2016)

Table 7 continued

Mushrooms species	Bioactive compound or extract	Activity and mechanisms		References
	Proteoglycan	Antitumor	Involvement of NK cells and induction ofgene expression of nitric oxide by transcription factor and NF-kappa B downstream signalling, interferon-γ and interleukin, that activate NK cells	Chaturvedi et al. (2018)
Boletus edulis	Polysaccharide (BEP)	Immunomodulatory	Reduction of tumor mass in Renca tumor bearing mice; stimulation of splenocytes proliferation, increase in NK cell and CTL activities in spleen	Wang et al. (2014a)
	Polysaccharides	Antioxidant activity		Zhang et al. (2018)
	Lectin	Hemagglutinating activity;		Zheng et al. (2007)
		Mitogenic activity in mouse splenocytes;		
		Antiviral	Inhibition of human immunodeficiency virus-1 reverse transcriptase	
	Phenolics	Antioxidative	Inhibition of lipid oxidation	Ma et al. (2018)
	Prepared for consumption mushrooms	Antioxidative	High antioxidant activity against ABTS, DPPH and in FRAP assay	Jaworska et al. (2015)
	Ethanolic and hot water extracts	Antioxidative		Tsai et al. (2007)
	Polysaccharide (BPS)	Antidiabetic	Inhibition of oxidative stress and inflammation in rats liver	Xiao et al. (2019)
Coprinus comatus	Ethyl acetate extract	Antitumor	Activity against ovarian cancer cell lines SKOV-3 and SW-626 and reduced viability of human ovarian cancer cells;	Venturella et al. (2019)
			Apoptosis induction in ovarian cancer cells (ES-2) via both extrinsic and intrinsic pathways	
	Aqueous suspension	Antioxidative	increase of antioxidative status of liver homogenate and prevention of histological changes in liver cross sections in oxidative stressed rats	Popović et al. (2010)
	Fruiting body extract	Antiaggregant	Inhibition of platelet aggregation induced by ADP via a P2Y12 receptor	Poniedziałek et al. (2019)
	Ethanolic and water extract	Antioxidant and scavenging property		Li et al. (2010)
	Laccase	Antiviral	Inhibition of human immunodeficiency virus type 1 (HIV-1) reverse transcriptase	Ma et al. (2018)
		Antitumor	Suppression of proliferation of tumor cell lines HepG2 and MCF7	Ma et al. (2018)
	γ-aminobutyric acid (GABA)	Hypotensive		Tsai et al. (2007)
Cyclocybe aegerita	Polysaccharides	Anti-ageing	Increased cell viability and β-Gal viability, prevention of G1-phase cell-cycle arrest, decreased mitochondrial membrane potential	Liu et al. (2020c)
		Antidiabetic	Inhibition of iNOS expression, reduction of blood glucose level	Liu et al. (2020c)

Table 7 continued

Mushrooms species	Bioactive compound or extract	Activity and mechanisms		References
	Water extract	Anti-angiogenic	In vitro inhibition of vascular endothelial growth factor (VEGF)-induced proliferation inHUVECs; down-regulation of intracellular reactive oxygen species (ROS) level and VEGF secretion in Caco-2 cells; decrease in the migration of endothelial cells (ECs)	Lin et al. (2017)
	Proteins	Antitumor	Against different tumor cell lines; stimulation of immune response; enhanced splenocyte cytotoxic activity and mRNA level of cytokines in mice	Liang et al. (2011)
	Ageritin (ribotoxin-like protein)	Antitumor	Cytotoxicity and cell death promoting effects towards CNS model cell lines (SK-N-BE(2)-C, U-251 and C6); extrinsic apoptotic pathway by initially activating caspase-8	Landi et al. (2017b) and Ruggiero et al. (2018)
	Galectin (AAL)	Antitumor	Anti-metastasis activity in breast cancer, anti-proliferation activity against 4T1 cells	Yang et al. (2018)
	Ceramide	Antitumor	Inhibition of the proliferation of stomach, breast and CNS cancer cell lines in vitro	Diyabalanage et al. (2008)
		Anti-inflammatory	Inhibition on cyclooxygenase enzymes COX-1 and -2	
	Hot-water and ethanolic extracts	Antioxidative		Tsai et al. (2006, 2007)
	Methanolic extract (FAF)	Antioxidative and cyclooxygenase (COX) enzyme inhibitory activity		Zhang et al. (2003)
Lactarius deliciosus	Methanolic extract	Antioxidant and free radical scavenging activity		Kosanić et al. (2016)
		Antimicrobial	Inhibition of bacteria (*Bacillus cereus, B. subtilis, Proteus mirabilis, E. coli, Staphylococcus aureus*) and fungi (*Aspergillus niger, Penicillium expansum, P. chrysogenum, Alternaria alternata, Trichoderma viride,Cladosporium cladosporioides, Mucor mucedo, Fusarium oxysporum, Candida albicans*)	
		Anticancer	Growth inhibition in HeLa, A549 and LS174 cell lines	
	Aqueous and/or ethanol extract	Antioxidative		Xu et al. (2019)
		Antihyperglycemic	Inhibitory effects on α-amylase and α-glucosidase	
Macrolepiota procera	Methanolic extract	Antioxidant and free radical scavenging activity;		Kosanić et al. (2016)
		Antimicrobial	Inhibition of bacteria (*Bacillus cereus, B. subtilis, Proteus mirabilis*) and fungi (*Aspergillus niger, Penicillium expansum, Alternaria alternata, Trichoderma viride,Cladosporium cladosporioides, Fusarium oxysporum, Candida albicans*)	
		Anticancer	Growth inhibition in HeLa, A549 and LS174 cell lines	

Table 7 continued

Mushrooms species	Bioactive compound or extract	Activity and mechanisms		References
	Mushroom extract	Antioxidant activity		Islam et al. (2019)
	Powder of freeze, dried and irradiated mushrooms	Antioxidant activity		Fernandes et al. (2013)
Russula virescens	Polysaccharide (RVP)	Antioxidant activity		Sun et al. (2010a, b)
	Phenolics			
Russula cyanoxantha	Phenolics	Antioxidant activity		
Tuber magnatum	Water and/or methanol extract	Anti-inflammatory	Inhibition of COX-1 and 12-LOX pathway products synthesis	Beara et al. (2014)
		Antitumor	Cytotoxicity against some tumour cell lines (HeLa, MCF7, HT-29)	
		Antioxidative		
Tuber melanosporum	Polysaccharides	Antitumor	Activities against A549, HCT-116, HepG2, HL-60, and SK-BR-3 cells lines	Lee et al. (2020) and Patel et al. (2017)
	Anandamide (endocannabinoid)	Antitumor	Inhibited on angiogenesis of highly invasive and metastatic breast cancer cells; Stimulation of non-apoptotic cell death in COX-2 overexpressed colorectal cancer cells	Lee et al. (2020) and Patel et al. (2017)
	Methanolic extract	Antioxidative	Inhibition of lipid oxidation	Villares et al. (2012)
Tuber spp.	Flavonoids	Antioxidative, anti-inflammatory, anti-mutagenic, and anticancer		Lee et al. (2020)
	Ergosterol	Antioxidant, anti-inflammatory, and antihyperlipidemic		Lee et al. (2020)
	Oleic acid	Antitumor	Suppression of overexpression of HER2; induction of cancer cell apoptosis	Lee et al. (2020)
		Hypocholesterolemic		
	L-tyrosine	Anti-depressant		Patel et al. (2017)

(Carrasco-González et al. 2017; Reis et al. 2017; Lavelli et al. 2018; Salehi 2019).

The potential of mushroom powder to enrich baked (bread, biscuits, and cakes) and extruded (breakfast cereals, snacks) cereal products with fiber for the production of fitness-promoting foods (low in calories, cholesterol, and fat) is remarkable. Gaglio et al. (2019) evaluated the effect of partially replacing wheat flour with *P. eryngii* powder (5 and 10% w/w) in baked bread; the fermentation process has not undergone any alterations, the final product had positive physical and organoleptic characteristics with the advantage of having higher concentrations of thiamin, riboflavin and pantothenic acid and, more importantly, supplied biotin, cobalamin, and cholecalciferol generally absent in wheat bread.

Another study on *P. eryngii* (Kim et al. 2010) demonstrated how biscuits supplemented with mushroom powder showed significantly increased total phenol compound content, ferric reducing antioxidant power (FRAP), and DPPH radical scavenging activity, maintaining appreciable organoleptic and rheological properties. Also, *A. bisporus* powder was evaluated by Kumar and Barmanray (2007) as a supplement for fortified biscuits, that showed a significantly higher protein content with good overall acceptability. *P. eryngii* β-glucan-rich fractions (BGRFs) have been tested as an ingredient of wheat semolina pasta (Kim et al. 2016), obtaining the best results in terms of qualitative, textural, and sensory characteristics with a concentration of 4%, in addition to higher beneficial properties.

Studies carried out by Lu et al. (2016, 2018) have shown that the inclusion of powdered *A. bisporus* and *B. edulis* mushrooms in wheat semolina allows to obtain a pasta with more fibre and less starch, therefore with a lower glycemic power and higher antioxidant properties. Equally positive results have been achieved in snack products supplemented with *A. bisporus* and *B. edulis* powder (Singla et al. 2009; Lu et al. 2020).

Mushrooms have also been tested to enrich other types of foods. Exploiting the high fiber and protein content, *A. bisporus* powder has been used for the production of functional meat products with better emulsion characteristics and textural properties (Kurt and Gençcelep 2018).

Barros et al. (2011) demonstrated that *B. edulis* extracts protect beef burgers from lipid peroxidation and also give them greater antioxidant potential, while a study by Stojković et al. (2015) revealed that the methanolic extract of *B. aureus* Schaeff. helps to increase the shelf-life of meat, protecting it from food contaminating bacteria. An interesting application of *Pleurotus* spp. concerns fortified dairy foods. A study carried out by Pelaes Vital et al. (2015) showed how adding *P. ostreatus* aqueous extract to milk leads to the production of yogurt with an increased *Streptococcus thermophiles* and *Lactobacillus bulgaricus* CFU, polyphenols content, and enhanced antioxidant activity, and improved rheological properties.

Soy milk added with polysaccharide extract of *P. eryngii* shows an increased vitality of *Bifidobacterium longum* and reduced pH during yogurt fermentation (Li and Shah 2016). The incorporation of *P. ostreatus* in the cheese mixture as a fresh and dried mushroom has resulted in cream cheese with higher ash, protein, and mineral contents, as well as an increase in lipolytic and proteolytic bacteria and excellent storage performances (Khider et al. 2017). The incorporation of *C. aegerita* powder has also proven to increase the antioxidant properties of cream cheese, as well as giving it more appreciated sensory characteristics (Petrović et al. 2015). The extract of *A. bisporus* has proved effective in preserving yogurt from the pathogen *Listeria monocytogenes* (Stojković et al. 2014). Moreover, a study conducted by Proserpio et al. (2019) involved the addition of *P. ostreatus* powder in vegetable soups, resulting in a product with a higher content of bioactive ß-glucans and good palatability at a concentration of 2%.

Although the results obtained so far are remarkably promising, much remains to be done; in addition to enlarging the fans of mushroom species potentially valuable as food fortifiers, further study is needed on various parameters such as the bioaccessibility of bioactive compounds, especially considering the different production steps that a processed product undergoes, their bioavailability, possible interactions with the food matrix and possible interferences with the bioavailability or absorption of the various nutrients. This path is even necessary so that their relevance and effectiveness can be recognized and thus ruled also from a legislative point of view, in order to achieve the important objective of large-scale marketing of healthy food products that promote physical well-being.

Conclusions

The review reveals the great potential of mushrooms in the production of mycochemicals that represent a rich source of drugs, nutraceutical, and functional food. The mycochemicals isolated and identified from mushrooms are bioactive compounds belonging to different chemical classes.

The present study describes the chemical composition of Italian wild and cultivated mushrooms as a source of bioactive metabolites for further development of drugs.

The application of mushrooms for health purposes is recent in the Western areas but still slowly growing. In European markets, nutraceuticals are not yet a widespread and established product and, in most cases, imported from Asia. Due to the vacant and imprecise regulations, we often have to deal with nutraceuticals of dubious composition and without guaranteed quality standards. Most Western countries, moreover, follow the rules of the WHO, DSHEA (Dietary

Supplement Health and Education Act), and EFSA (European Food Safety Agency) in which plant or MM extracts are dietary supplements. So clinical studies are not required before their introduction in the market. These markets, therefore, have enormous potential for development, which can only be achieved through intensive research and the spreading of knowledge to educate and raise awareness in this respect among consumers and society because very few people are still aware of the benefits and importance of MMs.

The research on medicinal mushrooms in Italy needs to undertake more extensive studies to ascertain the medicinal properties of the mushroom species.

The final objective of the newborn Italian Medicinal Mushrooms Society is to improve the quality of life and the state of health of people, also in the vision of an increasingly integrated medicine. The animal farming sector could also benefit from the inclusion of mushrooms, MMs supplements, or fortified feed in the animal diet, as well as, for example, from the possibility of using alternative and natural antibiotics and antivirals.

Besides, mushrooms represent an economic crop that fits with the circular economy and the recycling of agro-industrial wastes. Finally, mushrooms are also able to provide nutritional support in areas with malnutrition and economically depressed areas.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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