The Potential of Mushrooms in Developing Healthy Food and Biotech Products 11

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Abstract

Wild and cultivated edible and medicinal mushrooms have long been known by humans as a source of valuable food and medicines in Asian and European countries. Currently, only a small fraction of estimated fungal biodiversity has been investigated for their bioactivities and medicinal properties, while mushrooms possess a potential in pharmacy, medicine, cosmetics and food industry. In the kingdom of fungi, mushrooms taxonomically belong to phyla Basidiomycota (class Agaricomycetes) and Ascomycota (class Pezizomycetes) of the subkingdom Dikarya.

Mushrooms, such as truffles (*Tuber*), morels (*Morchella*), *Agaricus bisporus*, *Boletus edulis* and oyster mushrooms *(Pleurotus* species), are considered gourmet healthy food. Mushrooms (*Ganoderma* and *Trametes* species, *Hericium erinaceus*, *Lentinula edodes*, etc.) are also perspective sources for myco- pharmacological research as source of bioactive molecules (alkaloids, lipids, phenolics, polysaccharides, proteins, steroids, terpenoids, etc.) with more than 130 medicinal effects (anti-inflammatory, antimicrobial, antioxidant, antitumor, antiviral, cytotoxic, hepatoprotective, hypocholesterolaemic, hypoglycaemic, hypotensive, immunomodulatory, neuroprotective, etc.). There is scientific evidence of using mushroom-derived biotech products as dietary food, pharmaceuticals, cosmeceuticals and other products available in the market.

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The current review discusses recent advances in research on the biotechnological potential of mushrooms to develop novel biotech products and perspectives for their applications in human welfare.

Keywords

Biotech products · Cosmeceuticals · Medicinal · Mushrooms · Nutriceuticals · Pharmaceuticals

11.1 Introduction

Basidiomycota and Ascomycota fungi (classes Agaricomycetes and Pezizomycetes) of the subkingdom Dikarya, which develop epigeal and hypogeal fruiting bodies or mushrooms, are known to mankind not only as valuable gourmet foods, but also for their medicinal significance. They are producers of different bioactive compounds (polysaccharides, terpenoids, phenolics, polyketides, alkaloids, lectins, proteins, steroids, etc.) with potential pharmacological effects (anti-inflammatory, antioxidant, anti-proliferative, antiviral, hypocholesterolaemic, hypoglycaemic, hypotensive, immunomodulatory, neuroprotective, wound-healing, etc.) [1–34].

Mushrooms have been used by Eastern and Western civilisations since ancient times (Fig. 11.1). Among agaricomycete fungi medicinal *Ganoderma* species produce the highest diversity of pharmacologically active compounds [8, 27, 34–49].

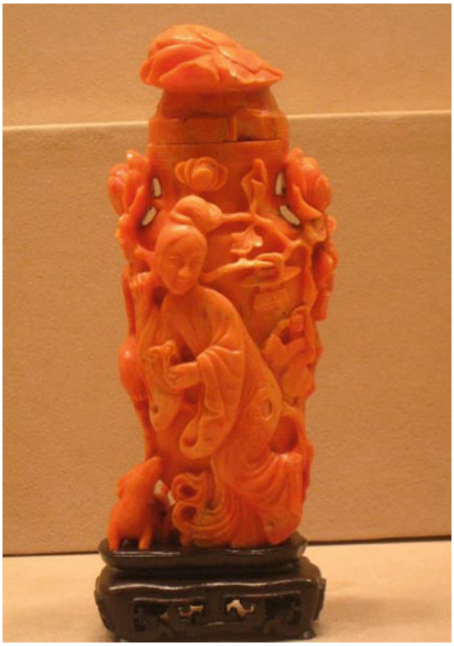

Fig. 11.1 Covered vase decorated with female figure holding Lingzhi fungus (*Ganoderma lucidum*). China, Qing Dynasty, 18th century, Worcester Art Museum, Massachusetts (from Wikimedia)

The medicinal properties were reported in edible agaricomycete oyster mushrooms (*Pleurotus cornucopiae*, *P. djamor*, *P. eryngii*, *P. giganteus*, *P. ostreatus*, *P. levis*, *P. pulmonarius*, *P. sajor-caju*, *P. tuber-regium).* They are producers of diterpenoid eryngiolide A, polysaccharides and other biomolecules, particularly with hypoglycaemic, hypocholesterolaemic, neurotoxic and cardioprotective effects [5, 8, 9, 50–65].

Highly prized edible ascomycete hypogeal mushrooms are *Tuber* (the true truffles), *Terfezia* and *Tirmania* (the desert truffles) [66], as well as *Morchella* (true morels) species which develop epigeal ascomata [67–69]. These mushrooms are biotechnologically cultivated and have significant economic value due to their excellent gastronomic and medicinal properties [5, 17, 70–75].

Currently, the pathways of biosynthesis of bioactive molecules and the related genes are largely understudied. Recent data for identification of genes and gene clusters of bioactive molecules (terpenoids, phenolics, polyketides, cyclic peptides, aegerolysins, lectins, ribosome-inactivating proteins, etc.) in medicinal and edible mushrooms has been reviewed [27, 76]. Genes for pharmacologically active molecules are found in only a restricted number of fungal taxa and species. Some medicinal mushrooms probably have genes for a higher variety of bioactive compounds than species being commonly neglected for exploitation [27, 77–79].

Meanwhile, wild and cultivable, edible and medicinal mushrooms may be considered as valuable sources to develop different health-enhancing biotech products, such as pharmaceuticals, nutraceuticals and cosmeceuticals [10, 17, 71, 80]. Advances in biology and biotechnological cultivation of selected taxonomic groups of edible and medicinal mushrooms will further assist in the production of novel mushroom-derived biotech products for human welfare.

In this chapter, we have reviewed advancements on the bioactive compounds of wild and cultivated mushrooms, besides the new perspectives for exploiting them to produce new biotech products.

11.2 Biotechnologically Important Edible and Medicinal Agaricomycete and Ascomycete Mushrooms

In 2004, Boa [81] listed 2327 species of mushroom that were consumed or have medicinal properties. This number was subsequently increased by Li et al. [82] to 2786 but warned that only 2006 could be considered as completely safe and only a few dozen are cultivated commercially.

The most popular are the white button mushroom (*Agaricus bisporus*), paddy straw mushroom (*Volvariella* spp.), oyster mushroom (*Pleurotus* spp.), enokitake mushroom (*Flammulina velutipes*), wood ear mushroom (*Auricularia* spp.) and shiitake (*Lentinula edodes*) [83–85].

Many species are known to produce bioactive metabolites, but the number of species specifically cultivated for their medicinal values is limited to fewer than a dozen species of *Ganoderma*, *Cordyceps militaris*, *Phellinus igniarius* and *Tremella*

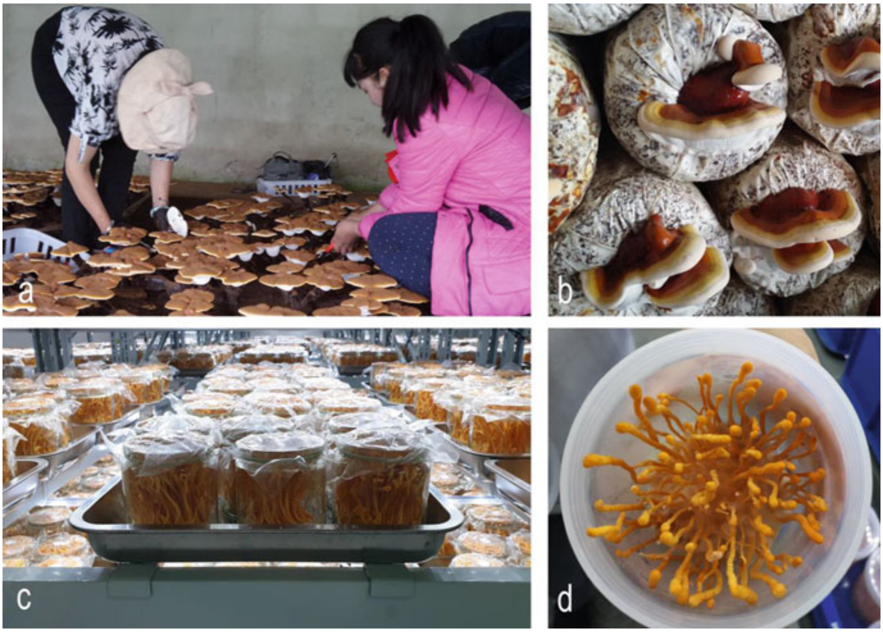

Fig. 11.2 Medicinal mushrooms cultivated in China: *Ganoderma leucocontextum* cultivation, Wei-Ping shade house, Tibet Academy of Agriculture and Animal Science (**a**, **b**), Lhasa Konen factory producing *Cordyceps militaris* (**c**, **d**) (Ian Hall pictures)

fuciformis, which are popular especially in Asian countries [17, Ian Hall and Wei Ping personal communication] (Figs. 11.2 and 11.3a).

A majority of the commercially cultivated mushrooms are saprobic feeding on dead or decaying organic matter. Their cultivation can be achieved by inoculating their mycelium in an appropriate substrate and choosing the correct combination of humidity and temperature. The cultivation of edible ectomycorrhizal mushrooms (EEM) is more complicated because most of these fungi need to establish a symbiotic relationship with a suitable host plant to complete their life cycle [87].

Nevertheless, the difficulties and most of the efforts in developing new methods for mushroom cultivation are devoted to EEM for their economic interest. In fact, the most sought-after mushrooms are EEM, like truffles (*Tuber* spp.), porcini (*Boletus edulis* s. l.), chanterelles (*Cantharellus cibarius*) and the milk-cap fungus (*Lactarius deliciosus*) [5, 17, 66, 88].

11.2.1 Nutritional Value of Edible Mushrooms

Edible mushrooms are regarded as an important food resource due to their high-quality protein content [89, 90] and their nutritional properties as excellent sources of vitamins and minerals, for their low-fat content and the large amounts of dietary

Fig. 11.3 Saprobic and ectomycorrhizal cultivated mushrooms: *Ganoderma lucidum* cultivated on agricultural wastes in the greenhouse of Bologna University (Federico Puliga picture) (**a**), *Morchella* cultivation in China (**b**), *Lactarius deliciosus* cultivation in New Zealand (Ian Hall picture) (**c**), *Tuber borchii* orchard in Bologna realized with plants inoculated with pure culture of mycelium (**d**), an ascoma found in the *T. borchii* orchard (**e**), a *Tuber melanosporum* ascoma found under a 3-year oak in South Africa (**f**)

fibre [17, 71, 91]. Although fresh mushrooms contain about 85–95% moisture content and only 3% of protein (from 19% to 37% of dry weight), they have a complete profile of essential amino acids, which can cover the requirements for adults [89].

Mushrooms can be a substitute for animal proteins, and they are particularly important in undeveloped countries, where meat is a limited resource [92]. Moreover, the use of mushroom protein source is a good solution to health and animal welfare concerns that have arisen through traditional meat production and consumption [93]. They are also an ideal food for those committed to a vegan diet and those who need a source for vitamins D and B12, which are scarce or lacking in plant-based diets [94, 95].

Many edible species contain also bioactive compounds, which have medicinal or cosmetic values (**see Parts 3 and 4**).

The button mushroom *(A. bisporus*) and shiitake (*L. edodes*), which are very popular edible mushrooms, possess nutritional proprieties and pharmacological activities [53, 96, 97]. The multiple health benefits of mushrooms are increasing their consumption per capita which has increased 21-fold over the last 56 years [82].

Morels (*Morchella* spp.), which are worldwide appreciated for their unique flavour, have been used in traditional Chinese medicine (TCM) and Western pharmacopeia for centuries, due to their health-related benefits [98]. *Lactarius deliciosus* is another excellent culinary mushroom with good nutritional proprieties which was also shown to have various pharmacological activities, including anticancer, antimicrobial, hypolipidaemic, anti-fatigue, antioxidant and immunomodulatory activities [99].

Although truffles (*Tuber* spp.) have proved to have nutritional and medicinal properties [100], their consumption is generally limited because of their prohibitive prices [17]. The most valuable species, the Italian white truffles (*Tuber magnatum*), the Périgord black truffle (*Tuber melanosporum*), bianchetto truffle (*Tuber borchii*) and Burgundy truffle (*Tuber aestivum*), are generally consumed in a few grams for flavouring other food. *Tuber magnatum* is the most expensive due to its unique taste and flavour, the limited geographical distribution and cultivation difficulties [101]. In the last season (autumn 2021), for example, its retail price ranged between 4000 and 6000 €/kg in Italy. Its prices are more higher in outside growing countries [17] or in dedicated auctions; in the white truffle auction of Alba, for example, an ascoma weighing 830 g was sold at the incredible price of 214.000 €/kg [88], https://www.rte.ie/news/newslens/2021/1115/1260065-white-truffle-italy/ in November 2021. The other truffles command lower prices which vary between 100 and 2000 €/kg depending on the species, the season, the origin and the size of the ascoma.

11.2.2 Progress in Biotechnological Cultivation and Usage

11.2.2.1 Cultivation of Saprobic Edible and Medicinal Mushrooms

The first attempts to cultivate mushrooms date back to the 600 AD when the first wood ear *Auricularia* mushroom cultivation was reported in China. However, until the advent of modern mushroom cultivation of fungus on the substrates was shear good luck and down to the spontaneous inoculation by spores [102].

Wood was the first substrate used for cultivation of ligninolytic mushrooms like *L. edodes* and *Auricularia* spp. *Agaricus bisporus* was the first mushroom species to be cultivated in compost made of a mixture of substrates like straw, corn cobs, horse and poultry manure, peat moss, gypsum and lime. The origin of biotechnological mushroom cultivation could be associated with the first use of pure cultures in *A. bisporus* by Constantin and Matruchot in 1894 [85]. Further improvement and development of modern technologies and breeding new strains enhanced mushroom productivity particularly over the past 50 years [103].

In 2020, the cultivated mushroom market was estimated at USD$ 16.7 billion (https://www.globenewswire.com/news-release/2020/04/27/2022477/0/en/Global-Mushroom cultivation-Industry-2020-to-2025-Economic-Viability-of-Mushroom-Cultivation-and-Trade-by-Developing-Countries-Presents-Opportunities.html) and is projected to witness significant growth due to the health benefits of mushroom consumption. Moreover, the necessity to find new food resources in order to satisfy the demand of increasing population and of protein from eco-sustainable sources is one of the challenges faced by the cultivation of mushrooms.

The cultivation of saprobic mushroom needs a short time, and the first production begins in a few weeks or maximum several months, depending on the fungal species and the strain, the substrate and climatic conditions [102]. Moreover, mushroom cultivation could utilize different agrowastes as substrates contributing to generating economic development in rural territories. The capability of mushrooms to develop on different wastes makes them the ideal candidates for developing circular economy systems. In this process, the use of the digestate, the material remaining after the anaerobic digestion of a biodegradable feedstock from biogas plants, as substrate for mushroom cultivation is an interesting alternative. Digestate is typically separated mechanically into liquid and solid fractions which are both commonly used as fertilizers [104, 105]. However, there are concerns in their direct use as fertilizer because they are a source of greenhouse gases (N_2O and CH_4), although less than the untreated biomass [106, 107]. Moreover, the solid fraction of digestate from agricultural feedstocks still contain recalcitrant organic compounds prevalent in the lignocellulosic components, which are not degraded during the anaerobic fermentation but may be an excellent carbon source for ligninolytic mushrooms. Fornito et al. [108] showed that *Cyclocybe aegerita*, *P. cornucopiae* and *P. ostreatus* are able to grow and fructify on corn digestate with a biological efficiency (19%, 80% and 103.3%, respectively) similar to those obtained on wood-straw-based traditional substrates. On the other hand, also the liquid fraction of digestate was successfully used in spruce sawdust fermentation for cultivation of *P. ostreatus*, *P. eryngii* and *G. lucidum* [109]. After mushroom cultivation, the spent substrate is useful as fertilizer due to the presence of nutrients and its protective activity against soil-borne diseases. In fact, it has been shown that the changes in microbial composition during mushroom mycelial growth in the substrate and the subsequent increased abundance of beneficial microbes improve its suppressive capacity against several pathogens [110, 111]. Alternatively, the spent substrate after mushroom lignin degradation can be reused in plants for biogas production or for extraction of bioactive molecules, such as enzymes, or for the extraction of chitin or as feed of animals and in particular invertebrates such as insects or earthworms [108, 112–115]. Worldwide new species and new varieties of mushrooms are being annually added to meet the increasing demand for new mushroom products.

One of the most recent successfully cultivated mushroom is the morel (*Morchella* spp.). In recent years, the outdoor cultivation of true morels has been successful and expanded to a large scale in China after more than 100 years of failures [116] (Fig. 11.3b). The species currently cultivated in China are the saprobic species, the black morels in the Elata clade, in particular *M. importuna*, *M. sextelata* and *M. eximia* [117].

Despite morels have been routinely cultivated in ordinary farmland soils, sometimes there are unsuccessful cases for unknown reasons. These failures could be due to unfavourable soil microbiota [117] or for some genetic and biological aspects which remain poorly understood. Several phases of the life cycle of morels have been not completely unravelled, like the mechanisms of fertilization, including the role of microconidia, the morphogenesis of microsclerotia and factors which trigger fruiting [118, 119].

Moreover, some *Morchella* species in the Esculenta clade establish trophic interactions with the roots of the plants, which at the same time resemble mycorrhizal, saprobic or pathogenic phases; this has not been adequately understood [120, 121]. Fundamental research on morels is obviously necessary to fill the knowledge gaps and for technological progress of *Morchella* for its artificial cultivation [118].

Cordyceps militaris is a medicinal fungus which in nature infects the larvae of lepidopteran host, and over the past decade it has been cultivated in China on artificial media (Fig. 11.2c, d). Several studies were carried out to improve the cultivation medium in order to increase fruiting body formation and extend its bioactive compounds, especially cordycepin [122, 123]. However, the most important of the entomogenous fungi is *Ophiocordyceps sinensis* which is collected in the high grassland areas primarily of Tibet, Nepal and Bhutan where it sells at very low prices. Recently the cultivation of *O. sinensis* fruiting bodies on artificial media on the host caterpillar *Thitarodes* sp. has been successfully established in laboratories of southern China where environmental conditions are mimicked in the wild Tibetan alpine meadows [124].

Ophiocordyceps robertsii is another but lesser known medicinal endoparasitic fungus of insects. Traditionally it is used by New Zealand Maori to produce a dye to colour the moko (body and face carving). A permanent culture was first developed by Wei-Ping Xiong and Ian Hall in 2019 (personal communication) and is now awaiting further study.

Recently, the submerged cultivation of medicinal mushrooms has shown to be a promising and reproducible alternative for the production of mushroom metabolites [125]. In submerged cultivation the mycelium of mushrooms is grown in a liquid medium in which nutrients are dissolved and oxygen supply is reinforced by agitation [126]. It can be achieved in flasks or bioreactor vessels which are more suitable at industrial levels. Using this technique, physical (temperature, aeration, agitation, etc.) and chemical (pH, medium composition, etc.) factors could be controlled ensuring biomass quality and standardization of metabolite production and opening up the possibility to obtain safely bioactive compounds by the inedible mushrooms [126].

11.2.2.2 Cultivation of Edible Ectomycorrhizal Mushrooms

The edible ectomycorrhizal mushrooms (EEM) live in an intimate association with the roots of suitable trees and shrubs in temperate, boreal and, to a lesser extent, tropical forests [127, 128] providing the host plant with soil nutrients and water and receiving in exchange carbon. The lifestyle of EEM complicates the methods for cultivating these fungi and extends the time of the first production.

Among these species, *T. melanosporum* (the Périgord black truffle) was the first EEM fungus to be successfully cultivated (Fig. 11.3f). Its cultivation was introduced in the early 1800s by the French farmer Joseph Talon. His method was quite simple and consisted of sowing acorns in soils suitable for truffle growth. Truffle cultivation improved considerably over last 70 years when the modern methods of cultivation were introduced. This consisted of inoculating seedlings or cuttings with truffle in greenhouses and then transplanting them in suitable sites. Initially, three different methods of inoculation were proposed: spore inoculum, mother plant technique and mycelial inoculation. Spore inoculum involves inoculating sterile young plants, a few months old, with truffle spores which are obtained by grinding truffles that are fresh, refrigerated or stored in moist sand, dried or frozen [129, 130]. The mother plant technique involves planting seedlings into the rooting zone of a plant known to be mycorrhized with the required truffle and mycelial inoculation using pure culture of *Tuber* mycelium. The mother plant technique was soon abandoned because of the high risk to spread contaminant ectomycorrhizal fungal species accidentally present on the mother plant. The mycelial inoculation was used only for experimental purposes and to overcome the difficulties in obtaining pure cultures of *Tuber* mycelium [130]. Thus, spore inoculum has become the method used by all the companies producing *Tuber* plants because it is simple and effective for most of the species of valuable *Tuber* spp. However, due to the high cost of *Tuber* ascomata, batches of truffles, which contain small, broken and often completely rotten ascomata, are often used as inoculum. That makes it very difficult for identification of any ascoma, and those of less valuable *Tuber* species can escape the control and are included in the inoculum. That increase the risk of contamination of the root of the plants with undesired mycorrhizal species, and, for example, plants which should be mycorrhized with *T. melanosporum* are instead infected with the similar but less valuable *Tuber brumale* or with other worthless *Tuber* spp. Fortunately, in the last 30 years, morphological and molecular methods to identify ascomata and mycorrhizas have been perfected [86, 130, 131]. In France and in some regions of Italy, both the ascomata used as inoculum and the mycorrhizas are routinely checked to avoid the production and commercialization of plants carrying mycorrhizas different from those declared by the nursery [132–134].

Since the truffle spores are derived by meiosis of a virtual zygote, they are genetically different and of unknown genotypes [135]. That could be a potential adaptive advantage when the soil and climatic condition of the plantation site are unknown but do not allow a genetic selection of the best fungal genotypes for each specific ecological condition and the possibility to improve the productive performances of truffle orchards. The recent positive results obtained in inoculating plants with mycelial pure culture and the first production obtained by planting seedlings inoculated with different mycelial strains of *T. borchii* open up the possibility of commercially applying this method [136] (Fig. 11.3d and e). This will allow selecting the strains producing ascoma of best aroma composition or more adaptable to climatic conditions, characters that seem to be genetically controlled [137, 138].

Mycelial inoculation is also applied to produce *Lactarius deliciosus* mycorrhizal plants. Its cultivation was introduced in New Zealand in the late 1990s; it spread later to Europe and was introduced into China around 2014. The fruiting body production has been estimated to be as high as 1–3 tonnes per hectare in New Zealand [139] (Fig. 11.3c).

11.3 Mushroom-Derived Bioactive Molecules

11.3.1 Polysaccharides

The polysaccharides (β-1,3 and β-1,6 glucans) are one of the major bioactive molecules in agaricomycete and ascomycetes mushrooms with significant immunomodulatory, antioxidant, antimicrobial and other medicinal effects. Fungal polysaccharides (β-glucans) lentinan, krestin, schizophyllan and pleuran with commercial application were extracted from *L. edodes*, *P. ostreatus*, *Trametes versicolor* and *Schizophyllum commune* [5, 8, 140–150].

The β-glucans and their bioactivity were also reported from other mushrooms, such as *A. bisporus*, *Auricularia auricula-judae*, *Ganoderma* spp. and *Suillus granulatus* [151, 152]. *Ganoderma* polysaccharides have particularly been suggested as a healthy dietary food for cancer patients [153].

11.3.2 Terpenoids and Phenolics

Inedible and edible medicinal mushrooms may be sources of phenolic compounds and derivatives. Fungal phenolics possess anti-carcinogenic, anti-inflammatory, antioxidant and anti-mutagenic effects [8, 26, 154–156].

Recent studies showed that *Agaricus campestris*, *A. bisporus*, *B. edulis*, *C. cibarius*, *Grifola frondosa*, *Macrolepiota procera*, *P. ostreatus*, *Russula alutacea*, *R. vesca*, *S. commune*, *T. versicolor*, *Trametes gibbosa* and *Volvariella volvacea* were considered as source of bioactive phenolics (flavonoids, β-carotene, lycopene, coumarins, phenolic acids) with different therapeutic effects [156–

164]. Among these, species from order Boletales (*Boletopsis leucomelas*, *Boletus grisea*, *Paxillus curtisii* and *P. panuoides)* are especially rich in pigments of various phenolic origins for potential medicinal exploitation [165].

A variety of bioactive terpenoids represents another unexploited group of lipid derivatives in mushrooms. The chemical structures of several fungal terpenoids have been determined [166, 167].

Edible and medicinal mushrooms, such as *Ganoderma* spp., *Pleurotus* spp., *Fomitopsis palustris*, *Fomitopsis betulina* and *Tricholoma pardinum*, contain lanostane triterpenoids (pardinols A–H and saponaceol B) with antibacterial, anti-mitotic, antiviral, cytotoxic, immunomodulatory and other therapeutic effects [8, 46, 147, 168–174].

The sesquiterpenoid eremophilanes with antibacterial, anti-inflammatory, anti-obesity, antiviral and cytotoxic effects were detected in *Xylaria* mushrooms [175], as well as in submerged cultures of *Inonotus* sp. [176]. The ergostane and lanostane triterpenoids were identified in *Antrodia cinnamomea* [177]. Cytotoxic sesquiterpenes derived from the fruiting bodies of *Russula* spp. [166], lanostane triterpenoids from *Piptoporus betulinus* [178] and hypoglycaemic triterpenes from medicinal mushroom *Wolfiporia cocos* [179] have also been reported. Bioactive meroterpenoid suillin and related pigments with antimicrobial, anti-mitogenic, anti-oxidant and apoptosis-inducing effects against human cancer cell lines were detected in *Suillus placidus* [180] and *Suillus bovines* [181]. Suillin was suggested as an effective agent to treat liver cancer. A new lipid peroxidation inhibitor bolegrevilol was detected in the edible mushroom *Suillus grevillei* [182].

11.3.3 Lipids and Sterols

Evaluation of lipid and sterol content (ergosterol, fungisterol, lanosterol, cholesterol, cerevisterol and derivatives) of mushrooms from *Amanita*, *Boletus*, *Lactarius*, *Suillus*, *Tricholoma*, *Tuber* and other genera showed that they differ in total lipid quantities and fatty acid composition [5, 8, 17, 163, 183]. Among 20 different fatty acids present in mushrooms, the more common are oleic, linoleic and palmitic acids followed by stearic acid. Mono- and polyunsaturated fatty acids, including oleic and linoleic, are considered as valuable food supplements for human diet and nutrition [6].

Steroids, lanostane and ceramide derivatives were originally isolated and identified from the methanolic extract of agaricomycete species *Scleroderma bovista* [184]. Among these, the lanostane derivatives showed significant anti-proliferative properties against human cancer cell lines HeLa, A2780, MDA-MB-231 and MCF-7.

11.3.4 Lectins

Mushrooms possess bioactive proteins, such as lectins, ribosome-inactivating proteins and fungal immunomodulatory proteins (FIPs).

Lectins are non-enzymatic proteins that specifically interact with sugars. They possess immunomodulatory, mitogenic, cytotoxic, antitumor and antimicrobial activities making them as potential therapeutic agents. Different lectins were isolated from fruiting bodies and mycelia of Agaricomycetes genera *Amanita*, *Boletus*, *Laccaria*, *Lactarius*, *Russula* and *Tricholoma* [185, 186]. Lectins with immunomodulating and hypotensive effects were isolated from *Tricholoma mognolicum* [187].

The potent antitumor and anti-proliferative lectins (homodimeric, 60 kDa) towards human hepatoma HepG2 and human breast cancer MCF-7 cells were isolated from *Russula lepida* and *R. delica* [188, 189]. These lectins against murine leukemic L1210 cells from *Lactarius flavidulus* [190] and haemolytic toxic lectin against murine and human leukemic cell lines were obtained from *Amanita virosa* [191]. Antiviral and anti-proliferative lectin derived from *B. edulis* inhibited human viral reverse transcriptase, and the proliferation of several malignant cell lines, by binding the neoplastic cell-specific T-antigen disaccharide Gal β1-3GalNAc, has been reported [189, 192]. A lectin from *Xerocomus (= Boletus) spadiceus* induced a mitogenic response in murine splenocytes [193], while ingestion of lectins from *Boletus venenatus* showed fatal toxicity in mice [194]. Lectin TBF-1 specific to the hypogeal ascomata was identified in *T. borchii* [70].

The galectins are a class of bioactive proteins that bind specifically to β-galactoside sugars and have been described in Agaricomycetes *Coprinopsis cinerea* and *Laccaria amethystina* [195, 196].

11.4 Medicinal Properties of Mushrooms

Mushrooms as medicines were recognized nearly 2000 years ago. They are rich source of pharmaceutical constituents for different exploration potential. Traditional medicine and scientific research data showed that both edible and inedible mushrooms possess promising pharmacological potential (antimicrobial, anti-inflammatory, antioxidant, antiviral, cardio-, hepato- and neuroprotective, cytotoxic, hypotensive, immunomodulatory, etc.) and may be considered sources of myco-pharmaceuticals, nutriceuticals or dietary supplements and cosmeceuticals [1, 5, 8, 9, 15, 17, 19, 28, 31–33, 140].

Edible medicinal agaricoid *Pleurotus* mushrooms are mainly known due to their hypoglycaemic, hypocholesterolaemic, neurotoxic and cardioprotective properties [5, 8, 9, 17, 50, 53–57, 59, 60].

The pharmacological potential of inedible bracket fungi, such as *Ganoderma* spp., *T. versicolor*, *Phellinus linteus*, *G. frondosa*, *Fomes fomentarius* and *Fomitopsis pinicola*, could be used to develop health-enhancing functional food products [8, 13, 197–200]. The extracts from mycelia and ascomata of the most priced medicinal ascomycete mushroom *Ophiocordyceps sinensis* and *C. militaris* possess immunomodulatory and cell apoptosis-inducing activities [201, 202].

Edible ascomycete mushrooms, such as morels and truffles, besides their excellent culinary values, have medicinal properties due to bioactive compounds, dietary fibres, vitamins, polysaccharides, proteins and trace elements. The fruiting bodies and mycelium of *M. esculenta* possess antioxidant activity because of linoleic acid and beta-carotene contents [67]. Polysaccharides isolated from *M. esculenta* showed anti-inflammatory, antitumor, antimicrobial and wound-healing properties [68, 203]. Many truffles and truffle-like fungi (*Picoa* spp., *Terfezia boudieri*, *T. claveryi*, *Tirmania nivea*, *T. pinoyi*, *T. melanosporum*, *Tuber indicum*, *T. sinense*, *T. aestivum* and *T. himalayense*) possess antioxidant, antimicrobial, anti-mutagenic, antitumor and neuroprotective properties [5, 72–75].

11.4.1 Antimicrobial and Antiviral Activity

The prevention and treatment of bacterial, fungal and viral diseases remain a serious problem in modern medicine. Agaricomycete and ascomycete mushrooms are known as active producers of antimicrobial and antiviral compounds: velutin and flammulin from *F. velutipes*; ganodermadiol, ganomycin and ganoderiol from *G. lucidum*; lentinan from *L. edodes*; schizophyllan from *S. commune*; krestin from *T. versicolor*; and others [8, 204–211].

The antimicrobial activities of extracts from *A. bisporus* and *T. gibbosa*, against Gram-positive and Gram-negative bacteria, as well as phytopathogenic and keratinophilic fungi, have been reported [212]. The bacteriostatic and bacteriocidical effects against *Helicobacter pylori* bacteria were revealed using ethanolic extracts of *A. bisporus*, *Coprinus comatus*, *C. militaris*, *F. velutipes*, *G. lucidum*, *G. frondosa*, *Hericium erinaceus*, *Hypsizygus marmoreus*, *Ganoderma applanatum*, *L. edodes*, *Ph. igniarius*, *P. eryngii* and *P. ostreatus* [37, 213, 214].

The aqueous extracts of edible ascomycete mushrooms *Picoa juniperi*, *T. claveryi* and *T. pinoyi* (desert truffles) showed in vitro antibacterial activities against Gram-positive human pathogenic reference strain *Staphylococcus aureus* ATCC 29213 and Gram-negative *Pseudomonas aeruginosa* strain ATCC 15442. The acid-soluble protein extracts of *T. pinoyi* and *T. claveryi* have minimum inhibitory concentrations (MIC) of 50 μg/mL against tested pathogens [215].

The antiviral activities of edible agaricoid mushrooms *B. edulis*, *L. edodes*, *P. ostreatus* and *Lignosus rhinocerotis* against herpes simplex virus (HSV) type 1, human papillomavirus (HPV) and dengue virus type-2 (DENV-2) were reported [209, 216, 217]. Extracts from mycelia of polyporoid species *Daedaleopsis confragosa*, *Datronia mollis*, *Ischnoderma benzoinum*, *Laricifomes officinalis*, *Lenzites betulina*, *T. gibbosa* and *T. versicolor* showed antiviral activity against influenza A virus (H_5N_1 and H_3N_2) [218]. It has been revealed that polysaccharides, glycoproteins, melanins, nucleosides, proteins and terpenoids from several Agaricomycetes exhibit antiviral effects against hepatitis, herpes, human immunodeficiency virus (HIV), influenza, West Nile viruses as well as orthopox viruses, including the variola virus [211]. Tested mushrooms were suggested as perspective agents to develop novel antiviral myco-pharmaceuticals.

Mycelia of several polyporoid *(Auriporia aurea*, *F. fomentarius* and *T. versicolor)* and agaricoid (*P. ostreatus*, *P. eryngii*, *F. velutipes* and *Lyophyllum shimeji)* mushrooms inhibited the reproduction of influenza A (H_1N_1) and herpes simplex (HSV-2) viruses [207]. Among tested samples *T. versicolor* 353 strain was detected as a source of low toxicity antiviral agent. The antiviral activity was reported in ascomycete *Morchella conica*, *M. esculenta* and *T. boudieri* [205]. However, antiviral mushroom-derived bioactive molecules and mechanisms of their action remain subjects for further research.

Several bioactive compounds of mushrooms (polysaccharides, proteins, terpenes, melanins, etc.) are exhibiting an antiviral activity with combination of immunomodulatory, immunosuppressive and anti-inflammatory properties which may be safely used in the prevention and treatment of respiratory viral infections [211, 219–221].

The coronavirus disease 2019 (COVID-19), a de novo pattern of pneumonia, has caused pandemic caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). COVID-19 is associated with several comorbidities; therefore, different preventive and curing therapies should be applied. Medicinal mushrooms may be a good candidate for preventive and therapeutic use against COVID-19 [61, 222]. The combination of immune cell activation with a moderate impact on inflammatory cytokines may be beneficial in patients with COVID-19 [223].

Rahman and coauthors [61] described Reishi or Lingzhi (*G. lucidum*) as the most suitable anti-COVID agent. Another potential candidate against the SARS-CoV-2 virus may be chaga mushroom (*I. obliquus*) commonly grown in Asia, Europe and North America. This bracket fungus is characterized by a wide range of antiviral compounds and it is used as a raw material in various therapies. Antiviral melanin from wild and cultivated *I. obliquus* strain is effective against the pandemic strain of influenza virus A/California/07/09 (H1N1 pdm09) [221, 224]. Other medicinal mushrooms are also promising; for example, cell-based studies show a reduction in the production of proinflammatory cytokines by β-glucan-rich extracts obtained from *L. edodes* in COVID-19 patients. Fruiting bodies and mycelia of agaricomycete mushrooms *Agaricus blazei* (AbM), *H. erinaceus* and *G. frondosa* have been reported as antiviral, antibacterial, immunomodulatory and anti-inflammatory agents and may be suited for treatment of pneumonia caused by COVID-19 infection. A mushroom extract-based biotech product Andosan™ containing extracts from these fungi has shown significant antibacterial and anti-inflammatory effects and increased survival in mice with pneumococcal sepsis. Therefore it can be suggested as a prophylactic or therapeutic agent against severe pneumonia that often complicates COVID-19 infection [222]. However, data with chemically well-defined fungal preparations to support COVID-19 patients are necessary to further evaluate for their medicinal properties at certain stages of the disease [223].

11.4.2 Immunomodulatory and Antitumor

The immunomodulatory activity is the most prominent medicinal property of mushrooms [8, 33, 47, 140, 153, 225–228]. β-Glucans schizophyllan, lentinan, krestin and grifolan, as well as proteins, glycoproteins and lipopolysaccharide (LPS), have been identified as immunomodulators. They are widely used in the treatment of several types of cancer [8, 33, 206]. Mushroom glucans prevent oncogenesis and exhibit antitumor effects by inducing immune response in the host [142, 144, 229–232]. They may also modify cell cycle-regulating genes and induce apoptosis [233].

Glucan grifolan or maitake D-fraction isolated from *G. frondosa* stimulated the production of granulocyte colony-stimulating factor (CSF) and recovery of peripheral blood leukocytes [234] and showed anti-metastatic effect [233, 235]. The immunomodulatory, cytotoxic and apoptosis-inducing effects of β-glucans from *Ganoderma* spp., *Inonotus obliquus* (Chaga mushroom) and *W. cocos* are supported by the presence of triterpenoids [227, 236]. The immunomodulatory polysaccharides isolated from *Macrocybe titans* and *Collybia radicata* were suggested for further application as food and pharmaceutical agents [228, 237]. A ganoderic acid and FIPs with anti-proliferative and apoptosis-inducing activities have been reported in different *Ganoderma* mushrooms [47, 238, 239].

Immunomodulatory, anticancer and anti-inflammatory effects were revealed in medicinal mushrooms *B. edulis* [240], *Coriolus* (syn. *Trametes*) *versicolor* [241], *Inonotus hispidus* [242], *L. edodes* [243], *P. ostreatus* [244] and *Taiwanofungus camphoratus* [245]. Further myco-pharmacological studies will promote the transfer of mushroom-derived biomolecules to clinically effective therapeutics [8, 140, 246].

11.4.3 Antioxidant and Anti-inflammatory

Edible and medicinal mushrooms are recognized as a natural source of phenolics, polysaccharides and terpenoids with antioxidant and anti-inflammatory effects [8, 19, 21, 43, 62, 153, 247–260].

The antioxidant activity due to high content in total phenols and flavonoids was revealed in methanolic extracts of 29 wild edible mushrooms. The extracts of *Cantharellus cibarius*, *C. cinereus*, *Craterellus cornucopioides* and *Hydnum repandum* exhibited high cytotoxicity and induced apoptosis-necrosis in A549 cells. As an active ingredient, anti-proliferative piceatannol was originally reported in tested species [261].

Fermentation broth samples of three *Ganoderma* spp. contain a large number of phenolic derivatives and flavonoids with antioxidant and antimicrobial activities and were suggested as source of antioxidant and antimicrobial agents [141, 251]. It was shown that the treatment with extract of *A. brasiliensis* improved the antioxidant defences, diminished by rheumatoid arthritis [252].

A significant antioxidant effect was revealed in methanolic extracts from mycelia of *Pleurotus* spp. The usage of mycelial extracts as dietary supplement can prevent the process of oxidative damage [50, 253].

Antioxidant and anti-proliferative effects were revealed in Boletales *(B. edulis)* and other edible and medicinal agaricoid mushrooms (*A. subrufescens*, *A. auricular-judae*, *F. velutipes*, *Ganoderma capense*, *H. erinaceus*, *L. edodes*, *Pleurotus djamor*, *S. luteus* and *W. cocos)* [40, 49, 249, 256, 258, 262–264].

Antioxidant and anti-aging activities of polysaccharides isolated from ascomycete fungus *Cordyceps cicadae* have recently been observed [265]. Anti-inflammatory effect of polysaccharides, as well as aqueous, ethanolic and methanolic extracts from *Lactarius rufus* [266], *L. edodes* [267], *P. giganteus* [51] and *L. rhinocerotis* [268], was revealed.

Further studies are needed to elucidate the antioxidant and anti-inflammatory potential of mushrooms and their usage as healthy food biotech products due to the synergistic effects of all the bioactive molecules present (polyphenols, polysaccharides, vitamins, carotenoids and minerals) [144, 155].

11.4.4 Anti-metabolic Syndrome

The metabolic syndrome (MS) is a pathological condition including hyperglycaemia, hyperlipidaemia, insulin resistance, obesity and hypertension. These symptoms are important signs of type 2 diabetes and increase the risk of cardiovascular diseases (CVD) [9, 18, 22, 269–271].

Currently, the existing drugs such as insulin, statins and angiotensin-converting enzyme (ACE) inhibitors used for the treatment of MS have limited therapeutic efficacy and several side effects. There are other drugs (e.g., HMG-CoA reductase, aldose reductase and α-glucosidase) which are also used in MS therapy. Nevertheless, considerable effort has been made to develop new preparations and pharmaceuticals to ameliorate the glucose and lipid metabolism without significant side effects.

Mushroom-rich nutrition is regarded as dietary healthy food to prevent and cure MS pathology. Recent studies revealed huge anti-MS potential in *A. bisporus*, *A. brasiliensis*, *G. lucidum*, *G. frondosa*, *H. erinaceous*, *Ph. linteus* and *Pleurotus* spp. [3, 8, 19, 38, 272–276]. Moreover, the eritadenine extracted from *L. edodes* has been identified as an anti-atherogenic agent with ACE-inhibitory activity [277]. New bioactive compounds including lanostane triterpenoids isolated from *G. lucidum* were suggested to control hyperglycaemia and hyperlipidaemia, as well as to cure the MS [35].

The hypolipidaemic and hypoglycaemic properties of several agaricoid and polyporoid species, such as *Calocybe indica*, *P. ostreatus*, *P. giganteus*, *V. volvacea* and *Inocutis levis*, have been reported [271, 278–280]. However, data concerning the molecular mechanisms of their therapeutic action are still not sufficient [281].

Hypolipidaemic and hypoglycaemic properties of agaricomycete and ascomycete mushrooms allow using them as a healthy food to prevent CVD [9]. Among these species *G. frondosa*, *L. edodes* and *P. ostreatus* are almost ideal for low-calorie diets due to a high content of fibre, proteins and microelements [282, 283].

Recent studies have demonstrated that bioactive molecules (i.e., terpenoids, peptides, isoflavones as biochanin A and formononetin, lanosterone derivative as fomiroid A and lovastatin) derived from *Boletus aestivalis*, *Clitocybe nuda*, *G. lucidum*, *G. frondosa*, *H. marmoreus*, *L. edodes* and *Pleurotus* spp. can regulate the levels of low, high-density lipoproteins, total cholesterol and fasting triglycerides and prevent the development of arterial hypertension, oxidative stress, diabetes and CVD [8, 9, 284].

11.4.5 Neuroprotective

The age-related neurodegenerative diseases (NDD) are affecting millions of people worldwide. Oxidative stress, mitochondrial dysfunction, inflammation and axonal transport deficits play a significant role in the development of NDD. The general strategies to prevent the progression of NDD are physical activity, stress-free lifestyle and healthy diet, enriched with different natural supplements. Therefore, it is urgent to explore natural neuroprotective agents, including myco-pharmaceuticals and myco-food to prevent and mitigate development and symptoms of age-related NDD [15, 16, 285, 286].

Hericium species [*H. coralloides*, *H. erinaceus*, *H. flagellum* (syn. *H. alpestre*)] are among the highly praised edible mushrooms, as producers of neuroprotective biomolecules, such as hericerin, hericenones, erinacines and corallocins [16, 274, 287–290].

Several medicinal mushrooms, such as *Antrodia camphorate* and *G. lucidum*, possess neurotrophic effects due to chemical contents of bioactive compounds (alkaloids, fatty acids, lectins, lipids, polysaccharides, phenolics, polyketides, terpenoids, sterols, etc.). They are considered natural agents in the management of different neurodegenerative disorders, including depression, Alzheimer's, Huntington's and Parkinson's diseases [16, 291–296].

The role of edible and medicinal agaricomycete and ascomycete mushrooms (*A. bisporus*, *A. brasiliensis*, *C. militaris*, *G. lucidum*, *G. frondosa*, *H. erinaceus*, *L. edod*es, *Lignosus rhinocerus*, *O. sinensis*, *P. giganteus*, *T. versicolor*, *Termitomyces albuminosus* and *T. fuciformis*) in the treatment of NDD and the study of molecular mechanisms of neuroprotective and cognitive effects have recently been reported [16, 296–299].

Further efforts are warranted to discover the neuroprotective mechanism of mushroom-derived biomolecules [8, 16, 285, 286, 300].

11.5 Advances in Production of Mushroom-Derived Biotech Products

A wide spectrum of bioactivities of mushroom-derived compounds could be used to develop health-enhancing biotech products for human and animal use [17, 301, 302]. Mushroom pharmaceuticals, nutriceuticals, nutraceuticals and cosmeceuticals possess different therapeutic effects, such as anticancer, antioxidant, anti-inflammatory, immunomodulatory, cardioprotective, neuroprotective, etc. [8–10, 14–16, 274, 287, 294, 295, 303–306].

Several edible and medicinal mushrooms (*A. subrufescens*, *Ganoderma* spp., *G. frondosa*, *H. erinaceus*, *L. edodes*, *Laetiporus sulphureus*, *Ph. linteus*, *P. ostreatus* and others) are considered a rich source of innovative biomedical compounds to develop myco-pharmaceuticals. They can be extracted not only from fruiting bodies but also from mycelial biomass and cultural broth [5, 8, 14, 17, 62, 301, 307, 308].

Nutraceutical ("nutrition" and "pharmaceuticals") is any substance which may be considered a food or part of the food and provides some medical or health-enhancing effects, including prevention and curing of the diseases. Agaricomycete and ascomycete mushrooms (*A. bisporus*, *Auricularia* spp., *Pleurotus* spp., *B. edulis*, *F. velutipes*, *L. edodes*, *V. volvacea*, *M. esculenta*, *T. borchii*, *T. melanosporum,* etc.) due to their volatile compounds are regarded not only as gourmet food but also nutraceuticals with high nutritional and dietary values for human wellness [5, 17, 283, 295, 310, 312, 321, 328, 330, 338, 341, 343, 344].

The nutraceutical and pharmaceutical potential of mushroom bioactive molecules derived from *A. bisporus* (lectins), *A. auricula-judae* (acidic polysaccharides), *G. frondosa* (grifolan, lectin), *Lentinus* (= *Pleurotus*) *sajor-caju* (lovastatin) and *O. sinensis* (cordycepin) has been evaluated. Several nutraceutical and pharmaceutical biotech products derived from these fungi were approved for clinical use in many countries [316, 326, 332, 339, 344].

The mushroom nutraceuticals and dietary supplements can be obtained from fruiting bodies, mycelia, sclerotia and spore powder. The supplementation of different types of health food products (dairy beverages, yogurts, bread, pasta, beer) with mushrooms increases their quality and nutritional values [17, 71, 80, 315, 317, 319, 320, 322, 324, 333, 344, 346, 347, 353].

Several white-rot agaricoid, polyporoid, hymenochaetoid and russoloid Agaricomycetes fungi are used in production of beverages, wine, beer, cosmeceuticals, prebiotics, functional foods and nutraceuticals, for stabilisation and delignification of feedstock, as well as in baking [340].

It was showed that polysaccharides isolated from cultivated ascomycete fungus *O. sinensis* modulate intestinal mucosal immunity and gut microbiota in cyclophosphamide-treated mice [352]. Agaricomycetes species *C. versicolor*, *G. lucidum*, *G. frondosa*, *H. erinaceus*, *I. obliquus* and *L. edodes* have also been reported as prebiotics due to fungal glucans regulating gut microbiota in the host [226, 327, 336, 345].

The vitamin-enriched mushroom dietary food could play an important role in the prevention of chronic diseases [334].

Currently, mycelial cultivation industry is progressing, and the production of mycelium-derived mushroom biotech products is constantly improving [125, 142, 143, 313]. Recent progress in fungal biology and biotechnology, genomics, proteomics and myco-pharmacology has contributed to usage of agaricomycete and ascomycete mushrooms in medicine and food industries [335].

Cosmeceuticals are the products between cosmetics and pharmaceuticals containing bioingredients with anti-aging, anti-inflammatory, antioxidant and anti-pigmentative effects.

Currently, the cosmetic industry is in a constant search for anti-aging (anti-collagenase, anti-elastase, anti-hyaluronidase, anti-inflammatory, antioxidant and anti-tyrosinase) biomolecules or extracts. Edible and medicinal mushrooms as unlimited source of bioactive compounds (phenolics, glucans and other polysaccharides, terpenoids) may be considered as valuable sources of cosmetic bioingredients used in formulation of skin and hair care organic cosmeceuticals, nutriceuticals and nutraceuticals [1, 10, 17, 30, 259, 311, 348, 351].

Wild or cultivable mushrooms, such as *A. subrufescens*, *A. bisporus*, *A. auricula-judae*, *O. sinensis*, *Ganoderma lingzhi*, *G. lucidum*, *G. frondosa*, *Hypsizygus ulmarius*, *I. obliquus*, *L. edodes*, *Polyporus* and *Phellinus* species, *S. commune*, *T. versicolor*, *T. fuciformis* and *Tuber* spp., are also incorporated in the formulation of many cosmetic products [1, 10, 11, 17, 29, 30, 325, 342, 351].

Numerous mushroom-derived cosmeceuticals (applied topically, i.e. creams, lotions and ointments) and nutricosmetics (administered *per os*) with different formulations are available in the market. Their usage is significantly high due to minimal regulation and safety compared to traditional drugs. The cosmetic brands used in mushroom ingredients are Bliss (Hut.com Ltd, Cheshire, UK), La Roche (F. Hoffmann-La Roche Ltd, Basel, Switzerland), Nu-Derm (Obagi Medical Products Inc., Irvine, CA, USA), SensiClear (Mission Scientific Skincare Inc., Gold River, CA, USA) and others [10, 17, 351].

11.5.1 Medicinal Mushrooms in Animal Alimentation

Recently, mushrooms have been receiving a great attention as supplement in animal alimentation [314]. Edible and medicinal mushrooms are used as organic food additives for pets for preventing cancer and supporting their optimal immune health [34], https://thenaturalpetdoctor.com/mushrooms-to-naturally-improve-pet-health/). Mushrooms, particularly *Ganoderma* and *Pleurotus* species, can be successfully used in poultry diets for improving the performance of broilers [323, 329]. They have different beneficial effects such as immunomodulatory, antibacterial, antiviral and anti-parasitic and can be used as growth promoters or as an alternative to antibiotics [329].

Infectious bursal disease (IBD), also called Gumboro disease, is one of the most widespread immunosuppressive avian diseases, caused by a highly contagious virus.

IBD vaccination has been used in the chicken industry worldwide to prevent IBD infection. However, IBD vaccines do not completely protect chicken against infectious diseases due to immunosuppressive effects [349]. Ogbe and collaborators [337] showed that the inclusion of about 0.2% of *G. lucidum* fruiting bodies to the feed enhances immune response of chicken vaccinated against IBD.

Coccidiosis is a crucial parasitic disease of the poultry industry which causes enormous global economic losses. Due to the increased resistance to the conventional anti-coccidiosis agents, there is a continuous need to find new anti-coccidials [318]. The anti-coccidial activity of aqueous extract of *G. applanatum* on broiler chicken was recently proved [309].

Least and not last, mushroom dietary supplementation can also improve the poultry meat quality. The inclusion of 10 or 20 g of *P. ostreatus*/kg in the diet of Japanese quails was effective in delaying the lipid oxidation of breasts and enhancing the colour, pH, water holding capacity, cooking loss weight and texture which are parameters to define meat quality [350].

An indirect use of mushrooms for animal alimentation is to use the spent mushroom substrate as feed sources for insects, as, for example, *Tenebrio molitor* larvae, which in turn can be used as feed for poultry or fish [331].

11.6 Conclusions and Future Prospectives

Agaricomycete and ascomycete mushrooms are a source of multifunctional bioactive compounds with broad spectrum of pharmacological activities which can be used to develop commercial biotech products, such as pharmaceuticals, nutriceuticals, nutraceuticals and cosmeceuticals. Edible mushrooms have a great impact on agriculture, environment and economic development in the society.

Advances in fungal biology and biotechnology, edible and medicinal mushroom cultivation industry, as well as myco-pharmacology are addressing to further exploitation of mushroom resources to improve human welfare and promote economic growth. The increased usage of mushrooms and mushroom-derived products can be expected. In exploitation of mushroom resources, it is important to direct the efforts toward their biotechnological cultivation for production of fruiting bodies, mycelia or spores to develop and formulate innovative and standardised mushroom products (nutraceuticals, dietary supplements or cosmeceuticals) and to establish suitable parameters for their quality control.

Further clinical and pharmacokinetic studies of mushroom-derived products and comprehensive assessment of their nutritional values will expand our knowledge for sustainable manufacturing of high-quality standardized biotech products.

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