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Current trends in health-promoting potential and biomaterial applications of edible mushrooms for human wellness

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ABSTRACT

Edible mushrooms are ubiquitous around the world due to their enormous health benefits. Mushrooms have been used as folk medicine and healthy food from ancient times but their health-promoting effects have not been explored. As a superfood, mushroom powder is an essential component of the human diet for improving health and immunity. Bioactive components present in them such as proteins, polysaccharides, terpenes, and lipids have recently sparked much attention to exhibit therapeutic properties such as anti-cancer, immunomodulatory, anti-hypercholesterolemia, antiviral, antidiabetic, and anti-inflammatory effects. Moreover, these isolated compounds have the potentiality to be used in dietary supplements and medicines. In addition, numerous bioactive compounds such as ergosterol, gallic acid, and cordycepin proved to be essential in preventing or reducing the severity of COVID-19. This review unveils a comprehensive understanding of the nutraceutical as well as the medicinal potential of mushrooms and their applications in food products for human wellness.

1. Introduction

Mushrooms are precious macrofungi, that belong to the fungal phylum basidiomycota having pharmaceutical and nutritional value. Although, among the 2000 varieties of mushrooms, only 200 have been identified as edible (Muszyńska et al., 2020; Y. Zhang et al., 2021). Button mushroom (*Agaricus bisporus*), oyster mushroom (*Pleurotus ostreatus*), and paddy straw mushroom (*Volvariella volvacea* L.) are commonly cultivated and widely consumed around the world (Argyropoulos et al., 2022; Y. Zhang et al., 2021). Mushrooms are necessary for diet owing to their low-fat content, high protein, and low-calorie levels, making them a promising vegan protein source (Kumar et al., 2021; Vamanu, 2012). Powdered mushroom can be added to the food products to enhance its enrichment with proteins, vitamins, minerals and fibres. The physio-chemical and sensory properties of cake can be improved by the addition of mushroom powder (Salehi, 2019) Mushroom contains plenty of all of the necessary amino acids needed by the human body for proper growth and tissue repair. Besides providing nutrition and relieving hunger, it also contributes to the improvement of physical and mental health, by prevention and treatment of diseases. Furthermore, it includes a variety of nutritional elements such as iron, magnesium, selenium, phosphorus, and vitamins such as folate, ascorbic acid, niacin, thiamine, pantothenic acid, and ergosterol (J. Y. Wu et al., 2021). Moreover, researchers have been attracted to its several bioactive compounds such as alkaloids, carotenoids, enzymes, lipids, phenolics, terpenes and tocopherols, β-glucans etc. (SK et al., 2021). They have been isolated from their fruiting bodies or cultivated mycelium having anti-inflammatory, antidiabetic, antitumor, immunomodulating, and antimicrobial activity making them very healthy dietary supplements for the body (Fukushima-Sakuno, 2020; J. Liu & Liu, 2018; SK et al., 2021). According to published research so far, it is difficult to distinguish between edible and medicinal mushrooms because many commonly consumed culinary species also have medicinal benefits (Jayachandran et al., 2017). Medicinal mushroom varieties have been extensively documented to heal and cure various maladies including colds, coughs, asthma, cancer, stomach, and hepatic problems (Motta et al., 2021). Owing to the plethora of medicinal applications, extensive research is going on mushroom metabolite extraction. The identification, separation, and categorization of the vital bioactive compounds found in mushrooms is now being studied intensively.

China is the leading producer, consumer and exporter of mushroom around the world followed by Japan, United States, Netherlands, Poland, Spain, France, Italy, Ireland, Canada, and the United Kingdom (C. Li & Xu, 2022; Thakur, 2020). According to the FAOSTAT, the global production share of china has increased from 70% in 2008 to 93% in 2021 (Fig. 1). Currently, around 12.74 million tonnes of mushrooms are

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consumed globally, and it is expected that production will increase up to 20.84 million tonnes by 2026 (El-ramady et al., 2022). The global mushroom harvest or cultivation has become an economically successful business due to the rising demand. The global market of edible mushrooms is increased from USD 42.42 billion in the year 2018 to USD 45.3 billion in 2020 and is expected to jump up to USD 62.19 billion in 2023, and USD 72.5 billion by 2027 at a compound annual growth rate (CAGR) of 7% from 2020 to 2027 (Niego et al., 2021).

The use of solid substrate medium is the recommended cultivation method for mushroom production. Solid-state cultivation is impacted by various parameters (such as pH, temperature, water content, and substrate heterogeneity), which up till now have not adequately handled, resulting in a non-guaranteed product quality (Junior Letti et al., 2018). Solid state fermentation technology is not as developed as submerged fermentation, and additional scientific and technological advancements are required to convert innovation into industrial-scale production. Due to the drawbacks of traditional field cultivation methods, an alternate way of producing edible mushrooms is needed. As a result, it's critical to concentrate on submerged mycelia growth, which is a quicker and more precise process than growing fruiting bodies. Submerged cultivation of mushrooms is a better alternative in which nutrients are added and oxygen is supplied by stirring in the fermentation medium to give high yield of mycelium biomass which can be obtained by vacuum filtration or centrifugation (Dudekula et al., 2020). Physical, chemical, and biological parameters such as temperature, agitation pH and inoculum can be easily be controlled using this approach (Dudekula et al., 2020).

Mushroom applications are not limited to medicinal and therapeutic purposes, but also in the bio-materials such as bio-composites for packaging applications, bio-leather, bio-foams, and insulation panels (Elsacker et al., 2020). The ability of mycelium to bind the agricultural by-products such as rice bran, wheat straw, and sawdust to make a three-dimensional complex network has been utilized to fabricate bio-composites with great strength (Gandia et al., 2021; Grobman, 2019; Manan et al., 2021; Vandelook et al., 2021). Owing to the ease of availability and low cost of agricultural wastes, these materials can be produced at a very low cost compared to the conventional materials. These materials are completely biodegradable and sustainable, having a great potential to replace petroleum-based plastics.

This review provides an overview of recent advancements in the submerged cultivation of mushrooms to be used in foods and pharma industries for human health. It also focuses on medicinal applications of some important bioactive metabolites. Additionally, this review provides crucial information focusing on the current trends in medicinal mushrooms for the prevention of severe acute respiratory syndrome coronavirus 2 (SARS-COV-2). Moreover, the reported scientific literature of mycelium-based biomaterials has been discussed to give a broad view of sustainable mushroom applications.

2. Submerged cultivation

Beginning in 1950, mushrooms have been cultivated by submerged fermentation to provide us the benefits of safe and reproducible products (Asadi et al., 2021). Submerged cultivation is a biotechnological technique in which liquid medium containing essential nutrient for mycelium growth is provided along with the suitable environmental conditions (Bentil et al., 2018). Cultivation parameters such as temperature, nutrients concentration, pH, and aeration can be controlled using this technique with reduced risk of contamination (Smiderle et al., 2012). Numerous studies has been conducted to investigate the optimized conditions for biomass and EPS production from various mushroom strains as shown in Table 1 (Asadi et al., 2021). reported the maximum concentration of EPS (3.35 g/l) under optimized condition using Taguchi orthogonal L9 array. The optimized cultivation conditions obtained are as pH 5.0, agitation speed of 150 rpm and temperature 28 °C (Supramani et al., 2019). reported the optimized conditions for cultivation of *G. lucidum* using response surface methodology to obtain the maximum biomass and EPS. The optimized conditions are obtained as pH 4, glucose concentration of 26.52 g/l and agitation speed of 103 rpm to give maximum biomass and EPS as 5.19 g/l and 2.64 g/l respectively. In addition, minerals such as Mg, Fe, K, Cu, Zn etc are added in minute quantity as supplements into the fermentation media to stimulate the growth of mushroom cells (Mleczek et al., 2021). Submerged cultivation of edible mushrooms produces mycelium biomass and many other health promoting bioactive metabolites as shown in Table 1. Mycelium cells grow by taking up the nutrients and metabolizing them, facilitated by agitation to produce mycelium biomass pellets. Globular mycelium pellets obtained in the submerged culture are influenced by agitation. Smaller pellet diameter is desirable in terms of high mycelium biomass because the fungal cells in the core region of a big pellet stop growing due to the unavailability of oxygen content and nutrients (Papaspyridi et al., 2012). Mycelium biomass can be produced in shake flask culture in small quantity while for the large-scale production of mycelium biomass, bioreactors are being employed. The mycelium growth formation is affected by agitation. *Pleurotus ostreatus* was cultivated in a bio reactor to produce mycelium biomass containing nineteen metabolites having pharmaceutical properties (Papaspyridi

Fig. 1. Production share (%) of mushrooms and truffles by country around the world *Source: (FAOSTAT data, 2021)*.

Table 1
Mycelium biomass production and its bioactive metabolites with their health benefits.

Mushroom Species	Fermentation Conditions	Productivity (g/l)		Other metabolites	Applications	Reference
		Biomass	EPS			
Agaricus bisporus	pH 6.4, 16 °C, 150 rpm, 26 days	12.67	1.20	β-*d*-glucans, Monounsaturated fatty acids, Ergosterol	Immunomodulating agent Anticholestrolic	Argyropoulos et al. (2022)
T. versicolor	pH 6.1, 28 °C, 220 rpm, 9 days	10.22	1.84	Phenols, polyketides, terpenes, steroids, β-*d*-glucans	Antioxidant, Antibacterial	Angelova et al. (2022)
Pleurotus flabellatus	pH 6, 25 °C, 120 rpm, 7 days	3.84	3.46	Terpenoids, Amino acids, Fatty acids	Antitumor, Antioxidant	Debnath et al. (2021)
Ganoderma lucidum	pH 5.0, 28 °C, 150 rpm, 6 days	5.22	3.35	glucan, Triterpenoids	Antiulcer, Antitumorigenic, Antidiabetic	Asadi et al. (2021)
Lentinula edodes	pH 5.0, 26 °C, 25 days, 52 rpm	5.88	0.40	IPS, Cortinellin, 1,2,4,6-Tetrathiepane	Antibacterial, Antifungal	(S. Sharma, Sharma, & Thakrele, 2016)
***Pleurotus* sp.**	28 °C, 140 rpm 7 days	19.5	2.56	β-glucans	Antitumor, antidiabetic, antimicrobial	Ahmad et al. (2018)
Flammulina velutipes	26 °C, 120 rpm, 8 days	3.22	1.20	Enokipodin A, Sterpuric acid,	Antibacterial, Antifungal	Diamantopoulou et al. (2014)
Phellinus badius	pH 5.5, 28 °C, 120 rom, 14 days	8.2	2.7	Tyrosine; Glutamine	Antitumor	Sonawane et al. (2020)
G. frondosa	28 °C, 150 rpm, 6 days	19.25	3.12	Glycoprotein, α tocopherol, Polyphenolics	Antitumor, antidiabetic, antiviral, antioxidant	Tao et al. (2018)
Cordyceps militaris	25 °C, 150 rpm,7 days under blue light illumination	15.60	2.4	cordycepic acid, adenosine; terpenoids; ergesterol	Antitumor, Antioxidant; Antidiabetic	Kho et al. (2016)
M. rotunda	pH 6.5, 26 °C, 120 rpm, 12 days	7.93	3.77	linoleic acid	Antitumor; Antioxidant	Dedousi et al. (2021)

et al., 2012). *Trichoderma harzianum* was cultivated to obtain six polysaccharides from its mycelium showing various bioactive properties such as anticancer, antioxidant, and enzyme inhibition activity (Saravanakumar et al., 2021). (S. Silva et al., 2012) has reported the production, purification, and characterization technique of polysaccharides derived from *Pleurotus ostreatus* for their antitumor properties.

3. Nutraceutical properties of edible mushrooms

According to various in vitro and *in vivo* studies, various bioactive components found in mushroom cell walls offer a variety of beneficial properties for human health (Fig. 2). However, a thorough investigation of their precise mechanism of action is yet unexplored (Bakratsas et al., 2021). A number of bioactive metabolites extracted from mycelium liquid culture such as phenolics, terpenes, polysaccharides, β-glucans, cordycepins etc. are reported showing their health promoting effects as antioxidant, anticancer, antiaging, anti-inflammatory, antitumor, and antidiabetic (J. Y. Wu et al., 2021). The potent bioactive molecules, such as chitin and chitosan present in the fungal cell wall helps in controlling the functions of the kidney, liver, and gastrointestinal tract.

3.1. Polysaccharides

Over 47 bioactive polysaccharide fractions have been reported in the past 30 years from the mushroom fruiting body, mycelium biomass, and culture medium by various extraction techniques (Maity et al., 2021). The cell wall of mycelium contains intracellular polysaccharides (IPSs), and cultivation medium contains secreted extracellular polysaccharides (Ubaidillah et al., 2015). IPS present in the cell wall can be extracted by cell disruption using ultrasonication and high pressure homogenization.

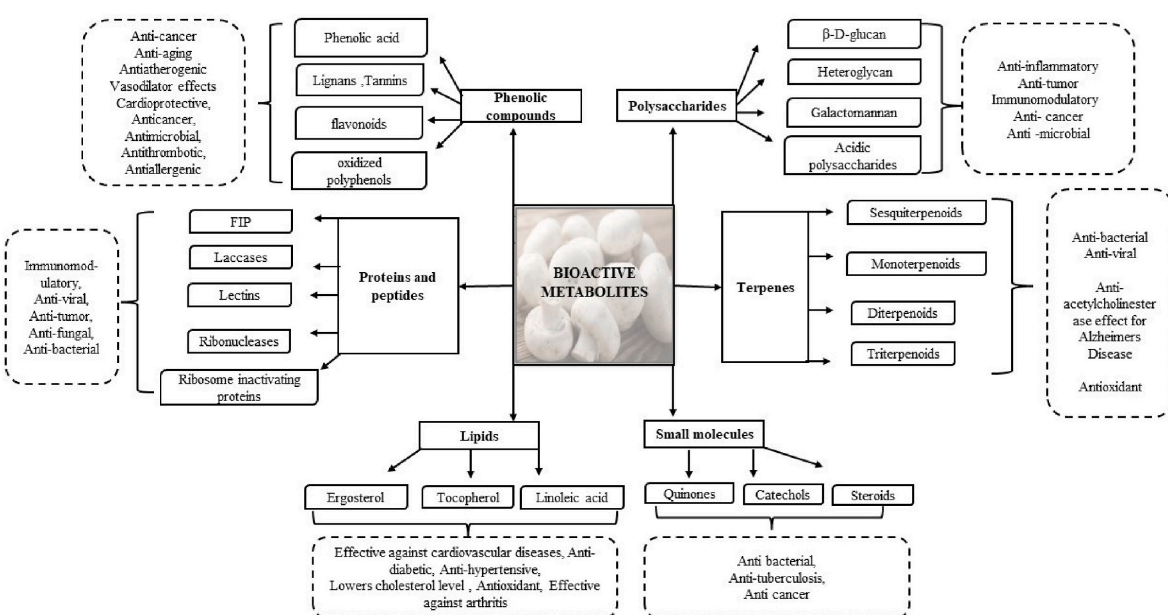

Fig. 2. Plethora of nutraceutical and medicinal important bioactive compounds from edible mushrooms.

When combined with proteins, they can create peptidoglycans and polysaccharide protein-complexes predominantly (Mishra et al., 2021). Additionally, polysaccharides have potential as prebiotics because they raise the presence of short-chain fatty acids in the body, which improve intestinal immunity (Moumita & Das, 2022). These prebiotics dramatically reduce the amount of harmful bacteria, such as *Klebsiella* and *Escherichia coli* in the *Gammaproteobacteria*, to extremely low levels while dramatically increasing the amount of helpful bacteria, such as *Lactobacillus* in the *Firmicutes* (Inyod et al., 2022). Long, complex chains of carbohydrates called polysaccharides are composed of neutral sugars and uronic acid monomers linked by glycosidic bonds (da Silva Campelo et al., 2021). They are important in biological mechanisms like embryonic development and protection from viral and bacterial infection (Zhao et al., 2016). Mushrooms contain a variety of polysaccharides, including heteropolysaccharides which are rich in glucose, galactose, mannose, rhamnose, fucose and xylose. The most common polysaccharide is glucan which is a major storage compounds, along with structural cell wall polysaccharides are also present (da Silva Campelo et al., 2021). These polysaccharides may contain one homoglycan or two or more heteroglycans, which offer several health advantages including lowering fat and glucose levels. Moreover, they help in boosting the immunity as well as enhance the functionality of macrophages (Yin et al., 2021). Polysaccharides such as β-glucans, specially β(1 → 3) and β(1 → 6) are commonly present in various mushrooms like *P. ostreatus, Agaricus bisporus, Lentiluna edodes, and Ganoderma lucidum.* Recent research has reported several promising medicinal and therapeutic benefits, such as anticancer, antitumor, antioxidant, anti-inflammatory, anti-radiation, anti-fatigue, anti-proliferative, hypoglycaemic treatment, antibiotic, hepatoprotective and hypotensive effects, immune-modulating effects, and blood cholesterol and fat reduction (Prateeksha et al., 2021; Rathore et al., 2017; Rizzo et al., 2021). The antitumor effect of the polysaccharides is associated with thymus-dependent immunological mechanism by which they induce the immune response in the host cell and not in the cancer cells directly (Smiderle et al., 2012). The previous reports demonstrated that the polysaccharides having molecular weight greater than 90 KDa shows better biological effects and antitumor activity due to their triple helix structure (Prateeksha et al., 2021; J. Zhang et al., 2019). These naturally occurring polysaccharides have gained much attention due to their unique bioactivities which are safe and efficient.

3.2. Proteins

Protein is a large complex molecule made up of long chains of amino acids which performs a crucial role in the human diet. Mushroom protein provides adequate nutrition to the human body and can reduce the consumption of meat for protein intake. Furthermore, meat analogues made from mushroom protein are said to have a meaty flavour due to their high content of sulphur amino acids and glutamic acid, which gives them an umami taste (González et al., 2020). They can be used as flavoring agents in food products while lowering sodium content without sacrificing sensory properties (González et al., 2020). Many proteins and peptides with intriguing biological properties are produced by mushrooms, including, lectins, fungal immunomodulatory proteins, ribosome-inactivating proteins, antimicrobial proteins, ribonucleases, and laccases (Kalač, 2013). Ribosome inactivating proteins shows enormous biological activities such as HIV-1 reverse transcriptase inhibitory, and anti-bacterial effects (Wong et al., 2008). Mushroom species such as *Pleurotus, Agaricus,* and *lentiluna edodes* are the most commonly cultivated, which provide a high protein to biomass ratio within a range of 10.5%–42% (Smiderle et al., 2012; J. Y. Wu et al., 2021). It is crucial to quantify and analyze the protein content in different mushrooms. There is a need to advance the techniques for enhancement of protein production. Carbon to nitrogen ratio, minerals, pH, temperature, sources of nitrogen and inoculum volume are the important factors that influenced mushroom production (Argyropoulos et al., 2022). investigated the protein content of different mushroom strains (*A. bisporus, A. subrufescens, P. ostreatus and P. eryngii*). The results showed the maximum protein content in *A. bisporus* as 4.702 g/l followed by 3.99 g/l in *P. ostreatus*, 1.91 g/l in *P. eryngii* and 0.612 g/l in *A. subrufescens* which is achieved at 26th day of cultivation. Glycoprotein has been isolated from mycelium biomass, showing antitumor effects (Cui et al., 2013). Bioactive proteins exhibit physiological effects in the digestive tract by improving the absorption of nutrients, suppressing enzymes, and stimulating the immune system to fight pathogens (Moumita & Das, 2022). Mycelium is a safe and efficient vegan protein source with essential amino acids. The various methods of protein quantification have been used so far, including the most reliable are Kjeldahl method, Lowry's method, and Bradford method (Araújo et al., 2017; Sissolak et al., 2019). Previous reports demonstrated that the submerged cultivation of mycelium produced high protein content than the fruiting body (L. C. Wang et al., 2012). (Chan et al., 2015) reported a comparative study between the protein content (37% dry weight) of mycelium which is more than twice the protein content (16% weight) of fruiting body. Proteins derived from mycelium contain essential amino acids including leucine, threonine, glutamic acid, valine, arginine, and aspartic acid (Chan et al., 2015). Non-essential amino acids, such as gamma-aminobutyric acid (GABA) and ornithine are also present in protein which functions as a neurotransmitter and precursor in the metabolic synthesis of arginine (Papaspyridi et al., 2012). The protein content is influenced by many factors such as mushroom type, carbon and nitrogen source, pH, and agitation (Chan et al., 2015). The effect of carbon sources (Glucose, xylose, galactose, and arabinose) on the protein content of *P. pulmonarius* was investigated and the results revealed that the xylose and arabinose are the best carbon sources which gave a protein content of 19.44% and 26.05% respectively (Smiderle et al., 2012). Apart from the synthetic carbon sources such as xylose, glucose, and sucrose, liquid agro-waste such as molasses can also be used as a carbon source for the submerged cultivation of mycelium. It is reported that submerged cultivation of *Morchella* mycelium using molasses as a culture medium produced 7.6% (w/w) protein (Kurbanoglu et al., 2004). J. Siew reported 17 essential and non-essential amino acids in mycelium biomass and fruiting body of *G. tsugae* var. *jannieae* and, the total amino acids found in mycelium biomass is two times higher than in the fruiting body (Chan et al., 2015). The optimum protein content and dry weight biomass from *Morchella fluvialis* was reported using response surface methodology (Rahgo et al., 2019). The results showed a maximum of 38% protein content with 28.7% of amino acids in them with the medium containing glucose (80 g/l) and soya bean powder (40 g/l). These properties of edible mushrooms makes them a potentially sustainable source of protein content that can be used in a variety of foods.

3.3. Enzymes

Numerous enzymes such as amylase, laccase, cellulase, and lipase have been isolated from the mushrooms that is quite essential for the nutrition of the body. Enzymes can be produced by solid-substrate cultivation using lignocellulosic wastes or submerged cultivation using lab media (Bentil et al., 2018). These enzymes can decompose lignocellulosic materials into water-soluble compounds with great nutritional importance. The most common enzymes extracted from mushrooms are laccase, lignin, peroxidase, xylanase as well as the hydrolytic enzymes called cellulases that can depolymerize cellulose into glucose (Jayachandran et al., 2017). These enzymes have a pivotal role in the food industry as they help in developing the flavour and colour of the food as well as in enhancing the nutritional quality of the food (Table 2). Cellulolytic enzymes such as xylanase, amylase, protease also have eminent roles in baking, bevereage industry (El-Gendi et al., 2022). Cellulase has enormous applications in textile wet pressing, garments softening, baking, food, pulp and paper industry (Bedade & Singhal, 2016). Cellulase has been used in the food and beverage industries to

Table 2
Enzymes derived from various edible mushrooms for the applications in food industry.

Enzymes	Edible mushroom strains	Application in food industry	References
Amylase	*Pleurotus ostreatus, Termitomyces* spp. *Agaricus blazei Lentinula boryana Pleurotus djamor* var. *roseus*	Breaking starch and dextrins. Production of chocolate syrup to avoid the thickening.	Saini et al. (2017)
Lignin peroxidase (LiP)	*Pleurotus sajor-caju Pleurotus chrysosporium*	Production of vanillin which is used as a flavoring agent in food and beverages. Production of organic acids such as succinic acid from lignin.	Gallage and Møller (2015)
Laccase	*Lentinus sajor-caju, Pleurotus giganticus, Panus* spp *Lentinula edodes, Pleurotus eryngii, Pleurotus ostreatus and Pleurotus sajors-caju*	Enhance the colour modification and appearance in beverage processing. Helps in stabilization of wine by selective polyphenol removal and stabilization of beer by removal of oxygen. Increase stability and strength of dough and reducing stickiness.	Mayolo-Deloisa et al. (2020)
Protease	*Lepista nuda, Termitomyces clypeatus, Oudemansiella radicata, Pleurotus sajor-caju, Pleurotus ostreatoroseus,*	Reduce mixing time and improve the texture and flavor of baked products. Highly used in liquification of starch-based products.	(Deniz, 2019; Omrane Benmrad et al., 2019)
Xylanase	*Pleurotus eryngii Termitomyces* spp.	Improves loaf texture in bread making. Higher amounts of arabinoxylo-oligosaccharides are good for health, preparation of food thickeners.	(Mandal, 2015; Silano et al., 2018; Simair et al., 2016)
Invertase (sucrase)	*Pleorotus ostreatus, Aspergillus* sp., *Lentinula boryana, Pleurotus djamor* var. *roseus and Pycnoporus* sp.	Catalytic agent for artificial sugar in confectionaries.	(Díaz-Godínez et al., 2016; Veana et al., 2018)
Tyrosinase	*Agaricus bisporus, Pleurotus florida, Pleaurotus dyjamore and Pleurotus oysterus*	Hydroxyl tyrosol as a food additive is used in production of black tea. Cereal processing to improve the bead structure, dairy industry to crosslink different proteins for prevention of syneresis and in meat industry to improve gelation.	(A. Sharma, Sharma, & Thakrele, 2016; Valipour & Arikan, 2016)
β-glucosidase	*Lentinus squarrosulus, Lentinula edodes, Ganoderma lucidum, Pleutorus ostreatus, Coprinus cinereus, Volvariella volvaceae, Laccaria bicolor, Agaricus bisporus*	Releases aromatic compounds from glycosidic precursors in fruit juices. Hydrolyze the isoflovanes to aglycones in soy-based foods imparting higher biological activity and absorption. Helps in releasing aromatic compounds that are used for improving the flavour and improve organoleptic properties of citrus.	(Ahmed et al., 2017; G. Singh et al., 2016)
Pectinase	*Lentinula boryana, Pleurotus djamor* var. *roseus*	Reduce viscosity and clarification of fruit juices. Extraction process and maximizing the yield of wine and vegetable oils.	Garg et al. (2016)
Lipase	*Cantharellus cibarius, Agaricus bisporus, Lentinus edodes, Antrodia cinnamomea*	Flavour development and processing of dairy foods.	Raveendran et al. (2018) (M. K. Singh et al., 2014)

hydrolyze cellulose during the dehydration of coffee beans and to extract fruits and vegetables juice (Galano et al., 2021). (Morais et al., 2005) reported that the *P. ostreatus* produced xylanase, laccase, β-glucosidase, manganese dependent and independent peroxidases in a culture medium containing agricultural wastes and glucose as a carbon source. The results revealed a significant increase in the enzymes productivity when agricultural waste extract is added to the culture medium. There are several applications of hydrolytic enzymes produced by various microorganisms in the food industry, environmental bioremediation, and the biosynthetic process sector. Laccase is a multi-copper enzyme that oxidise phenolic compounds by reducing oxygen to water eliminating one electron from the aromatic substrate, resulting in the formation of phenoxyl radicals (Bettin et al., 2011). It has numerous applications in the pharmaceuticals, nutrition, and cosmetics. Previous reports have shown a tremendous catalytic potential of laccase enzyme within a broad range of temperature and pH (Bettin et al., 2011). (Bedade & Singhal, 2016) demonstrated that the 0.5 w/v carboxymethyl-cellulose was an efficient carbon source which increased cellulase activity up to 1.70 U/ml within a week at a pH of 7 (Bentil et al., 2018). compared the cellulase activity in liquid and solid-state cultivation and found that the cellulase activity is much higher in liquid cultivation than the solid-state with the banana peel as the most efficient substrate for cellulase production. Recovery of endo-hydrolase is a substantial issue in production of enzymes when insoluble, fibrous agricultural wastes are used as substrates (Bentil et al., 2018). In case of basidiomycetes, this enzyme recovery challenge becomes more severe because of the presence of extracellular enzymes in the mycelial hyphae and the substrate.

3.4. Lipids

A distinct class of bioactive metabolites produced from mushrooms are lipids that includes triglycerides, oils, phospholipids, sterols, and fatty acids. Mushroom lipids are primarily mono and polyunsaturated fatty acids, having high unsaturated to saturated fatty acid ratio, making them a good source of lipids (Sande et al., 2019). Lipids play a significant role in the normal functioning of the body. They form the structural building component of cell membrane. The most common fatty acids found in mushrooms are linoleic acid, palmitic acid, and oleic acid (Kalač, 2013). Lipids intake and its synthesis within the body is quite necessary for various functions like energy storage, thermal insulation, and safety of internal organs (Sande et al., 2019). Out of the numerous lipids, fatty acids comprises of simple structures composed of carboxylic acids obtained from hydrocarbon chains containing 4 to 36 carbons, which are rich in energy rich fats and oils. Sterols are another class of lipids consisting of multiple hydrophobic ring structures of which ergosterol is the most common precursor to vitamin D (Ahmad et al., 2021; SK et al., 2021). Ergosterol has numerous health benefits, including prevention of heart disease and lowering cholesterol (Kumar et al., 2021). Agitation of culture media has positive effect on the production of lipids (Diamantopoulou et al., 2014). reported that, after 24 days of cultivation for *Pleurotus pulmonarius* in agitated condition, the lipids production were 3.7 g/l while in static condition, only 1.03 g/l of lipids were produced. It may be due to the insufficient supply of oxygen in static conditions. There are few reports indicating the reduction of lipids in liquid cultures of *P. sajor-caju* (Mukhopadhyay & Guha, 2015) and *V. volvacea* (Diamantopoulou et al., 2012). Lipid production was not a dominant event in the aforementioned cases. In contrast, significantly higher lipid quantities were synthesized during the initial growth stages, whereas cellular lipid degradation took place during the late growth phase (Smiderle et al., 2012). found that the unsaturated fatty acids are widespread in *Pleurotus pulmonarius* mycelium biomass, containing linoleic acid as the most prevalent, within the range of 33–68% of all fatty acids depending on the carbon source. When glucose is used as a carbon source in the growth medium, the maximum concentration of linoleic acid was obtained whereas palmitic acid was obtained as 17.3% of total fatty acids when xylose is used as a carbon source in the growth media. Apart from the nutritional aspect, fatty acids also contribute to the taste and aroma of mushrooms. Unsaturated fatty acids such as oleic acid (Omega-9), linoleic acid (Omega-6), and linolenic acid (Omega-3) present in mushrooms are the healthiest for human body among all the fatty acids.

3.5. *Terpenes*

Terpenes are the class of bioactive metabolites that have been isolated from the mushrooms for their pharmacological properties, including anticancer, antimalarial, antiviral, and antibacterial properties (J. Liu & Liu, 2018). Terpenes are categorized on the basis of isoprene unit they contain as monoterpenes, Sesquiterpenes, diterpenes and triterpenes. Terpenoids are a modified class of terpenes with different functional groups and an oxidized methyl group moved or removed at various places (Fukushima-Sakuno, 2020). Retapamulin, an antibiotic has been derived from pleuromutilin which is a tricyclic diterpenoid having antimicrobial properties (Dasgupta & Acharya, 2019). Ganoderic acid, a triterpenoid produced by *Ganoderma lucidum* can induce cell apoptosis in cancer cells while causing minimal toxicity in normal bystander cells (Kolniak-Ostek et al., 2022). The majority of terpenoids with various type of structures are biologically active and are used to treat various ailments around the world (Fig. 3). (Chen et al., 2014) reported four novel sesquiterpenoids; inonotic acid A, 3-O-formyl inonotic acid A, inonotic acid B and 3,6-hydroxycinnamolide from *Inonotus rickii* and tested for cytotoxic activity against five distinct human cell lines; human myeloid leukemia, lung cancer, hepatocellular carcinoma, human colon cancer cells and breast cancer. Monoterpenes and sesquiterpenoids from *Pleurotus cornucopiae* and *Flammulina velutipes* were isolated, and tested for their cytotoxic activity against cancer lines with remarkable results (Fukushima-Sakuno, 2020; S. Wang et al., 2013). Terpenoids from the chaga mushrooms showed satisfactory binding property to the spike of SARS-COV-2 (Elshemey et al., 2022). Additionally, the analyses and binding free energies of the top two compounds (GRP78- Oleanolic acid and GRP78- Inonotsulide A) show that they bind with GRP78 (Glucose regulated protein-78) with strength and stability. Lanostane is a triterpenoid isolated from the mushrooms having anticancer properties. Ganorbifoins A and Ganorbifoins B are the two novel lanostane isolated from the fruiting body of *Ganoderma orbiforme* showing great potential for NO generation inhibition and antidiabetic activity (Yang et al., 2022). In a recent study, inotodiol, a lanostane triterpenoids proved to be an antiaging compound as it protects the human skin by blocking the MAPK(mitogen-activated protein kinase)-NOX5 (NADPH oxidase 5)and NF-κB (nuclear factor kappa-light-chain-enhancer of activated B cells) signalling pathways (Lee et al., 2022).

4. Medicinal properties of mushroom

Ancient Chinese literature mentions the usage of mushrooms for medicinal purposes. Recent developments in biochemical technology have made it possible to isolate and purify a number of important metabolites, which have potent antioxidant, antidiabetic, antiviral and

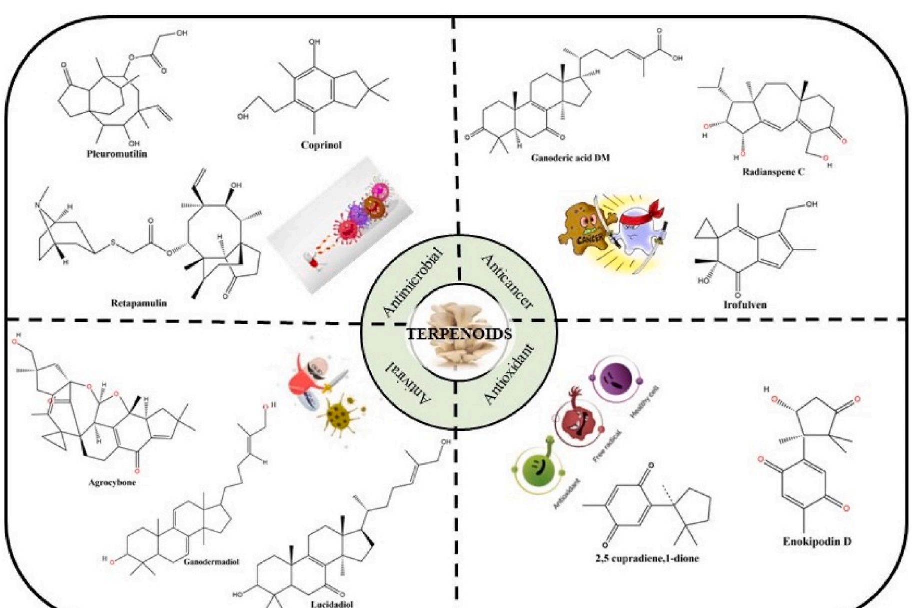

Fig. 3. Classification of terpenoids based on their therapeutic properties.

anticancer properties (Fig. 4). They are generally biological response modifiers that interact well with immune system to regulate different components of the host's response, which may have a variety of therapeutic benefits (Rathore, Prasad, et al., 2019). The biomedicinal significance can be increased in a novel way by enriching mushroom biomass with bioactive components such as polyphenolcarboxylic compounds. Bioactive compounds present in mushrooms such as, chitin, α and β-glucans, mannans, xylans, and galactans are valuable source of prebiotics (Vamanu & Gatea, 2020). Mushroom bioactive compounds derived from *Ganoderma lucidum*, Hericium *erinaceus*, *Lentinula edodes* and *Grifola frondosa* have been reported to modify gut microbiota and promote health (M. Li et al., 2021). *G. frondosa* polysaccharides were reported to reduce obesity and improve liver function, which was attributed with increase in *Allobaculum, Bacteroides, and Bifidobacterium* in the gut (X. Li et al., 2019). Another study found a correlation between the enrichment of *Parabacteroides goldsteinii* in the gut and the anti-obesogenic and anti-diabetic effects from *Hirsutella sinensis* polysaccharides (T. R. Wu et al., 2019). It is much simpler to restore the gut microbiota by enhancing the bioavailability of mushroom's metabolites than using commercial medicinal substitutes (Vamanu & Gatea, 2020)

4.1. Anticancer

Mushrooms demonstrate anticancer properties through stimulating lymphocytes, which are considered as cancer-fighting immune cells. A detailed review of the anticancer properties of active metabolites derived from *P. ostreatus* is reported with their biological mechanism (Mishra et al., 2021). Polysaccharides including lentinan and schizophyllan are the main active metabolites which are of great interest for their anticancer properties (Mishra et al., 2021). demonstrated *Pleurotus* spp. in tests to be a powerful agent for suppressing the growth, angiogenesis, proliferation, and metastasis of cancer cell lines while minimizing the immunosuppression without causing any damage to the normal cells. In recent years, selenium-enriched polysaccharides have received a lot of interest for their anticancer potential (Y. Zhang et al., 2020). investigated the anticancer activity of a new selenium polysaccharide fraction (Se-POP-3) generated by *P. ostreatus* at the cellular level. Se-POP-3 has been shown to be able to cause apoptosis and prevent the migration of cancerous cells in in vitro tests using cancer and healthy cell lines. Mushroom bioactive metabolites such as lentinan, hispolon, calcaelin, krestin illudin S, psilocybin, lectin, Hericium polysaccharide A and B (HPA and HPB), schizophyllan, laccase, ganoderic acid etc are reported to have anticancer potential (Nzekoue et al., 2022). *P. linteus* extract is said to have antimutagenic properties and to help prevent cancer by activating NAD(P)H:quinone oxidoreductase and glutathione S-transferase activities (Mishra et al., 2021).

(X. Li et al., 2017) studied the effect of β-glucan modified with AuNR (gold nanorods) for cancer phototherapy (PTT). To increase the stability and mitigate the cytotoxicity of AuNRs for cancer PTT, they used *Pleurotus tuber regime* (PTR) sclerotial β-glucans as biocompatible coatings to enclose individual second near-infrared (NIR-II) responsive AuNRs into nanohybrids. The results proved that the β-glucans have high potential for the development of biomaterial derived functional nanohybrid system with a high degree of stability and minimal cytotoxicity. Several pure mushroom polysaccharides is used therapeutically in China, Japan, and Korea without any reported short or long-term negative effects.

4.2. Antidiabetic

Although a variety of synthetic medications are available to treat the diabetes but their long term usage is related to several adverse impacts. This has switched the focus of research to medicinal mushrooms, which are considered relatively harmless. Many mushroom species such as *A. bisporus, A. subrufescens, Coprinus comatus, Inonotus obliquus, G. lucidum, Cordyceps sinensis, P. linteus,* and *Pleurotus* spp., are quite capable of controlling blood sugar levels and diabetic complications (D. D. De Silva et al., 2012). Mushrooms contain natural insulin-like compounds and enzymes that contribute in the breakdown of sugar and starch in food while also improving insulin resistance (Chopade et al., 2012). Mushrooms are also acknowledged to have substances that helps in the healthy functioning of the living system. The homopolysaccharides found in mushrooms influence insulin metabolism via modifying insulin release in the hormone signalling pathway (Kumar et al., 2021). Mushroom constituents have anti-obesogenic and anti-diabetic actions by controlling appetite, nutritional digestion, and absorption (Stojkovic et al., 2019). reported in vitro anti-diabetic properties of six medicinal mushrooms: *C. comatus (O.F.Müll.) Pers., Cordyceps militaris (L.) Fr., I. obliquus (Ach. ex Pers.) Pilát, Morchella conica Pers., Agaricus blazei Murrill,* and *Phellinus linteus Berk*. Methanolic extracts of these mushrooms were used in in vitro experiments for α-amylase and α-glucosidase enzyme inhibition. G. frondosa rich in vanadium (GFRV) significantly reduced blood glucose levels in hyperglycemic rats (D. D. De Silva et al., 2012). (Seto et al., 2009) reported that the water extract of G. Lucidum in diabetic mice dramatically reduce the blood glucose content by

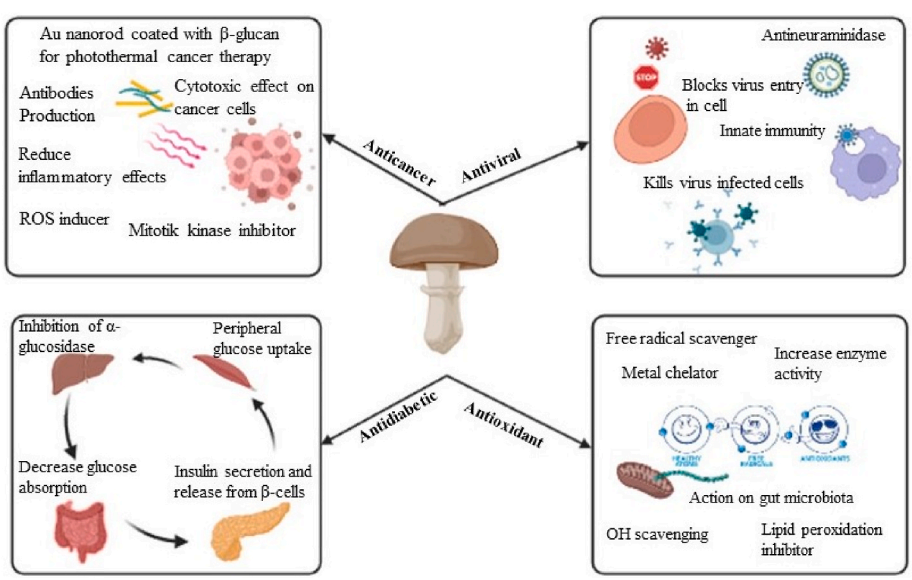

Fig. 4. Prebiotic medicinal effects of edible mushrooms.

inhibiting the liver gene expression of phosphoenolpyruvate carboxykinase (PEPCK). Intake of *Pleurotus ostreatus* exhibited a strong hypoglycemic impact in diabetic mice and can improve hyperlipidemia and the impaired kidney functions (Ravi et al., 2013). A tremendous scope lies in the anti-diabetic effects of mushroom metabolites. Therefore, it is necessary to investigate the feasibility of converting these mushroom extracts into appropriate medicinal products.

4.3. Antiviral

Mushroom bioactive metabolites inhibit viral infection by primarily targeting viral entry, genome replication, as well as modulating immune response. Antiviral properties of sulphated polysaccharides have been demonstrated, and they are being studied for the treatment of HIV, and RSV infections (M. Zhang et al., 2004). A tyrosinase and its one isoform isolated from *Agaricus bisporus* have shown great potential against hepatitis C virus (HCV) (Lopez-Tejedor et al., 2021). Herpes simplex virus type 1 (HSV-1) is one of the most common viral infections in children and adults. Acyclovir is a nucleoside derivative that has been a staple treatment for HSV-1 management as it prevents the synthesis of viral DNA (Urbancikova et al., 2020). However, acyclovir also has a wide range of side effects and a limited bioavailability, which can restrict its long-term use in kids (Urbancikova et al., 2020). showed that β-glucan had a promising therapeutic impact on the duration and intensity of HSV-1 infection. The antiviral potential of several selected gallic acid derivatives against SARS-COV-2 has been investigated by molecular docking (Umar et al., 2021). reported that the 4-O-(6-galloylglucoside) could be the promising compound to inhibit the SAR-Cov-2 proteins as it shows the best binding energy against the SARS-COV-2 proteins.

4.3.1. Anti-Covid-19

Coronavirus Disease 2019 (COVID-19) is now a global pandemic caused by the (SARS-CoV-2). Because of the urgent need for promising, reliable, and safe treatment of COVID-19, scientists have turned their attention to protease inhibitors as promising cures (Fig. 5). Numerous reports of the immune boosting ability of medicinal mushrooms have been analysed for Covid-19 treatment (Rangsinth et al., 2021). Mushrooms can help to therapeutic or preventive add-on therapies for COVID-19 disease, and also for the immunological response and detrimental inflammation (Hetland et al., 2021). (Rangsinth et al., 2021) reported natural compounds exhibiting anti-HIV protease that were extracted from dietary and medicinal mushrooms. Using molecular docking, they investigated 36 bioactive compounds for their efficacy as SARS-CoV-2 major protease inhibitors. Furthermore, in silico ADMET analysis was used to evaluate drug-likeness properties such as metabolism, absorption, excretion, distribution, and toxicity. The results showed that, 25 out of 36 bioactive metabolites have the ability to block the primary viral protease (Echer et al., 2022). demonstrate the therapeutic benefits of *Pleurotus* spp., including their antihyperlipidemic, antiatherogenic, antihypertensive, antioxidant, anti-inflammatory, anticholesterolemic, and antihyperglycemic activities, which may be linked to a decrease in the severity of COVID-19. Chaga mushroom is reported to have the potent enzymatic and robust system as a result of their parasitic nature, which is associated with the reduction of COVID-19-related inflammatory reactions (Fanila Shahzad, Diana Anderson, 2020). Due to the ability to reduce nasopharyngeal inflammation, chaga mushrooms have been used extensively in traditional medication in Asian countries and even in some areas of Europe. In addition, the β-glucans derived from the *Lentinula edodes* have been proven to defend against a variety of viral infections and may help to lower the main cytokines involved in the cytokine storm seen in severe instances of COVID-19 (Fanila Shahzad, Diana Anderson, 2020). Recent research suggests that medicinal mushrooms may benefit respiratory disorder and lung infection, therefore they can also relieve people with COVID-19 (Table 3). Thus, by increasing the immune system's resistance to COVID-19, medicinal mushrooms might have a preventative impact (Murphy et al., 2020). (Suna et al., 2022) demonstrates the effectiveness of vitamin C in the treatment of SARS-CoV-2 due to its antioxidant, antiviral and anti-inflammatory effects, and ability to stimulate the immunity.

4.4. Antioxidant

Mushrooms are a natural source of antioxidants which include oxidative-resistant substances such as flavonoids, phenols, tocopherols, carotenoids, and ascorbic acid. Phenolic acids, such as p-hydroxybenzoic acid, Tyrosine, catechol, tri-cinnamic acid, vanillic acid, and p-coumaric acid, are a few phenols found in mushrooms (Stojanova et al., 2021). Numerous in vitro research on several species of mushrooms have demonstrated that their alcoholic and aqueous extracts rich in the phenolic compound have a strong antioxidant effect. The bioactive capacities of the mushroom extract to donate hydrogen, chelate metals, and scavenging superoxide and free radicals can be used to define its antioxidant pathways (Suna et al., 2022). The classification of phytocomponents that accounts for the anti-oxidant effect of different types of mushrooms is phenolic compounds. The usage of edible mushrooms as a dietary source of natural antioxidants is due the presence of large amounts of phenolic components and its significant antioxidant qualities (Anusiya et al., 2021). (C. Sharma et al., 2019) assessed the antioxidant

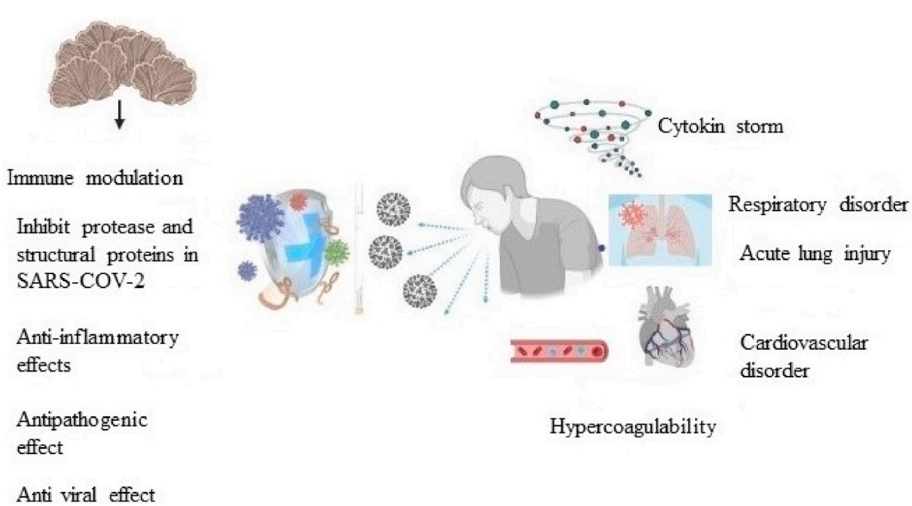

Fig. 5. Possible preventive action of mushrooms from SARS-COV-2.

Table 3
Antiviral mechanism of bioactive metabolites from various mushroom species.

Disease	Virus	Metabolite	*Mushroom strain*	Mechanism	Reference
Covid-19	SARS-CoV-2 (+)ssRNA	Polysaccharides	*Inonotus Obliquus*	Inhibit NO induction and pro inflammatory cytokines hence preventing cytokine storm.	Van et al. (2009)
		Ergosterol	Auricularia polytricha, Lentinula edodes	Anti-inflammatory activity and may have the potential to inhibit SARS-CoV-2 main protease	Sillapachaiyaporn et al. (2019)
		Colossolactone VIII, Colossolactone G	Ganoderma colosum	Inhibit SARS-CoV-2 main protease. Inhibit SARS-CoV-2 main protease.	El Dine et al. (2008)
		Velutin	Flammulina velutipes		(H. Wang & Ng, 2001)
		Gallic acid	Agaricus bisporus, Ganoderma lucidum, Pleurotus ostreatus	Hydroxy and ketone groups present in polyphenols play a role in amino acid interactions within SARS-CoV-2 main protease (Mpro)	Umar et al. (2021)
		Cordycepin	Cordyceps militaris	Inhibition of viral protease hence preventing the assembly of viral particles	Verma (2020)
Acquired immunodeficiency syndrome (AIDS)	Human immunodeficiency virus (HIV) (+)ssRNA	Laccase	*Pleurotus eryngii, Tricholoma giganteum*	Inhibits HIV-1 reverse transcriptase Inhibits HIV-1 reverse transcriptase	(H. X. Wang & Ng, 2004)
		lectin	*Pleurotus citrinopileatus, Agaricus bisporus*	Inhibits HIV-1 reverse transcriptase	(Y. R. Li et al., 2008)
		Ubiquitin-like Protein	*Pleurotus ostreatus*		(H. X. Wang & Ng, 2000)
		Polysaccharide and Heteropolysaccharide	*Ganoderma lucidum*	Increased CD4^{+} T-lymphocyte	El-Mekkawy et al. (1998)
Herpes	Herpes simplex virus HSV-1 and HSV-2 (dsDNA)	β-glucans	*Pleurotus tuber-regium*	The antiviral effect is caused by binding of sulphated β-glucans to the viral particle.	(M. Zhang et al., 2004)
		Polysaccharide fraction	*Pleurotus ostreatus*	Inhibits intra cellular replication	Urbancikova et al. (2020)
		Polysaccharide (Sulphated derivative)	*Agaricus brasiliensis*	Inhibition of viral attachment and expression of ICP27, UL42, gB, and gD proteins	Yamamoto et al. (2013)
		Proteoglycans	*Ganoderma lucidum*	They bind to HSV specific glycoproteins and prevents attachment and penetration of viral particles.	(J. Liu et al., 2004)
		Triterpinoids (ganoderone A, lucialdehyde B, ganodermadiol)	*Ganoderma pfeifferi*	Inhibition of viral replication.	Trigos and Suárez-Medellín (2011)
Hepatitis	Hepatitis C virus(HCV) (+)ssRNA	Tyrosinases	*Agaricus bisporus*	Selective hydroxylation of tyrosine residues in viral proteases.	Lopez-Tejedor et al. (2021)
		laccase	*Pleurotus ostreatus*	Inhibits the replication and entry of Hepatitis C virus in the peripheral red blood cells and and hepatoma HepG2 cells.	Seo and Choi (2017)
Influenza	Influenza A virus Segmented(−)ssRNA	β-glucans	*Pleurotus tuber-regium, Pleurotus pulmonarius*	The antiviral effect is caused by binding of sulphated β-glucans to the viral particle hence inhibiting viral replication.	(M. Zhang et al., 2004)
		Phenolic compounds (hispolon and hispidin)	*Inonotus hispidus*	Inhibition of viral replication	Ali et al. (2003)
		Acidic Polysaccharide	*Cordyceps militaris*	Increased levels of NO, iNOS, IL-1β, IL-6, IL-10, and TNF-α in cells.	Ohta et al. (2007)
		Peptidomannan	*Lentinus edodes*	Interferon induction	Suzuki et al. (1979)

TNF: Tumor necrosis factor IL: Interleukins.

properties of *Ganoderma Lucidum* on the basis of total flavonoid content (TFC), total phenolic content (TPC), and DPPH free radical scavenging activity. The ability of phenolic antioxidants to scavenge free radicals inhibits the oxidation of lipids, and the activity rises with the molecules containing hydroxyl groups. Excessive reactive oxygenated species (ROS) production is responsible for oxidative stress in the body, which play a crucial role in the beginning of diseases such as Alzheimer's disease, diabetes, atherosclerosis, cerebral ischemia, hypertension, cancer, and also ageing processes (Maity et al., 2021). Natural antioxidants such as polysaccharides are metabolites that interact with ROS to reduce the chance of chronic diseases in human body. Polysaccharides from mushrooms such as *Agraicus bisporus, Agaricus brasiliensis, trichoderma harzianum, Tricholoma mongolicum Imai, V. Volvacea, L. edodes* and *P. ostreatus* are reported to have strong antioxidant characteristics (Puttaraju et al., 2006; Saravanakumar et al., 2021; Stojković et al., 2014; Zhao et al., 2016). (Maity et al., 2014) identified antioxidant activity of a branched β-D-glucan (PS–I) in an alkaline culture of the edible fungus *Entoloma lividoalbum* (Kosanic et al., 2013). evaluated the in vitro antioxidant activity of the methanol and acetone extracts of mushrooms; *A. rubescens, L. apparatus, C. cibarius,* and *R. cyanoxantha*. The results showed the highest antioxidant activity of acetone extract of *Russula cyanoxantha* mushrooms when compared to other extracts. On the basis of TFC, TPC, and DPPH free radical scavenging activity, the antioxidant activities of the methanolic and acetonic extracts of the mushrooms, Boletus edulis, Leccinum carpini and Boletus aestivalis was examined (Kosanić et al., 2012). The study revealed that the acetonic extract of *Boletus edulis* has stronger antioxidant activity. In addition, a substantial correlation between antioxidative activity and total flavonoid and phenolic contents was also evaluated (Stojanova et al., 2021). reported the antioxidant activity of edible mushrooms; *Coriolus versicolor, Suillus granulatus and Fuscoporia torulosa*. Aquous extract of *Fuscoporia torulosa* showed the highest antioxidant activity on the basis of DPPH radical scavenging activity. It implies that mushrooms can be used as a good source of naturally occurring antioxidants as well as for medicinal purposes in the treatment of various diseases.

5. Mushroom powder in food products

Mushrooms have a distinct texture with a pleasant aroma, taste, and flavour that distinguishes them from other foods. Overall, the addition of mushroom powder in food products increased consumer acceptance by improving mouth feel and juiciness (Kour et al., 2022). In the post-pandemic era of SARS-CoV-2 (COVID-19), consumers are now focused on improving their antioxidant activity through diet. Therefore, it is important to use dried mushroom powder to create added-value coproducts and assess their nutritional and functional properties in terms of human health. The mushroom powder is used in food products, specifically in the preparation of mushroom bread, pasta, biscuits, cakes, sauces, and breakfast cereals etc. (Y. Liu et al., 2022; Szydłowska-Tutaj et al., 2021). The addition of mushroom powder in appropriate quantity can enhance the nutritional value of food products. The addition of shiitake mushroom in noodles increased the antioxidant abilities up to 15% over wheat flour noodles (L. Wang et al., 2020). A diet with a high (GI) glycaemic index would result in a sharp rise in blood glucose levels and acute metabolic diseases (Rathore, Sehwag, et al., 2019). reported that the incorporation of *calocybe indica* powder into cookies considerably improved the content of protein, fibre, β-glucans, antioxidants, and minerals. The cookies exceptional amounts of β-glucan make them hold a place in the low GI food category, giving diabetic patients another option to choose such a large bakery item (Y. Liu et al., 2022). investigated the effect of *Pleurotus eryngii*, and Cantharellus cibarius *powder on the physio-chemical, sensorial and digestibility of bread. The results indicated that using mushroom powder as a high-value ingredient enhance the nutrient quality and lower the GI of bread. Pasta made with semolina, Lentinula edodes, and* Boletus edulis *mushrooms was discovered to have healthier qualities such as a reduced risk of glycemic response and an increased antioxidant capacity (*Lu et al., 2018*). Puree soups and sauces made from edible mushrooms are popular dishes in many countries due to their improved nutritive and sensory flavour.* Many mushrooms are now used as nutraceuticals, and there are a wide range of therapeutic products with healing properties derived from them that are easily available in markets such as polysaccharide krestin product (PSK), pleuromutilin, and pleuromutilin.Considering the highly valued advantages of mushrooms as a nutritious, tasty, and flavorful food, as well as their health benefits, further research into mushroom diversity appears necessary for discovering the magnificent potential of mushrooms as a source of secondary metabolites.

6. Mushroom based sustainable biomaterials

Mushroom is not only considered for their nutritional and pharmaceutical applications but they are also used in production of various materials such as bio-leather, mycelium bio-composites, mycelium biofoams etc. The right packaging materials can preserve food quality; for this reason, it is crucial to use safe and green packaging materials. Numerous biomaterials are currently being researched for use in the food industry as packaging materials that might serve as pathogens or bacterial control agents (R et al., 2021). Chitin is a primary component in the cell wall of hyphae. Chitosan which is a deacetyled derivative of chitin, is a safe food supplement approved by FDA (R et al., 2021). It can undergo chemical processing to create a variety of food packaging biomaterials with superior physiochemical properties. Because of the numerous biological properties of cellulose and chitin and present in mushroom such as biodegradability, antibacterial properties, antioxidant activity, and non-toxicity, have paved their path in biobased packaging materials (Yu et al., 2020). The properties of the final product is dependent on the concentration of polysaccharides, chitin, and proteins present in the mushroom cell wall (Manan et al., 2021). A compact lattice structure is formed when the mycelium colonizes and binds the substrate completely. This compact structure can be obtained according to the desired shape using the mould.

6.1. Bio-composites

The mycelium-based material is a crucial step toward a sustainable circular economy. Any lignocellulosic agricultural waste such as sawdust, wheat bran, rice husk, cotton hulls, etc., can be utilized to fabricate high-valued bio-composites using fungal mycelium as a natural binder (Raman et al., 2022). These bio-materials can replace the existing petroleum-based plastics such as polystyrene, polypropylene, high-density polyethylene, etc., due to their low cost and superior properties (Abhijith et al., 2018). A lightweight and strong composite material are obtained by mycelium forming a three-dimensional network with the solid organic substrate which can be used as a packaging material (Robertson et al., 2020). There are few challenges in the production of these materials due to the insufficient knowledge of the relation between the nutrients and growth conditions requirement with the final material properties (Jose et al., 2021). The mycelium contains chitin, a biopolymer responsible for the stiffness and strength of the biomaterial. The quality of the final mycelium bio-composite can be tested by compressive strength, tensile strength, water absorption, density, fire retardancy etc. (Joshi et al., 2020). It has been reported that some parameters significantly affect the properties of the obtained bio-composite, such as fungal strain, substrate composition, and inoculum size (Joshi et al., 2020). Mycelium bio-composites research is underway, and there are still few technological gaps that must be filled to fabricate the bio-composites with desired thermo-mechanical properties.

6.2. Leather

Mushroom derived leather is an emerging and sustainable alternative for the animal-based leather. Mushroom derived leather is produced by mycelium biomass which can be obtained by submerged fermentation or solid-state fermentation (Raman et al., 2022; Vandelook et al., 2021). The submerged fermentation uses the lab media for mycelium growth. The lab media for mycelium production includes carbon source (Glucose, dextrose, lactose, starch, sucrose etc) and nitrogen sources (Peptone, yeast, malt extract etc) (Bisko et al., 2020). In solid state fermentation, ligno-cellulosic wastes such as sawdust and rice husk is used for the growth of the mycelium. The mycelium grows outwards in search of oxygen which leads to a mycelium mat formation on the surface of solid substrate (Jones et al., 2021). After the formation of mycelium mat on the surface, it is removed from the solid substrate and hot pressed to inhibit the fungal growth. The obtained mat is chemically treated to enhance its properties. Few patents have been registered by companies such as Ecovative Design LLC (Eben Bayer and Gavin Mclntyre, 2017; Eben Bayer et al., 2012; O'Brein & Meghan, 2020), Mycoworks Inc (Ross, 2012), and Mycotechnology Inc (Bentangan & Mohamad, 2020) for the production of mycelium based materials. The mat obtained from solid substrate is treated with a plasticizer such as glycerol, ethylene glycol, or sorbitol to improve its strength (Vandelook et al., 2021). The gluing property of mycelium has been utilized for the production of fabrics, and bio-composites, but there is still much scope for the development of these materials.

7. Conclusions and future aspects

The use of edible mushrooms as healthy foods and dietary supplements is estimated to increase dramatically in the near future. In the past few years, there has been a tremendous rise in interest across the globe in mushrooms due to its immune boosting ability, flavour, taste and many other health benefits. The bioactive metabolites specially polysaccharides and terpenoids from edible mushrooms have medicinal effects, including anti-cancer, anti-tumor, anti-diabetic, anti-oxidation, anti-aging, anti-viral, immune-boosting, anti-hyperglycemic effects and many others. β-glucans exhibit immunological and antioxidant activity by stimulating macrophage dependent immune cells and protect against the damage of free radicals. Au and Ag nanoparticles extracted from the mushrooms are proved to have anti-cancerous effects without any serious side-effects but this research is still in its initial stage. The medicinal value of mushrooms as a natural antiviral remedy against SARS-COV-2 has been addressed in this review. Several bioactive metabolites such as gallic acid, and ergosterol have strong binding affinity for the spike of SARS-COV-2 virus. The mushroom's bioactive metabolites have the potential to advance medicine research in the future to treat and prevent medical disorders. The extraction methods of secondary metabolites and their applications in controlling various diseases are not much explored. Although the results of several in vitro research have really been proved to be very hopeful, but more rigorous and in-depth studies are still required for confirmation. In addition, the importance of mushrooms is not limited to their nutritional and medicinal value but also in the biodegradable and sustainable materials that have less toxicity and provide superior mechanical properties. There is a need to introduce these materials into the market as antimicrobial food packaging material. Due to the superior thermal stability, hydrophobic nature, and excellent mechanical properties of mycelium-based materials, they can potentially replace conventional packaging materials, construction materials, and animal leather which are expensive, and have significant emission. However, their mechanical properties are affected by several parameters including type of feed stock substrate, mushroom strain, and fabrication protocols including sterilization, incubation duration, and drying process. The current challenge lies in the regulation of these parameters in order to minimize the cost of production and in turn maximize the productivity and quality.

Declaration of competing interest

The authors would like to declare no conflict of interest in the preparation of manuscript.

Data availability

No data was used for the research described in the article.

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