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Review article

A comprehensive review on multifunctional bioactive properties of elm oyster mushroom *Hypsizygus ulmarius* (Bull.) Redhead (Agaricomycetes): Current research, challenges and future trends

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ABSTRACT

Mushrooms have evolved as a nutritional powerhouse, harnessing a diverse spectrum of bioactive molecules to fortify human health. *Hypsizygus ulmarius* represents a pioneering species within the oyster mushrooms distinguished by its unique characteristics and potential abilities. It is characterized by its large fruiting bodies, which have a meaty flavor and excellent taste. Additionally, this mushroom has a high yield and biological efficiency. This mushroom also holds significant importance globally and is cultivated in China, Japan and other Asian nations due to its favorable growth conditions, exceptional nutritional value, and medicinal attributes. This review focuses on the nutrition and bioactive molecules present in this mushroom species and their further implications in medicine, agriculture, biotechnology for the development of new anti-bacterial agents and their potential industrial uses for human health. This review aims to provide more recent information on the above aspects. *Hypsizygus ulmarius* shows great potential as a valuable source of several nutrients and bioactive chemicals that may have therapeutic qualities. The immunomodulatory, anti-oxidant, anti-inflammatory and potential anti-cancer properties of this mushroom provide opportunities for further future research in the creation of beneficial functional foods, dietary supplements and pharmaceutical interventions to enhance human health.

1. Introduction

Mushrooms encompass a diverse array of macrofungi, which can grow either below ground or above it, emerging from underground mycelium through a fruiting process. It has been approximated that our natural world hosts around 1.5 million species of fungi,

Abbreviations: ALT, Alanine transaminase; AST, Aspartate transaminase; ALP, Alkaline phosphatase; LDH, Lactate dehydrogenase; LPO, Lipid peroxide; HPO, Hydroperoxide; PCO, Protein carbonyls; GST, Glutathione-S-transferase; GR, Glutathione reductase; TAOC, Total antioxidant capacity; DMP, Dimethyl phthalate; FBG, Fasting blood glucose; Ara, Arabinose; Man, Mannose; Glu, Glucose; GlcA, Glucuronic acid; GalA, Galactuonic acid; PT, Prothrombin time; TT, Thrombin time; APTT, Activated partial thromboplastin time.

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including mushrooms. Our understanding is limited to only about 10 percent of these species. The number of mushrooms expected to grow on the earth ranges from 1,50,000 to 1,60,000 species. Among them, approximately 16,000 mushroom species have been described. Out of them, more than 3000 species belonging to 31 genera are recognized as premium edibles and culinary delights due to their distinctive taste, flavor, aroma, texture, and digestibility. In the Indian context, over 300 edible mushroom species belonging to 70 genera have been documented in the literature [1]. In terms of cultivation, approximately 80 mushroom species have been subjected to experimental growth, while only around 20 species are cultivated commercially. Notably, only 4 to 5 species are being extensively produced across different regions of India. Within commercial mushrooms, the *Pleurotus* genus stands out as a diverse group of edible species and ranks third globally in production [2].

The latest statistical data on mushroom cultivation globally indicates significant growth and diversification in production. *Pleurotus* mushrooms play a substantial role in the global mushroom industry and alone contribute around 25 percent in the global mushroom industry and contribute around 25 percent of the total cultivated mushrooms worldwide [3]. In 2017, world mushroom production was distributed among various genera, with *Agaricus*, *Pleurotus*, *Lentinula* and *Auricularia* being at the top [4]. The annual growth rate of mushroom production is estimated at 6–7 percent, with cultivation expanding to over 100 countries [5]. *Pleurotus ostreatus* is highlighted as the second most cultivated edible mushroom globally, following *Agaricus bisporus* [6]. The current production of *P. ostreatus* is approximately 3 million metric tons per year, grown on various lignocellulosic substrates [7]. Global mushroom production has experienced substantial growth over the years, with an increase from 6.1 million tonnes in 1997 to 12.2 million tonnes in 2002 [8]. By 2026, the worldwide mushroom economy will reach 20.84 million tons [9]. While oyster mushrooms and shiitake dominate global production, the button mushroom is commercially the most important in Europe, the USA and Australia [10]. China alone produces 64 percent of all edible mushrooms and 85 percent of oyster mushrooms [11]. The mushroom industry has recently experienced substantial growth, with diverse genera contributing to mushroom production and consumption globally.

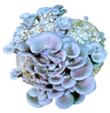
Mushrooms are widely acknowledged for their nutritional and medicinal advantages on a global scale. Mushroom production effectively transforms agro-industrial wastes into valuable resources and nutritious rich food. Cultivating mushrooms on wooden logs not only aids in managing forest wastes but also enhances forest health, promoting sustainable forestry practices [12]. This approach holds great potential for promoting sustainable agriculture and forestry, both inside India and abroad [13]. *Hypsizygus ulmarius* (Bull.) Redhead, commonly known as elm oyster or blue oyster mushroom, is a novel species of oyster mushroom that is becoming increasingly popular among small and marginalized farmers due to its ease of growth on various agro-industrial wastes such as soybean, sawdust, wheat straw, paddy straw, sugarcane trash, bagasse etc. [14,15]. Cultivating edible mushrooms not only can recycle agricultural wastes but also helps address the protein deficiency prevalent among a large population in the country [16,17]. The cell walls of edible and medicinal mushrooms contain bioactive chemicals that have been studied both *in vitro* and *in vivo*, these molecules have a diverse spectrum of functional features, including antioxidant, anti-inflammatory, antitoxic, antibacterial, anticancer and hypoglycemic activities [18]. However, the detailed mechanisms of their effects are yet to be explored. Bioactive molecules and mycochemicals present in different types of mushrooms and the health advantages associated with them are presented in Table 1 and Fig. 1.

Fungi, including yeast, mushrooms and bracket fungi, have been extensively utilized as food for many centuries [57]. Mushrooms have a rich history of providing both nutritional and medicinal benefits due to their valuable bioactive compounds [58]. A wide variety of edible mushrooms provide a wide variety of necessary elements, including proteins, vitamins, minerals, carbohydrates, low fat, fibers and amino acids [59–61]. Mushrooms have a nutritional importance comparable to grains, fruits, milk and meat because they provide a unique combination of essential components. Therefore, mushrooms function as a vital addition to a well-rounded diet. Mushrooms have a low-calorie content but are abundant in essential nutrients such as vitamin B-complex, selenium and copper. These nutrients are crucial for metabolic functions, immunological function and overall well-being [62]. Furthermore, mushrooms serve as a rich source of premium protein, making them a better vegetarian choice. Additionally, they contain dietary fiber, aiding in digestion and satiety [63]. The diverse nutritional profile of mushrooms and their versatility in culinary applications highlight their significance in promoting overall health [34,64–66]. The nutritional composition of major medicinal mushrooms has been presented in Table 2. Even though the literature on the nutritional and bioactive components of edible and medicinal mushrooms is quite extensive, but a comprehensive review on a new novel species of oyster mushroom i.e., *Hypsizygus ulmarius* is missing. Therefore, the purpose of this review is to compile and organize current information on this mushroom's nutritional and bioactive components, as well as its potential as a source of nutraceuticals. An extensive literature search was conducted across multiple databases including PubMed, Web of Science, Scopus and Google Scholar to retrieve the necessary information. The search encompassed the research papers, which served as bibliographic references for the publications that were examined for the intended purpose. This review aims to analyze existing literature to provide a thorough overview of the research on the versatile bioactive properties, nutritional value of medicinal mushrooms and their use in functional food products. The main aim of the review was to examine the pharmacological and therapeutic characteristics of elm oyster mushroom (*H. ulmarius*). The present review intends to deliberate the nutraceutical potential, therapeutic properties, bioactive compounds and health benefits of *H. ulmarius* for maintaining and promoting healthy lifestyles to enhance well-being and treat chronic diseases (Fig. 2).

2. Importance, classification, morphology, nutritional and bioactive properties of *Hypsizygus ulmarius*

Hypsizygus ulmarius, a saprophytic fungus, can be readily introduced to any region across the globe. Though it resembles other oyster mushrooms in appearance, this relatively rare and promising mushroom species has a different morphology and greater biological efficiency. Its rapid growth and strong resistance against competing organisms make its cultivation more cost-effective and less labor-intensive. Additionally, its appealing bluish color and ability to thrive in sub-tropical conditions make it a promising choice for

Table 1
List of important medicinal mushrooms, their bioactive components and health benefits.

Sr. No.	Mushroom species (basidiocarps)	Scientific name	Common name	Family	Bioactive components	Health benefit	Reference
1.		*Hypsizygus ulmarius* (Bull.) Redhead	Elm oyster or blue oyster	Lyophyllaceae	Exopolysaccharide (HUP-2), Tannins, Coumarin, Alkaloids, Steroids, Anthraquinone, Saponins, Lovastatin, β-glucan, Phenolic compounds	Anti-inflammatory, Antioxidant, Cholesterol regulation, Anticancer, Antimicrobial, Antitumor, Cardioprotective, Antibacterial, Antifungal	[19–21]
2.		*Hypsizygus marmoreus* (Peck) Bigelow	Brown beech	Lyophyllaceae	Phenolic compounds, Flavonoids, Marmorin	Antitumor, Antibacterial, Antifungal, Antioxidant	[22]
3.		*Ganoderma lucidum* (Curtis) P. Karst	Reishi	Ganodermataceae	Ganoderic acids, Ganodermanontriol, Ganoderiol polysaccharides, Triterpenoids, Germanium, Nucleosides, Nucleotides, β-glucan	Anti-metastatic, Antitumor, Antiviral, Anti-HIV, Anti-modulatory, Liver protection, Prevents cholesterol synthesis, Anti-aging and Cardioprotective	[23,24]
4.		*Ganoderma microsporum* (Mont.) Murrill	Lingzhi	Ganodermataceae	Protein GMI	Immunomodulatory	[25]
5.		*Lentinula edodes* (Berk.) Pegler	Shitake	Marasmiaceae	Genistein combined polysaccharide (GCP), Lentinan, Glucan, Mannoglucan, Fucomannogalactan, Lentin, Catechin, Flavonoids, Eritadenine	Immunomodulatory, Antitumor, Anti-inflammatory, Antifungal, Antioxidant, Antibacterial, Hypolipidemic activity, Anticancer, Immunosuppressive effects	[26,27]
6.	 	*Lentinula polychrous* (Berk.) Pegler & T.W.K. Young & *Lentinula squarrosulus* (Mont.) Pegler	Lentinula spp.	Polyporaceae	Catechin	Antioxidant	[28]
7.		*Cordyceps militaris* (L.) Fr.	Caterpillar fungi	Cordycipitaceae	Cordycepin, Lectins, Lovastatin, Adenosine, Ergosterol, Mannitol	Anti-inflammatory, Treat lung infection, Hypoglycemic activity, Anti-depressant activity, Anti-obesity, Anticancer, Energy and stamina booster, Anti-hypersensitive, Antiasthma, Cellular health properties	[29,30]
8.		*Cordyceps sinensis* (Berk.) Sacc.	Winter worm	Ophiocordycipitaceae	Cordycepin, Cordymin (peptide)	Antioxidant, Immunosuppressive, Anti-inflammatory	[29]
9.		*Hericium erinaceous* (Bull.) Pers.	Lions mane	Hericiaceae	Hericenones, Erinacines, Ergosterol, Resorcinols, Hericene A	Congestive function support, Nerve health, Neuroprotective effects, Anticancer, Gastroprotective effects, Immunostimulant, Anti-hypercholesterolemic	[31]
10.		*Trametes versicolor* (L.) Loyd.	Turkey tail	Polyporaceae	Grifoian, Krestin, PSK, PSP, Lanostane type tetracyclic triterpenoid sterol, Fungisterol, β-sitosterol, β-1-3 and β-1-4 glucans	Immunomodulatory, Anticancer, Promote gut health, Anti-invasive, Anti-Hyperlipidemic activity	[30,32]

(continued on next page)

Table 1 (*continued*)

Sr. No.	Mushroom species (basidiocarps)	Scientific name	Common name	Family	Bioactive components	Health benefit	Reference
11.		*Inonotus obliquus* (Ach. ex Pers.) Pilat	Chaga	Hymenochaetaceae	Triterpenes, Polysaccharides, Polyphenols, Flavonoids, Inotodiol (Ino), Lanosterol (LAN), Trametenolic acid (TA), Ergosterol	Antioxidant, Anticancer, Antibacterial, Anti-inflammatory, Lower bad cholesterol, Immune system modulator, Reduce oxidative stress	[33,34]
12.		*Grifola frondosa* (Dicks.) Gray	Maitake	Meripitaceae	Lectins, Polysaccharides, Grifolan, β-glucans, Heteroglycans, MD-fraction, Ex-fraction, MZ-fraction, MT-alpha-glucan	Decrease blood glucose, Improve insulin secretion and ovulation, Antiviral, Anti-arthritic, Antidiabetic, Anticancer, Anti-obesity	[30,35]
13.		*Pleurotus ostreatus* (Jacq. ex Fr.) P. Kumm.	Pearl oyster	Pleurotaceae	Proteins, Peptides, Glycoprotein, Proteoglycans, Pleuran, Glucans, Laccase, Pleurostrin	Immunomodulatory, Hyperglycemia, Nutrient rich, Antitumor, Antioxidant, Antiviral, Antifungal, Blood sugar control	[36,37]
14.		*Schizophyllum commune* Fr.	Split gills	Schizophyllaceae	Schizophyllan hydroxybenzoic acid, Tocopherol, Protocatechuic acid, β-glucans, Polysaccharides	Anticancer, Antimicrobial, Neuroprotective effects	[38,39]
15.		*Wolfiporia extensa* (Peck.) Ginns	China root	Polyporaceae	N-(3-chlorophenly) naphthyl carboxamide polysaccharides, Triterpenoids, Fatty acids, Porio cocos polysaccharides (PCP), Carotenoids, Flavonoids, Carnitine, Choline, Coenzyme-Q, Dithiolthiones, Phytosterols, Phytoestrogens, Glucosinolates, Polyphenols, Taurine	Analgesic effects, Anti-inflammatory, Gastricatony dizziness, Nephrosis, Diuretic, Stimulant, Carminative, Purification of blood, Used for venereal disorders and skin-related infections, Laxative and tonic properties	[40,41]
16.		*Flammulina velutipes* (Curtis) Singer	Valvet foot	Physalacriaceae	Peptiglycan polysaccharide, Flammulin, FVP (Flammulin polysaccharide protein), Pro flamin, Aprolamin, Flavonoids	Anticancer, Antiallergy, Antibacterial, Antiviral, Anti-inflammatory, Immunity booster, Antiasthama, Anti-hypercholesterolemic properties	[30,42]
17.		*Morchella esculenta* Fr.	Yellow morel	Morchellaceae	Polysaccharides, Phenols, Tocopherols, Polyunsaturated fatty acids	Antioxidative, Immunomodulatory, Anti-inflammatory, Immunostimulating, Antitumor, Antiviral, Antiaging properties	[35,43]
18.		*Tremella fuciformis* (Berk.)	Snow fungus	Tremellaceae	*Tremella fuciformis* polysaccharide (TFPS), Fatty acids, Flavonoids, Trace elements, Ergosterol, Protein hydrolysates	Tonic herbs, Beauty and hydrations, Healthy cellular aging, Neuroprotective, Anti-inflammatory, Anticancer, Control cholesterol and obesity	[44,45]
19.		*Tremella mesenterica* Retz.	Golden jelly fungus	Tremellaceae	Glucurono-xylomannan polysaccharide	Hypoglycemic, Immunomodulatory	[46]

(*continued on next page*)

Table 1 (*continued*)

Sr. No.	Mushroom species (basidiocarps)	Scientific name	Common name	Family	Bioactive components	Health benefit	Reference
20.		*Auricularia auricula* Judae (Bull.) J. Schrot.	Wood ear	Auriculaiaceae	Glucan, Acidic polysaccharides, Acidic heteroglycans	Heart health, Immune and tonic, Antioxidant, Antitumor, Immunobooster, Digestive health, Lower cholesterol, Hypoglycaemic activity	[47,48]
21.		*Russula emetica* (Schaeff.) Pers.	Sickner	Russulaceae	Marasmane sesquiterpenes (Lactapi peranol A&E), Rulepidanol sesquiterpenes, Rulepidadines A&B, Ellagic acid, Rutin, Quercetin, Apigenin	Antimicrobial, Antioxidant, Treatment for liver diseases, Eye problems, Chest distress, HIV-1 and AIDS treating	[49,50]
22.		*Russula lepida* Sarnari	Rosy russula	Russulaceae	Lectin (glycoprotein)	Antitumor	[51]
23.		*Agaricus bisporus* (J.E. Lange) Imbach	White button mushroom	Agaricaceae	Pyrogallol, Hydroxybenzoic acid derivatives, Flavonoids, Proteins, Estrogen, Lectin	Anti-inflammatory, Antioxidant, Anti-inflammatory	[52,53]
24.		*Agaricus subrufescens* Peck.	Almond mushroom	Agaricaceae	Glycoprotein, β-(1, 3)-glucan, with β-(1,6)-glucan branch	Immunomodulatory, Anti-inflammatory	[54]
25.		*Boletus edulis* (Bull.) Fr.	King bolete	Boletaceae	Glucans, Polysaccharides	Anti-inflammatory	[55]
26.		*Psilocybe* spp.	Magic mushroom	Hymenogastraceae	Psilocybin	Anti-depressant (Psychotherapy)	[56]

commercial mushroom cultivation in our country. This mushroom when compared to other edible oyster mushrooms, demonstrates significantly higher yield and biological efficiency. Consequently, it can potentially become a prominent mushroom in the future [76,77].

Hypsizugus ulmarius is commonly known as elm oyster mushroom, which belongs to the Kingdom- Fungi and Class- Agaricomycetes (Fig. 3). Other names including *Agaricus ulmarius*, *Lyophyllum ulmarius* and *Pleurotus ulmarius* [78]. It has also earned the name 'blue oyster mushroom' due to its bluish color during the pinhead stage [79]. German mycologist Rolf Singer first described the genus *Hypsizygus* in 1947. This genus contains five species *viz*., *H. tessulatus*, *H. ulmarius*, *H. cicinatus*, *H. marmoreus* and *H. elongatipes* [80]. The taxonomy of the *H. ulmarius* is not yet fully understood. The classification of this oyster mushroom species as part of the genus *Hypsizygus* is based on its possession of several key characteristics that are shared with other members of the same genus. In this species, the gills are primarily detached from the stipe and do not extend downwards (adenate), whereas in *Pleurotus* species, the gills do extend downwards. In addition, the stipe of *H. ulmarius* lacks an annulus (rings) and is centrally attached to the cap, whereas in other *Pleurotus* species, the stipe is typically off-center [1]. Earlier, according to Volk [81], *H. ulmarius* was classified as *P. ulmarius* but later was placed under the genus *Hypsizygus*. However, in 1984, Canadian Mycologist Scott Redhead relocated this species to its present taxonomic classification, *Hypsizygus ulmarius*. This decision was made due to the ecological and physical resemblance to another species within the *Hypsizygus* genus. *Hypsizygus ulmarius* is a novel species of oyster mushroom characterized by its large fruiting bodies, blue pinheads, excellent taste with a robust flavor, attractive appearance and a texture that is both firm and succulent with good-keeping quality [82]. However, there is still a lot of knowledge to acquire on the phylogenetic connection among the genus *Hypsizygus* [83,84].

Throughout the broad category of edible mushrooms, *H. ulmarius* stands out as one of the most significant species. In India, Rai [85] cultivated this mushroom for the first time. It is one of the important mushroom widely grown in China, Japan and other Asian countries, owing to its low-cost production technology and high yield. On a dry weight basis, it is a noteworthy source of various important nutritional components. Additionally, it contains 23.6 percent protein, 2.2 percent fat, 52.4 percent carbohydrates and 12.9 percent fibers [86]. Proteins are indispensable for the body, playing a crucial role in supporting growth, tissue repair and maintaining vital bodily structures. They are versatile macromolecules that provide the building blocks for muscles, organs and enzymes, and contribute to immune function, transport oxygen and act as signaling molecules. Without a sufficient protein intake, the body would

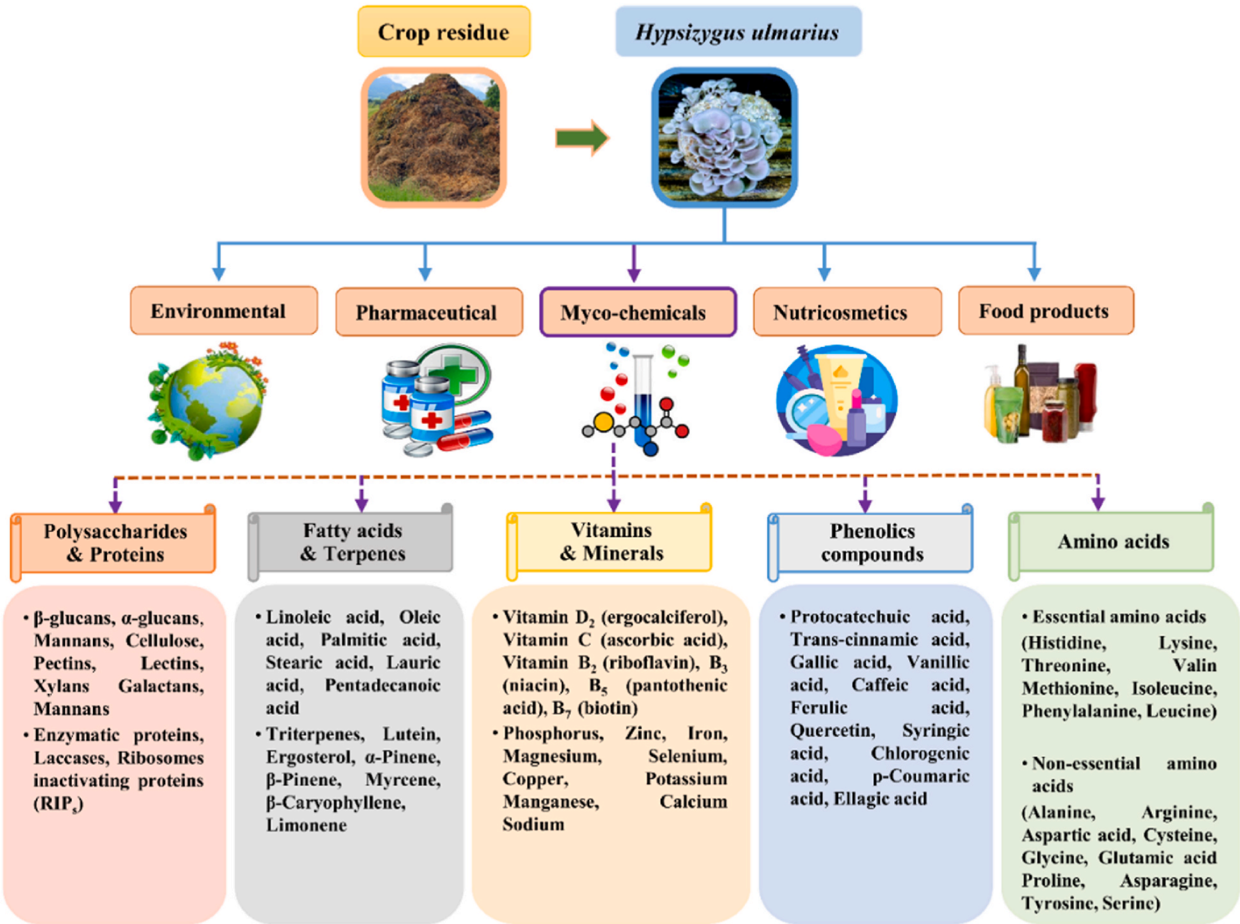


Fig. 1. Multifarious uses of *Hypsizygus ulmarius* in environment sustenance, pharmaceuticals, nutricosmetics and food products, focusing mycochemicals.

struggle to recover from injuries, maintain healthy cells, or effectively carry out various biochemical processes, highlighting the vital importance of this nutrient for overall health and well-being. This mushroom can contribute significantly to meeting the body protein requirements. It is particularly beneficial for individuals following vegetarian diets as it provides a good source of protein [87]. Moreover, Yogachitra [67] reported the highest mycelial protein (27.8 %) in the dried powder of *H. ulmarius*. The fat content (2.2 %) indicates that this mushroom is relatively low in fat. Through the consumption of foods that are low in saturated and trans fats, it becomes easy to maintain low cholesterol levels and also lower the likelihood of developing heart illnesses. It appears that mushrooms have the potential to be a useful source of energy because they contain a high percentage of carbohydrates, specifically 52.4 percent. Because carbohydrates are the major source of fuel for the body, they supply the essential energy that is required for a variety of bodily activities as well as physical activity. Furthermore, this mushroom contains 12.9 percent fiber and because it encourages regular bowel movements and helps prevent constipation, dietary fiber is a vital component in the process of maintaining digestive health. In addition to this, it can assist in regulating blood sugar levels, reducing cholesterol levels and advancing a sensation of fullness, which is beneficial to body weight management.

Hypsizygus ulmarius had been grown on several substrates [88–90] under specific physiological conditions [189,190] and it showed a good profile of vitamins, minerals and proximate composition [76,86]. Karthika and Murugesan [91] analyzed the composition of dried fruit bodies of *H. ulmarius*, revealing significant variations in macronutrient content. Their findings indicated that the protein concentration was notably higher than that of carbohydrates and lipids within the fruit bodies, underscoring the nutritional richness of protein in this particular fungal species. Human diets require certain vitamins, which can be made from readily available agro-industrial wastes by growing mushrooms [76]. One of the primary compounds responsible for mushroom antioxidant benefits is β-carotene, which is also the precursor to vitamin A [92]. Jose and Geetha [93] found in their study that the concentration of β-carotene in *H. ulmarius* dried powder was recorded as 195.58 μg/g of dried mushroom sample, which was higher than in *P. florida* (125.24 μg/g) and *Calocybe gambosa* (187.68 μg/g). The presence of vitamin B_1 content (0.78–0.943 mg/100g) in different agro-wastes was found to be comparatively higher than in cereals (0.29–0.33), fruit (0.02–0.03) and egg (trace-0.04) [94]. Nakalambe et al. [95] however, found vitamin B_1 content ranged from 0.05 to 0.94 mg/100g in this mushroom. This mushroom is a source of adequate

Table 2
Proximate composition of major medicinal mushrooms.

Sr. No.	Mushroom species	Moisture (g/100 g, fw[a]/dw[b])	Crude protein (g/100 g dw)	Crude fat (g/100 g dw)	Carbohydrates (g/100 g dw)	Ash (g/100 g dw)	Energy (kcal/100 g dw)	Reference
1.	*Hypsizygus ulmarius*	89.29 ± 0.70 (fw)	24.50 ± 1.02	3.80 ± 0.72	40.74 ± 1.50	7.96 ± 0.80	372	[67]
2.	*Hypsizygus marmoreus*	90.18 ± 0.75 (fw)	19.60 ± 1.50	4.09 ± 0.02	68.56 ± 1.55	7.75 ± 0.91	177	[68]
3.	*Ganoderma lucidum*	5.60 ± 0.16 (dw)	9.20 ± 0.32	1.10 ± 0.01	8.36 ± 4.40	1.0 ± 0.00	378	[69]
4.	*Lentinula edodes*	7.30 ± 0.10 (dw)	18.50 ± 0.16	0.80 ± 0.01	68.30 ± 4.70	5.59 ± 0.30	387	[69]
5.	*Cordyceps militaris*	7.70 ± 0.61 (dw)	29.70 ± 0.42	2.90 ± 0.18	54.30 ± 5.50	5.40 ± 0.16	317	[69]
6.	*Hericium erinaceous*	6.20 ± 0.14 (dw)	20.80 ± 0.43	5.10 ± 0.11	61.10 ± 3.60	6.80 ± 0.22	346	[69]
7.	*Trametes versicolor*	61.60 ± 1.34 (fw)	8.12 ± 2.04	0.93 ± 0.70	38.37 ± 1.08	2.42 ± 1.04	393	[70]
8.	*Inonotus obliquus*	3.50 ± 0.36 (dw)	2.40 ± 0.44	1.70 ± 0.25	10.30 ± 0.44	2.40 ± 0.44	358	[34]
9.	*Grifola frondosa*	4.80 ± 0.08 (dw)	18.30 ± 0.34	5.30 ± 0.09	66.90 ± 8.40	4.70 ± 0.07	355	[69]
10.	*Pleurotus ostreatus*	8.20 ± 0.07 (dw)	33.50 ± 0.22	2.30 ± 0.07	48.90 ± 2.70	7.10 ± 0.06	345	[69]
11.	*Schizophyllum commune*	69.8 ± 0.02 (fw)	24.42 ± 0.02	–	5.31 ± 0.01	6.02 ± 0.60	334	[71]
12.	*Flammulina velutipes*	5.0 ± 0.13 (dw)	23.40 ± 0.19	2.10 ± 0.10	61.20 ± 4.30	8.30 ± 0.08	378	[69]
13.	*Morchella esculenta*	4.20 ± 0.49 (dw)	7.50 ± 0.40	2.80 ± 0.10	75.0 ± 0.40	14.60 ± 0.30	467	[72]
14.	*Tremella fuciformis*	5.50 ± 0.18 (dw)	13.0 ± 0.12	2.10 ± 0.08	72.90 ± 6.40	6.50 ± 0.14	326	[69]
15.	*Auricularia auricula*	88.90 ± 0.02 (fw)	56.92 ± 0.01	–	18.67 ± 0.01	3.15 ± 0.30	327	[71]
16.	*Russula emetica*	84.58 ± 1.01 (fw)	16.84 ± 0.05	1.99 ± 0.44	43.38 ± 3.71	37.78 ± 5.20	354	[73]
17.	*Agaricus bisporus*	90.09 ± 0.07 (fw)	24.43 ± 0.10	3.06 ± 0.03	53.10 ± 0.56	9.17 ± 0.52	335	[74]
18.	*Agaricus subrufescens*	89.27 ± 0.17 (fw)	31.53 ± 0.91	1.33 ± 0.29	53.80 ± 2.25	7.73 ± 0.31	353	[75]
19.	*Tricholoma giganteum*	85.30 ± 0.21 (fw)	16.12 ± 1.72	4.28 ± 0.10	74.57 ± 0.69	5.03 ± 0.80	254	[68]
20.	*Boletus edulis*	83.12 ± 1.18 (dw)	18.54 ± 1.30	5.76 ± 0.40	69.86 ± 1.20	5.84 ± 0.20	159	[68]

[a] fw-fresh weight.
[b] dw-dry weight.

vitamin B_2 also, which is required by all classes of people except during pregnancy and lactation. The riboflavin content (0.28–0.503 mg/100g) was more than that of vegetables (0.01–0.3 mg/100g) and common cereals (0.11–0.18 mg/100g) [94]. In addition, the niacin content (1.72–2.81 mg/100g) is an important vitamin for humans to consume, and research has shown that consuming 1–5 g of niacin daily aids in the regulation of blood cholesterol levels [96]. This mushroom also exhibited an excellent vitamin C content (7.56–8.64 mg/100g) and vitamin A (5.77–8.33 mg/100g) concentration in fruit bodies harvested from different substrates. It has been suggested that vitamin C possesses elements that are both medicinal and antioxidant in nature. On the other hand, a lack of these vitamins can result in a variety of adverse effects, including blindness, rough and peeling skin, dry mucous membranes, suppression of growth, decreased resistance to infections and problems in bone formation and modulation [97]. Mushrooms are the sole non-animal dietary item that contains vitamin D, making them the unique natural vitamin D source for vegetarians [98]. *Hypsizygus ulmarius*, offers a multitude of health benefits across different body organs. Its consumption promotes heart health by lowering cholesterol levels and supporting cardiovascular function, the high dietary fiber content of this food promotes digestion, avoids constipation and supports a healthy gut microbiome. Additionally, beneficial compounds in *H. ulmarius* support liver health by aiding detoxification and protecting liver cells, bolster the immune system against infections and viruses and may even have neuroprotective effects, reducing the risk of neurodegenerative diseases. Its antioxidants and anti-inflammatory properties contribute to skin health, while essential minerals like calcium (Ca), phosphorus (P) and magnesium (Mg) support bone density and strength. Incorporating *H. ulmarius* into the human diet provides a delicious and nutritious way to enhance the health of various organs throughout the body (Fig. 4).

Mushrooms are rich sources of Ca, Mg, P, potassium (K) and salt, all of which are vital for human nutrition [99]. These elements are crucial for the development of robust bones and teeth, the restoration of damaged tissues, and the maintenance of osmotic equilibrium [100]. Minerals like Ca (0.080 %), Mg (0.040 %), P (0.0194 %) and K (0.700 %) are abundant in *H. ulmarius* [93]. The high mineral

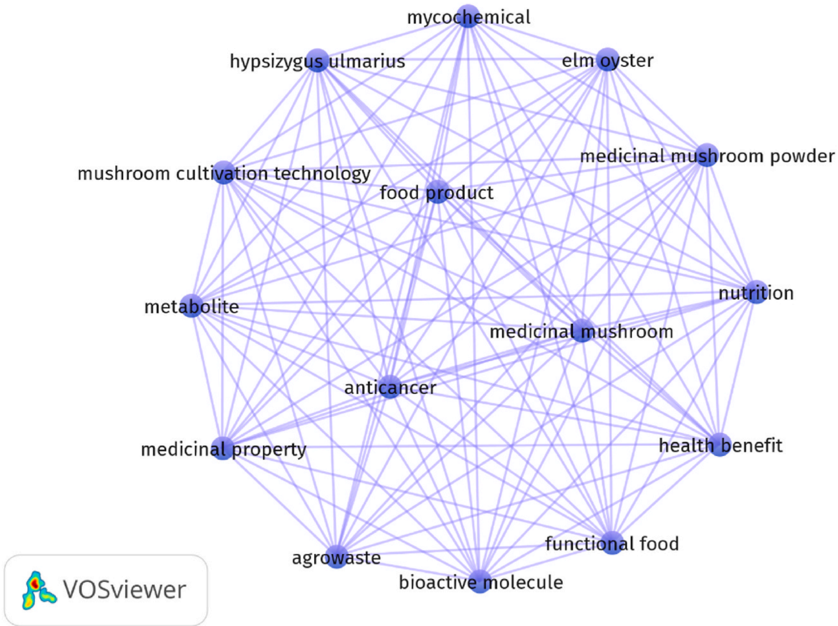


Fig. 2. A glossary of key terminology related to this review, created with the VOS viewer.

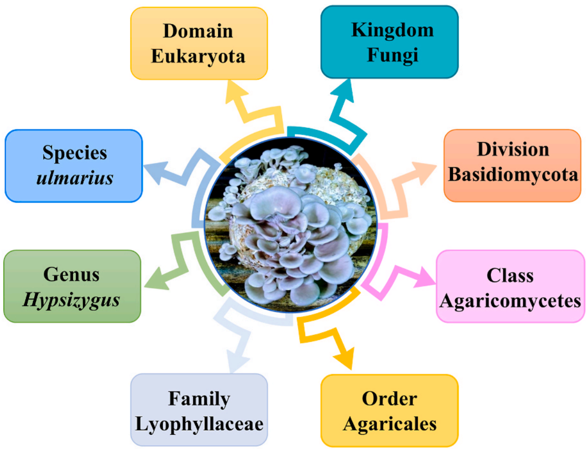


Fig. 3. Scientific classification of the elm oyster mushroom (*Hypsizygus ulmarius*).

content in this mushroom can be attributed to its ability to efficiently utilize the nutrients present in various substrates influenced by environmental conditions. The mineral composition of this mushroom exhibits comparatively higher quantities than other mushrooms [101]. A low sodium (Na) content (0.024 %) makes it beneficial for patients suffering from specific kidney, heart diseases and hypertension issues [93]. Sunday et al. [76] emphasized in their research that this mushroom is a valuable reservoir of phytochemicals, proximate components and essential mineral nutrients crucial for maintaining optimal health. Mycochemicals found in various *Pleurotus* species and their corresponding health benefits have been enlisted in Table 3.

Among commercially cultivated oyster species, *H. ulmarius* contains a high concentration of proteins, carbohydrates, dietary fibers, unsaturated fatty acids, enzymes and minerals [67,76]. Edible mushrooms are highly esteemed worldwide for their unique characteristics, nutritional composition and therapeutic benefits [61,127]. Recently, there has been a growing public fascination with these gastronomic marvels due to their diverse range of secondary metabolites with numerous potential uses. The mycochemical analysis of *H. ulmarius* has revealed significant bioactive constituents, including polysaccharides and phenolic compounds. These compounds are crucial for the medicinal properties in mushrooms, contributing to their antioxidant, anti-inflammatory and immune-boosting effects [19]. The presence of these chemicals is essential for the therapeutic characteristics of the mushroom, as they contribute to its antioxidant, anti-inflammatory and immune-enhancing actions. The existence of these bioactive substances highlights the therapeutic capabilities of *H. ulmarius*, rendering it helpful in both traditional and modern medicine. Furthermore, they function as a vital supply of

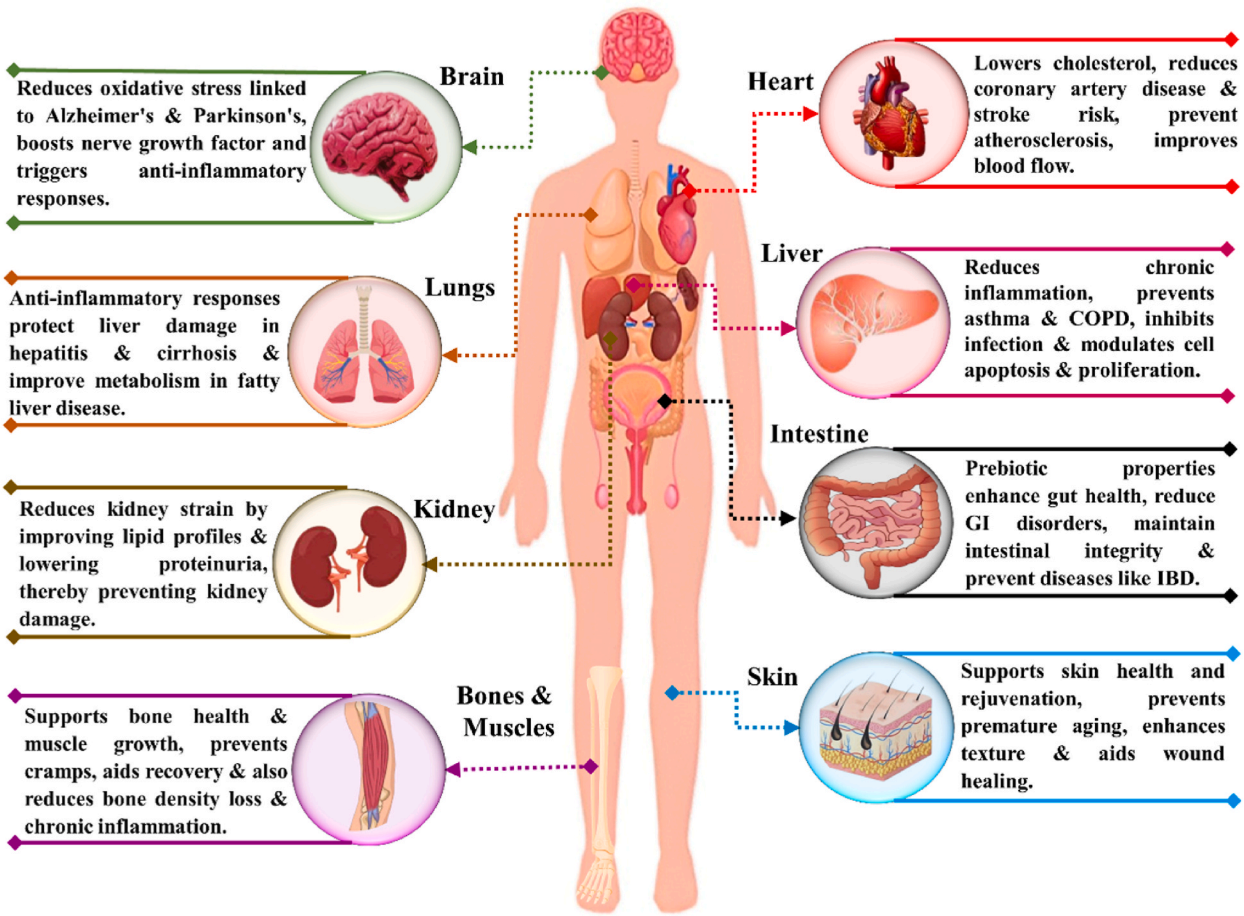


Fig. 4. Potential health benefits of *Hypsizygus ulmarius* mycochemicals in modulating the immune system in the human body.

sustenance and vitality, rendering them very appropriate for inclusion in dietary formulations. This fungus exhibits promising properties that make it suitable for use in the pharmaceutical, medicinal and food industries. It has also demonstrated anticancer effects, the ability to reduce cholesterol levels and positive impacts on cardiovascular health [128,129]. The significant presence of alkaloids, phenols, flavonoids and saponins in this mushroom strongly suggests its medical significance. These bioactive chemicals have pharmacological capabilities and can be used for antibacterial, anticancer, antiviral, antidiabetic, anti-inflammatory and antioxidant purposes [20,128,129] (Fig. 5).

3. Multifunctional bioactive properties and health benefits of *Hypsizygus ulmarius*

3.1. Antioxidant activities

Mushrooms are considered a valuable source of antioxidants due to the presence of phenolic compounds, mycochemicals and other polysaccharides [86]. The antioxidant properties of mushrooms are attributed to the presence of a range of chemicals such as phenols, flavonoids, vitamins, peptides, polysaccharides, carotenoids and alkaloids, which are associated with their bioactive components [67,76,93]. *Hypsizygus ulmarius* extract contains a high concentration of antioxidants, which shield the body from oxidative stress induced by free radicals. These free radicals can contribute to healthy aging. The antioxidants in *H. ulmarius* extract promote overall well-being by neutralizing free radicals. Various extracts from *H. ulmarius*, including aqueous ethanolic extracts from the fruiting body and mycelia, as well as purified exo-polysaccharides ethanol and methanol extracts from the mycelia, have been studied for their antioxidant effects. These extracts have demonstrated strong antioxidant capabilities in various tests assessing their ability to scavenge free radicals, hydroxyl radicals and 2,2-azino-bis-3-ethylbenzothiazoline-6-sulphonic acid (ABTS) radicals, as well as their capacity to prevent lipid peroxidation and estimate phenol levels [76,93]. According to Al-Faqeeh et al. [19], the fruiting bodies of *H. ulmarius* contain a diverse range of compounds. The methanolic extract shows the presence of alkaloids, tannin, phenolic compounds, flavonoids, anthraquinone, saponin, coumarin and steroids. It was noted that the petroleum ether fraction of the methanolic extract had a higher concentration of phytochemical components compared to the ethyl acetate fraction. The 2,2-Diphenyl-1-picrylhydrazyl (DPPH)

Table 3
List of different *Pleurotus* mushroom species (Pleurotaceae), their bioactive components and health benefits.

Sr. No.	Mushroom species (basidiocarps)	Scientific name	Common name	Bioactive components	Health benefit	Reference
1.		*Pleurotus ostreatus* (Jacq. Ex Fr.) P. Kumm.	Pearl oyster	β-glucans, α-glucans, Proteins, Polysaccharides, Proteoglycans, Lovastatin, Ergosterol	Anticancer, Antitumor, Immunomodulatory, Anti-hypercholesterolemic, Anti-inflammatory, Antioxidant, Antiviral, Antifungal, Blood sugar control	[36,37]
2.		*P. florida* (Fr.) P. Kumm.	White oyster	Polysaccharides, Lovastatin, Lectins	Anti-hypercholesterolemic, Antioxidative, Anti-inflammatory	[102, 103]
3.		*P. eryngii* (Dc.) Quel.	King oyster	Ergothioneine, Proteins	Anti-atherogenic, Antifungal	[104, 105]
4.		*P. sajor-caju* (Fr.) Sing.	Indian oyster	β-glucans, Lovastatin, Ergosterol	Anti-hypercholesterolemic, Hypoglycemic, Anti-arthritic	[106, 107]
5.		*P. cystidiosus* O. K. Miller	Angel oyster	Ergosterol, Proteins	Antifungal, Antibacterial	[108]
6.		*P. citrinopileatus* Sing.	Golden oyster	Polysaccharides, Proteoglycans, Lectin, Phenols	Antitumor, Antiviral, Antioxidative	[109, 110]
7.		*P. cornucopiae* (Paulet) Rolland	French horn oyster	Heteroglycan, Polysaccharides, D-mannitol, Peptides	Immunomodulatory, Anti-hypertensive	[111, 112]
8.		*P. columbinus* (Berk.) Sacc.	Blue roundhead	Phenols, Flavonoids, Alkaloids, Steroids, Lectins, Hemicelluloses, Polysaccharides, Peptides and Proteins	Antioxidant, Antitumor, Immunomodulatory, Antigenotoxic, Antimicrobial	[113]
9.		*P. pulmonarius* (Fr.) Quel.	Lung oyster mushroom	β-glucans, Polysaccharides, Proteins	Antinociceptive, Antifungal	[114]
10.		*P. tuber-regium* (Rumph. Fr.) Sing.	Tuber oyster	Flavonoids, Tannins, Alkaloids, Phenols	Antioxidative	[115]
11.		*P. flabellatus* (Berk. & Broome) Sacc.	Fan oyster	Polysaccharides, Peptides, β-glucans	Anti-inflammatory, Antioxidant	[116]
12.		*P. nebrodensis* (Inzenga) Quel.	Italian oyster	β-glucans, α-glucans, Proteins	Anticancer, Antiviral	[117]
13.		*P. abalonus* Han. Chen & Cheng	Abalone oyster	Polysaccharides, Peptides	Antiviral, Hypoglycemic	[118, 119]

(*continued on next page*)

Table 3 (*continued*)

Sr. No.	Mushroom species (basidiocarps)	Scientific name	Common name	Bioactive components	Health benefit	Reference
14.		*P. eous* (Berk.) Sacc.	Straw oyster	Fatty acid esters, β-glucans	Antibacterial, Antinociceptive	[120, 121]
15.		*P. djamor* (Rumph. ex Fr.) Boedijn	Pink oyster	Lovastatin, Ergosterol, Thiamine, Riboflavin	Antibacterial, Antioxidant, Antimicrobial	[122]
16.		*P. ostreatoroseus* Sing.	Pink flamingo	Polysaccharides, Phenols	Anti-inflammatory, Antioxidant, Hypoglycemic	[123]
17.		*P. populinus* (Jacq.) P. Kumm.	Poplar oyster	Polysaccharides, Peptides, Proteins	Antioxidant, Anti-inflammatory	[107]
18.		*P. fossulatus* (G. Cunn.) Sing.	Brown oyster	Terpenoids, Phenols, Alkaloids, Steroids, Lectins	Anticancer, Anti-inflammatory	[124]
19.		*P. sapidus* (Schulzer) Sacc.	Forest oyster	Polysaccharides, Phenylalanine, Tyrosine, Lysine	Antioxidant, Anti-inflammatory, Antimicrobial	[125]
20.		*P. ferulae* (Berk. & Broome) Sacc.	Mediterranean oyster	Polysaccharides, Proteoglycans, Phenols	Anticancer, Antitumor, Antimicrobial	[126]

assay of mushroom extracts and ascorbic acids was determined and IC-50 values for methanolic extracts, petroleum ether fraction, ethyl acetate fraction and ascorbic acids were determined to be 8.4, 7.44, 6.77 and 3.77 μg/ml respectively in *H. ulmarius* fruiting bodies. Babu and Rao [130] and Usha and Suguna [131] found that the methanolic extract of *H. ulmarius* cap and stipe had moderate radical and scavenging activity (IC-50 was 1.24 and 1.56 mg/ml), respectively. Shivashankar and Premkumari [86] showed that ferrous ions have a positive impact since they are the most potent pro-oxidants in the food system. The methanolic extracts of the cap and stipe showed outstanding chelating capacity (44.5–58.5 %) and reducing power (2.53 and 2.46). Similarly, ferric-reducing antioxidant power was also excellent, while the H_2O_2 scavenging activity was found (46.8 %) in *H. ulmarius* stipe. Usha and Suguna [131] substantiated the presence of total phenolic contents in *H. ulmarius* CO2 and IIHR Hu1 strains, which were measured at 8.59 mg/g and 6.12 mg/g, respectively. The reducing power of methanolic extracts positively correlated with concentration, and both strains displayed reducing powers of 0.89/2.5 mg/ml. Greeshma et al. [128] and Govindan et al. [20] have emphasized the antioxidant characteristics of *H. ulmarius*. Greeshma et al. [128] observed that extracts from *H. ulmarius* have a strong ability to scavenge free radicals. They attributed these effects to the presence of phenolic chemicals, flavonoids and polysaccharides. Govindan et al. [20] further elucidated this concept by discovering bioactive molecules such as ergothioneine and glutathione, which have a role in reducing oxidative stress. In addition, they proposed that *H. ulmarius* has the ability to inhibit chronic diseases associated with oxidative damage, emphasizing its capacity as a great reservoir of natural antioxidants for integration into nutraceuticals and functional foods. In addition to this, Lee et al. [132] and Liu et al. [133] have reported the antioxidative properties of *H. marmoreus*. Further, Lee et al. [132] found that total phenol is mostly found in cold water extract with respect to hydroxyl radical scavenging activity. Kala et al. [84] performed a recent study analyzing the brown and white types of *H. marmoreus*, the results indicated that the mycelium *in vitro* cultures of these kinds serves as a good reservoir of indole compounds, bioelements, glucans and lovastatin. In addition, it was observed that the presence of zinc (Zn) and manganese (Mn) salts in enriched cultures of white varieties of *H. marmoreus* led to an increase in the levels of Na, Ca, Zn, 5-methyl tryptamine, melatonin, protocatechuic acid, sterol and total glucans. The potential to acquire *H. marmoreus* species with a high concentration of specific substances suggests future pharmaceutical applications for this species. The findings from the preceding discussion indicate that the methanolic extracts and their fractions exhibit significant antioxidant activity, making these mushrooms a promising source of antioxidants.

Similarly, Thimmaraju and Seedevi [134] extracted and refined polysaccharides from *H. ulmarius* that exhibit strong antioxidant properties, as demonstrated by their ability to scavenge DPPH and ABTS radicals. These polysaccharides have demonstrated potential as anticancer agents against A549 cells, a type of human lung carcinoma. *Hypsizygus ulmarius* polysaccharides (HUP-1) exhibited antioxidant properties, with a 61.60 percent inhibition rate on DPPH scavenging activity and an 85.08 percent inhibition rate on ATBS

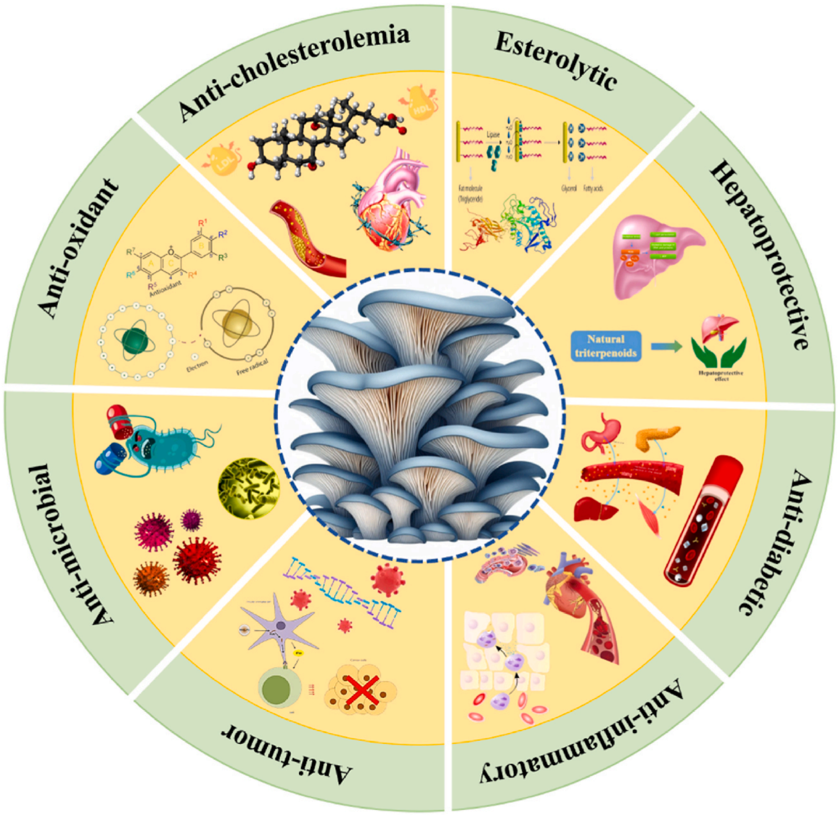


Fig. 5. Major nutraceutical properties of *Hypsizygus ulmarius*.

scavenging activity. Furthermore, it demonstrated a 70.0 percent suppression rate against A549 cells, a kind of human lung cancer. The bioactive properties of HUP-1 were closely linked to their molecular weight and the composition of monosaccharides. Hence, the high antioxidant and anticancer characteristics of HUP-1 suggest that it could become an effective chemotherapeutic choice for lung cancer in the future pharmaceutical industry. In a previous study by Moharib et al. [135] suggested that polysaccharides extracted from *P. sajor-caju* and *Lactuca sativa* demonstrated anticancer properties against breast (MCFT), liver (HEPG2), cervical (HELA) and colon (HCT-116) carcinoma cell lines. Another study revealed that exo-polysaccharides extracted and refined from *H. ulmarius* effectively suppressed the proliferation of MCF breast cancer cells at a dosage of 1.0 mg/ml. The exo-polysaccharides of *P. ostreatus* had notable anticancer characteristics, resulting in a reduction in the viability of cancer cells [136]. Seedevi et al. [137] subsequently examined the chemical composition and biological characteristics of a polysaccharide obtained from *P. sajor-caju* and proposed its antioxidant and anticancer properties. The ethanol extract of *H. ulmarius* has exhibited properties that counteract the effects of oxidation, reduce inflammation and inhibit the growth of tumors [20,138]. Thimmaraju and Govindan [139] examined the structural conformational properties of polysaccharides obtained from the *H. ulmarius* mushroom. The polysaccharide extract derived from *H. ulmarius* exhibited a distinct crystalline structure and was identified as a monosaccharide with a molecular weight of 252.96 kDa. The composition included 1.96 percent rhamnose, 22.76 percent galactose, 16.51 percent mannose and 19.43 percent glucose, with N-acetyl-glycosidic bonds being the primary constituent of HUP-2. This polysaccharide demonstrated significant antioxidant activity, with DPPH radical scavenging capacities ranging from 17.08 percent to 56.90 percent, ABTS radical activity ranging from 8.02 percent to 71.44 percent at concentrations between 0.5 and 2.5 mg/ml and superoxide radical scavenging activity ranging from 8.02 percent to 63.03 percent. These findings highlight the potent antioxidant properties of *H. ulmarius* polysaccharides, indicating their potential therapeutic applications. The mushroom extract also exhibited strong antioxidant activity and showed notable inhibitory and cytotoxic effects on PC3 cells via HUP-2. The HUP-2 exhibits diverse biological applications, rendering it a potential source for incorporation into functional foods and further investigation as a promising novel antioxidant. According to Seedevi [140], the crude polysaccharide and α-L-rhamnose isolated from *Grateloupia lithophila* exhibited ABTS radical scavenging activity within the range of 25.04–74.46 percent and 33.01 to 87.32 percent, respectively at doses of 25–125 μg/ml.

Hypsizygus ulmarius antioxidant pathway protects against oxidative stress and related damage. Bioactive components such as phenolic compounds, flavonoids, polysaccharides and tocopherols make this mushroom a good source of antioxidants. These compounds work together to fight free radicals, which are highly reactive molecules that can damage cells, proteins and DNA. *Hypsizygus ulmarius* includes antioxidant phenolic chemicals and flavonoids that scavenge free radicals to protect cells. This mushroom also contains antioxidant polysaccharides that boost antioxidant enzymes like superoxidase dismutase (SOD), glutathione peroxidase (GPx) and catalase (CAT). Free radical neutralization and reactive oxygen species (ROS) removal depends on these enzymes. Tocopherols, vitamin E, are also present in *H. ulmarius*, these lipid-soluble tocopherols also act as powerful antioxidants. Their main job is to protect cell membranes from oxidation. *Hypsizygus ulmarius* boosts antioxidant defenses and removes free radicals, lowering oxidative stress, inflammation and improving health. Consuming this mushroom in a balanced diet might prevent oxidative stress-related chronic diseases such as cardiovascular disease, neurological disorders and cancer (Fig. 6a).

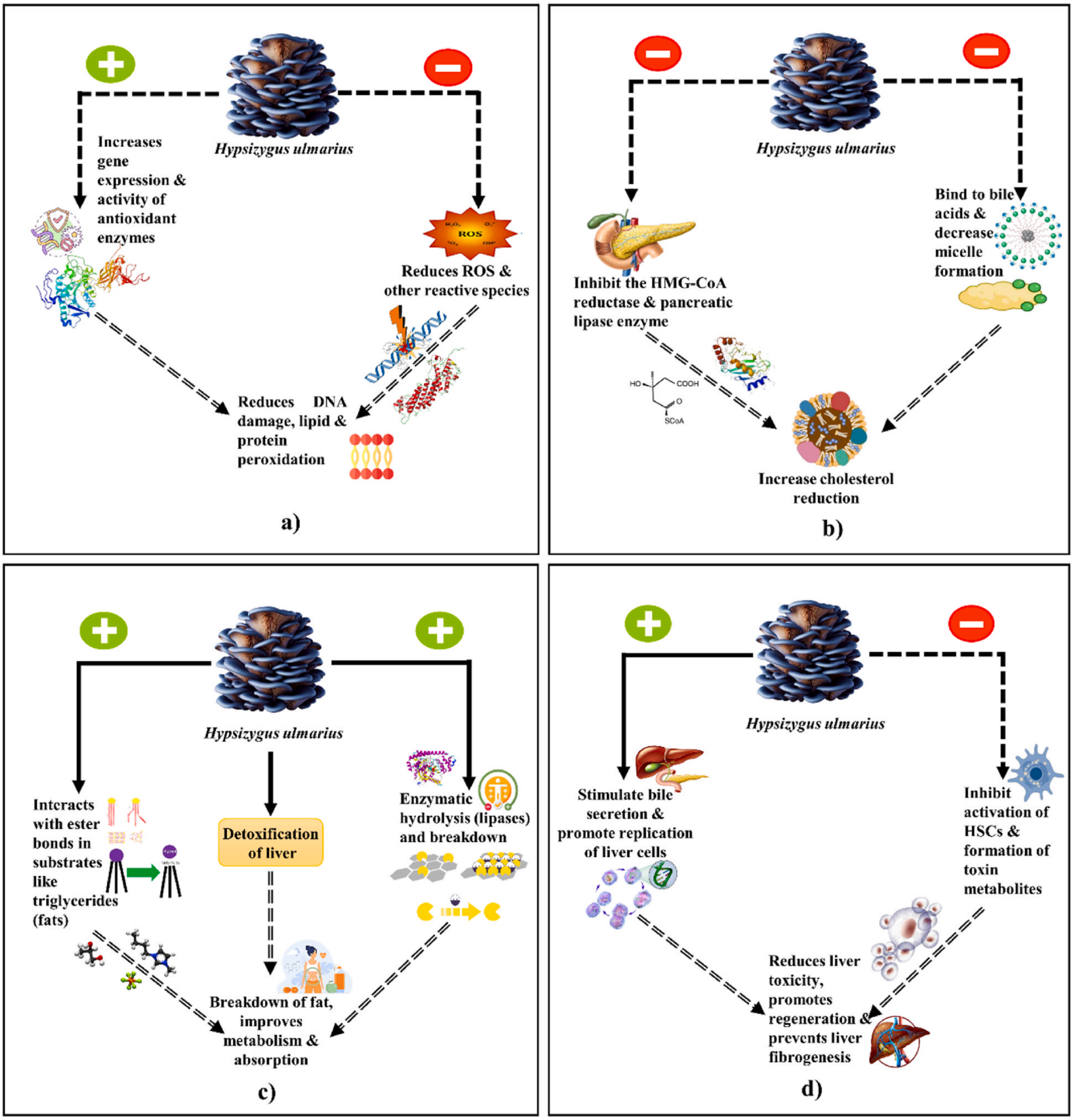


Fig. 6. **a)** Antioxidant mechanism linked to defense against damage caused by oxidative stress; **b)** Anti-cholesterolemic mechanism inhibiting HMG-CoA reductase, increasing LDL receptors and promoting bile acid excretion; **c)** The mechanism of action of esterolytic involves the hydrolysis of cholesterol esters, resulting in the liberation of free cholesterol that enhances cholesterol metabolism and facilitates its excretion, resulting in liver detoxification; **d)** The hepatoprotective mechanism functions by decreasing oxidative stress, regulating inflammatory pathways and increasing liver enzyme function.

3.2. Anti-hypercholesterolemia property

Mushrooms are a nutritious food choice, abundant in proteins, vitamins, minerals and relatively low in calories and fat content. Their proportion in the global diet is progressively growing on a daily basis [141]. The therapeutic effects of *H. ulmarius* and other edible or wild mushrooms have historically been extensively recorded. Presently, many regions of the globe are experiencing a resurgence of fascination with conventional therapies. Unhealthy eating patterns, excessive consumption of fatty foods and an inactive lifestyle have led to a significant rise in the prevalence of metabolic disorders such as obesity and hyperlipidemia. Hypercholesterolemia refers to elevated amounts of cholesterol in the bloodstream. It increases the likelihood of developing early arteriosclerosis, which is characterized by the narrowing and hardening of arteries. This condition often leads to heart attacks, particularly at a young age. Reducing cholesterol levels decreases the likelihood of developing heart disease and stroke. Certain plants and drugs have demonstrated superior efficacy in reducing cholesterol levels. Lovastatin is a naturally occurring compound present in certain foods such as red yeast, rice, and oyster mushrooms [142]. Lovastatin is utilized therapeutically in both free acid and lactone forms. It lowers blood cholesterol levels, possesses antifungal qualities, and exerts anticarcinogenic effects. The therapeutic efficacy of lovastatin derived from mushrooms is significant in the treatment of hypertension, hypercholesterolemia and cancer [143]. The solid-state fermentation (SSF) and submerged fermentation (SMF) methods of *H. ulmarius* yielded the highest concentrations of lovastatin, with ratios of 0.323 and 0.336, respectively, at a wavelength of 238 nm. The lovastatin yield extracted from SSF was 0.28 mg/ml, while it was 0.31 mg/ml from SMF [144]. Further, *H. ulmarius* polysaccharide has modest antioxidant activity and protects the liver against damage caused by alcohol consumption. In experiments, HUP decreased the activities of certain enzymes in the blood, lowered oxidative stress markers and enhanced levels of antioxidants and lipid profiles in rats that were inebriated with alcohol. These effects were similar to those observed with silymarin. *Hypsizygus ulmarius* polysaccharide demonstrated the ability to normalize histological alterations, indicating its potential as a functional diet for safeguarding against oxidative stress and acute alcoholic liver injury [20]. *Hypsizygus ulmarius* is an edible, easily cultivable with higher yield and biological efficiency and rich in lovastatin, which has anticarcinogenic properties that would pave further development of new drug formulations for heart disease.

Hypsizygus ulmarius decreases cholesterol in a complicated way that benefits cholesterol control. This mushroom contains bioactive components such as β-glucans, sterols and dietary fiber, which regulate cholesterol metabolism. The β-glucans, a common soluble fibre in *H. ulmarius*, help eliminate bile acids from the body by binding to them in the colon. The liver synthesizes bile acids from cholesterol and replaces them with circulating cholesterol upon removal, this lowers blood cholesterol. Sterols, plant-derived compounds with a similar structure to cholesterol, compete with cholesterol for intestinal absorption, reducing diet-derived cholesterol uptake. *Hypsizygus ulmarius* high fiber content also affects cholesterol levels by binding to cholesterol molecules in the digestive system and preventing absorption into the bloodstream. Mycochemical such as lovastatin present in *H. ulmarius* also inhibit cholesterol-producing enzymes, boosting its cholesterol-lowering effects. *Hypsizygus ulmarius* lowers 'bad' low-density lipoprotein (LDL) cholesterol and raises 'good' high-density lipoprotein (HDL) cholesterol in several ways. This reduces the risk of atherosclerosis and coronary artery disease (Fig. 6b).

3.3. Esterolytic activity

Esterases are enzymes that facilitate the hydrolysis of many types of esters, both endogenous and exogenous. They are present throughout nature and can be found in animals, plants, and microorganisms [145]. Microbial esterases are of considerable interest because of their potential application in biotechnology. Edible mushrooms that belong to the fungi class are valuable foods and good enzyme sources. *Hypsizygus ulmarius* mushroom is rich in antioxidants and proven for its antidiabetic activity [67]. The work undertaken by Ravikumar et al. [146] offers comprehensive information on the occurrence, refinement and characterization of laccase enzymes in *H. ulmarius*. Laccase enzymes are a type of multi-copper oxidases that have a significant function in oxidising phenolic and non-phenolic substrates. This activity is vital for many biological activities, such as the breakdown of lignin, bioremediation and the production of bioactive chemicals. Shivashankar and Premkumari [86] assessed the esterolytic activity from the extracts of *H. ulmarius*. The extract had the highest activity in 2 mM of 1-napthyl acetate as a substrate. The effect of an alternate product (p-nitrophenol) on esterase activity was found to be 10 mM. The overall metal ions study on this mushroom indicates that esterase activity was inhibited completely with the addition of ferrous sulfate, showing residual activity of 4.02 percent, and it increased with the addition of copper sulfate, showing relative activity of 110.90 percent as compared with other mushroom esterases. The metal ions, such as magnesium chloride, nickel sulfate and sodium chloride maintain enzyme activity with relative activity of 96.18 percent, 94.54 percent and 92.36 percent, respectively. *Hypsizygus ulmarius* has shown the ability to achieve this through several means, such as mycoremediation. For instance, fungi utilize the enzyme laccase to facilitate the decomposition of lignin in the host tissue. Because of the enzyme's broad substrate specificity, it can be employed for biodegradation of various materials, including plastics. Ongoing research is being conducted to investigate the factors influencing laccase synthesis to harness this enzyme's diverse applications. Furthermore, the laccase enzyme generated by *H. ulmarius* has demonstrated the ability to break down different colors, making it potentially valuable for water treatment purposes [146].

Hypsizygus ulmarius esterolytic process reveals its potential health benefits. Esterolytic activity hydrolyzes fats and oils esters. Lipases in this mushroom speed up the breaking of ester bonds in triglycerides, the primary components of dietary lipids. These enzymes break down triglycerides into glycerol and fatty acids to aid in fat digestion and absorption. The esterolytic activity of *H. ulmarius* could contribute to lipid metabolism regulation by breaking down lipids for both energy production and storage. This mushroom improves fat digestion, preventing adipose tissue and hepatic fat formation. This minimizes the risk of obesity, hyperlipidemia and other metabolic problems. *Hypsizygus ulmarius* ability to break down esters may impact the absorption of fat-soluble vitamins and bioactive compounds, boosting its nutritional value (Fig. 6c).

3.4. Hepatoprotective properties

Edible mushrooms contain bioactive compounds with significant health benefits [128,129]. The unique growth and development of mushrooms in their natural environment led to the accumulation of several bioactive components, including phenolic compounds, polysaccharides, steroids and terpenes. These chemicals possess significant promise and are valuable for enhancing human health. The aforementioned studies align with the current research, indicating that HUP, derived from *H. ulmarius*, is a polysaccharide with a hepatoprotective action and a decreased molecular weight. *Hypsizygus ulmarius* exhibits a protective effect against ethanol-induced liver damage, demonstrated through several mechanisms. Pre-treatment with this mushroom reduces serum markers of liver injury such as ALT, AST, ALP and LDH, as well as liver oxidation markers like LPO, HPO and PCO in alcohol-intoxicated rats. Additionally, it helps restore enzymatic antioxidants (SOD, GPx, CAT, GST and GR) and non-enzymatic antioxidants (GSH, Vitamin C and TAOC) in the liver and serum. The polysaccharides in *H. ulmarius* show modest free radical scavenging activity, prevent lipid peroxidation and possess iron-reducing capabilities. These actions collectively contribute to its liver-protective mechanism by inhibiting lipid peroxidation, maintaining antioxidant defences and reducing oxidative stress [20]. Based on these findings, HUP has the potential to be utilized as a non-toxic health nourishment and an effective liver protectant.

There is evidence that several kinds of mushrooms, including *Ganoderma lucidum*, *Phellinus rimosus* and *Pleurotus* species, possess considerable hepatoprotective qualities [43,147,148]. Both the mycelia and aqueous ethanolic extract of the *H. ulmarius* had significantly high levels of hepatoprotective action. Treatment with the extracts resulted in a reduction in elevated levels of liver function enzymes, including serum glutamate oxaloacetate transaminase, serum glutamate pyruvate transaminase and alkaline phosphate. Additionally, the treatment increased the levels of antioxidants that had been depleted in the liver tissues of aged rats [128]. In addition, the histological examination of liver tissues demonstrated that the mushroom extract considerably reduced the liver damage caused by carbon tetrachloride. This was accomplished by either regenerating hepatocytes or boosting the activity of the liver. Because it is an edible fungus, the hepatoprotective characteristics of this mushroom have been put to substantial use in the production of dietary supplements or nutraceuticals, notably for the treatment of liver illness or the symptoms of liver disease.

Hypsizygus ulmarius hepatoprotective mechanism shows promising results for liver health. Toxins, pollutants and oxidative stressors constantly bombard the liver, which performs several metabolic functions, if left unchecked, they can damage and malfunction it. The mushroom also contains antioxidants, polysaccharides and phenolic compounds that protect the liver. Antioxidants reduce oxidative stress and protect liver cells by detecting and eliminating free radicals and ROS. Elm oyster mushroom polysaccharides also enhance superoxide dismutase, CAT and GPx. This boosts liver detoxification and reduces oxidative stress. The presence of bioactive substances in *H. ulmarius* also reduces liver inflammation and prevents hepatitis and cirrhosis progression. Elm oyster mushrooms may also promote healthy liver cell proliferation and reduce scar tissue formation (Fig. 6d).

3.5. Antidiabetic activity

Mushrooms possess significant potential as functional foods for diabetes management, owing to their bioactive compounds that exhibit antidiabetic properties and contribute to glycemic control. Several mushroom species are particularly efficient in regulating blood glucose levels and managing diabetes complications. Studies have revealed that mushrooms such as *Agaricus bisporus*, *A. subrufescens*, *Cordyceps sinensis*, *G. lucidum, Coprinus comatus* and *Poria cocos* have demonstrated hypoglycemic effects [149]. Diabetes mellitus (DM) is a prevalent metabolic disorder characterized by high blood glucose levels due to β-cell dysfunction in the pancreatic islets of Langerhans, leading to insulin deficiency. This condition significantly impacts human health, healthcare systems and the economy [20]. Approximately 150 million people have been suffering from this metabolic disease in the world and it is anticipated that the number will be more than double in the coming years [150]. The most common kind of diabetes, type-2 DM, affects about 90 percent of diagnosed persons. Many commercial medications manage blood sugar, but they have negative effects and no impact on long-term diabetes outcomes. Polysaccharides from therapeutic edible mushrooms like *G. lucidum*, *Hericium erinaceus* and *Pleurotus* species have been studied for their antidiabetic properties. These non-toxic chemicals reduce blood glucose and assist in managing diabetes complications [151]. *Hypsizygus ulmarius* also exhibits hepatoprotective properties, its hot water-extracted polysaccharide effectively scavenges DMP radicals, reduces cupric ions and decreases lipid peroxidation [20]. The application of two separate dosages (50 mg and 100 mg/kg body weight, twice a day) of water extracts containing HUP to diabetic rats induced by Streptozotocin (STZ) resulted in a notable elevation in insulin and protein levels in the serum of the treated diabetic rats, when compared to non-diabetic rats. The water extracts of *H. ulmarius* showed a reduced effect on the activities of marker enzymes. Subsequently, Govindan et al. [20] identified that the polysaccharide derived from this particular mushroom possesses therapeutic potential for the treatment of type-2 DM.

Hypsizygus ulmarius polysaccharide exhibited a moderate level of inhibition against α-amylase and α-glucosidase, suggesting that it has the potential to be a natural and safe inhibitor of digestive enzymes. The implementation of HUP resulted in decreased bandwidth, lowered levels of FBG, elevated insulin levels, increased glycogen storage, restored liver and kidney function, improved serum lipid metabolism, and consequently reduced oxidative stress and lipid peroxidation. The results indicate that extracts from *H. ulmarius* have positive effects on diabetes management by enhancing glucose regulation and enzyme function. Consequently, these extracts hold promise as natural substitutes for antibiotics. Meera et al. [152] conducted research to evaluate the antidiabetic effect of *H. ulmarius* in Streptozotocin Nictinamides Diabetes (STZ-NAD) induced diabetic rats. The study emphasized that the aqueous extract of *H. ulmarius* exhibited an antidiabetic effect. The study exerts a beneficial action against pathological alteration caused by the presence of superoxide and hydroxyl radicals in Streptozotocin induced diabetes, and this could be due to different types of active principles of *H. ulmarius* aqueous extract, each with a single or a diverse range of biological activities. Furthermore, the study observed that the aqueous extract of *H. ulmarius* significantly reduced the activity of the marker enzymes aspartate aminotransferase, alanine aminotransferase, and alkaline phosphatase as well as the gluconeogenic enzymes glucose-6-phosphatase and fructose-1,6-bisphosphatase in the serum, liver and kidney of diabetic-induced rats, compared to untreated diabetic controls. Additionally, the activities of glycolytic enzymes, hexokinase and phosphoglucose isomerase, were notably increased in the diabetic-induced rats treated with the extract, compared to the untreated group.

The antidiabetic properties of *H. ulmarius* demonstrate its potential to regulate blood glucose levels. Uncontrolled diabetes, marked by insulin resistance or reduced insulin efficacy, can lead to significant health complications. Elm oyster mushrooms include bioactive compounds such as polysaccharides, β-glucans and dietary fiber that regulate glucose metabolism and insulin sensitivity. *Hypsizygus ulmarius* polysaccharides block glucose absorption from the digestive system, lowering blood sugar. Thus, they prevent post-meal blood sugar spikes. Moreover, β-glucans moderate glucose levels by enhancing insulin sensitivity and signal transmission in

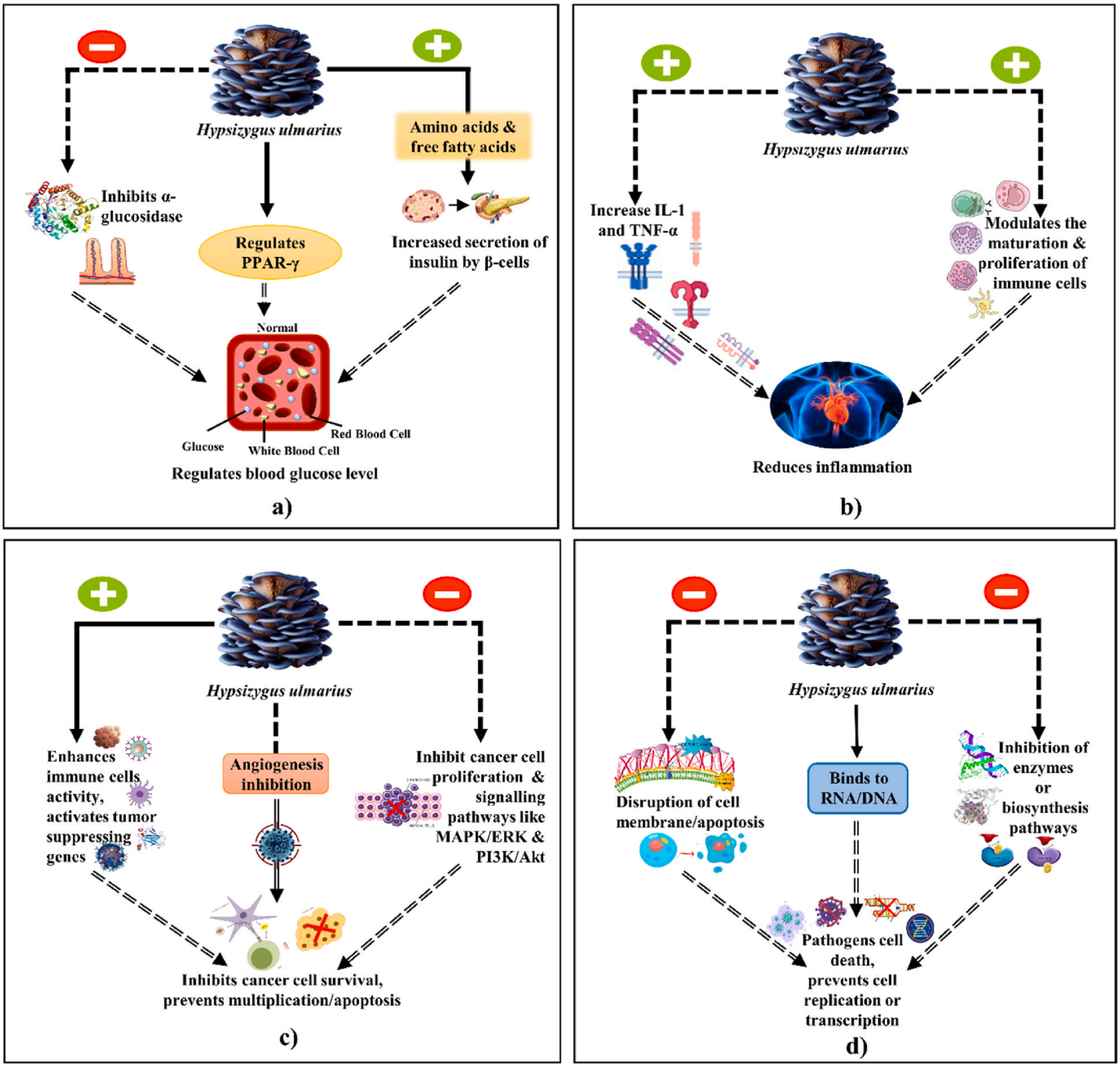


Fig. 7. a) The antidiabetic mechanism involves the release of insulin and the regulation of blood glucose levels by inhibiting the enzyme (α-glucosidase); **b)** The anti-inflammatory mechanism functions by inhibiting pro-inflammatory cytokines, decreasing NF-κB activation and regulating COX-2 production; **c)** Antitumor mechanism stimulates immune cells and inhibits cancer cells; **d)** The antimicrobial mechanism involves the rupture of microbial cell membranes, the suppression of DNA/RNA synthesis, and the interference with protein synthesis pathways.

peripheral tissues like muscle and adipose tissue. As a result, cells absorb more glucose and use it for energy, lowering blood sugar. Elm oyster mushroom high fiber content slows carbohydrate digestion, steadily releasing glucose into the bloodstream, decreasing blood sugar spikes. Some *H. ulmarius* bioactive compounds are antioxidant and anti-inflammatory, these qualities may minimize diabetes-related oxidative damage and inflammation. Elm oyster mushrooms potentially modulate blood sugar levels and enhance insulin sensitivity in individuals with diabetes (Fig. 7a).

3.6. Anti-inflammatory activity

Studies on the fruiting body and mycelia of *H. ulmarius* have demonstrated that this mushroom species exhibits noteworthy antioxidant, anti-inflammatory and antitumor properties [20,128,138,153]. The consumption of *H. ulmarius* may be beneficial in several disorders influenced by free radicals due to its therapeutic attributes. The mushroom's anti-inflammatory properties offer long-term comfort to individuals afflicted with inflammation and arthritis. A study was conducted on mice to investigate the effects of administering extracts from the fruiting body and mycelia of *H. ulmarius* at various doses (250, 500 and 1000 ml/kg). Both acute and chronic inflammation were induced in the right hind paws of mice. The results demonstrated a paw thickness reduction in chronic and acute inflammation. The mycelial extract exhibited a stronger effect as compared to the fruiting bodies extract, particularly at a dose of 1000 ml/kg. In acute inflammation, the mycelial extract achieved 63.0 percent inhibition, while the fruit body extract achieved only 53.0 percent inhibition. Similarly, the chronic inflammation of the mycelial extract showed 55.0 percent inhibition. Whereas, the fruiting body extract exhibited 42.0 percent inhibition. These findings highlight the anti-inflammatory activity potential of *H. ulmarius* extract [129].

Hypsizygus ulmarius has an anti-inflammatory mechanism that has the ability to reduce inflammation in the human body. Chronic inflammation can cause cardiovascular, immunological and metabolic illnesses. Phenolic chemicals, polysaccharides and ergosterol in elm oyster mushrooms are anti-inflammatory. The antioxidant phenolic components reduce inflammation by eliminating free radicals and oxidative stress. Elm oyster mushroom polysaccharides influence inflammatory immune cells and cytokines. This reduces pro-inflammatory signals and cytokines. This slows the inflammatory cascade and tissue damage from chronic inflammation. It also includes vitamin D precursor ergosterol, it reduces inflammation by inhibiting prostaglandins and leukotrienes. Elm oyster mushrooms target multiple inflammatory pathways to reduce inflammation and improve health naturally (Fig. 7b).

3.7. Antitumor activity

Mushrooms are a rich source of bioactive compounds with potential medicinal uses, including immune modulation and treatment of immune-deficient disorders like cancer, tumors, HIV and tuberculosis. Compounds from *Pleurotus* mushrooms can enhance or regulate immune responses, while *A. bisporus* may lower breast cancer risk by reducing aromatase activity and estrogen production. Additionally, species like *G. lucidum*, *H. erinaceus* and *Pleurotus* spp. have demonstrated antidiabetic properties, aiding in blood sugar regulation and diabetes management [52]. Mushroom polysaccharides or polysaccharide-protein complexes boost the body natural immune responses and have demonstrated antitumor effects in both animals and humans [154]. The polysaccharides in mushrooms, particularly β-d-glucan like lentinan from *L. edodes*, exhibit notable antitumor effects, primarily by enhancing immune function rather than directly inducing cell death. These polysaccharides (β-glucan, chitin, cellulose) are found mainly in mushroom fruit bodies, mycelia, and culture and play a significant role in immune modulation to inhibit tumour growth [154,155].

Jose and Geetha [93] evaluated the anticancer properties of *G. lucidum*, *P. florida*, *P. djamor*, *H. ulmarius* and *C. gambosa* mushrooms against cervical cancer cell lines. The *G. lucidum* extract, when used at a dose of 20.0 μg/ml, significantly decreased the vitality of cancer cells to 54.85 percent. This inhibition of cancer cells was the highest among all other mushrooms tested. The concentration of *C. gambosa* extract at 200 μg/ml resulted in a 60.92 percent reduction in the viability of malignant cells. Kao et al. [156] in their studies also reported the anticancer capabilities of *G. lucidum*. Gao and Zhou [157] also investigated the cancer-preventive effects of *G. lucidum* extract. Sumathy et al. [158] have documented the inhibitory effects of *C. indica* extract on the growth of breast cancer cells. At 200 μg/ml concentration, the mushroom extracts from *P. florida*, *P. djamor* and *H. ulmarius* reduced the viability of cervical cancer cell lines to 65.52 percent, 69.47 percent and 65.69 percent, respectively [93]. In a study conducted by Lavi et al. [159], it was observed that a water-based extract of polysaccharides from *P. ostreatus* had the ability to inhibit growth and promote cell death in colon cancer cells. In another study, Xu et al. [160] found that *P. pulmonarius* had a substantial impact in inhibiting cancer growth both in the laboratory and in living organisms. Additionally, it was seen that *P. pulmonarius* increased the effectiveness of chemotherapy treatments by making cancer cells more sensitive to their effects. The harmful effect of these mushroom species on human liver cells was also evaluated. The *G. lucidum* extract showed a 33.69 percent decrease in the viability of normal liver cells at a concentration of 200 μg/ml, which is lower compared to the loss in viability observed in malignant cells. At a concentration of 200 μg/ml, the extracts of *P. florida*, *P. djamor*, *H. ulmarius* and *C. gambosa* showed reductions in liver cell viability of 27.28 percent, 25.48 percent, 20.98 percent and 26.75 percent, respectively. These reports have been supported by the research conducted by Pepovic et al. [161]. According to their findings, the extracellular polysaccharides derived from *G. lucidum* showed strong suppression of the human hepatocarcinoma cell line, indicating potential antitumor capabilities. The anticancer potential of extensively studied edible and medicinal mushrooms species is summarized in Table 4.

Thimmaraju et al. [21] recently isolated and purified polysaccharide (HUP-1) from the fruiting bodies of *H. ulmarius*. They then acetylated this polysaccharide (AC-HUP-1), which enhanced its physical and chemical properties and biological activity. The compound was subjected to acetylation in order to improve its physicochemical properties and bioactivities, culminating in the formation of AC-HUP-1. The chemical and FTIR spectrum analyses demonstrated clear differences in functionality and activity between HUP1 and AC-HUP-1, verifying the effectiveness of the acetylation process. *Hypsizygus ulmarius* polysaccharides have an acetyl group with a degree of substitution (DS) of 0.34. The high-performance size exclusion chromatography (HPSEC) results demonstrate a reduction in the molecular weight of the modified acetylated derivatives. The polysaccharides, whether in their native state or altered through acetylation, displayed different molar ratios of Ara, Man, Glu, GlcA, and GalA. When subjected to tests using radical scavengers such as ABTS, DPPH, N, N-dimethly-p-phenlyendiamine (DMPD), superoxide and OH radicals, the AC-HUP-1 exhibited superior antioxidant activity compared to HUP1. Furthermore, AC-HUP-1 has demonstrated remarkable efficacy in reducing power when tested with Prussian blue, cupric ion, ferric ion and phospho-molybdenum. Furthermore, it exhibited improved efficacy in the lipid peroxidation inhibition assay. The polysaccharides HUP1 and AC-HUP-1 exhibited inhibitory effects on five different types of cancer cells (HT29, PC3, HeLa, Jurkat and HepG-2) within a dosage range of 10–320 μg/ml. The acetylated derivative of HUP1 had a more pronounced effect, as assessed by the MTT (3-(4, 5-dimethylthiazolyl-2)-2, 5-diphenyltetrazolium bromide) assay. The AC-HUP-1 exhibited notable anticoagulant properties by dramatically increasing the duration of APTT, PT and TT in comparison to HUP1. Therefore, the process of acetylation modification has the capacity to improve the physical, chemical and biological characteristics of polysaccharides, rendering them appropriate for use in the food, nutraceutical and pharmaceutical industries.

Hypsizygus ulmarius shows potential in cancer prevention and treatment due to its bioactive compounds, such as polysaccharides, β-glucans and phenolics. These components activate immune cells like macrophages, NK cells and T-lymphocytes to detect and eliminate cancer cells. The β-glucans modulate immune and cytokine functions, while phenolics reduce oxidative stress by neutralizing free radicals, this successfully prevents tumour development and illness transmission. *Hypsizygus ulmarius* also slows tumour growth by inhibiting angiogenesis and the creation of new blood vessels. The mushroom targets multiple tumor growth and progression pathways to prevent and treat cancer naturally (Fig. 7c).

3.8. Antimicrobial activity

Research into new antibiotics has begun due to drug-resistant bacteria. Recently, edible mushrooms have become notable sources of bioactive compounds for therapeutic use [170,171]. Mushrooms possess several types of natural antifungal and antibacterial compounds to serve in the ecosystem. It has been known that extracellular secretion by bacteria possesses antibacterial activities [172,173]. Several bacterial species, such as *Staphylococcus aureus*, *Bacillus subtilis* and *Escherichia coli* possess antibacterial activities [174]. Mushroom extracts contain bioactive compounds like phenols, flavonoids, terpenoids, tannins, alkaloids and polysaccharides, which offer antimicrobial protection [67]. Al-Faqeeh et al. [175] reported the notable impacts of the *H. ulmarius* fruiting body extract on five bacterial species. *Lentinula edodes* is the most well-researched mushroom species and it exhibits a wide-ranging antibacterial effect against both gram-positive and gram-negative bacteria [176]. The fungus synthesizes lanthionine as a bioactive compound and demonstrates antibacterial, antifungal, cytostatic, antioxidant, anticancer and immunomodulatory properties [26]. Fujita et al. [177] examined the ability of volatile compounds produced by *H. marmoreus*, to limit the growth of *Alternaria brassisicola*. The results showed that these compounds greatly decreased both mycelial growth and conidial germination, by 60 and 100 percent, respectively. Khan and Chandra [178] demonstrated that the extracts of *A. bisporus*, *A. campestris* and *Amanita pantherine* had the highest inhibitory ability against *Pseudomonas putida* and *Microsporium canis*.

Table 4
List of important mushroom species studied for anticancer properties.

Sr. No.	Scientific name	Common name	Type of cancer	Bioactive components	Reference
1.	*Hypsizygus ulmarius* (Bull.) Redhead	Elm oyster or blue oyster	Cervical cancer	Exopolysaccharide (HUP-2), β-glucan, Phenolic compounds	[93]
2.	*Phellinus linteus* (Berk. & M.A. Curtis)	Black hoof mushroom	Colon cancer	Mannans, β-glucans	[162]
3.	*Inonotus obliquus* (Ach. ex Pers.) Pilat	Chaga	Colon cancer	Lanosterol, Ergosterol	[163]
4.	*Pleurotus ostreatus* (Jacq. Ex Fr.) P. Kumm.	Pearl oyster	Sarcoma cervical cancer	Polysaccharides, β-glucans, α-glucans, Ergosterol	[164]
5.	*P. pulmonarius* (Fr.) Quel.	Lung oyster mushroom	Liver cancer	Protein complex, β-glucans, Polysaccharides	[160]
6.	*P. florida* (Fr.) P. Kumm.	White oyster	Cervical cancer	Mannans, β-glucans, Lectins	[93]
7.	*P. djamor* (Rumph. ex Fr.) Boedijn	Pink oyster	Cervical cancer	Ergosterol, β-glucans	[93]
8.	*Schizophyllum commune* Fr.	Split gills	Breast, lung, colon cancer	Polysaccharides, β-glucans, Ergosterol	[165]
9.	*Cordyceps militaris* (L.) Fr.	Caterpillar fungi	Lung, skin cancer	Cordycepin, Ergosterol, Mannitol	[166]
10.	*Ganoderma lucidum* (Curtis) P. Karst	Reishi	Colon cancer	Polysaccharides, Triterpenoids, β-glucans	[167]
11.	*Grifola frondosa* (Dicks.) Gray	Maitake	Liver cancer	Lectins, Polysaccharides, Grifolan, β-glucans	[168]
12.	*Agaricus bisporus* (J.E. Lange) Imbach	White button mushroom	Breast cancer	Pyrogallol, Proteins, Estrogen, Lectin	[52]
13.	*Lentinula edodes* (Berk.) Pegler	Shitake	Prostate cancer	Lentinan, Glucans, Mannoglucan, Lactripin-1	[169]
14.	*Trametes versicolor* (L.) Loyd.	Turkey tail	Breast cancer	Krestin, β-sitosterol, β-1-3 and β-1-4 glucans	[32]
15.	*Calocybe gambosa* (Fr.) Donk	St. George mushroom	Cervical cancer	Polysaccharides, Lectin, β-glucans	[93]
16.	*Calocybe indica* P&C	Milky mushroom	Breast cancer	Lectin, β-glucans	[158]

The antifungal properties of mushroom extract and isolated antifungal components, which include both large molecular weight compounds such as peptides and proteins, as well as low molecular weight compounds including sesquiterpenes, other terpenes, steroids, organic acids and quinones, have been documented by Alves et al. [179]. Low molecular weight molecules like terpenes and griffin offer potent antifungal effects. Rufuslactone, a sesquiterpene, effectively combats phytopathogenic fungi, including *Botrytis*, *Alternaria* and *Fusarium* species [180]. Phenolic acids, such as p-hydroxybenzoic and cinnamic acids, have been found to help combat *Trichoderma* and *Penicillium* species [181]. The methanolic extract shows strong efficacy against *S. aureus*, methicillin-resistant *S. epidermidis* and *Candida albicans*, when compared to its fractions. Its antibacterial activity was tested against gram-positive and gram-negative bacteria, demonstrating inhibition of *P. aeruginosa*, *Proteus mirabilis*, *Klebsiella pneumoniae*, and *Enterococcus faecalis* [175]. Akyuz and Kirbag [182] revealed that the extracts of *A. bisporus* and *P. florida* showed stronger inhibitory effects on gram-negative bacteria compared to gram-positive bacteria. The petroleum ether fraction exhibited antibacterial activity against *P. aeruginosa* and *E. coli*, whereas the ethyl acetate fraction showed antimicrobial activity specifically against *P. aeruginosa* and *K. pneumoniae*. However, Angelini et al. [183] found that there is antibacterial action against both gram-positive and gram-negative bacteria, as well as yeasts from mycelial solid cultures of *H. marmoreus*.

One of the primary mechanisms through which *H. ulmarius* exhibits antimicrobial activity is via the production of laccase, an enzyme known for its ability to oxidize phenolic compounds and degrade various environmental pollutants, including dyes. Ravikumar [186] demonstrated that laccase from *H. ulmarius* effectively decolorized multiple dyes without the need for additional redox mediators, indicating its potential utility in bioremediation processes. Furthermore, Illuri et al. [187] reported that *H. ulmarius* efficiently produces mycelial biomass and laccase, suggesting its commercial viability for enzyme production. The enzymatic activity of laccase is enhanced by the presence of metal ions, such as copper, which can significantly increase laccase production and activity, as noted in studies on other fungal species [188]. In addition to enzymatic activity, *H. ulmarius* has been explored for its ability to synthesize nanoparticles, which also exhibit antimicrobial properties. Manimaran et al. [171] explore the eco-friendly synthesis of silver nanoparticles (AgNPs) from *H. ulmarius*. The Hu-AgNPs, confirmed through various analyses (UV–visible spectroscopy, XRD, FTIR etc.) averaged 20 nm in size and displayed a strong negative surface charge. They showed effective antibacterial properties against both gram-positive and gram-negative bacteria and dose-dependent cytotoxicity against lung cancer cells (A549), reducing cell viability by 64.31 percent at 24 h. Shivashankar et al. [184] demonstrated the biosynthesis of silver nanoparticles (AgNPs) using *H. ulmarius* via a nitrate-dependent reductase and shuttle quinone extracellular process, with optimal synthesis achieved at 3 mM $AgNO_3$. The resulting AgNPs exhibited surface plasmon resonance at 386 nm, indicating successful nanoparticle formation. These AgNPs showed significant bactericidal activity against *S. aureus* and *P. aeruginosa*, with maximum inhibition zones of 0.15 mm (0.5 mg/ml) and 0.17 mm (0.4 mg/ml), respectively. This study highlights the potential of *H. ulmarius* in the eco-friendly production of antimicrobial nanomaterials for biomedical applications. Moreover, Manimaran et al. [191] reported the antibacterial and anticancer potential of titanium dioxide (TiO_2) nanoparticles synthesized using extracts from *H. ulmarius*. The study indicates that these mycosynthesized nanoparticles could serve as an effective agents against various bacterial strains, further emphasizing the mushroom's role in developing novel antimicrobial agents. The phytochemical composition of *H. ulmarius* also contributes to its antimicrobial properties. Preliminary qualitative screening revealed a total phenolic content of 30.5 mg/g, which suggests a significant presence of bioactive compounds that may contribute to its antimicrobial effects [86]. Also, the polysaccharides extracted from *H. ulmarius* have been shown to possess antioxidant, anti-inflammatory and antitumor activities, which may also correlate with antimicrobial properties [128,139]. The antioxidant activity of these polysaccharides can play a role in protecting against oxidative stress, which is often a contributing factor in microbial infections. This multifaceted approach to antimicrobial activity through enzymatic action, nanoparticle synthesis and phytochemical composition positions *H. ulmarius* as a promising candidate for further research and application in the field of natural antimicrobials.

Hypsizygus ulmarius extracts demonstrate antimicrobial activity against various bacteria, suggesting their potential as natural antibiotic alternatives. The fungus produces diverse secondary metabolites, which may attack bacterial cells or inhibit their growth, likely as a defense mechanism. These antibacterial compounds have promising applications in medicine, agriculture and biotechnology as novel antibacterial agents with therapeutic potential [171,175,191]. The impact of edible and medicinal mushrooms on human well-being at a global scale is seen as a significant advancement toward a non-green revolution [61,185]. *Hypsizygus ulmarius* exhibits a robust antibacterial mechanism highlighting its potential as a natural effective and safe environmental agent for treating diverse human infections. It contains polysaccharides (especially β-glucans), peptides, and phenolic compounds, each contributing uniquely to its antimicrobial effects. The β-glucans enhance immunity by activating macrophages, natural killer cells, and other immune cells that target pathogens. Peptides disrupt bacterial and fungal cell membranes, causing cell lysis, while phenolics inhibit microbial growth by interfering with cellular metabolism and DNA replication. Additionally, its high moisture content and low pH limit microbial growth, further supporting its role in infection control and health promotion. The mushroom naturally fights infections and promotes health by targeting several microbial proliferation and survival pathways (Fig. 7d).

4. Future trends and scope of research on *Hypsizygus ulmarius*

Mushrooms are healthy and contain several nutraceutical components that can prevent and treat disease. They contain several bioactive substances, including biological components and secondary metabolites. Although studies often use crude extracts or combinations of metabolites, specific chemicals must be isolated to determine their effects. Improving submerged culture and using genetic editing can boost chemical yields. Mushrooms as a therapeutic bioactive chemical source require extensive investigation and clinical trials. *Hypsizygus ulmarius* has abundant nutritional content, mycochemicals and prospective health benefits thus, more research is needed to discover its medicinal potential completely. Research on *H. ulmarius* should focus on many critical areas to maximize its nutritional, bioactive and therapeutic potential. To understand their therapeutic effects, novel bioactive chemicals must be isolated and identified utilizing advanced analytical methods, including chromatography, mass spectrometry and nuclear magnetic resonance spectroscopy. After identification, these substances can be examined for their mechanisms, pharmacokinetics and synergistic effects. Mycelial growth conditions must be optimized to increase bioactive chemical production. To create cost-effective and scalable production processes, temperature, pH, carbon and nitrogen sources, aeration and agitation must be carefully adjusted using advanced bioprocess engineering approaches. Gene knockout, gene overexpression and CRISPR-Cas9 can alter metabolic pathways and regulatory processes to increase bioactive chemical production. High-yield strains can be bred to produce increased amounts of bioactive compounds for medicinal use. *Hypsizygus ulmarius* therapeutic and health-promoting properties must be proven by extensive clinical trials and validation investigations. These trials should assess its therapeutic effects on cancer, diabetes, liver diseases, neurodegenerative disorders and cardiovascular conditions and include pharmacokinetic studies to understand bioactive compound absorption, distribution, metabolism and excretion. To assure quality, safety and efficacy for clinical use, *H. ulmarius* products must be regulated and standardized. The potential for *H. ulmarius* to provide nutrition, mycochemicals and medicinal properties with health-promoting actions makes it a promising novel and sustainable food source for future generations.

5. Conclusions

Across the world, underdeveloped nations are facing poverty, unemployment, malnutrition, food insecurity and pollution. The production and consumption of mushrooms, which are functional foods rich in biologically valuable components and nutrients offer protective and therapeutic benefits against many diseases. Mushrooms have numerous bioactive compounds, including cellular components and secondary metabolites, which benefit human health. In the fields of pharmacology, microbiology, biotechnology and food science, mushrooms are valuable resources, making fungi-based nutraceuticals better than synthetic drugs. Systematic research is needed to understand their long-term benefits to maximize the medical benefits of fortified food nutraceuticals and cosmetic preparations. *Hypsizygus ulmarius* shows significant promise as both an edible and medicinal mushroom, offering a wide array of health benefits. Nutritionally, it is rich in proteins, minerals and dietary fiber, making it a wholesome food. Its medicinal and therapeutic properties are highlighted by the presence of bioactive compounds, particularly polysaccharides, which modulate the immune system by activating key immune cells such as macrophages, natural killer cells and T-lymphocytes. These properties make *H. ulmarius* a potential adjunct in cancer therapy because it boosts the immune response against tumor cells. Additionally, its antioxidant and anti-inflammatory properties contribute to the prevention of chronic diseases, including cardiovascular and neurodegenerative conditions and offer benefits in managing inflammatory conditions like arthritis. Its extracts also exhibit anticancer effects and antimicrobial properties, making it a promising candidate for natural antibiotics. The rich composition of bioactive compounds in *H. ulmarius* supports its use as a nutritious food source and as a functional food with significant health benefits, paving the way for improved health and well-being through its inclusion in daily diets and medicinal practices.

Consent to publish

All authors have read, approved and consented to the publication of this manuscript.

Informed consent

Upon acceptance of the article for publication, the author will transfer the copyright to the journal.

Data availability

The data collected and analyzed during this study is included in this published article, and the data utilized to support the findings of this review are included in the references at the end of the article.

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CRediT authorship contribution statement

Aditya: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Neeraj:** Writing – review & editing, Validation, Resources, Project administration. **J.N. Bhatia:** Writing – review & editing, Validation, Supervision, Project administration. **Ajar Nath Yadav:** Writing – review & editing, Validation, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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