polysaccharides

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Review

The Glucans Mushrooms: Molecules of Significant Biological and Medicinal Value

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Abstract: Mushroom polysaccharides, key components of fungal cell walls, exhibit various biological properties and hold significant medicinal and industrial value. These polysaccharides are known for their medicinal properties like antitumor, antioxidant, anticancer, immunomodulatory, and antiviral properties. Mushroom polysaccharides, particularly β-glucans, α-glucans, and chitin, have been associated with various health benefits. β-glucans are well studied for their bioactivities, while α-glucans and chitin have gained attention for their prebiotic, antimicrobial, and wound-healing properties. The therapeutic effects of these polysaccharides are closely linked to their chemical structures, including molecular weight, monosaccharide composition, and glycosidic bond types. This work aims to review the studies on mushroom polysaccharides, with a particular focus on their structural composition to deepen medicinal properties of mushroom polysaccharides. Also, the extraction methods and the pharmaceutical application of polysaccharides will be revised in this work.

Keywords: polysaccharides; biological activity; extraction method; pharmaceutical application

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1. Introduction

For centuries, mushrooms have been used in traditional medicine due to their important properties. In Asian countries, they are used in the treatment of cardiovascular and metabolic diseases, hypertension, hyperlipidemia, and gastrointestinal disorders. Nutritionally, mushrooms are considered a valuable food as they are rich in important nutrients such as polyphenols, proteins, minerals, and dietary fibers. Vitamins including B-group vitamins, ascorbic acid, tocopherols, vitamin D2, phenolics, and pigments are also present in mushrooms. Additionally, they are low in fats, approximately 0.1–8%, sodium, and simple sugars [1,2]. Edible mushrooms are also rich in bioactive compounds like polysaccharides, proteins, and phenols. These compounds contribute to their use as prebiotics and food supplements [3,4]. Studies suggest that the interaction of multiple compounds in mushrooms can enhance their bioactive properties, indicating a possible synergistic effect [5]. Among these components, polysaccharides are key bioactive components, offering a range of biological activities such as anti-inflammatory, antibacterial, antitumor, antidiabetic, immunomodulatory, antihypertensive, antidepressant, antiradiation, anticoagulant antihyperlipidemic, antiviral, antioxidant, and liver protective effects, highlighting their significant medicinal potential [3]. Recent studies demonstrate that polysaccharides can also exhibit regulatory effects on gut microbiota [6] and antitumor activity due to the stimulation of immune responses via macrophage or lymphocyte [7].

Mushroom polysaccharides represent an important class of biopolymers that can be found in the fungal cell wall, form intracellular energy reserves, or be released externally as mechanisms of defense or help in its adhesion to other surfaces [8]. The fungal cell wall contains large amounts of chitin, mannans, and glucans that provide the cell with strength,

elasticity, and the ability to maintain shape, protecting it from mechanical and osmotic stress and from the external environment. Furthermore, the cell wall regulates the flow of substances into and out of the cell [9]. In recent years, there has been an exponential increase in research on fungal polysaccharides due to their unique properties, biological characteristics, and applications in various fields. Fungi can be sustainably cultivated to produce polysaccharides, which offers a significant advantage. Furthermore, several studies have demonstrated that fungal polysaccharides exhibit low toxicity and good biocompatibility, crucial elements for pharmaceutical applications [10–12].

Conventional extraction methods for edible mushroom polysaccharides include hot water extraction and alkaline- or acid-extraction [13]. In addition to these, a wide range of innovative extraction methods are available, such as microwave-assisted extraction (MAE), ultrasonic–microwave synergistic extraction (UMSE), ultrasonic-assisted extraction (UAE), enzyme-assisted extraction (EAE), subcritical water extraction (SWE), pulsed electric field-assisted extraction (PEFAE), aqueous two-phase extraction (ATPE) [2].

In this work, the chemical structure of polysaccharides, extraction methods, and biological properties will be explored by analyzing recent studies on the subject. Additionally, attention will be given to their pharmaceutical applications.

2. Methodology

To conduct this review, an extensive search was performed across multiple scientific databases, including PubMed, Elsevier, ResearchGate, Scopus, and Google Scholar. The search encompassed publications from 1995 to 2024, providing both a broad historical perspective and contemporary insights. A total of 101 publications were collected and rigorously assessed. The search strategy was meticulously designed to cover a wide range of relevant literature, employing English MeSH (Medical Subject Headings) descriptors to ensure consistency and comprehensiveness. The review specifically focused on studies evaluating the biological activities of mushroom β-glucans. For this purpose, a targeted search within the PubMed database was conducted, limited to articles published between 2018 and 2024, to include the most recent and pertinent findings. To maintain the quality and relevance of the selected studies, several criteria were applied. Only articles published in English that evaluated the β-glucan properties of medicinal mushrooms were included. Duplicate articles, review articles, and studies on isolated, commercially acquired molecules were excluded. This approach ensured that the review concentrated solely on the effects of β-glucans from mushrooms. By implementing these methods, the review aimed to provide a comprehensive and detailed analysis of the types and sources of bioactive β-glucans from mushrooms, their extraction methods, and the integration of medicinal mushroom β-glucans into food and nutraceutical products.

3. Structure and Function of Polysaccharides: Focus on Chitin, Glycogen and β-Glucans

Among the macromolecules found in nature, polysaccharides are among the most abundant. These complex carbohydrates are produced by a wide range of organisms, including plants, animals, fungi, and bacteria [14]. In terms of structure, they are long complex chains of carbohydrates made up of glycosidic linkages joining over ten monomers. Natural polysaccharides come in a wide variety of structural forms. Polysaccharides can be broadly divided into two groups: heteropolysaccharides, which contain multiple types of monomers, and homopolysaccharides, which contain only one type of monomer [15]. The branched chains, monosaccharide concentration, molecular weight (MW), and structural conformations of each polysaccharide source are unique. Polysaccharides are involved in important biological processes, such as cell identification, energy storage, structure, embryonic development and cellular immunity from infection by viruses and bacteria [16].

In edible mushrooms, heteropolysaccharides are the predominant form. As Ruthes et al. [17] noted, heteropolysaccharides are distinguished by their varied monosaccharide composition, unique headgroup configurations, and specific bonding patterns. Understanding the molecular weight of these polysaccharides is crucial for appreciating their

characteristics and functionalities. Typically, the molecular weight of edible mushroom polysaccharides ranges from a few thousand to several million Daltons. Techniques such as ultrafiltration, osmolality testing, and high-performance liquid chromatography are employed to determine the molecular weight of these polysaccharides [18].

Fungal cell walls are noted for their robust structure, composed of cellulose or chitin, and reinforced with a matrix of α-glucans, β-glucans, and glycoproteins [19]. Chemically, chitin consists of 1,4-N-acetyl-D-glucosamine units. It is insoluble in water and highly durable, playing a crucial role in fungal cell walls across the Eukaryota kingdom, where it is widespread [20]. The chitin content in fungi varies significantly among species. For instance, commercially cultivated white button mushrooms [*Agaricus bisporus* (J.E. Lange) Imbach] contain 6–8% chitin by dry weight, with less than 1.0% (0.8–0.9%) found in their caps and stems. In contrast, oyster mushrooms have lower chitin levels, ranging from 2.15 to 5% by dry weight, with higher concentrations in the caps compared to the stems (cap-to-stem chitin ratio: 1.25–1.30) [21]. The chitin level in mushrooms' fruiting bodies directly impacts their digestibility due to the limited chitinase activity in the digestive systems of animals and humans. Beyond its nutritional role, chitin is a vital component of dietary fiber, significantly contributing to the fiber intake necessary for proper digestion [22].

Chitosan, a natural polysaccharide, is a primary derivative of chitin. It becomes known as "chitosan" when chitin undergoes deacetylation to a degree of at least 50% [23]. In its natural state, chitin contains a higher proportion of N-acetyl glucosamine compared to glucosamine, while in chitosan, the glucosamine content surpasses that of N-acetyl glucosamine [23]. The economic importance of both chitin and chitosan stems from their notable biological and mechanical properties, including bio-renewability, biodegradability, and bio-functionality [24].

Glucans are the primary polysaccharides present in mushrooms. The macromolecular structure of mushroom β-glucans consists of D-glucose monomers connected by glucosidic bonds at two distinct positions: 1,3 linkages form the linear framework, while 1,6 linkages create the primary branching. In contrast, the less common α-glucans in mushrooms feature α-type linkages [25]. Despite all β-glucans having the same type of glycosidic bond linking glucose molecules, their structural characteristics can differ greatly. These differences include variations in chain length, glycosidic bond positions, degree of branching, and three-dimensional structures. The structural and physical properties of β-glucans vary depending on species, cultivars, growing conditions, drying methods, and isolation/extraction techniques. These variations result in significant changes in the intensity and nature of their biological activity [26].

Glycogen, a notable type of homopolysaccharide, exhibits properties similar to starch (sometimes referred to as animal starch). In mushrooms, glycogen constitutes 5–15% of the dry weight. For the fruiting bodies of *Lentinula edodes* (Berk.) Pegler (also known as shiitake), glycogen levels were found to be between 2 and 10% of the dry matter [27]. These levels varied depending on the source of the spawn and environmental conditions during cultivation. Younger fruit bodies tend to contain less glycogen than their mature counterparts [28].

4. Extraction Methods of Mushroom Polysaccharides

The structure, biological activity, extraction rate, and purity can be impacted by different extraction methods [29]. The cell wall structure determines the best extraction method to use, and the recovered polysaccharides can be further purified by combining other methods such ethanol precipitation, fractional precipitation, acidic precipitation with acetic acid, and so forth. The like dissolves like rule states that since it is soluble in water but insoluble in organic solvents like ether, acetone, and alcohol, it can be extracted using water extraction and the polysaccharides may then be precipitated out of the extract using ethanol. Hot water extraction combined with alcohol precipitation is the most widely used extraction technique for edible mushroom polysaccharides, followed by alkaline- or acid-extraction, and has the advantages of being easy to apply and requiring little equipment. To

extract polysaccharides from edible mushrooms more effectively, different techniques such subcritical water extraction, enzyme-assisted extraction, microwave-assisted extraction, and ultrasonic extraction are becoming more and more popular.

4.1. Hot Water Extraction

Hot water extraction is preferable for certain fungal polysaccharides due to their solubility properties. For instance, glucans such as β-glucan are effectively extracted using hot water, as they dissolve readily in water. Similarly, mannans and galactomannans, composed of mannose and a combination of galactose and mannose, respectively, are water-soluble and benefit from hot water extraction. Xylans, made up of xylose units, and chitosan, a deacetylated derivative of chitin, also exhibit water solubility, making hot water an ideal extraction method for these polysaccharides [2,9].

This technique uses hot water at high temperatures (50 to 100 °C) for a specific amount of time (1.5 to 5 h) to extract water-soluble polysaccharides from mushrooms [13]. It has the clear benefits of cheap operating costs and few equipment needs. Unfortunately, there are a number of drawbacks to this extraction method, including a lengthy treatment period, excessive energy consumption, and a high working temperature [30]. An increase in treatment temperature generally improves the extraction efficiency of polysaccharides from mushrooms using the hot water extraction method [31–33]. The procedure is submerging the cells in hot water, which causes them to expand and absorb water. This causes the cell walls to break, which lowers the barrier of the polysaccharide mass transfer. The polysaccharides are then dissolved by the hot water. It is important to remember that the temperature, length, material-to-liquid ratio, and the number of extraction cycles all affect how effectively polysaccharide extraction occurs. There are no appreciable differences in the monosaccharide content or functional group of polysaccharides extracted at varying temperatures. Nevertheless, as the temperature rises, the molecular weight of high molecular weight polysaccharides decreases, possibly as a result of thermal breakdown. Moreover, it was demonstrated that a high extraction temperature positively affected the β-(1→3)/(1→6)-glucan yield and content while having no discernible effect on the degree of branching. High temperatures exceeding 100 °C, however, have the potential to degrade β-glucans. Research findings indicate that the triple-helix structure vanished after 15 min at temperatures greater than 150 °C [34]. Another crucial component of HWE is the extraction duration, where a longer extraction period typically results in a higher extraction yield [33,35,36]. Because it is easy to use and reasonably priced, hot water extraction is a popular technique for removing polysaccharides from materials, both in lab settings and in commercial production [37]. But the high extraction temperature may cause structural harm to the polysaccharides, which would mean high costs for recovery of the reagent and purification [38].

4.2. Alkaline- or Acid-Extraction

In alkaline- or acid-extraction, alkalis like NaOH or KOH and acids like HCl or ammonium oxalate are used to help release the polysaccharides from mushrooms during the extraction process and are typically carried out in order to enhance the recovery of polysaccharides from mushrooms during subsequent extraction stages, after hot water extraction [39]. This technique causes the destruction of cell walls by acidic and alkaline treatments, and also causes the degradation of the coarse fiber structure and hydrolyzable linkages between glucan and the cell wall protein (such as those with an O-linked side chain). This releases intracellular polysaccharides and allows for the extraction of the acid- and alkali-soluble fractions as well as the conversion of water-insoluble components into water-soluble ones. In alkaline extraction, strong bases like NaOH or KOH are used, which can efficiently extract polysaccharides such as chitosan, β-glucans, and mannans by breaking down the cell wall components and enhancing solubility. Acid extraction, using acids like HCl or ammonium oxalate, is particularly effective for extracting acid-soluble polysaccharides like galactomannans and xylans. In comparison, hot water extraction is

a milder method that involves using hot water to solubilize polysaccharides like glucans and mannans. While it is effective for extracting water-soluble polysaccharides, it may not be as efficient in breaking down the cell walls as the alkaline or acid methods. Hot water extraction is often used as a preliminary step before subsequent acid or alkaline extraction to maximize polysaccharide recovery. Acid and alkaline extraction methods are more effective for breaking down cell walls and extracting a broader range of polysaccharides, although they may compromise the biological activity of the polysaccharides [40,41]. Among the many benefits of acid–base extraction are its high extraction efficiency, minimal energy usage, and quick processing time. It is fundamental to acknowledge that the biological activity of the isolated polysaccharides may be compromised by this procedure.

4.3. Enzyme-Assisted Extraction

Enzymes can efficiently accelerate the hydrolysis and disintegration of the fungal cell wall matrix, hence facilitating the release of the polysaccharide components that are contained within the cells. The benefits of Enzymatic Assisted Extraction include low energy requirements, low working temperature (generally mild circumstances), high specificity, ease of use, environmental friendliness, high efficiency, and low energy requirements [17,42]. Enzymatic assisted extraction often preserves the bioactivity of polysaccharides by preventing disruption to their three-dimensional molecular structure [43]. The basic idea behind the enzyme-assisted extraction of polysaccharides from edible mushrooms is to use certain enzyme catalysts, like trypsin, cellulase, and neutral protease, to hydrolyze the polysaccharides enzymatically. The goal of polysaccharide extraction is accomplished by the enzymatic action, which makes it easier to separate the polysaccharides from the solvent or water. A number of benefits come with using enzyme-assisted extraction to extract polysaccharides from edible mushrooms, including mild extraction conditions, increased selectivity, lower energy consumption, and improved extraction efficiency. However, one of the primary drawbacks of enzymatic assisted extraction is the very expensive cost of enzymes [44].

4.4. Ultrasound-Assisted Extraction

The ultrasonic-assisted extraction technique has been extensively explored as an alternative for the efficient recovery of bioactive ingredients. It uses ultrasonic cavitation to break tiny bubbles and generate a significant amount of pressure that accelerates cell rupture. During this process, ultrasonic waves vibrate edible mushrooms, causing cavitation bubbles that rupture cells and speed up mass transfer [45]. This technique can be combined with the solvent extraction method to significantly lower the extraction temperature and duration, which makes it a viable extraction approach for molecules that are thermally unstable, like polysaccharides [46].

Concurrently, the ultrasonic vibration effect improves intracellular substance release and dissolution, leading to a notable increase in substance extraction efficiency. For substances that are susceptible to heat, ultrasonic extraction is thought to offer some protection when compared to traditional heating methods. Compared to conventional hot water extraction, it has been observed that UAE may efficiently promote the extraction of macromolecules (such as polysaccharides) from edible mushrooms and raise the yield by 52–129% [47].

4.5. Microwave-Assisted Extraction

Microwave-assisted extraction is another possible efficient extraction technique. It is a process that involves using a suitable solvent in a microwave reactor to extract different chemical components from natural plants, minerals, or animal tissues. To achieve the goal of dispersing the contents, the basic idea is that heating causes water in the target cells to evaporate, creating extreme pressure that eventually causes the cells to burst. The variable speeds at which different polar compounds absorb microwave energy are exploited in microwave-assisted extraction. During this process, some compounds undergo a molecular

acceleration movement frequency, which cause heat production and vibrations. Consequently, the breakdown of cell walls and membranes occurs, leading to minuscule apertures that expedite the release of polysaccharide constituents. According to Wang et al. [47], the microwave-assisted extraction method is generally a moderate and extremely effective extraction technique that may preserve the biological activity of polysaccharides to a greater extent. Likewise, the structure and molecular weight of polysaccharides are influenced to some extent by microwave-assisted extraction. It also has equipment requirements that are particular and may not be suited for large-scale applications [48].

The extraction time, treatment temperature, and microwave power are crucial variables to take into account while using microwave-assisted extraction to extract polysaccharides from mushrooms. According to a study by Xu et al. [48], excessive microwave power lowers the extraction yield of polysaccharides because it disrupts molecular connections [49]. A longer extraction duration facilitates the dissolution of polysaccharides in the extraction media by promoting the medium's subsequent heat accumulation and absorption of microwave radiation. Extended treatment times, however, may result in polysaccharide breakdown.

4.6. Subcritical Liquid Extraction

Subcritical water extraction, also called hot pressurized water extraction, is a novel method that keeps water liquid by using hot water under high pressure. This technique involves maintaining water in a liquid form at temperatures above boiling point (between 100 and 374 °C) while applying enough pressure (1 to 22.1 MPa). As a result, subcritical water has distinct characteristics from ambient pressure water at room temperature. Water can dissolve polar, moderately polar, and non-polar substances, including polysaccharides with a larger molecular weight under subcritical circumstances because they lower the water's dielectric constant and viscosity [50]. In addition, the subcritical water's ionization constant rises noticeably with temperature, approaching that of an acidic solution and facilitating chemical reactions such the hydrolysis and ether bond breakdown of polymer links without the need for a catalyst. Here, temperature is a key factor. Higher temperatures (above 100 °C) encourage the extraction yields of insoluble compounds with higher molecular weight and fractions made of different structures, such as proteoglucans or heteroglucans, while lower temperatures (under 100 °C) generally increase the yield of water-soluble substances (MW < 3.5 kDa) [50,51]. However, above a critical temperature and pressure, the chain conformation and structure of polysaccharides are sensitive, which impacts the polysaccharides' biological activity [52].

4.7. Aqueous Two-Phase Extraction

The aqueous two-phase extraction is a green method of separating bioproducts and makes use of the target products, preference partitioning within the biphasic system. In order to create structural incompatibility and the salting-out effect, respectively, two structurally different polymers (polyethylene glycol (PEG), Dextran, etc.) or one polymer/short-chain alcohol/surfactant/ionic liquid and inorganic salt (sulfate, phosphate, and carbonate salts) are mixed above critical concentration to form the two-phase system [53,54]. To achieve the best extraction efficiency for aqueous two-phase extraction, factors including the concentration and choice of phase-forming components, operating temperature, pH, and recycling possibilities should all be considered.

5. Types and Sources of Bioactive β-Glucans from Mushrooms

Lentinan, a glucan produced by the edible mushroom *Lentinus edodes* (Berk.) Pegler, also known as the Shiitake mushroom, is one of the most prevalent and thoroughly researched medicinal fungal polysaccharides [54]. It features a main chain of β-(1,3)-D-glucose residues with β-(1,6)-D-glucose side groups attached (one branch for every third main chain unit) and has an average molecular weight of around 500,000 Da. [55].

A similar polysaccharide, schizophyllan (also known as sizofiran), is synthesized by the edible mushroom *Schizophyllum commune Fr*. [56]. Typically, it has a molecular weight ranging from 100,000 to 200,000 Da and adopts a triple-helical conformation [57]. These two polysaccharides are among the most extensively studied immunomodulating microbial β-(1,3)-D-glucans [58], and both have been commercialized as innovative therapeutics for cancer treatment [59,60].

Ganoderma lucidum P. Karst., a medicinal mushroom from the Basidiomycetes family, has been used in traditional East Asian medicine as a dry powder or hot water extract. It produces ganoderan, a bioactive glucan with variable molecular weight and branching, especially from the water-soluble fraction of the fruit body. Additionally, *G. lucidum* produces heteroglucans and proteoglucans with immunostimulating properties [61].

Agaricus blazei Murrill, an edible and medicinal mushroom from Brazil, contains several antitumor polysaccharides in its fruit body [62]. These include β-(1,6); β-(1,3) glucan, acidic β-(1,6); α-(1,3) glucan, and acidic β-(1,6); α-(1,4) glucan, all with a β-(1,6) glycopyranose main chain. It also has an antitumor water-soluble proteoglucan with a α-(1,4) glucan main chain and β-(1,6) branches, and immunostimulating heteroglucans with glucose, galactose, mannose, and other sugars. In bioreactor cultures, *A. blazei* produces an extracellular proteoglucan with high molecular weight and significant antitumor properties [42].

Other immunostimulating biopolymers from Basidiomycota include grifolan, a gel-forming β-(1,3)-D-glucan with β-(1,6) glucosidic bonds every third glucopyranosyl residue from *Grifola frondose* Gray, and krestin, a proteoglucan with a β-(1,3)-D-glucan chain from *Trametes versicolor* Pilàt, commercialized in Asia as an effective immunostimulant [63]. The culinary oyster mushroom *Pleurotus ostreatus* P. Kumm and related species produce bioactive β-glucans, such as pleuran, an insoluble β-(1,3/1,6)-D-glucan, which is a potential nutraceutical [63]. The Tremella group of edible medicinal mushrooms (*T. mesenterica* (Schaeff.) Pers., *T. fuciformis* Berk., *T. auriantica* (Bab.) Grove, *T. cinnabarina* Bull.) have a high polysaccharide content (60–70% of the fruiting body). Tremella acidic polysaccharide is a glucuronoxylomannan with a linear backbone of α-1,3-linked D-rhamnose and side chains of xylose and glucuronic acid [64].

6. Medicinal Properties of Fungal Polysaccharides

6.1. Antimicrobial Effects

Various fungal biopolymers exhibit efficacy against bacterial and viral infections in vitro and in vivo by boosting phagocytosis by neutrophils and macrophages [65] (Figure 1). For instance, lentinan is active against tuberculosis, *Listeria monocytogenes*, *Salmonella enteritis*, and *Staphylococcus aureus* [66]. It also reduces *Escherichia coli* populations in piglet intestines [66]. Glucans from baker's yeast and *Sclerotinia sclerotiorum* (Lib.) Fuckel control *Mycobacterium tuberculosis* and methicillin-resistant *S. aureus*, respectively [67]. Extracts from various *Agaricus* and *Pleurotus* species show significant antibacterial activity against *S. aureus*, *Bacillus subtilis*, and *B. cereus* [68–70]. Fungal glucans like scleroglucan and ganoderan possess antiviral properties against *Rubella* virus and herpes virus [71]. Schizophyllan boosts immune responses in hepatitis *B. virus* patients, while lentinan fights influenza and polioviruses [72–74]. Notably, lentinan, acidic proteoglucan from *G. lucidum*, and glucans from *G. frondosa* and *T. versicolor* are employed as anti-HIV drugs, enhancing host resistance and reducing toxicity of conventional medications. This antiviral action is believed to involve increased interferon-gamma release and enhanced PBMC proliferation [75,76].

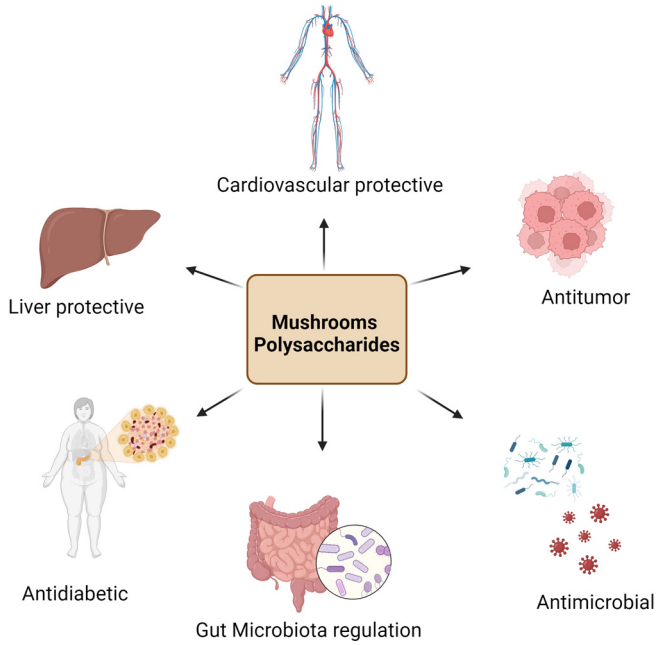

Figure 1. Principal medicinal properties of mushroom polysaccharides.

6.2. Antioxidant Effects

Polysaccharides from *T. versicolor*, *L. edodes*, and *Agaricus* mushrooms exhibit significant antioxidant properties (Figure 1), attributed to their chelating abilities that inhibit lipid oxidation [77]. This is linked to the presence of β-glucan and phenolic compounds (primarily tyrosine and ferulic acid) covalently bonded to the main β-glucan chain [78]. Methanolic extracts of *G. lucidum* and *G. tsugae* glucans and proteoglucans also show antioxidant effects by scavenging reactive oxygen species implicated in oncogenesis and food lipid oxidation [79]. Additionally, a polysaccharide from *G. lucidum* reduces oxygen-free radical production, counteracting the respiratory burst induced by peripheral mononuclear cells in murine peritoneal macrophages, suggesting an anti-aging role [80]. *G. lucidum* peptidoglucan application largely prevents macrophage necrosis induced by t-butyl hydroperoxide (tBOOH), safeguarding mitochondria, endoplasmic reticulum, and macrophage microvilli from oxidative damage and malfunction [81].

6.3. Cholesterol-Lowering, Blood Sugar-Reducing, and Prebiotic Benefits

Most fungal polysaccharides discussed are indigestible in the human gut, making them valuable sources of dietary fiber. They slow glucose release and reduce cholesterol accumulation in the blood [82]. Glucans from various fungi like *Lentinus edodes*, *G. lucidum*, *S. commune*, among others (Figure 1), have demonstrated hypolipidemic and hypoglycemic effects in both animals and humans [83,84]. Some act synergistically to combat hyperlipidemia and hyperglycemia [85]. These effects are attributed to bile acid interruption and slowed glucose absorption. Lentinan, for instance, is effective in reducing lipoprotein levels in blood [85]. *Pleurotus* mushroom extracts have shown promise in reducing atherogenic plaques [86]. However, substances other than polysaccharides, like lovastatin, may contribute to cholesterol synthesis inhibition [85]. Daily consumption recommendations range from 5 to 10 g for healthy individuals to 20 g for those with certain health conditions [87]. Edible mushroom polysaccharides also display hypoglycemic effects, with *G. frondosa* glucans showing significant antidiabetic and anti-obesity properties [85]. *Tremella mesenterica* glucuronoxylomannan regulates glycemic responses and may serve as a hypoglycemic agent or functional food component for diabetic individuals [88].

6.4. Immunostimulating and Antitumor Effects

Numerous research articles describe the therapeutic effects of fungal polysaccharides, termed Biological Response Modifiers (BRMs), for their ability to modulate immune responses and combat various health issues [89,90]. These polysaccharides trigger immune reactions against tumors, infections, and inflammations, while also regulating hormone synthesis and immune cell production [91] (Figure 1). Their structural features, such as molecular weight and conformation, influence their medicinal properties [92]. Polysaccharides like lentinan and schizophyllan aid in cancer treatment by enhancing immune responses and mitigating chemotherapy side effects [91,93]. Ganoderan from *G. lucidum* and glucans from *Agaricus blazei* show promise in cancer therapy, enhancing survival rates and immune function [94,95]. Extracts from *P. ostreatus* and *Pleurotus tuber-regium* demonstrate apoptosis induction in cancer cells [87]. These polysaccharides stimulate immune cells, increase cytokine production, and enhance phagocytosis, contributing to their therapeutic effects [96].

7. Integration of Medicinal Fungal Polysaccharides in Food and Nutraceutical Products

"Mushroom nutraceuticals" refers to refined polysaccharides, partially refined fruit body extracts, or dried biomass from mycelium or fruiting bodies of mushrooms. These are consumed as dietary supplements in forms like capsules, tablets, powders, syrups, and solutions, believed to modulate immune response and enhance health [85]. Many companies in Asia and beyond produce these products. Despite extensive literature on the medicinal properties of fungal biopolymers and their potential pharmaceutical use, their application as functional food components is less studied, with limited research on their bioactivity in foods. Food processing and interactions with food components may reduce the bioactivity of these polymers [97]. For example, ganoderan is degradable by pectinases and dextranases, affecting its efficacy in enzyme-containing foods. Similarly, the antitumor activity of lentinan and other biopolymers decreases when they interact with carrageenans [98]. This highlights the need for in vivo studies using realistic food matrices to validate health claims for functional foods containing these polysaccharides. Determining the appropriate dose for bioactivity without toxicity is also crucial for declaring a food "functional" [99]. Nevertheless, studies show promising results. For instance, glucans from *L. edodes* successfully replaced wheat flour in baked foods, creating low-calorie, fiber-rich functional foods. Up to 2% concentrations improved pasting parameters, batter viscosity, and elasticity without affecting air-holding capacity or hardness [100]. Similar studies found that adding *L. edodes* β-glucans to noodles as a partial wheat flour replacement conferred antioxidant and hypocholesterolemic effects and improved quality characteristics [53].

8. Conclusions

β-glucan are set to become a focal point of research due to their potential applications across various industrial fields. Scientific studies emphasize their multifunctional properties, and there is a rising consumer trend favoring "clean label" products devoid of additives. These factors are driving the development of new functional ingredients like β-glucans. Presently, β-glucan finds extensive use in the food, pharmaceutical, and cosmetic industries. The diversity of β-glucan molecules is notable, stemming not only from their sources (such as cereals, mushrooms, and yeast) but also within individual species of mushroom or fruiting bodies. Their properties can be further altered by varying extraction and purification methods. Therefore, additional studies are crucial to establish standardized methods for the extraction and purification of β-glucan. It is also important to examine their structure, including branching patterns and any associated amino acids, proteins, or other substituents. Such research will allow for a detailed evaluation of their mechanisms of action and possible therapeutic advantages.

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