Nutraceutical Properties of Oyster Mushrooms (Pleurotus spp.): A Comprehensive Review with Special Reference to Indian Varieties

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Abstract: Oyster mushrooms (Pleurotus spp.) represent one of the most widely cultivated and consumed edible mushroom genera globally, recognized for their exceptional nutritional profile and diverse therapeutic properties. This review comprehensively examines the nutraceutical potential of oyster mushrooms, with particular emphasis on the varieties cultivated in India. Oyster mushrooms contain a rich array of bioactive compounds, including polysaccharides (β glucans), ergothioneine, lovastatin, phenolic compounds, flavonoids, terpenoids, and essential amino acids. These biomolecules exhibit multifaceted pharmacological activities encompassing antioxidant, anti inflammatory, immunomodulatory, antitumour, antidiabetic and antihyperlipidaemic effects. A comparative analysis of Indian oyster mushroom varieties reveals significant species dependent variations in nutraceutical composition. Pleurotus florida demonstrates the highest protein content (22–25% dry weight) and superior antioxidant enzyme activity, while pigmented species such as Pleurotus djamor exhibit enhanced antioxidant capacity attributable to their melanin, carotenoid, and flavonoid pigments. The cholesterol content across Indian varieties ranges from 0.6–0.8% dry weight, underscoring their suitability as low cholesterol functional foods. Furthermore, this review addresses the emerging applications of oyster mushrooms in functional food product development, sustainable production through agro industrial waste valorization, and bio fortification strategies to enhance nutraceutical content. The findings collectively position oyster mushrooms as promising candidates for next generation nutraceutical interventions, bridging traditional dietary practices with modern evidence based therapeutic applications.

IndexTerms: oyster mushrooms, nutraceuticals, bioactive compounds, antioxidants, Indian varieties, functional foods

I. Introduction

1.1 Background and Rationale

In recent decades, the increasing prevalence of non-communicable diseases such as cardiovascular conditions, diabetes, and certain cancers has necessitated a fundamental reevaluation of the connection between nutrition and health. Consumers and researchers alike are increasingly looking beyond basic nutrition toward functional foods and nutraceuticals that can offer tangible therapeutic benefits (Al-Obaidi *et al.,* 2021; Morris *et al.,* 2016; Sathvara & Afuwale, 2024). Among the natural sources that have attracted considerable scientific and commercial interest, edible mushrooms stand out for their unique ability to combine high nutritional value with a wide spectrum of bioactive properties (Ho *et al.,* 2020; Lakhanpal & Rana, 2005; Rathore *et al.,* 2017).

Within the diverse world of edible fungi, the genus *Pleurotus*—commonly known as oyster mushrooms—has emerged as a particularly promising candidate for nutraceutical development. Not only are these mushrooms appreciated for their delicate flavour and texture, but they also contain a remarkable array of health-promoting compounds (Corrêa *et al.,* 2016; Oloke, 2017; Wal *et al.,* 2023). Oyster mushrooms are now cultivated on a large scale across the globe, owing to their adaptability to various agro-industrial by-products and their relatively short growth cycle (Bulam *et al.,* 2022; Enshasy *et al.,* 2015; Sreedharan *et al.,* 2025).

The genus *Pleurotus* includes several distinct species, such as the classic grey oyster (*P. ostreatus*), the white oyster (*P. florida*), the pink oyster (*P. djamor*), the golden oyster (*P. citrinopileatus*), as well as *P. pulmonarius*, *P. sajor-caju* and *P. sapidus* (Khatun *et al.,* 2015; Medihi *et al.,* 2024; Owaid *et al.,* 2017). Each species possesses its own organoleptic characteristics and, as accumulating evidence suggests, a subtly different nutraceutical profile. This diversity offers exciting possibilities for tailoring mushroom-based interventions to specific health needs (Devi *et al.,* 2024; Kumar, 2020; Tiupova *et al.,* 2025).

What makes oyster mushrooms truly compelling from a nutraceutical standpoint is the sheer variety of bioactive molecules they contain. Phenolic compounds, flavonoids, terpenes, polysaccharides (notably β-glucans), ergothioneine, and even the natural statin lovastatin have all been identified in *Pleurotus* species (Deepalakshmi & Sankaran, 2014; Ishara *et al.,* 2022; Moloi, 2018; Raseetha, n.d.). These constituents work together—often synergistically—to confer antioxidant, anti-inflammatory, immunomodulatory, antitumour, antidiabetic, and antihyperlipidaemic effects (Araújo *et al.,* 2025; Patel *et al.,* 2012; Wal *et al.,* 2023). It is therefore not surprising that oyster mushrooms are increasingly being labelled as "superfoods" or plant-based nutraceutical foods (Lebeque *et al.,* 2018; Valverde *et al.,* 2015; You *et al.,* 2022).

1.2 Objectives and Scope

The present review aims to provide a comprehensive and up-to-date synthesis of the nutraceutical properties of oyster mushrooms, with a special focus on the varieties that are cultivated and consumed in India (Khatun *et al.,* 2011; Khatun *et al.,* 2015). India's climatic conditions and growing agricultural infrastructure have made it a significant producer of several *Pleurotus* species, yet the regional nutraceutical potential remains underexploited relative to global developments.

Specifically, this review will address the following key areas: (1) the macro- and micro-nutrient composition of *Pleurotus* species; (2) the major bioactive compounds identified in oyster mushrooms and their known mechanisms of action; (3) a species-specific characterization of Indian oyster mushroom varieties, drawing on both published data and comparative analyses; (4) the health-promoting effects documented through preclinical and, where available, clinical studies; (5) current applications of oyster mushrooms in functional food product development; and (6) emerging trends in sustainable cultivation, including agro-industrial waste valorization and bio fortification strategies (Ho *et al.,* 2020; Singh *et al.,* 2025).

By bridging the international literature with region-specific data from India, this review seeks to inform both researchers and industry stakeholders about the largely untapped nutraceutical potential of Indian oyster mushroom varieties (Khatun *et al.,* 2011; Owaid *et al.,* 2017). Ultimately, we hope to encourage further research, standardized cultivation practices, and the development of evidence-based oyster mushroom products that can contribute meaningfully to public health.

II. Nutritional Composition of Oyster Mushrooms:

2.1 Macronutrient Profile

A balanced macronutrient composition is one of the defining features that make oyster mushrooms a valuable component of a healthy diet. Across the *Pleurotus* genus, carbohydrates constitute the largest fraction on a dry weight basis, followed by protein, dietary fibre, and a very low content of lipids (Effiong *et al.,* 2024b; Khatun *et al.,* 2015; Painuli *et al.,* 2020). This pattern is consistent among most cultivated species, although absolute values vary depending on the specific mushroom strain, the growth substrate, and the harvesting stage (Enshasy *et al.,* 2015; Lesa *et al.,* 2022; Owaid *et al.,* 2017).

Detailed proximate analyses have shown that carbohydrate levels in *Pleurotus* species typically range from 64.8% to nearly 80% of dry matter, while protein can vary between 10.5% and 23.3% (Effiong *et al.,* 2024b; Kumla *et al.,* 2025; Upadhyaya *et al.,* 2017). Fat content remains remarkably low, generally between 0.6% and 4.4%, which underscores the suitability of oyster mushrooms for low-energy and heart-healthy dietary patterns. For the widely consumed *Pleurotus ostreatus*, specific studies have reported approximately 80 g of carbohydrates, 10 g of protein, and only 2 g of fat per 100 g of dry weight (Effiong *et al.,* 2024b; Salata *et al.,* 2018). However, it is important to recognise that substrate composition and post-harvest processing can shift these numbers substantially (Effiong *et al.,* 2024a; Maray *et al.,* 2018; Singh & Sharma, 2022).

The protein content of oyster mushrooms deserves particular emphasis. Unlike many plant-based foods, *Pleurotus* species provide all the essential amino acids, making them an exceptionally high-quality protein source for vegetarians and those seeking to reduce animal protein intake (Khatun *et al.,* 2015; Salata *et al.,* 2018). Under optimal growing conditions, the protein content of *Pleurotus* has been reported to reach as high as 27.19% of dry weight, highlighting the influence of cultivation practices on nutritional quality (Effiong *et al.,* 2024b; Khatun *et al.,* 2015). Moreover, oyster mushrooms contain no cholesterol and very little fat, which together make them an attractive food for cardiovascular health promotion and weight management (Lesa *et al.,* 2022; Oloke, 2017; Wal *et al.,* 2023).

2.2 Mineral and Vitamin Content

Beyond the major macronutrients, oyster mushrooms are an excellent source of a wide range of essential minerals and trace elements (Painuli *et al.,* 2020; Upadhyaya *et al.,* 2017). The mineral profile typically includes substantial amounts of potassium, phosphorus, calcium, magnesium, sodium, zinc, copper, and iron (Effiong *et al.,* 2024b; Obodai *et al.,* 2014; Owaid *et al.,* 2017). Importantly, when cultivated on clean, non-contaminated substrates, oyster mushrooms do not accumulate toxic heavy metals such as lead, silver, arsenic, mercury, or antimony, confirming their safety for regular consumption (Owaid *et al.,* 2017).

From a nutritional standpoint, the low sodium content of oyster mushrooms—usually well below 100 mg per 100 g fresh weight—is particularly noteworthy. This makes them compatible with low-sodium diets recommended for individuals with hypertension or kidney disease (Lesa *et al.,* 2022; Owaid *et al.,* 2017). In addition, they provide a good array of B-complex vitamins, including riboflavin, niacin, and folate, as well as ascorbic acid (vitamin C) (Lesa *et al.,* 2022; Salata *et al.,* 2018).

One of the most distinctive nutritional features of oyster mushrooms is their content of ergosterol, a fungal sterol that serves as a precursor to vitamin D (Giavasis, 2014; Salata *et al.,* 2018). When the mushrooms are exposed to ultraviolet (UV) light—either during growth or after harvest—ergosterol is converted into biologically active vitamin D_2. This property offers a plant-based, practical strategy to address the widespread prevalence of vitamin D deficiency, especially in populations with limited sun exposure (Giavasis, 2014; Valverde *et al.,* 2015). Thus, the mineral and vitamin composition of oyster mushrooms complements their macronutrient profile, further strengthening their position as a functional food with wide-ranging health benefits.

III. Bioactive Compounds and Their Health-Promoting Properties:

The nutraceutical value of oyster mushrooms stems directly from their remarkable ability to produce a diverse array of bioactive secondary metabolites. These molecules, ranging from high-molecular-weight polysaccharides to low-molecular-weight phenolics and terpenoids, act individually and synergistically to exert a wide spectrum of health benefits (Corrêa *et al.,* 2016; Giavasis, 2014; Niego *et al.,* 2021). Table 1 summarizes the principal classes of bioactive compounds identified in *Pleurotus* species, along with their major reported pharmacological activities, as compiled from multiple studies (Araújo *et al.,* 2025; Khan *et al.,* 2020; Sreedharan *et al.,* 2025).

Table 1. Major bioactive compounds identified in *Pleurotus* spp. and their reported health benefits (Araújo *et al.,* 2025; Deepalakshmi & Sankaran, 2014; Giavasis, 2014; Moloi, 2018).

Bioactive Compound Class	Specific Compounds	Reported Health Effects
Polysaccharides	β-Glucans (Pleuran), heteropolysaccharides	Immunomodulation, antitumour, prebiotic, cholesterol-lowering
Phenolic Compounds	Phenolic acids, flavonoids, coumaric acid, ferulic acid	Antioxidant, anti-inflammatory, neuroprotective
Amino Acid Derivatives	Ergothioneine	Potent antioxidant, cytoprotective, anti-ageing
Polyketides	Lovastatin	Cholesterol-lowering (HMG-CoA reductase inhibition)
Sterols	Ergosterol	Vitamin D precursor, immunomodulatory
Terpenoids	Triterpenoids	Anti-inflammatory, antitumour
Peptides	Lectins	Immunomodulatory, antiproliferative
Pigments	Melanin, carotenoids, flavonoids	Antioxidant, natural food colorant

Sources: Compiled from Corrêa et al. (2016); Deepalakshmi & Sankaran (2014); Giavasis (2014); Khan et al. (2020); Niego et al. (2021).

3.1 Polysaccharides

Among all bioactive constituents of oyster mushrooms, polysaccharides—particularly β-glucans—have received the most extensive research attention (Giavasis, 2014; Khan *et al.,* 2020). β-Glucans are glucose polymers with mixed β-(1→3) and β-(1→6) linkages. The specific β-glucan found in *Pleurotus ostreatus*, known as pleuran, is water-soluble and recognized as a primary immunomodulatory agent (Giavasis, 2014; Khan *et al.,* 2020).

The mechanism by which β-glucans modulate immune function involves binding to pattern recognition receptors on the surface of innate immune cells. Key receptors include Dectin-1 and Toll-like receptor 2 (TLR2), which are expressed on macrophages, neutrophils, and natural killer cells. Activation of these receptors triggers a cascade of intracellular signals that enhance phagocytic activity, stimulate the production of pro-inflammatory cytokines (such as interleukin-1β and tumour necrosis factor-α), and improve the host's defence against microbial pathogens (Al-Obaidi *et al.,* 2021; Giavasis, 2014; Rathore *et al.,* 2017).

Beyond immune modulation, β-glucans contribute to cardiovascular health through a distinct mechanism. In the intestinal lumen, they bind to bile acids, preventing their normal enterohepatic reabsorption. The liver must then use circulating cholesterol to synthesize new bile acids, thereby lowering blood cholesterol levels (Giavasis, 2014; Lesa *et al.,* 2022). This cholesterol-lowering effect complements the action of lovastatin, another bioactive found in oyster mushrooms. Clinical studies have already demonstrated that pleuran is effective in reducing the incidence of recurrent respiratory tract infections, underscoring the translational relevance of these findings (Giavasis, 2014; Khan *et al.,* 2020).

3.2 Ergothioneine

Ergothioneine is a naturally occurring thiol-containing amino acid derivative that is synthesised exclusively by fungi and certain cyanobacteria. Over the past decade, it has emerged as a signature antioxidant compound in oyster mushrooms (Khan *et al.,* 2020; Niego *et al.,* 2021). Among dietary sources, *Pleurotus* species are among the richest in ergothioneine, which acts as a potent scavenger of reactive oxygen species (ROS). Its unique stability and efficient cellular uptake—mediated by the specific transporter OCTN1—make it particularly effective in protecting cells from oxidative damage (Khan *et al.,* 2020; Morris *et al.,* 2017).

The physiological relevance of ergothioneine lies in its ability to mitigate oxidative stress, a common underlying factor in many chronic diseases, including cardiovascular disorders, neurodegenerative conditions (such as Parkinson's and Alzheimer's disease), and metabolic syndrome (Lesa *et al.,* 2022; Wal *et al.,* 2023). Importantly, the concentration of ergothioneine in oyster mushrooms is substantially higher than in most other dietary sources, reinforcing their role as functional foods specifically targeted at oxidative stress-mediated pathologies (Khan *et al.,* 2020; Niego *et al.,* 2021).

3.3 Lovastatin

Lovastatin is a naturally occurring polyketide that belongs to the statin class of HMG-CoA reductase inhibitors. Several *Pleurotus* species produce lovastatin as a secondary metabolite, and this compound is largely responsible for the cholesterol-lowering properties attributed to oyster mushrooms (Deepalakshmi & Sankaran, 2014; Patel *et al.,* 2012). By inhibiting HMG-CoA reductase—the rate-limiting enzyme in cholesterol biosynthesis—lovastatin reduces endogenous cholesterol production, particularly lowering low-density lipoprotein (LDL) levels and improving the overall lipid profile (Deepalakshmi & Sankaran, 2014; Wal *et al.,* 2023).

Beyond its primary lipid-modulating action, lovastatin exhibits additional pleiotropic benefits. These include anti-inflammatory and antioxidant activities that contribute to cardiovascular risk reduction independently of cholesterol lowering (Patel *et al.,* 2012; Sreedharan *et al.,* 2025). Notably, the lovastatin content of *Pleurotus* mushrooms varies considerably among species and even among different strains of the same species. Some strains, when cultivated on specific substrates, show markedly enhanced lovastatin synthesis (Khan *et al.,* 2020; Singh & Sharma, 2022). This variability opens up opportunities for targeted strain selection and optimised cultivation practices aimed at maximising the nutraceutical efficacy of oyster mushroom products (Kumar, 2018; Singh & Sharma, 2022).

3.4 Phenolic Compounds and Flavonoids

Phenolic compounds and flavonoids constitute another major group of antioxidants in oyster mushrooms (Effiong *et al.,* 2024; Fakoya *et al.,* 2020). Comprehensive phytochemical screening has identified a range of phenolic acids—including coumaric acid and ferulic acid—as well as various flavonoids and other polyphenolic derivatives (Effiong *et al.,* 2024; Okunlola *et al.,* 2021). These compounds exert their antioxidant effects through multiple mechanisms: direct neutralisation of free radicals, chelation of transition metals (thereby preventing metal-catalysed oxidative reactions), inhibition of lipid peroxidation, and modulation of redox-sensitive signalling pathways that are implicated in chronic inflammation and carcinogenesis (Gupta *et al.,* 2017; Khatun *et al.,* 2009).

An interesting observation is that coloured oyster mushroom varieties—such as the pink *P. djamor* and the golden *P. citrinopileatus*—contain additional pigment-associated antioxidants, including carotenoids, melanin, and certain flavonoids (Medihi *et al.,* 2024; Owaid *et al.,* 2017). These pigments not only give the mushrooms their distinctive visual appeal but also contribute to a higher total antioxidant capacity compared to white varieties. In fact, several studies have reported an inverse relationship between pigmentation intensity and antioxidant capacity, with the most deeply pigmented species showing the highest free-radical scavenging activity (Bulam *et al.,* 2022; Medihi *et al.,* 2024).

3.5 Other Bioactive Constituents

In addition to the major compound classes discussed above, oyster mushrooms contain several other bioactive molecules that add to their nutraceutical potential. Lectins—carbohydrate-binding proteins—have been isolated from *Pleurotus* species and shown to possess immunomodulatory and antiproliferative properties (Deepalakshmi & Sankaran, 2014; Niego *et al.,* 2021). Terpenoids, another group of secondary metabolites, exhibit documented antimicrobial and anti-inflammatory activities. The mycochemical repertoire of *P. ostreatus* also includes various essential amino acids, (glyco) proteins, and other nitrogen-containing metabolites (Sarma *et al.,* 2018; Wal *et al.,* 2023).

What makes the bioactive profile of oyster mushrooms so impressive is the synergistic interplay among these diverse compounds. Rather than relying on a single molecule, the overall health-promoting effect—whether antioxidant, immunomodulatory, or anticancer—emerges from the combined action of multiple constituents acting on different molecular targets (Corrêa *et al.,* 2016; Patel *et al.,* 2012). This holistic, food-based synergy is one of the key advantages of using whole mushrooms or minimally processed extracts as nutraceuticals, as opposed to isolated single compounds.

IV. NUTRACEUTICAL CHARACTERISATION OF INDIAN OYSTER MUSHROOM VARIETIES:

India, with its diverse climatic zones and steadily expanding agricultural infrastructure, has become a significant cultivator and consumer of oyster mushrooms (Khatun *et al.,* 2011; Pattanayak & Das, 2022). Several *Pleurotus* species are now grown year-round in the plains of India, offering a rich and accessible resource for nutraceutical development (Khatun *et al.,* 2015; Owaid *et al.,* 2017). However, the full nutraceutical potential of Indian varieties remains insufficiently characterized compared to their counterparts in Europe, North America, and East Asia. This section provides a species-specific analysis of the available data on Indian *Pleurotus* cultivars, with emphasis on protein content, antioxidant enzyme profiles, phenolic composition, and cholesterol-lowering attributes.

4.1 *Pleurotus florida* (White Oyster Mushroom)

Among Indian oyster mushroom varieties, *P. florida* stands out for its exceptional protein content and superior antioxidant enzyme activity (Khatun *et al.,* 2015; Owaid *et al.,* 2017). Analyses conducted on specimens cultivated in the plains of India revealed protein content ranging from 22–25% dry weight, the highest reported among commonly cultivated Indian *Pleurotus* species (Khatun *et al.,* 2015).

The antioxidant properties of *P. florida* were characterized by both enzymatic and non-enzymatic mechanisms (Khatun *et al.,* 2015). Reducing power, chelating activity on Fe^{2+}, and total phenol content were significantly higher in *P. florida* compared to *P. pulmonarius* and *P. citrinopileatus* (Khatun *et al.,* 2015). Regarding antioxidative enzymes, *P. florida* demonstrated the highest peroxidase and superoxide dismutase (SOD) activity, indicating potent cellular defence mechanisms against oxidative stress (Khatun *et al.,* 2015). The cholesterol content of Indian *P. florida* was found to be 0.6–0.8% dry weight, confirming its low-cholesterol, protein-rich food profile (Owaid *et al.,* 2017).

Bio fortification studies have further demonstrated that the nutraceutical properties of *P. florida* can be enhanced through exogenous supplementation (Singh & Sharma, 2022). Zinc oxide nanoparticle (ZnONP) supplementation (20 and 40 ppm) significantly increased mycelial growth, yield parameters, and the content of phenols, flavonoids, and total antioxidants in *P. florida* (Singh & Sharma, 2022). Along with these, macro- and micro-nutrient concentrations were also elevated, confirming the utility of bio fortification for enhancing the nutritive potential of oyster mushrooms (Singh & Sharma, 2022).

4.2 *Pleurotus citrinopileatus* (Golden Oyster Mushroom)

The golden oyster mushroom, *Pleurotus citrinopileatus*, is easily recognized by its distinctive golden-yellow pigmentation. In Indian studies, this species ranks second in protein content among the cultivated *Pleurotus* varieties, with reported values of 20–22% dry weight (Khatun *et al.,* 2015). The yellow colouration is primarily due to the presence of carotenoids and flavonoids, which also contribute substantially to the mushroom's overall antioxidant capacity (Medihi *et al.,* 2024).

Comparative analyses have revealed that *P. citrinopileatus* exhibits a particularly high capacity for inhibiting lipid peroxidation (76.65%), suggesting a specific efficacy in protecting cellular membranes from oxidative damage (Khatun *et al.,* 2015). Although its reducing power and total phenol content are somewhat lower than those of *P. florida*, the unique pigment composition of *P. citrinopileatus* offers additional health benefits. Carotenoids can serve as precursors to vitamin A, supporting vision and immune function, while the flavonoid fraction may exert anti-inflammatory effects (Medihi *et al.,* 2024; Owaid *et al.,* 2017). Thus, while not the most protein-dense species, *P. citrinopileatus* holds promise for applications where antioxidant and eye-health benefits are prioritised.

4.3 *Pleurotus pulmonarius*

Pleurotus pulmonarius, also referred to as the Phoenix oyster or Indian oyster mushroom, shows a protein content of 15–18% dry weight, which is the lowest among the three species commonly cultivated in the plains of India (Khatun *et al.,* 2015). However, lower protein content does not diminish the nutraceutical value of this species; rather, *P. pulmonarius* compensates with a distinctive enzymatic antioxidant profile (Abidin *et al.,* 2016; Khatun *et al.,* 2015).

While peroxidase and SOD activities are lowest in *P. pulmonarius* compared to *P. florida* and *P. citrinopileatus*, this species demonstrates the highest catalase (CAT) activity (Khatun *et al.,* 2015). Catalase is responsible for decomposing hydrogen peroxide into water and oxygen, thereby preventing the formation of highly reactive hydroxyl radicals. This specialised role makes *P. pulmonarius* particularly valuable in contexts where hydrogen peroxide-mediated oxidative stress is a concern. The cholesterol content of *P. pulmonarius* falls within the same low range (0.6–0.8% dry weight) as other *Pleurotus* species, reaffirming the genus-wide consistency of its low-cholesterol characteristic (Owaid *et al.,* 2017). Additionally, extracts of wild *P. pulmonarius* collected from Northeast India have been reported to possess high antioxidant activity, highlighting the potential of locally sourced strains (Mansuri *et al.,* 2017,).

4.4 *Pleurotus djamor* (Pink Oyster Mushroom)

The pink oyster mushroom, *Pleurotus djamor*, has attracted increasing attention for both its striking colour and its nutritional properties (Nayak *et al.,* 2021; Bulam *et al.,* 2022). Beyond its pleasant pink appearance and appealing sensory attributes, *P. djamor* offers high nutritional value and has been proposed as a natural food colorant in addition to being a functional food (Bulam *et al.,* 2022; Medihi *et al.,* 2024).

Antioxidant profiling of six oyster mushroom species cultivated in North East India revealed that the pink-coloured *P. djamor* exhibited the highest antioxidant activity among all varieties tested, followed by *P. ostreatus* and the grey mushroom *P. sajor-caju* (Mansuri *et al.,* 2017). White species such as *P. florida*, *P. sapidus*, and *P. citrinopileatus* showed comparatively lower antioxidant activity. This strong inverse relationship between pigmentation intensity and antioxidant capacity is consistent with the broader phytochemical principle that pigmented compounds—including melanin, carotenoids, and flavonoids—serve dual roles as pigments and potent antioxidants (Medihi *et al.,* 2024).

The practical health implications of this high antioxidant capacity are supported by studies showing that *P. djamor* powder can effectively reduce the risk of lifestyle-related diseases, including diabetes, and help alleviate malnutrition (Nayak *et al.,* 2021). Furthermore, *P. djamor* has demonstrated promising hypoglycaemic effects in experimental models, positioning it as a potential complementary intervention in diabetes management (Nayak *et al.,* 2021). From a sustainability perspective, the ability of *P. djamor* to biotransform agro-industrial waste—such as agave bagasse and corn stover—into polyphenols, organic acids, and bioactive polysaccharides offers an environmentally friendly route to nutraceutical production (Cruz-Moreno *et al.,* 2025; Zotti *et al.,* 2025). Thus, *P. djamor* exemplifies the convergence of environmental sustainability, visual appeal, and human nutrition.

4.5 *Pleurotus sajor-caju*, *P. sapidus*, *P. cystidiosus* and Other Species

Several additional *Pleurotus* species have been documented in the Indian context, each contributing distinct nutraceutical attributes (Atri *et al.,* 2013; Owaid *et al.,* 2017).

- ***Pleurotus sajor-caju*** (grey oyster mushroom): This species exhibits moderate antioxidant activity, positioned between the highly pigmented *P. djamor* and the white species (Mansuri *et al.,* 2017). It has been extensively studied for its nutritional composition and has demonstrated significant prebiotic content (Obodai *et al.,* 2014).
- ***Pleurotus sapidus***: As a white oyster mushroom variety, *P. sapidus* shows antioxidant activity comparable to other white species, with lower capacity than pigmented varieties (Mansuri *et al.,* 2017). However, its mild flavour profile and good nutritional composition make it valuable for food product development where a strong mushroom taste may be undesirable (Arora *et al.,* 2018).
- ***Pleurotus cystidiosus***: This wild species, collected from different localities in Northwest India, has been evaluated for its nutritional and nutraceutical composition (Atri *et al.,* 2013). Mineral analysis revealed substantial amounts of calcium, magnesium, sodium, potassium, copper, zinc, and iron (Atri *et al.,* 2013).
- ***Pleurotus floridanus* and other wild species**: Five wild culinary-medicinal species—*P. floridanus*, *P. pulmonarius*, *P. sapidus*, *P. cystidiosus*, and *P. sajor-caju*—collected from Northwest India were found to contain ascorbic acid, phenols, carotene, and lycopene (Atri *et al.,* 2013). Total phenolic

compounds ranged from 6.76 to 16.92 mg/100 g gallic acid equivalents, while β-carotene ranged from 0.134 to 0.221 µg/100 g (Atri *et al.,* 2013). Fatty acid analysis showed a predominance of monounsaturated fatty acids (37.17–68.29%) over saturated fatty acids (26.07–47.77%), a profile generally considered cardio protective (Atri *et al.,* 2013).

4.6 Comparative Assessment of Indian Varieties

A comparative summary of key nutraceutical parameters for the principal Indian oyster mushroom varieties is presented in Table 2. The data are compiled from several independent studies (Atri *et al.,* 2013; Khatun *et al.,* 2015; Mansuri *et al.,* 2017; Owaid *et al.,* 2017).

Table 2. Comparative nutraceutical parameters of major Indian *Pleurotus* species (compiled from Atri *et al.,* 2013; Khatun *et al.,* 2015; Mansuri *et al.,* 2017; Owaid *et al.,* 2017).

Parameter	***P. florida***	***P. citrinopileatus***	***P. pulmonarius***	***P. djamor***
Protein (% dw)	22–25	20–22	15–18	Moderate
Cholesterol (% dw)	0.6–0.8	0.6–0.8	0.6–0.8	ND
Total Phenolics	Highest	Moderate	Lowest	High
Peroxidase activity	Highest	Moderate	Lowest	ND
SOD activity	Highest	Moderate	Lowest	ND
CAT activity	Moderate	Lowest	Highest	ND
DPPH scavenging	94.02%	Moderate	Moderate	Highest
Lipid peroxidation inhibition	Moderate	76.65%	Moderate	Moderate
Antioxidant ranking	2nd	3rd	4th	1st

Protein content of *P. djamor* is comparable to other *Pleurotus* species but systematic quantitative data for this parameter in Indian varieties requires further investigation. ND = not determined.

Several key observations emerge from this comparative assessment (Khatun *et al.,* 2015; Mansuri *et al.,* 2017):

- **Protein content ranking:** *P. florida* > *P. citrinopileatus* > *P. pulmonarius*. This order has been consistently replicated across multiple independent studies, confirming the superior protein-rich status of *P. florida* among Indian oyster mushroom varieties (Khatun *et al.,* 2015).
- **Antioxidant capacity ranking:** *P. djamor* > *P. ostreatus* > *P. sajor-caju* > white species (*P. florida*, *P. sapidus*, *P. citrinopileatus*). This pattern is consistent with the principle that pigmentation (melanin, carotenoids, flavonoids) is associated with enhanced antioxidant capacity (Medihi *et al.,* 2024).
- **Enzymatic antioxidant distribution:** Each species exhibits a distinct enzymological profile that may be optimised for specific functional applications (Khatun *et al.,* 2015). *P. florida* demonstrates superior peroxidase and SOD activity, indicating strong protection against mitochondrial superoxide. In contrast, *P. pulmonarius* uniquely exhibits maximum CAT activity, suggesting a specialised role in decomposing hydrogen peroxide. This diversity opens the possibility of using specific species for targeted oxidative stress pathways.
- **Phenolic content:** The total phenolic compound range (6.76–16.92 mg/100 g gallic acid equivalents among wild Northwest Indian species) is comparable to, or even higher than, many conventional

plant-based antioxidant sources. This reinforces the value of Indian oyster mushrooms as dietary antioxidants (Atri *et al.,* 2013).

Taken together, the data on Indian oyster mushroom varieties reveal substantial species-dependent variation in nutraceutical properties. While *P. florida* is the best choice for protein supplementation, *P. djamor* offers unparalleled antioxidant capacity, and *P. pulmonarius* provides a unique catalase-rich profile. This diversity should be leveraged in future nutraceutical product development and dietary recommendations tailored to specific health needs.

V. Health-Promoting Effects: Mechanisms and Evidence:

The diverse array of bioactive compounds found in oyster mushrooms translates into a wide spectrum of health-promoting effects. These range from direct antioxidant and anti-inflammatory actions to more complex immunomodulatory, antitumour, antidiabetic, and antimicrobial activities. While much of the current evidence comes from in vitro and animal studies, a growing number of human trials and clinical observations support the traditional and emerging uses of *Pleurotus* species. This section critically examines the major health benefits attributed to oyster mushrooms, with an emphasis on underlying mechanisms.

5.1 Antioxidant Activity

Oxidative stress, resulting from an imbalance between the production of reactive oxygen species (ROS) and the capacity of endogenous antioxidant defences, is a common pathogenic factor in many chronic diseases, including cardiovascular disorders, neurodegeneration, and cancer. Oyster mushrooms possess a formidable arsenal of antioxidant compounds that help counteract oxidative damage (Effiong *et al.,* 2024a; Jaworska *et al.,* 2015; Kaur *et al.,* 2022).

The antioxidant capacity of *Pleurotus* extracts has been extensively characterized using a variety of in vitro assays. These include the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, the ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)) radical scavenging assay, the ferric reducing antioxidant power (FRAP) assay, and metal chelating assays (Effiong *et al.,* 2024a). A comparative study of commercially available mushrooms reported that *P. ostreatus* exhibited the highest total phenolic content (3.95 ± 0.05 mg GAE/g dry weight) and total flavonoid content (2.17 ± 0.06 mg CE/g dry weight) among the species tested (Kaur *et al.,* 2022). Moreover, the DPPH, ABTS, and FRAP values for *P. ostreatus* were significantly higher than those of other commercially grown mushrooms (Jaworska *et al.,* 2015; Kaur *et al.,* 2022).

The antioxidant mechanisms of oyster mushrooms are dual in nature. On one hand, low-molecular-weight compounds such as phenolic acids, flavonoids, ergothioneine, ascorbic acid, and carotenoids directly neutralize free radicals and chelate pro-oxidant metal ions (Gupta *et al.,* 2017; Khan *et al.,* 2020). On the other hand, mushroom polysaccharides and other bio actives can upregulate the expression and activity of endogenous antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) (Khan *et al.,* 2020; Morris *et al.,* 2016). This dual mechanism distinguishes mushroom-derived antioxidants from many synthetic single-compound antioxidants, potentially offering superior cytoprotective efficacy through synergistic interactions among multiple bioactive constituents (Morris *et al.,* 2016; Valverde *et al.,* 2015).

5.2 Anti-inflammatory and Immunomodulatory Effects

Chronic inflammation is now recognized as a key driver of many non-communicable diseases, including atherosclerosis, rheumatoid arthritis, inflammatory bowel disease, and metabolic syndrome. Oyster mushrooms have demonstrated significant anti-inflammatory and immunomodulatory activities in both preclinical and early clinical studies (Das *et al.,* 2023; Wal *et al.,* 2023).

The primary mediators of immunomodulation in *Pleurotus* are the β-glucans. These polysaccharides bind to pattern recognition receptors—particularly Dectin-1 and Toll-like receptor 2 (TLR2)—on the surface of macrophages, dendritic cells, and natural killer cells. This binding activates intracellular signalling cascades that lead to enhanced phagocytosis, increased production of pro-inflammatory cytokines (such as interleukin-1β, tumour necrosis factor-α, and interferon-γ), and improved resistance to microbial pathogens (Al-Obaidi *et al.,* 2021; Giavasis, 2014; Morris *et al.,* 2017). Importantly, the immunomodulatory effect is context-dependent: low to moderate concentrations typically enhance immune function, while very high doses may produce immunosuppressive effects. This bell-shaped dose-response curve must be carefully considered when formulating nutraceutical products (Giavasis, 2014).

On the anti-inflammatory side, oyster mushroom extracts have been shown to inhibit the activation of nuclear factor kappa B (NF-κB), a master transcription factor that drives the expression of many pro-inflammatory genes. They also suppress cyclooxygenase-2 (COX-2) expression and reduce the synthesis of prostaglandin E_2, a key mediator of inflammation and pain (Das *et al.,* 2023; Wal *et al.,* 2023). The presence of multiple anti-inflammatory compounds—polysaccharides, phenolic acids and triterpenoids—suggests that the overall effect is achieved through synergistic, multi-target mechanisms rather than a single pathway (Corrêa *et al.,* 2016; Patel *et al.,* 2012).

5.3 Antitumour Activity

The potential of oyster mushrooms as anticancer agents has attracted considerable research interest. Numerous preclinical studies have documented the antitumour activity of *Pleurotus* extracts against various cancer cell lines, including breast, colon, liver, lung, and gastric cancers (Patel *et al.,* 2012; Sarma *et al.,* 2018; Sreedharan *et al.,* 2025).

The mechanisms underlying this activity are multifaceted. First, β-glucans exert indirect antitumour effects by stimulating the host immune system to recognise and destroy malignant cells. Activated macrophages and natural killer cells release cytokines and cytotoxic molecules that selectively target cancer cells while sparing normal tissues (Giavasis, 2014; Khan *et al.,* 2020). Second, certain *Pleurotus* extracts have been shown to induce apoptosis (programmed cell death) in cancer cells through both the intrinsic (mitochondrial) and extrinsic (death receptor) pathways. Third, some bioactive compounds inhibit angiogenesis—the formation of new blood vessels that tumours require for growth and metastasis (Sarma *et al.,* 2018; Sreedharan *et al.,* 2025).

Lovastatin, besides its cholesterol-lowering role, also exhibits antiproliferative activity against cancer cells. It disrupts the mevalonate pathway, which is essential for the post-translational prenylation of proteins involved in oncogenic signalling. This leads to cell cycle arrest and, in some cases, apoptosis (Deepalakshmi & Sankaran, 2014; Patel *et al.,* 2012). The dual mechanism of lovastatin—simultaneously addressing cardiovascular risk and cancer cell proliferation—makes oyster mushrooms uniquely valuable for comprehensive chronic disease prevention (Sreedharan *et al.,* 2025; Wal *et al.,* 2023). A recent review has highlighted the emerging role of oyster mushrooms as a functional food for complementary cancer therapy, suggesting that regular consumption may serve as a safe and effective adjunct to conventional oncological treatments (Sreedharan *et al.,* 2025).

5.4 Antidiabetic and Antihyperlipidaemic Effects

Metabolic syndrome, characterized by insulin resistance, dyslipidaemia, hypertension, and abdominal obesity, is a major public health challenge worldwide. Oyster mushrooms have shown considerable promise in managing two key components of metabolic syndrome: hyperglycaemia and hyperlipidaemia (Ishara *et al.,* 2022; Lesa *et al.,* 2022; Wal *et al.,* 2023).

The antihyperglycaemic effects of *Pleurotus* are mediated primarily through the inhibition of carbohydrate-digesting enzymes. Specifically, oyster mushroom extracts have been shown to inhibit α-glucosidase and α-amylase, the enzymes that break down complex carbohydrates into absorbable monosaccharides. By slowing carbohydrate digestion and glucose absorption, these extracts attenuate postprandial blood glucose spikes (Kumla *et al.,* 2025; Lesa *et al.,* 2022). Additionally, β-glucans improve insulin sensitivity through indirect mechanisms involving the gut microbiota and the secretion of incretin hormones such as GLP-1 (glucagon-like peptide-1) (Giavasis, 2014; Khan *et al.,* 2020).

The cholesterol-lowering effects of oyster mushrooms operate through at least three complementary mechanisms. First, lovastatin directly inhibits HMG-CoA reductase, the rate-limiting enzyme in cholesterol biosynthesis (Deepalakshmi & Sankaran, 2014). Second, β-glucans bind to bile acids in the intestinal lumen, preventing their reabsorption and forcing the liver to use circulating cholesterol for the synthesis of new bile acids (Giavasis, 2014). Third, other bioactive compounds—such as eritadenine and certain phenolic acids—may contribute to lipid regulation through additional pathways. The combination of these mechanisms within a single whole food matrix offers advantages over isolated statin therapy, including a reduced risk of adverse effects and the added benefit of pleiotropic cardio protective actions (Patel *et al.,* 2012; Wal *et al.,* 2023). Importantly, the cholesterol content of all *Pleurotus* species is consistently low (0.6–0.8% dry weight), making them suitable for incorporation into lipid-lowering dietary regimens (Owaid *et al.,* 2017).

5.5 Antimicrobial Activity

The search for new antimicrobial agents has intensified due to the rising prevalence of antibiotic-resistant pathogens. Oyster mushrooms have demonstrated antimicrobial activity against a range of Gram-positive and Gram-negative bacteria, as well as certain pathogenic fungi (Al-Obaidi *et al.,* 2021; Fakoya *et al.,* 2020; Morris *et al.,* 2017).

The bioactive compounds responsible for this activity include lectins, terpenoids, phenolic compounds, and low-molecular-weight secondary metabolites (Deepalakshmi & Sankaran, 2014; Niego *et al.,* 2021). The mechanisms vary: some compounds disrupt bacterial cell membranes, others inhibit the synthesis of essential macromolecules, and still others interfere with quorum sensing—the cell-to-cell communication system that bacteria use to coordinate virulence. While the antimicrobial efficacy of crude mushroom extracts is generally moderate compared to conventional antibiotics, the multi-target nature of these natural products may reduce the likelihood of resistance development. This is a particularly attractive feature in the era of antimicrobial resistance (Al-Obaidi *et al.,* 2021; Fakoya *et al.,* 2020).

5.6 Other Documented Health Benefits

In addition to the major effects discussed above, oyster mushrooms have been associated with several other health-promoting actions (Corrêa *et al.,* 2016; Rathore *et al.,* 2017):

- **Neuroprotective effects:** Ergothioneine accumulates in the brain via the OCTN1 transporter and has been shown to protect neurons from oxidative damage. This property may be relevant for the prevention or delay of neurodegenerative disorders such as Parkinson's and Alzheimer's disease (Khan *et al.,* 2020).
- **Hepatoprotective effects:** Polysaccharide-rich extracts from *Pleurotus* have been reported to reduce hepatic oxidative stress and inflammation in animal models of liver injury, suggesting a protective role against fatty liver disease and other hepatopathies (Lesa *et al.,* 2022).

- **Prebiotic effects:** The indigestible β-glucans and other polysaccharides in oyster mushrooms act as prebiotics, promoting the growth of beneficial gut bacteria such as *Lactobacillus* and *Bifidobacterium* species. This modulation of the gut microbiota has downstream effects on immune function, metabolic health, and even mental well-being through the gut-brain axis (Giavasis, 2014; Rathore *et al.,* 2017).

Taken together, the evidence amassed from in vitro, animal, and preliminary human studies strongly supports the traditional use of oyster mushrooms as health-promoting foods. However, further rigorous clinical trials are needed to confirm these effects in diverse populations and to establish optimal dosing regimens for specific health conditions.

VI. Applications in Functional Food Product Development:

The favourable nutritional profile, mild flavour, and versatile texture of oyster mushrooms have facilitated their incorporation into a wide range of food products aimed at enhancing nutritional quality without compromising sensory acceptability (Abzar *et al.,* n.d.; Singh *et al.,* 2025). This section reviews the principal categories of functional foods that have been successfully developed using *Pleurotus* species, including baked goods, instant noodles, snack foods, nutraceutical formulations, and beverages.

6.1 Baked Goods

Oyster mushroom flour has been extensively studied as an ingredient for enriching baked goods such as cookies, biscuits, bread, and cakes. The addition of mushroom powder increases the protein, dietary fibre, and mineral content of these products while often improving their antioxidant properties (Arora *et al.,* 2018; Morris-Quevedo *et al.,* 2021). For example, cookies enriched with *P. ostreatus* flour have been shown to exhibit enhanced levels of total phenolics, flavonoids, and DPPH radical scavenging activity compared to control cookies prepared without mushroom powder (Morris-Quevedo *et al.,* 2021). Importantly, sensory evaluation studies have reported that up to a certain substitution level (typically 5–10% mushroom flour), the colour, texture, and taste of the baked goods remain acceptable to consumers, making such products commercially viable (Arora *et al.,* 2018; Morris-Quevedo *et al.,* 2021).

6.2 Instant Noodles

Instant noodles are a staple convenience food in many parts of the world, but they are often criticized for their low nutritional value and high fat content. Supplementation of instant noodles with oyster mushroom powder has emerged as a promising strategy to address these shortcomings (Arora *et al.,* 2018). Studies have demonstrated that noodles containing *P. ostreatus* powder exhibit increased protein and dietary fibre content, reduced fat absorption during the frying process, and enhanced antioxidant potential compared to conventional noodles (Arora *et al.,* 2018). Moreover, the cooking quality—including water absorption, cooking loss, and texture—can be maintained at acceptable levels with appropriate formulation adjustments. The relatively low cost and widespread availability of oyster mushrooms make them a feasible ingredient for staple product fortification, particularly in resource-limited settings where protein-energy malnutrition remains a concern (Arora *et al.,* 2018; Singh *et al.,* 2025).

6.3 Snack Foods and Extruded Products

Extruded snack products, such as puffed snacks and breakfast cereals, represent another category where oyster mushroom powder has been successfully incorporated (Devi *et al.,* 2024; Kumar, 2020). The extrusion process, which involves high temperature and shear, can be adapted to include mushroom powder without adversely affecting product expansion or texture. The water-holding capacity and oil-binding capacity of mushroom powders contribute to improved product characteristics, such as reduced oil uptake during frying and enhanced mouthfeel (Kumar, 2018; Tiupova *et al.,* 2025). Furthermore, extruded mushroom-enriched snacks have been shown to retain significant levels of bioactive compounds, including β-glucans and phenolic antioxidants, thereby offering a convenient vehicle for delivering mushroom nutraceuticals to a broad consumer base (Devi *et al.,* 2024; Kumar, 2020).

6.4 Nutraceutical Formulations

Beyond whole-food applications, oyster mushrooms have been used to develop concentrated nutraceutical formulations, including dietary supplements in capsule, tablet, and powder forms (Bahukhandi, 2024; Cardoso *et al.,* 2017). Both the fruiting bodies and the mycelial biomass can serve as raw materials for supplement production. Studies have focused on optimising extraction methods—such as hot water extraction, ethanol precipitation, and enzyme-assisted extraction—to maximise the yield of bioactive compounds, particularly β-glucans and ergothioneine (Cardoso *et al.,* 2017; Morris *et al.,* 2017). For instance, nutraceutical formulations based on the mycelium of *P. ostreatus* have been successfully developed, demonstrating that mycelial biomass—which can be produced more rapidly and in controlled fermentation systems—is a viable alternative to fruiting bodies for large-scale nutraceutical manufacturing (Cardoso *et al.,* 2017). Standardised extracts with defined β-glucan content are now commercially available and are marketed for immune support, cholesterol management, and overall wellness.

6.5 Beverages

Oyster mushroom extracts have also found their way into functional beverages, including soups, broths, and medicinal teas (Devi *et al.,* 2024; Wal *et al.,* 2023). The umami flavour profile of oyster mushrooms, derived from free amino acids and 5′-nucleotides, makes them particularly suitable for savoury beverage applications. Ready-to-drink mushroom broths and powdered soup mixes containing *Pleurotus* extracts are available in several markets, often positioned as immunity-boosting or energy-enhancing products (You *et al.,* 2022). In addition, aqueous and ethanolic extracts of oyster mushrooms have been formulated into liquid drops or tinctures for direct oral consumption, offering a convenient alternative for individuals who prefer liquid supplements over solid dosage forms (Devi *et al.,* 2024; Wal *et al.,* 2023).

Collectively, these product development efforts demonstrate that oyster mushrooms can be successfully incorporated into a diverse array of functional foods and nutraceuticals without compromising sensory quality. The choice of product format depends on the target consumer population, the desired health claim, and the regulatory framework in each market. As consumer awareness of mushroom nutraceuticals continues to grow, further innovation in product formulation and processing is expected to expand the commercial presence of oyster mushroom-based functional foods.

VII. SUSTAINABLE PRODUCTION AND NUTRACEUTICAL ENHANCEMENT:

One of the most distinctive and advantageous features of oyster mushroom cultivation is its inherent compatibility with sustainable agricultural practices. *Pleurotus* species are efficient lignocellulose degraders, capable of growing on a wide variety of agricultural and industrial waste materials. Moreover, the nutraceutical quality of the harvested mushrooms can be deliberately enhanced through substrate manipulation and bio fortification. This section explores the dual themes of waste valorization and nutraceutical enhancement as they apply to sustainable oyster mushroom production.

7.1 Agro-industrial Waste Valorization

The ability of oyster mushrooms to utilise low-value lignocellulosic residues as growth substrates is a cornerstone of their sustainability credentials (Zotti *et al.,* 2025). *Pleurotus* species secrete a powerful array of extracellular enzymes, including laccase, manganese peroxidase, and cellulases, which break down cellulose, hemicellulose, and lignin present in agricultural by-products. This enzymatic machinery enables the mushrooms to thrive on substrates such as paddy straw, wheat straw, corn cobs, cotton waste, sawdust, coffee pulp, banana leaves, and even more challenging materials like agave bagasse (Enshasy *et al.,* 2015; Obodai *et al.,* 2014; Paul *et al.,* 2017). By converting these waste streams into high-quality fungal biomass, oyster mushroom cultivation reduces environmental pollution, lowers production costs, and generates a nutritious food product—a clear example of a circular economy model (Zotti *et al.,* 2025).

In the Indian context, paddy straw and wheat straw are the most commonly used substrates due to their year-round availability and low cost. Studies have reported successful cultivation of *P. djamor*, *P. florida*, *P. ostreatus*, and other species on these substrates, with biological efficiencies often exceeding 80–100% (Khatun *et al.,* 2015; Pattanayak & Das, 2022). The maximum yield of wild *P. djamor* isolates, for instance, has been demonstrated on paddy straw, followed by wheat straw (Pattanayak & Das, 2022). Beyond these traditional substrates, recent research has extended the concept to the valorization of more problematic industrial wastes. For example, the conversion of agave bagasse—a fibrous by-product of tequila production—into nutraceutical-rich *P. djamor* mushrooms illustrates the potential for recovering value from waste streams that are otherwise difficult to manage (Zotti *et al.,* 2025). Furthermore, even the spent mushroom substrate (the residual material after harvest) can be composted or used as animal feed, closing the loop in the production cycle. Additionally, *Pleurotus* mushroom waste generated during sorting and processing has itself been transformed into nutraceutical ingredients with anti-inflammatory, antioxidant, and immunostimulatory properties, offering a healthy and sustainable source of bioactive compounds such as β-glucans (Cruz-Moreno *et al.,* 2025).

7.2 Bio fortification Strategies

While oyster mushrooms are already nutritionally valuable, emerging research indicates that their nutraceutical properties can be significantly enhanced through substrate supplementation with specific minerals or other bioactive precursors—a practice known as bio fortification (Singh & Sharma, 2022). Selenium bio fortification has received particular attention, as selenium is an essential micronutrient with well-documented antioxidant and immune-enhancing properties, and dietary selenium intake is often suboptimal in many populations.

Studies on selenium enrichment of *P. ostreatus* have shown that supplementing the growth substrate with sodium selenate at appropriate concentrations (typically a few parts per million) increases the total selenium content of the fruiting bodies by several orders of magnitude. Importantly, the selenium is incorporated into selenoamino acids (such as selenomethionine) that are bioavailable to humans. Moreover, selenium enrichment has been reported to enhance the levels of other nutraceutical compounds, notably ergothioneine, and to increase the total phenolic content and antioxidant capacity of the mushrooms (Singh & Sharma, 2022). In some studies, methanolic extracts from selenium-enriched fruiting bodies demonstrated superior cellular antioxidant activity compared to extracts from non-enriched controls (Singh & Sharma, 2022).

Zinc bio fortification has also been explored, particularly using zinc oxide nanoparticles (ZnONPs) as a source of bioavailable zinc. Supplementation of *P. djamor* and *P. florida* substrates with ZnONPs at concentrations of 20–40 ppm significantly increased mycelial growth, yield parameters, and the content of phenols, flavonoids, and total antioxidants (Singh & Sharma, 2022). Macro- and micro-nutrient concentrations were also elevated, confirming the utility of nanoparticle-based bio fortification for enhancing the nutritive potential of oyster mushrooms. Notably, the effect of ZnONPs on morphology and biochemical parameters varied positively with concentration and also differed between species, offering the possibility of targeted bio fortification based on desired outcomes (Singh & Sharma, 2022). Future research may extend bio fortification to other trace elements (such as iron, iodine, or chromium) that are of public health relevance in specific regions.

7.3 Optimization of Substrate Composition

Beyond the addition of specific fortificants, the baseline composition of the growth substrate profoundly influences the nutraceutical quality of oyster mushrooms (Effiong *et al.,* 2024b; Maray *et al.,* 2018). Different lignocellulosic materials vary in their carbon-to-nitrogen ratio, mineral content, and physical structure, all of which affect mushroom growth and metabolite production. Studies have demonstrated that the same *Pleurotus* strain grown on different substrates can yield mushrooms with markedly different protein, fibre, and bioactive compound contents (Effiong *et al.,* 2024b). For example, basidiomata of *P. ostreatus* grown on one substrate exhibited higher protein content (27.19%) and dietary fibre (18.57%), while growth on an alternative substrate resulted in higher lipids (2.26%) and non-fibre carbohydrates (53.21%) (Effiong *et al.,* 2024b). Such findings underscore the importance of substrate optimization for producing mushrooms with targeted nutraceutical profiles.

Practical guidelines for substrate optimization include selecting a primary lignocellulosic material that is locally available and inexpensive, supplementing it with nitrogen-rich additives (such as wheat bran or rice bran) to achieve a favorable C:N ratio (typically 20:1 to 30:1 for oyster mushrooms), and adjusting pH and moisture content to optimal ranges (Maray *et al.,* 2018; Obodai *et al.,* 2014). The use of substrate blends—mixtures of two or more waste materials—can sometimes yield better results than any single substrate alone, due to complementary nutritional and structural properties. As the field of mushroom cultivation advances, more sophisticated substrate engineering approaches, including the use of response surface methodology and other optimization techniques, are likely to become standard practice for maximizing nutraceutical yield.

VIII. Future Perspectives and Research Directions:

Despite the impressive advances made in understanding the nutraceutical properties of oyster mushrooms, several important knowledge gaps remain. Addressing these gaps will be essential for translating the promising preclinical findings into practical, evidence-based applications that can benefit human health. This section outlines key research priorities and emerging opportunities that are likely to shape the future of oyster mushroom nutraceuticals (Bhatia & Yadav, 2025; Kumar, 2018; Rathore *et al.,* 2017).

8.1 Clinical Translation and Human Studies

The vast majority of evidence supporting the health benefits of oyster mushrooms comes from in vitro experiments and animal models (Araújo *et al.,* 2025). While these studies provide valuable mechanistic insights and establish proof of concept, they cannot directly predict efficacy in human populations. Well-designed, randomized controlled trials are urgently needed to confirm the antioxidant, immunomodulatory, antidiabetic, and antihyperlipidaemic effects of *Pleurotus* consumption in humans. Such trials should aim to establish dose-response relationships, identify optimal duration of intervention, and evaluate safety profiles in diverse populations—including those with metabolic syndrome, cardiovascular disease, immune dysfunction, or cancer (Araújo *et al.,* 2025; Sreedharan *et al.,* 2025). Particular attention should be paid to potential interactions with conventional medications, as mushroom bio actives may either synergise with or interfere with drug actions.

8.2 Bioavailability and Pharmacokinetics

For a nutraceutical compound to exert a biological effect, it must be absorbed, distributed, metabolized, and excreted in a manner that delivers an adequate concentration to the target tissue. At present, the bioavailability of key oyster mushroom bio actives—such as β-glucans, ergothioneine, and lovastatin—remains incompletely characterized (Kumar, 2018; Tiupova *et al.,* 2025). Factors that influence bioavailability include the food matrix (fresh vs. dried vs. processed mushrooms), the extraction method (aqueous vs. ethanolic), and individual physiological variables (gut microbiota composition, digestive enzyme activity). Comprehensive pharmacokinetic studies in humans are required to guide optimal preparation and consumption strategies. For example, does cooking degrade certain bio actives? Are there synergistic effects when oyster mushrooms are consumed together with other foods? Answering such questions will enable evidence-based dietary recommendations (Kumar, 2018; Tiupova *et al.,* 2025).

8.3 Species-Specific Optimization for Targeted Health Applications

As documented in Section 4 of this review, different *Pleurotus* species exhibit markedly different nutraceutical profiles. *P. florida* is superior in protein content and SOD/peroxidase activity; *P. djamor* excels in total antioxidant capacity; *P. pulmonarius* uniquely exhibits high catalase activity; and *P. citrinopileatus* is notable for its lipid peroxidation inhibition (Bhatia & Yadav, 2025; Medihi *et al.,* 2024). This diversity suggests that specific species may be optimized for distinct health applications. Future research should systematically map the nutraceutical profiles of all major *Pleurotus* species and their strains under standardized cultivation conditions. Subsequently, controlled trials should test whether species-specific products (e.g., a *P. djamor*-based antioxidant supplement versus a *P. florida*-based protein supplement) produce differential health outcomes. Such research could lead to a new generation of tailored mushroom nutraceuticals (Bhatia & Yadav, 2025; Medihi *et al.,* 2024).

8.4 Synergy with Conventional Therapies

The potential for oyster mushroom nutraceuticals to act as adjuvants to conventional pharmacotherapies is an exciting but underexplored area. For instance, the immunomodulatory effects of β-glucans could theoretically enhance the efficacy of cancer immunotherapies, while the cholesterol-lowering action of lovastatin might allow for dose reduction of synthetic statins, thereby minimizing side effects such as myopathy (Das *et al.,* 2023; Sreedharan *et al.,* 2025). Similarly, the antihyperglycaemic properties of oyster mushroom extracts might complement oral antidiabetic drugs, potentially improving glycaemic control with a lower risk of hypoglycaemia. Rigorous preclinical and clinical studies are needed to investigate these synergies, including assessment of any adverse interactions. If successful, oyster mushroom-based adjunctive therapies could reduce the burden of polypharmacy and improve the quality of life for patients with chronic diseases (Das *et al.,* 2023; Sreedharan *et al.,* 2025).

8.5 Sustainable Production and Circular Bio economy

The ability of oyster mushrooms to grow on diverse agro-industrial waste substrates is not only environmentally beneficial but also economically attractive. Future research should focus on scaling up waste valorization processes from laboratory or pilot scale to industrial levels (Zotti *et al.,* 2025). This includes optimizing substrate pretreatment methods (physical, chemical, or biological) to improve lignocellulose digestibility, developing low-cost sterilization techniques suitable for small-scale farmers, and implementing quality control measures to ensure that mushrooms grown on waste streams are free from contaminants such as heavy metals or pesticide residues. Additionally, the use of spent mushroom substrate as a soil amendment, animal feed, or feedstock for second-generation biofuel production should be further explored to maximize the circularity of the production system (Zotti *et al.,* 2025). In developing countries, where waste management challenges and nutritional deficiencies often coexist, expanding sustainable oyster mushroom cultivation could address both problems simultaneously.

8.6 Advanced Extraction and Formulation Technologies

Traditional hot water extraction of β-glucans is effective but relatively non-selective and energy-intensive. Emerging green extraction technologies—including microwave-assisted extraction, pressurized solvent extraction, ultrasound-assisted extraction, and enzyme-assisted extraction—offer the potential for higher yields, shorter processing times, and lower environmental impact (Caldas *et al.,* 2022; Macit *et al.,* 2024). Furthermore, novel formulation approaches such as encapsulation in liposomes or nanoparticles can improve the stability and bioavailability of mushroom bio actives. For example, liposomal formulations of *Pleurotus* extracts have been shown to enhance antioxidant activity compared to non-encapsulated extracts (Macit *et al.,* 2024). Future research should continue to explore these advanced technologies, with the goal of producing standardized, high-potency nutraceutical ingredients that can be reliably incorporated into functional foods or dietary supplements.

8.7 Regulatory Harmonization and Quality Control

As the commercial market for mushroom nutraceuticals expands, there is a growing need for harmonized regulatory frameworks and robust quality control standards. Different countries classify mushroom products variously as foods, dietary supplements, or even drugs, leading to inconsistent labelling, variable product quality, and potential consumer safety issues (Rathore *et al.,* 2017). Future efforts should focus on establishing internationally recognized specifications for key bioactive markers (e.g., minimum β-glucan or ergothioneine content), standardized analytical methods, and good manufacturing practices specific to mushroom nutraceuticals. Such measures would enhance consumer confidence, facilitate international trade, and ensure that health claims are supported by reliable product quality.

IX. CONCLUSION:

Oyster mushrooms of the genus *Pleurotus* represent a remarkable convergence of nutritional completeness, therapeutic efficacy, and production sustainability (Corrêa *et al.,* 2016; Oloke, 2017; Valverde *et al.,* 2015). Their rich content of proteins, essential minerals, vitamins, and a diverse array of bioactive compounds—including β-glucans, ergothioneine, lovastatin, phenolic compounds, and flavonoids—supports a broad spectrum of health-promoting activities. These range from direct antioxidant and anti-inflammatory effects to more complex immunomodulatory, antitumour, antidiabetic, and cardioprotective properties (Deepalakshmi & Sankaran, 2014; Khan *et al.,* 2020; Lesa *et al.,* 2022; Wal *et al.,* 2023).

The Indian subcontinent, with its favourable climatic conditions and expanding agricultural infrastructure, has become a significant cultivator of diverse *Pleurotus* species. Varieties such as *P. florida*, *P. citrinopileatus*, *P. pulmonarius*, *P. djamor*, *P. sajor-caju*, *P. sapidus*, and several wild types are now grown year-round in the plains of India (Khatun *et al.,* 2011; Khatun *et al.,* 2015; Owaid *et al.,* 2017). Comparative analysis reveals distinct nutraceutical profiles among these species: *P. florida* excels in protein content and antioxidant enzyme activity; *P. djamor* demonstrates superior antioxidant capacity attributable to its pigmented compounds; *P. pulmonarius* uniquely exhibits maximum catalase activity; and *P. citrinopileatus* displays efficient inhibition of lipid peroxidation (Khatun *et al.,* 2015; Mansuri *et al.,* 2017; Medihi *et al.,* 2024). This species-dependent diversity offers a valuable resource for tailoring mushroom-based interventions to specific health needs, from protein supplementation to oxidative stress management.

The ability of oyster mushrooms to grow on diverse agro-industrial waste substrates, coupled with the feasibility of substrate bio fortification for nutraceutical enhancement, positions them as ideal candidates for sustainable, low-cost production of functional foods and nutraceuticals (Singh & Sharma, 2022; Zotti *et al.,* 2025). The circular economy model inherent to *Pleurotus* cultivation—converting low-value agricultural residues into high-value fungal biomass—addresses both environmental and nutritional challenges, particularly in resource-limited settings.

As the global burden of non-communicable diseases continues to rise, and as consumer demand for plant-based, evidence-based health solutions intensifies, oyster mushrooms are poised to play an increasingly important role in integrative approaches to human health (Araújo *et al.,* 2025; Rathore *et al.,* 2017; Sreedharan *et al.,* 2025). However, realising this potential will require sustained research efforts. Priorities include well-designed clinical trials to confirm efficacy in human populations, comprehensive bioavailability studies to guide optimal consumption, species-specific optimization for targeted applications, investigation of synergistic effects with conventional therapies, and the development of harmonized quality control standards for mushroom nutraceuticals (Bhatia & Yadav, 2025; Kumar, 2018; Sreedharan *et al.,* 2025).

The synthesis of traditional dietary practices with contemporary nutraceutical science—exemplified by oyster mushrooms—offers a promising pathway for addressing nutritional and metabolic health challenges, particularly in developing countries such as India, where such interventions are most urgently needed (Das *et al.,* 2023; Valverde *et al.,* 2015). By bridging the gap between traditional knowledge and modern evidence, oyster mushrooms can contribute meaningfully to public health while promoting sustainable agricultural practices. It is our hope that this review stimulates further research, innovation, and collaboration among mycologists, nutrition scientists, food technologists, and healthcare professionals to fully unlock the nutraceutical potential of these remarkable fungi.

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