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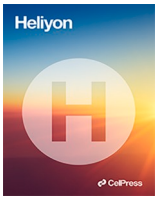

Review article

Comprehensive review on oyster mushroom species (Agaricomycetes): Morphology, nutrition, cultivation and future aspects

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ABSTRACT

Huge volumes of organic matter are produced on earth via photosynthesis and their disposal is a serious threat to the environment and public health all over the world. Nevertheless, these agricultural wastes possess a chemical composition conducive to mushroom cultivation. Lignocellulosic wastes, comprising cellulose, hemicellulose and lignin, offer vital nutrients for mushroom growth. Oyster mushrooms are well known for their unique ability to degrade lignocellulosic materials, making them valuable contributors to the process of organic waste decomposition and nutrient cycling in ecosystems. Employing agricultural by-products as a substrate for mushroom cultivation presents a sustainable approach to waste reduction and the production of nutritionally enriched food. Cultivating oyster mushrooms, presents an economically feasible and environment friendly method of transforming waste materials into highly nutritious food. These edible mushrooms are widely grown worldwide, comprising around 27 percent of the total global production. Oyster cultivation has rapidly increased in Asia due to its low production technology, easy availability of substrates, temperature tolerance and high yield capacity. Oyster mushrooms are sought after as a functional food due to their appealing taste, aroma, flavor, nutritional benefits and medicinal properties. They contain high levels of protein, fiber, vitamins B complex, C and D_2, as well as minerals like potassium, phosphorus, selenium, zinc and essential amino acids. These mushrooms are versatile, as they thrive in both tropical and temperate regions without requiring complex controlled environmental conditions for growth. This review article provides insights into the cultivation aspects of important oyster species including a novel species called *Hypsizygus ulmarius*. Oyster mushroom cultivation is rapidly growing in developing countries, where it can contribute to food security for the world's growing population, which is expected to reach 9.7 billion by 2050.

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1. Introduction

Mushrooms have become well-known globally for their nutritional and therapeutic properties. Cultivating them serves as a beneficial bioconversion method, transforming waste materials into potentially valuable resources. This approach shows promising potential for sustainable agriculture and forestry, not only in India but also on a global scale. Worldwide, approximately 15,000 species of mushrooms are known, 2000 are used for human consumption and more than 700 have medicinal properties. However, less than 100 species are cultivated commercially. Additionally, the global mushroom market was estimated to be worth $46.1 billion in 2020. It is expected to grow at a compound annual growth rate (CAGR) of 9.5 percent from 2021 to 2028, reaching a value of $86.6 billion by 2025, highlighting that edible mushrooms are a powerful agro-industrial sector worldwide [1]. Among the various mushroom species, oyster mushrooms are the most commonly cultivated ones. They rank as the second-largest cultivated mushroom type worldwide. China leads in oyster mushroom production, contributing 74.00 percent of the total global output. Other countries involved in oyster mushroom production include Italy, Poland, Netherlands, Romania, Republic of Korea, Spain, Lithuania and India [Fig. 1]. The *Pleurotus* genus, which includes oyster mushrooms, has garnered significant research attention due to its lignolytic characteristics as a white-rot fungus. Apart from being edible and savory, these mushrooms possess essential bioactive compounds that have various biological impacts. Owing to their simple and cost-effective cultivation techniques, high biological efficiency and nutritional and medicinal benefits, oyster mushrooms are widely popular and cultivated throughout the world [2].

Oyster mushrooms have gained global recognition for their nutritional and therapeutic advantages. Their cultivation serves as an effective bioconversion method, converting waste materials and wood into potentially valuable resources. This practice holds significant potential for sustainable agriculture and forestry both in India and at the global level [1]. The oyster mushroom holds a prominent position among the widely grown cultivated mushrooms worldwide. This mushroom is the second most commonly grown in the world, after the white button mushroom [3]. This popularity is particularly evident in regions like Southwest Asia, India, Europe and Africa [Fig. 2]. When it comes to advantages over other edible mushrooms, oyster mushroom cultivation boasts numerous benefits. Notably, it exhibits rapid growth across a broad temperature range (10-30°C) and thrives at a pH level of 6.0–8.0 [4]. Additionally, it releases a diverse array of enzymes capable of breaking down lignocellulosic biomass in substrates, resulting in high yields.

Oyster mushrooms, scientifically known as *Pleurotus* species, belong to the class Agaricomycetes, the order Agaricales and the family Pleurotaceae. They are commonly found in temperate and tropical forests, occurring naturally on decomposing logs or occasionally on dried trunks of both deciduous and coniferous trees. These mushrooms have fruit bodies that are distinctively shell or spatula-shaped [Table 1, Fig. 3] and come in various shades, such as white, cream, grey, yellow, pink, light brown and blue, depending on the specific species, also emit a unique sweet like anise or licorice (liquorice) scent. Oyster mushrooms are considered for producing protein-rich food from different agricultural wastes without the need for composting. The cultivation of a specific species of oyster mushroom was first experimented by Flack in Germany in 1917, on stumps and wood logs. Subsequently, cultivation techniques were practiced in USA by individuals named Block, Taso and Hou. India also initiated the cultivation of various oyster mushroom species in the early 1960s, with commercial cultivation starting in the mid-1970's. *Hypsizygus ulmarius* commonly called elm oyster or blue oyster, is one of the species of oyster mushroom which is similar to presently grown oyster mushroom in the world but differ in morphology and biological efficiency. Taxonomically, *H. ulmarius* is a Basidiomycetes fungus belonging to the class Agaricomycetes, family Lyophyllaceae of the order Agaricales. The genus was originally described by Singer [5], *H. ulmarius* gained its name from the elm trees themselves (*Hypsi* 'high', *Zygus* 'yoke' while *ulmarius* 'elm tree') and it reflects the fact that the fruit body usually occurs high

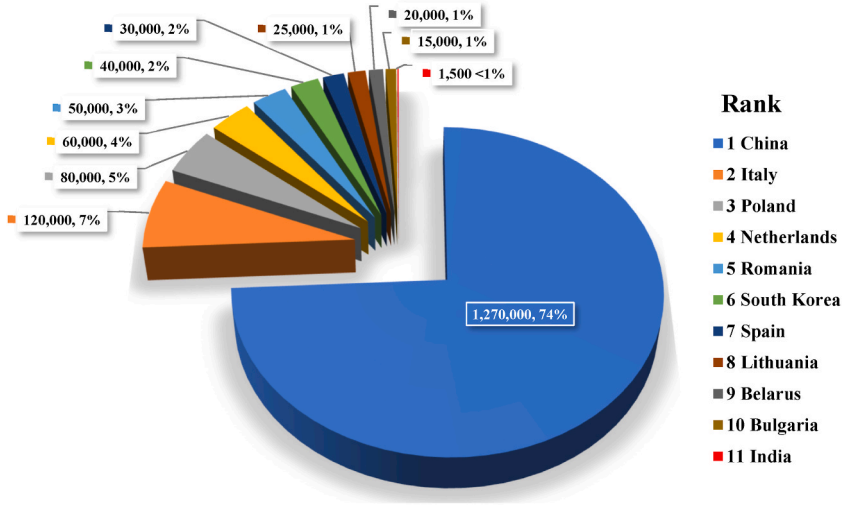

Fig. 1. Global oyster mushroom production share (tons).
Source: Oyster mushroom cultivation global market report 2022 (Report ID 6370334).

up on the trunks of large trees. The specific epithet '*ulmarius*' means elm trees. This oyster mushroom species was placed under the genus *Hypsizygus* because it shares several similar key characteristics with other members of the genus *Hypsizygus.* Gills are mainly free from the stipe and are not decurrent (adenate) in this species while, in *Pleurotus* species gills are decurrent. Additionally, the stipe of *H. ulmarius* does not have any rings (annulus) and is connected almost in the center of the cap while, in other *Pleurotus* species generally the stipe is off-center. *Hypsizygus ulmarius* is a novel species of oyster mushroom with large fruiting bodies, blue-colored pinheads, higher yield, palatable with meaty flavour, attractive shape, fleshy with an excellent taste and keeping quality [6]. The *Pleurotus* genus comprises more than 40 recorded species globally and in recent years, 25 of these species have been successfully cultivated in different parts of the world. Some of the most important and commonly cultivated ones include *P. ostreatus, P. ostreatus* var. *florida, P. djamor, P. eryngii, P. tuber-regium, P. citrinopileatus, P. populinus, P. cystidiosus, P. cornucopiae, P. pulmonarius, H. ulmarius* (elm oyster mushroom) etc.

The oyster mushroom is renowned for its culinary use and serves as a valuable dietary component [4,7]. Abundant in proteins, lipids, vitamins, carbohydrates, amino acids, minerals and fibers, these mushrooms boast a wealth of nutritional benefits [Table 2]. Moreover, they are remarkably low in calories, fat, cholesterol and sodium, making them an excellent choice for health-conscious individuals. Incorporating oyster mushrooms into diets may contribute to a reduction in the risk of various health issues, including obesity, diabetes, cancer and heart diseases, while simultaneously enhancing the body's immune system. Beyond their nutritional value, these mushrooms contain a range of bioactive compounds like peptides, polysaccharides, fatty acids, oligosaccharides, glycoproteins, lectins, terpenoids and nucleosides, which have been utilized in traditional medicine to combat various ailments. Furthermore, oyster mushrooms have been found to possess a plethora of health-promoting properties, including antioxidant, antidiabetic, anticancer, antimicrobial, anti-inflammatory, antihypertensive, antiatherogenic, anti-hyperglycemic and immunomodulating properties, solidifying their reputation as a highly beneficial and versatile natural remedy [1,8,9].

Oyster mushrooms, are highly nutritious and they are low in calories, making them suitable for weight maintenance or loss and also helps to regulate blood sugar levels. *Pleurotus* mushrooms are a good source of proteins, containing all essential amino acids necessary for tissue repair and muscle growth. They are rich in vitamins, particularly B group of vitamins, which support energy metabolism, red blood cell production and the nervous system. These mushrooms also provide various minerals like potassium, phosphorus, copper, selenium and zinc which are crucial for physiological processes and overall health [21,22]. *Pleurotus* mushrooms possess antioxidant properties due to bioactive compounds, protecting the body against free radicals and potentially reducing the risk of chronic diseases. They are cholesterol-free, low in fat and thus beneficial for heart health. These mushrooms also contain unique bioactive compounds such as polysaccharides and β-glucans, which have immune-modulating and anticancer properties. While the nutritional composition may vary among different *Pleurotus* mushroom species, they generally offer similar beneficial properties. Adding *Pleurotus* mushrooms to your diet can provide a flavorful and nutrient-dense option to support overall health and well-being [23].

Pleurotus mushrooms possess antioxidant properties due to compounds like phenols and polysaccharides, that help protect against oxidative stress and reduce the risk of chronic diseases. Certain species, such as *P. ostreatus*, exhibit immune-modulating effects, enhancing immune responses and supporting immune system function. Some *Pleurotus* mushrooms have anti-inflammatory properties, potentially reducing inflammation and associated symptoms. Compounds found in these mushrooms, such as polysaccharides and triterpenoids, show potential anticancer properties by inhibiting cancer cell growth and inducing apoptosis. Certain *Pleurotus* mushrooms can help regulate cholesterol levels, inhibiting cholesterol synthesis and promoting its excretion. Additionally, *Pleurotus* mushrooms demonstrate antimicrobial and antiviral activity against various pathogens, suggesting their potential as natural alternatives to conventional antimicrobial agents [24].

The primary significance of this mushroom lies in its economic importance both as a food and medicinal resource for humans.

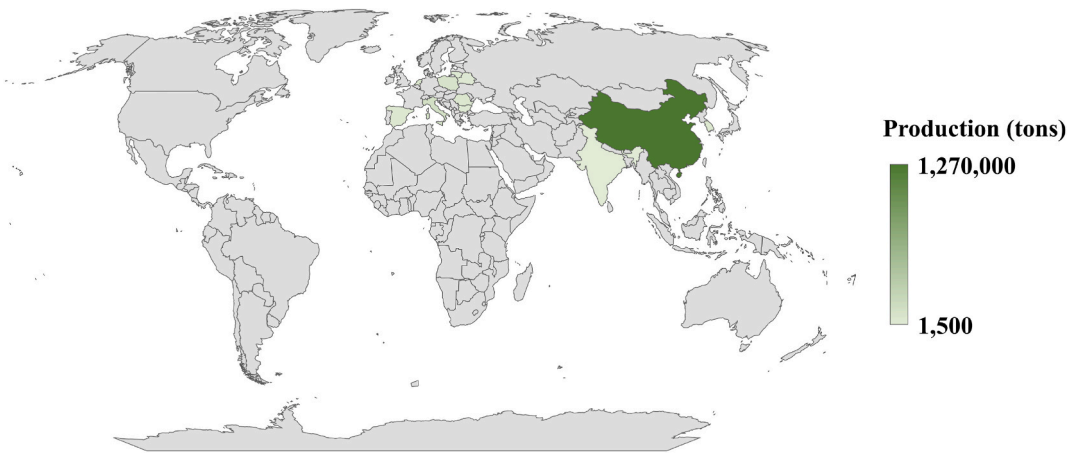

Fig. 2. Share of major countries producing oyster mushrooms in the world, figure generated through Microsoft Excel.
Source: Oyster mushroom cultivation global market report 2022 (Report ID 6370334).

Mushrooms offer a potential solution to the global food crisis due to their cost-effective cultivation on diverse substrates, including waste materials. Each year, a vast amount of organic matter through photosynthesis is produced on earth [25]. However, a significant portion of this organic matter remains unused by humans and animals, leading to environmental concerns. Mushroom cultivation presents an effective approach for transforming environmental waste into alternative nutritious food sources [26,27]. Oyster mushrooms, in particular, demonstrate a remarkable ability to break down lignocellulosic residues from agricultural fields and forests, converting them into protein-rich and nutritious food i.e., mushrooms [28–30]. Successful mushroom cultivation hinges on various factors, including nutrient media, temperature, pH, substrate type and supplements, which individually or in combination influence the yield and biological efficiency. Despite the fact that suitable climatic conditions and other resources are available, the pace of production of oyster mushrooms is slow in India. India produced only 1500 tons of oyster mushrooms in the year 2022 in which Bihar, Maharashtra and Orissa are the leading producers [Figs. 4 and 5]. This review will delve into the existing literature for the period between 2001 to 2023 for obtaining an overview of research in the field over the last 22 years on morphology, nutrition, cultivation and also the future areas to be undertaken ensuring a prosperous and resilient future for generations to come [Fig. 6]. The review elucidates research trends in oyster mushrooms focusing on more than 22 commonly grown oyster mushroom species in different parts of the world.

2. Cultivation aspects of important oyster mushroom species

2.1. Influence of nutrient media on mycelial growth, biomass production and cultural characteristics of different oyster mushroom species

The growing medium is the primary factor that holds the utmost significance in mushroom production. This medium provides vital nutrients essential for the development of mycelium. When the medium is nutritionally enriched, it facilitates abundant growth of the mycelium by fulfilling all the nutritional requirements and creating optimal physical conditions for vegetative growth. Studying their physiological and nutritional aspects becomes even more crucial in the context of mushrooms. The success or failure of mushroom cultivation largely relies on a thorough and accurate comprehension of their nutritional and environmental needs.

Various carbon sources support mycelial growth, including glucose, fructose, starch, maltose, sucrose, mannose, cellulose, lignin and pectin. Mycelium has the capability to utilize ethanol as a carbon source, but it does not thrive when provided with citrate, oxalate and various other organic acids. The nitrogenous sources that *Pleurotus* species prefer include corn steep liquor, soybean cake powder, yeast powder, asparagine, serine, glycine, aniline and ammonium sulphate. These sources are all organic or inorganic compounds that can be used to provide nitrogen to the mushrooms. They have been shown to promote growth and yield in *Pleurotus* species. However, utilization of urea is relatively limited. For each *Pleurotus* species to achieve an optimal growth rate and production, specific media and environmental conditions are essential [31,32].

Sardar et al. [33], found that potato dextrose agar (PDA) was the suitable medium for the growth of *Pleurotus* species. Pant et al.

Table 1
Morphological description of genus *Pleurotus*.

Sr. No.	Morphological characteristic	Description
1.	Cap shape	Shell-shaped or fan-shaped, with a broad, convex to flat cap.
2.	Cap size	The diameter ranges from 5 to 25 cm.
3.	Cap colour	Varies depending on the strain, but is commonly found in shades of white, grey or tan. Can also exhibit blue, purple, yellow or pink hues.
4.	Cap surface	Smooth and often velvety, with some wrinkles or ridges also dry in some cases but can become slightly slimy when dumped.
5.	Cap texture	Smooth and often slightly wrinkled.
6.	Gills attachment	Decurrent (running down the stem).
7.	Gills colour	White when young, but turning cream to light yellow as the mushroom matures, also hints of pink or lilac.
8.	Gills arrangement	Dense or closely spaced.
9.	Stem	Short, stubby and lateral, attached to the cap eccentrically (off-center) but varies in length and thickness.
10.	Stem size	Varies between 2 and 10 cm in length and 1–5 cm in thickness.
11.	Stem colour	Whitish to cream-colored or pale grey but also can develop brown spots with age.
12.	Stem surface	Smooth and sometimes fibrous or silky.
13.	Flesh texture	Thick, firm and succulent.
14.	Flesh colour	White to creamy in colour.
15.	Odor	Mild to slightly fragrant, often with a hint of anise or almond.
16.	Spore print	White to light yellow or pale yellow.
17.	Spore shape	Elongated, ellipsoid and cylindrical.
18.	Spore size	Approximately 5–10 μm long.
19.	Spore surface	Smooth.
20.	Habitat	Saprotrophic grows on dead or decaying hardwood trees, logs or stumps.
21.	Climate	Found in tropical, subtropical and temperate regions depending upon species type.
22.	Cultivating season	Can occur throughout the year depending upon species type.
23.	Distribution	Widely distributed across the globe, particularly in temperate and subtropical regions.

[34] conducted an evaluation of various media, including corn meal agar (CMA), malt extract agar (MEA), PDA, and oat meal agar (OMA), for the growth of *P. ostreatus*. Among these, PDA exhibited the maximum mycelial growth, measuring 8.38 cm, followed by MEA with 7.72 cm, while CMA showed the minimum mycelial growth of 6.81 cm. Kumar and Kushwaha [35] also reported that PDA was the most suitable medium for various *Pleurotus* species based on their study. In another study, Singh and Singh [36] investigated the impact of six different media, *viz.,* PDA, chickpea extract agar (CEA), pigeonpea extract agar (PEA), barley extract agar (BEA), OMA and black gram extract agar, on the radial growth of *P. djamor*. After 8 days of incubation, the OMA medium showed the maximum mycelial growth (8.83 cm) and growth rate (1.10 cm/d), followed by the BEA medium with 8.40 cm of mycelial growth and a growth rate of 1.03 cm/day.

Bhadana [37] reported the highest mycelial growth (80–90 mm) for various mushrooms, including *P. djamor* (8d), *P. florida* (7d), *P. eryngii* (7d) and *P. flabellatus* (8d), when grown in OMA, PDA and pearl millet extract agar medium. Mohammed [38] on the other hand, observed the highest growth in *P. sapidus*, *P. florida* and *P. sajor-caju* on MEA, followed by PDA medium, while the least growth was seen in water agar medium after an 8-day incubation period. Mahadevan and Shanmugasundaram [39] found that MEA, PDA and YMA (Yeast mannitol agar) medium resulted in highly abundant mycelial growth rate and density for *P. sapidus*, with GPA (Glucose peptone agar), SDA (Sabouraud's dextrose agar) and CDA (Czapek's dox agar) medium showing lower growth rates. Kartik et al. [40] also validated that PDA and MEA proved to be the optimal growth media for mycelium development across various oyster mushroom species. Similarly, Munsar et al. [41] observed that the PDA medium promoted the best mycelial growth of oyster mushrooms compared to YMA and MS (Murashige and Skoog) medium. Nguyen and Ranamukhaarachchi [42] demonstrated that PDA was the most suitable medium for the growth of *P. eryngii* and *P. ostreatus*, while YMA and MEA media supported better mycelium extension. Furthermore, wheat extract agar (WEA) medium was found to be the most effective for promoting the growth of the mycelium of *P. ostreatus*, taking only 9 days to cover a Petriplate of 9 cm diameter, whereas PDA and YEA (Yeast extract agar) medium required 10 and 11 days, respectively [43]. Amirtham and Siva [44] discovered that MCA (Mushroom complete agar) media was the most effective medium, providing the maximum biomass and excellent mycelial growth for *P. ostreatus*. In contrast, CDA was the least stimulatory and supported the poorest biomass of *P. ostreatus* mushroom.

Singh and Kushwaha [45] investigated the growth of *H. ulmarius* by utilizing various types of media. These include MEA, PDA, OMA, CMA, potato carrot agar (PCA), WEA, CDA and YEA. They concluded that MEA and WEA media provided the most favorable conditions for growth, leading to significant mycelial growth of 90 mm. Additionally, PDA medium also proved to be supportive of good growth. Wang and Patil [46] observed that *H. ulmarius* could grow on six different media and six broth media, showing varying preferences. The fungus showed a preference for MEA and its broth media. Jatav et al. [47] confirmed these findings, reporting that the maximum growth of *H. ulmarius* occurred on MEA 1.0 percent medium (79.88 mm), followed by MEA 2.0 percent medium (79.25 mm). Chandravanshi [48] investigated the radial growth and colony characteristics of *H. ulmarius* on six different solid culture media i.e.,

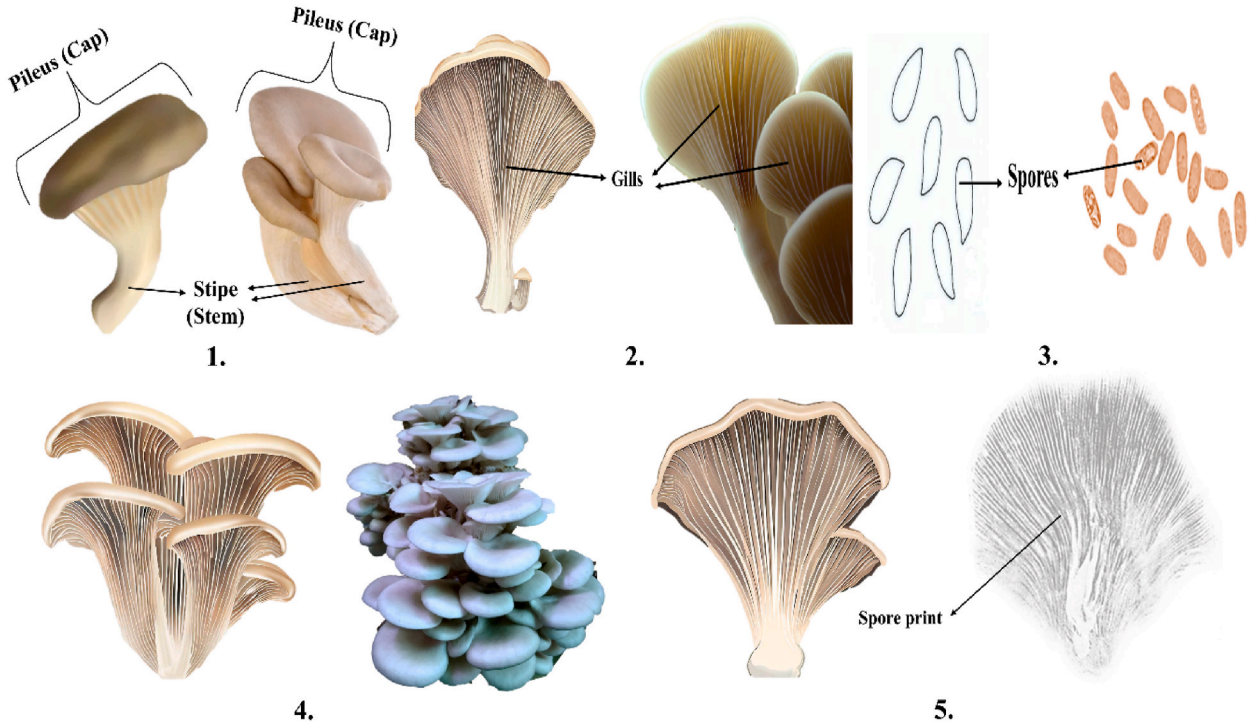

Fig. 3. Oyster mushroom morphology, 1. Pileus and Stipe; 2. Gills; 3. Spores; 4. Sporocarp bunch; 5. Spore print.

Table 2
Proximate composition of different oyster mushroom species.

Sr. No.	Mushroom species	Moisture (%)	Protein (%)	Fat (%)	Carbohydrates (%)	Fiber (%)	Ash (%)	Reference
1.	*Pleurotus ostreatus*	86.00	3.40	3.20	5.10	3.40	1.18	[10,11]
2.	*Pleurotus sajor-caju*	87.00	3.26	1.10	5.09	2.97	1.10	[10]
3.	*Pleurotus cystidiosus*	86.73	1.54	3.10	6.31	8.74	9.62	[12]
4.	*Pleurotus cornucopiae*	88.90	3.00	3.90	4.25	2.07	7.65	[13]
5.	*Pleurotus pulmonarius*	89.30	2.68	1.80	4.60	4.94	7.07	[14]
6.	*Pleurotus tuber-regium*	87.13	2.21	1.20	4.00	1.08	2.97	[8]
7.	*Pleurotus citrinopileatus*	88.90	3.00	3.90	4.25	2.07	7.65	[13,15]
8.	*Pleurotus flabellatus*	94.00	2.20	0.90	6.02	1.20	3.24	[16,9]
9.	*Pleurotus abalonus*	89.70	3.60	1.00	4.30	1.50	2.30	[13,9]
10.	*Pleurotus eryngii*	92.40	2.90	2.90	4.50	1.60	5.40	[17]
11.	*Pleurotus florida*	89.20	2.13	2.30	5.60	7.80	6.40	[18]
12.	*Pleurotus fuscus*	89.90	3.60	1.99	4.20	1.80	3.30	[13,9]
13.	*Pleurotus populinus*	87.80	3.50	2.31	4.55	1.40	4.30	[13,9]
14.	*Pleurotus subcaesarius*	89.10	3.22	1.90	5.90	4.60	5.10	[13,9]
15.	*Pleurotus djamor*	87.13	3.55	1.72	4.47	1.46	5.90	[19]
16.	*Hypsizygus ulmarius*	87.80	4.40	2.20	5.24	1.29	5.30	[20]

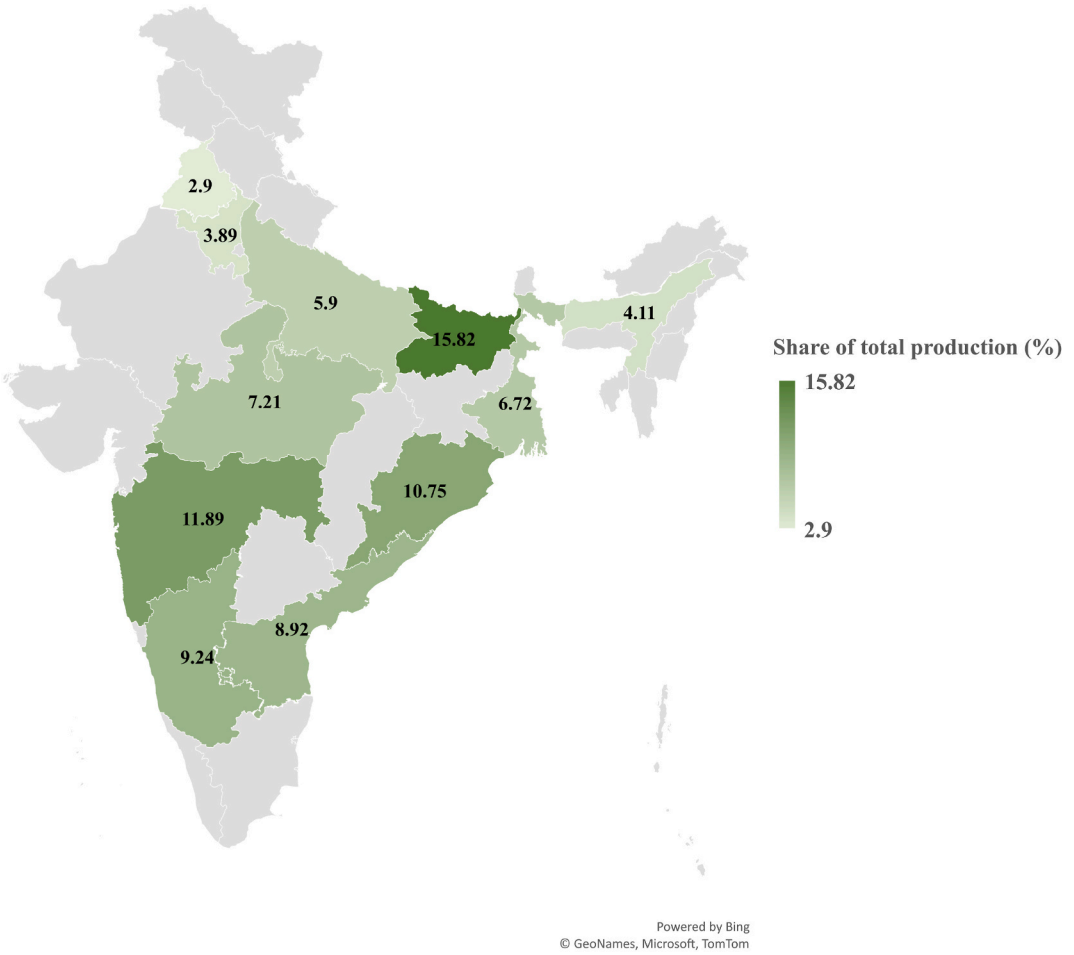

Fig. 4. State wise share of oyster mushroom production in India, figure generated through Microsoft Excel.
Source: National Horticulture Board India website, https://nhb.gov.in/

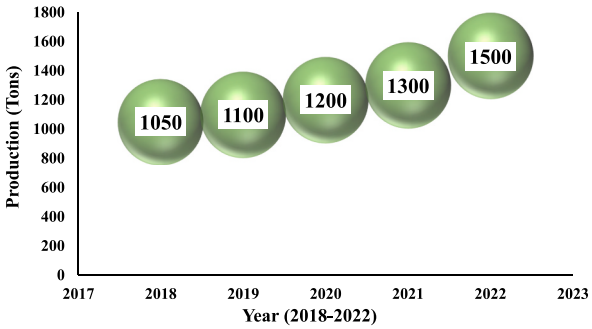

Fig. 5. Growth in the production of oyster mushrooms in India from 2018 to 2022.
Source: National Horticulture Board India website, https://nhb.gov.in/

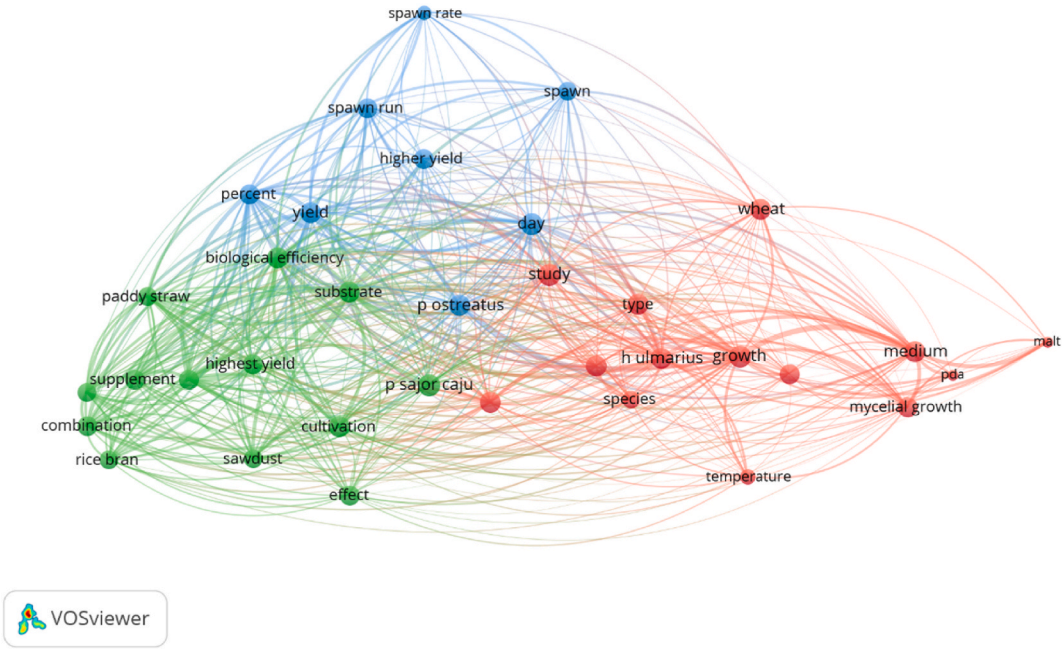

Fig. 6. An overview of the important terms associated with this review, generated by VOS viewer.

PDA, malt yeast extract agar (MYE), complete agar medium (CAM), Asthana & Hawker's medium (A&H), Richard's medium (RM) and rose bengal agar (RBA) medium. Potato dextrose agar medium showed the greatest radial growth (76.00 mm), followed by MYE medium (69.8 mm). Complete agar medium (CAM) had the least radial growth (60.00 mm). In contrast, Kushwaha et al. [49] studied the cultural variability of *H. ulmarius* and found that MEA supported the maximum growth of the test fungus followed by WEA and PDA medium. Doshi et al. [50] and Anonymous [51] evaluated CMA, CDA, MEA, PDA, OMA, potato malt extract agar (PMEA), PCA and tapioca dextrose agar (TDA) media for the mycelial growth of *H. ulmarius* and found that PDA and PMEA medium supported the maximum growth.

According to a study conducted by Sumi and Geetha [52], it was found that PDA was highly effective in facilitating the growth of *H. ulmarius*. Similarly, another research by Mishra et al. [53] also confirmed that PDA provided the optimal conditions for the mycelial growth of *H. ulmarius*. Kumar and Eswaran [54] evaluated nine different media and found that maximum mycelial growth was found on PDA and PMEA (90 mm) followed by MEA (81.00 mm), CMA (78.6 mm), TDA (76.7 mm), OMA (72.4 mm), CDA (70.00 mm) and PCA (64.5 mm) showed minimum yield. Baghel [55] conducted research on the impact of various culture media on the growth of *H. ulmarius* and found that PDA resulted in significantly higher radial growth (89.00 mm), followed by WEA (81.50 mm), while MYE medium showed the least growth (69.75 mm). Shendge [56] tested various media and determined that PDA medium and V-8 juice agar

medium exhibited significantly higher (each of 90.00 mm) radial growth of fungus, closely followed by MEA medium (84.40 mm). The biomass production of the fungus was maximum (13.56 g and 1.27 g fresh and dry weight, respectively) in V-8 juice liquid medium and minimum (1.02 g and 0.036 g fresh and dry weight, respectively) was noticed in Ashby's mannitol liquid medium. Aditya et al. [57] conducted a study examining the influence of various solid and liquid nutrient media on the mycelial growth, cultural traits and growth of *H. ulmarius*. Potato dextrose agar was found to be the most favorable medium for mycelial growth, reaching (76.20 mm). Malt extract agar was the second most favorable medium, with a mycelial growth of 59.40 mm. Carrot extract broth was the most favorable medium for biomass production, with a dry weight of 0.5 g. Asthana and Hawker's medium was the least favorable medium for biomass production, with a dry weight of 0.04 g. The mycelial expansion growth in all media was white, cottony and fluffy, with concentric patterns. However, CDA medium supported light, thin, transparent white growth that was only visible under light illumination.

2.2. Temperature and pH effects on mycelial growth, biomass production and cultural characteristics of different oyster mushroom species

Temperature and pH are critical factors that significantly influence the growth of vegetative mycelium in the fungus. According to Yadav [58] observations, cultivation of *H. ulmarius* was effectively accomplished by maintaining temperatures between 13 and 33°C and a relative humidity range of 45–95 percent. The optimal conditions for maximum mycelial growth and yield of *H. ulmarius* were found to be between 20 and 28°C for temperature and 75–90 percent for relative humidity. These findings suggest that *H. ulmarius* can be cultivated effectively during the months of July to November and February to March, excluding extremely cold or hot seasons. Wang and Patil [46] conducted studies to find out the effect of temperature on the growth of *H. ulmarius* and observed that the fungus failed to grow at 5 and 10°C on the lower side and at 35 and 40°C on the higher side. Significantly maximum growth was recorded at 25°C and there was a decrease in growth on either side of 25°C which was the optimum temperature. The optimal temperature of 371 strains belonging to 9 species of edible mushrooms was studied by Imtiaj et al. [59]. They reported that the most suitable temperature for mycelial growth was 25°C and the optimal range of temperature was 20–30°C. Similarly, Sethi et al. [60] and Sharma et al. [61] also found maximum biomass at 25±1°C followed by 30±1, 20±1 and 15 ± 1°C in the case of *H. ulmarius*. Rout et al. [62] reported that *H. ulmarius* received better growth at 25°C and the extent of mycelial growth was reduced drastically above or below the incubation temperature of 25°C. It was recorded that the growth was completely inhibited at temperatures of 10, 35 and 40°C. An ideal temperature of 25°C has been reported by Singh and Kushwaha [45]; Kumar and Eswaran [54]; Sumi and Geetha [52] and Sharma et al. [61] for maximum mycelial growth and biomass of *H. ulmarius*.

Hu et al. [63] evaluated the eight temperature regimes *viz.*, 15, 18, 20, 22, 25, 28, 30 and 32°C for *P. ostreatus* mycelial development and found that the mycelial growth differed significantly under different test temperatures. The temperate of 22°C was found to be optimum for the mycelial development of *P. ostreatus*. Shruti et al. [64] in their study found that a temperature of 25°C was optimum for the mycelial development of *P. eryngii*. However, Hoa et al. [65] studied the influences of different temperature regimes affecting the mycelium growth of two different oyster mushrooms species i.e., *P. ostreatus* and *P. cystidiosus* and concluded that the optimal temperature for mycelium growth of both oyster mushroom species was obtained at 28°C.

The concentration of hydrogen ions in the substrate is crucial for the fungus growth. Many types of mushrooms thrive and develop fruit bodies best in a medium that is slightly acidic to slightly basic. Wang and Patil [46] observed that *H. ulmarius* produced the highest dry mycelial weight at pH 6.0. Singh and Kushwaha [45], found that pH 7.0 was most suitable for the growth of *H. ulmarius*. Sethi et al. [60] in their studies recorded that the maximum biomass of *H. ulmarius* (20.8 g per L) was obtained at pH 6.0. However, Kumar and Eswaran [54] reported maximum mycelial growth (90 mm) and biomass (1.28 g) of *H. ulmarius* at pH 7.0. Similarly, Sharma et al. [61] in their studies also supported the above findings and reported that pH 7.0 was most favorable for the maximum mycelial growth (90 mm) and biomass production (2.5 g per 250 ml) of said species. Sumi and Geetha [52] also showed the highest mycelial growth at pH 7.0 followed by pH 8.0 but thick colony growth was observed at pH 8.0 compared to pH 7.0. According to Singh and Kushwaha [45]; Kushwaha et al. [49] and Kumar and Eswaran [54], pH 7.0 was ideal for growth and biomass production of *H. ulmarius*. Hence, based on the above findings it is therefore concluded that, maximum mycelial growth and biomass of *H. ulmarius* occurred at pH ranging from 6.0 to 8.0.

To determine the effect of pH levels on the hyphal growth of *P. ferulae*, Zhao and Cui [66] conducted a series of experiments and found that pH levels ranging from 5.0 to 7.5 were found most suitable for the hyphal growth of *P. ferulae*. The growth of two types of mushroom species *viz.*, *P. columbinus* and *P. pulmonarius* was the focus of Fallal et al. [67] study, where they examined how various pH levels affected their development. Their findings indicated that both species exhibited optimal growth when the pH was maintained at 7.0. Yadav and Ramchandra [68] , examined how pH affected various strains of *Pleurotus* mushrooms, specifically PL-1, PL-2, PL-3, PSC-1 and PSC-2 and concluded that maintaining a pH level of 7.0 proved to be beneficial for the growth of all *Pleurotus* strains examined. Aditya et al. [69] studied the effect of different temperature regimes and different levels of pH on the growth and cultural characteristics of *H. ulmarius* and found that the best pH for mycelial growth was 8.0 followed by 7.0, while the optimal temperature was 25.0°C. At this temperature, the mushroom showed maximum diametric growth (77.7 mm) after 5 days of incubation. Further deviations from these conditions led to a significant decrease in growth and the cultural characteristics of the mushroom varied in terms of mycelium colour and growth type.

2.3. Grain substrates used for quality spawn preparation of different oyster mushroom species

The production of edible mushrooms relies heavily on the quality of spawn, which is the starting and base material for cultivation [70]. The production of spawn is a highly sophisticated process that demands extensive expertise, specialized knowledge and meticulous attention from individuals engaged in mushroom cultivation technology. This fundamental process is the cornerstone of the entire mushroom industry and represents a significant limitation for mushroom cultivation globally [71]. Sinden [72] was the first to use grains for making spawn and since then, various researchers have suggested different types of grains for spawn preparation, including rye grains [73,74], ragi grains [75,76] and jowar grains [77].

Several studies have been conducted to determine the best grains for spawn development of different mushroom species. Chandravanshi [48] investigated the spawn preparation of *H. ulmarius* on various grains and reported that maize grains had the earliest spawn development. Sumi and Geetha [78] however, evaluated that paddy grains were superior for the spawn production of *H. ulmarius* which completed the spawn run in 18.5 days. Moreover, Sharma [79] demonstrated that sorghum grains proved to be a favorable substrate for the preparation of spawn. They facilitated accelerated and improved vegetative growth of *H. ulmarius* as compared to wheat and bajra grain spawn.

Khatri and Aggarwal [80] conducted a study where they used different cereal grains for spawn preparation of *P. florida* and found that the jowar (sorghum) grains were the most suitable for early spawn preparation for *P. florida*. Rathod et al. [81] reported that bajra (pearl millet) and wheat grains were preferred substrates for commercial spawn production of *P. florida*. Pathmaishini et al. [82], indicated that using kurakkan spawn (finger millet) led to a faster spawn running process, quicker pinhead formation, enhanced fruit body formation and higher yield in cultivating *P. ostreatus*, in comparison to other spawn types like maize, sorghum and paddy. Stanley [83] conducted a study evaluating six different grain substrates for cultivating *P. pulmonarius* and *P. tuber-regium* mushrooms. The grain substrates tested included wheat, yellow maize, guinea corn, millet, red sorghum and white maize. The results of his study clearly indicated that white maize exhibited the highest growth rate among all the grain substrates tested. Red sorghum was identified as the second-best grain substrate for both mushroom species. Aditya et al. [84] evaluated seven different grains *viz*., wheat, barley, maize, bajra, oat, sorghum and paddy grains for the production of quality spawn of *H. ulmarius*. Their study revealed that bajra grains were the most favorable substrate for accelerated and improved growth, taking just 11 days. Following bajra, sorghum, wheat and maize grains also supported growth, but to a lesser extent. Bajra grains exhibited the highest linear growth (50.52 mm) and growth rate (0.39 mm/h) among all the grains. On the other hand, barley grains exhibited the minimum linear growth (42.30 mm) and growth rate (0.26 mm/h), requiring the longest time for complete colonization of the grains, which took 19 days. The best grains for spawn development of different mushroom species may vary, but pearl millet, sorghum, wheat and paddy grains have all been shown to be effective for quality spawn preparation.

2.4. Influence of spawning rate on yield and biological efficiency of different oyster mushroom species

Mushroom spawn pertains to the development of mushroom mycelium on a particular substrate, serving as the foundational material for fostering mushroom growth. The quality of spawn is considered crucial in mushroom production. Grain spawn is commonly used because it spreads through the substrate quickly and is also easy in the process of spawning. Eira [85] found that the quantity of inoculum (spawn) should not surpass 10 percent of the substrate weight in order to prevent a substantial decline in biological efficiency (it refers to the ratio of the harvested mushroom's fresh weight to the dry substrate's weight used for cultivation). In commercial production, the recommended range is typically between 7 percent to 10 percent [86]. Deviating from this range can result in financial losses. Moreover, increasing the size of the inoculum has been shown to enhance the utilization of the solid substrate and promote the activity of laccase, which is a crucial enzyme in the growth of mushrooms. A higher spawning rate results in a shorter time for mycelial colonization, primordial formation and the first flush of the mushroom crop, while also reducing the chance for competing organisms to invade the cultivation environment [87]. Royse et al. [88], concluded that a greater concentration of nutrients in the initial mycelial growth material, known as spawn, can provide more energy for the growth and development of mycelium. However, it is important to note that using a lower amount of spawn may not be enough to start the growth process, while using too much can hinder growth through competitive inhibition. Therefore, it is important to maintain an optimal level of inoculum amount, as exceeding this limit can result in a decline in laccase production. This decline occurs due to the rapid depletion of nutrients caused by excessive spawn. Consequently, reduced metabolic activities can be enhanced by supplementing the basal media with various inducer compounds such as copper sulphate [89].

Chandravanshi [48] evaluated different spawning rates (3.0, 5.0, 7.0 and 9.0 %) on the yield of *H. ulmarius* and found that spawn rates of 9.0 (692.0 g) and 7.0 (671.0 g) percent gave more yield and both were at par with each other. Significantly less yield (572.2 g) was obtained from 3.0 to 5.0 percent spawning rates. Shendge [56] working on the cultivation of *H. ulmarius* also corroborated the above results and reported that spawning rates of 10.0, 9.0, 8.0 and 7.0 percent gave significantly higher yield on the soyabean substrate.

Biswas and Kuiry [90] examined various spawning rates (1.0, 2.0, 3.0, 4.0 and 5.0 %) to achieve higher yields of *P. florida*. They concluded that a higher spawning rate resulted in a shorter spawn run period, increased the yield of *P. florida* and recommended higher

Table 3
Influence of various spawning doses on biological efficiency of different oyster mushroom species.

Sr. No.	Mushroom species	Substrate	Grains used	Spawn dose (%)	Spawn run period (d)	Biological efficiency (%)	Reference
1.	*P. ostreatus*	Saw dust	Finger millet	2.0	21	30.76	[82]
				2.0	22	16.57	
			Maize				
				2.0	32	11.99	
			Paddy				
				2.0	23	25.38	
			Sorghum				
2.	*P. sajor-caju*	Wheat straw	Wheat	5.0	10	67.40	[100]
3.	*P. florida*	Wheat straw	Wheat	5.0	12	52.10	[100]
			Paddy	5.0	13.5	97.60	[78]
		Paddy straw					
			Maize	5.0	16.33	50.33	[98]
		Wheat straw		6.0	15	53.33	
			Maize				
				5.0	20	51.66	
			Bajra				
				6.0	18.33	54.00	
			Bajra				
				5.0	19	51.00	
			Paddy				
				6.0	17.33	55.00	
			Paddy				
				6.0	20	53.00	
			Wheat				
4.	*P. pulmonarius*	Wheat straw	Wheat	0.5	19.13	67.15	[97]
					17.40	72.50	
				1.0			
					15.00	75.83	
				2.0			
					13.63	78.65	
				4.0			
					12.27	80.67	
				6.0			
					10.50	84.33	
				8.0			
5.	*H. ulmarius*	Paddy straw	Paddy	5.0	18.50	109.07	[78]
			Wheat	4.0	19.50	98.12	[55]
		Wheat straw					
			Wheat	1.0	31.33	32.92	[56]
		Wheat straw		2.0	25.45	40.56	
			Wheat				
				3.0	22.84	54.93	
			Wheat				
				4.0	20.12	93.22	
			Wheat				
				5.0	15.45	113.45	
			Wheat				
				6.0	14.00	117.65	
			Wheat				
				7.0	13.67	129.19	
			Wheat				
				8.0	13.67	135.97	
			Wheat				
				9.0	13.67	150.67	
			Wheat				
				10.0	13.67	153.95	
			Wheat				
			Pearl millet	1.0	22.66	97.13	[99]
		Wheat straw		2.0	21.67	98.00	
			Pearl millet				
				3.0	18.33	105.17	
			Pearl millet				
				4.0	15.68	121.13	
			Pearl millet				
				5.0	12.66	132.33	
			Pearl millet				
			Pearl millet	5.0	11.00	128.00	[84]
		Wheat straw					

(*continued on next page*)

Table 3 (*continued*)

Sr. No.	Mushroom species	Substrate	Grains used	Spawn dose (%)	Spawn run period (d)	Biological efficiency (%)	Reference
				5.0	13.00	121.80	
			Sorghum				
				5.0	15.00	125.33	
			Wheat				
				5.0	16.00	123.33	
			Maize				
				5.0	17.00	126.67	
			Oat				
				5.0	17.50	120.53	
			Paddy				
				5.0	19.00	118.67	
			Barley				

spawn doses during unfavorable seasons. However, Royse [13] found that the maximum yield of *P. cornucopiae* was achieved at a spawn rate of 3.75–5.0 percent. Ram and Pant [91] observed that a higher spawn dose led to a rapid spawn run in *P. sajor-caju* and *P. flabellatus*, the spawn run was very fast at a 5.0 percent spawn rate in all substrates. Bhatii et al. [92] examined the impact of various spawn rates on the growth, development and yield of *P. ostreatus*, their findings revealed that using a spawn rate of 70 g per kilogram of dry substrate weight, the cultivation of oyster mushrooms displayed several favorable outcomes. These included an accelerated and abundant production of mushrooms, a reduced time for the maturation of fruiting bodies and an increased quantity of flushes and fruiting bodies per cultivation bag. Smita [93] also demonstrated that a higher biological efficiency was achieved with an 8 percent spawn dose and there were no significant differences in yield between 6.0, 8.0 and 10.0 percent spawn doses. Dahmardeh [94] studied the impact of different spawning rates on the yield and biological efficiency of *P. ostreatus* and found that a spawn rate of 5.0 percent yielded the highest (1247.6 g/kg substrate) with the highest biological efficiency (62.3 %), followed by a spawn rate of 4.0 percent (1212.30 g/kg substrate). Chauhan [95] evaluated different spawning rates (1.0, 2.0, 3.0, 4.0 and 5.0 %) for the yield and biological efficiency of *P. djamor*, the fastest spawn run was observed at a spawn rate of 5.0 percent, followed by 4.0, 2.0 and 1.0 percent. The results further indicated that the maximum biological efficiency of the mushroom was achieved at a high spawn rate of 5.0 percent.

Wallman [96] conducted a study to investigate how different amounts of spawn (45, 90 and 180 g) affected the growth of mycelium, initiation of primordia and yield of *P. ostreatus* on rape and wheat straw. He found that the shortest time required for these processes was 13 days when using 180 g of spawn, while the longest time was 20 days when using 45 g of spawn. The highest yield and shortest time for fruit body formation were achieved with the largest amount of spawn (180 g). Pal et al. [97], investigated the various spawn doses influencing the yield of *P. pulmonarius* on wheat straw. Their findings revealed that the spawn run period required for mycelium growth was the shortest (10.50 d) when the spawn was applied at a rate of 8.0 percent. As the spawn rate decreased to 6.0, 4.0, 2.0, 1.0 and 0.5 percent, the time for the spawn run increased. Additionally, reducing the spawn rate resulted in a decrease in yield. The results further demonstrated that the highest biological efficiency, a measure of yield, was achieved at an 8.0 percent spawn rate, reaching 84.33 percent. Furthermore, the study found that increasing the spawn rate resulted in a faster spawn run however, when comparing a 4.0 percent to an 8.0 percent spawn rate, no noteworthy disparity in the final yield was noted. In other words, the

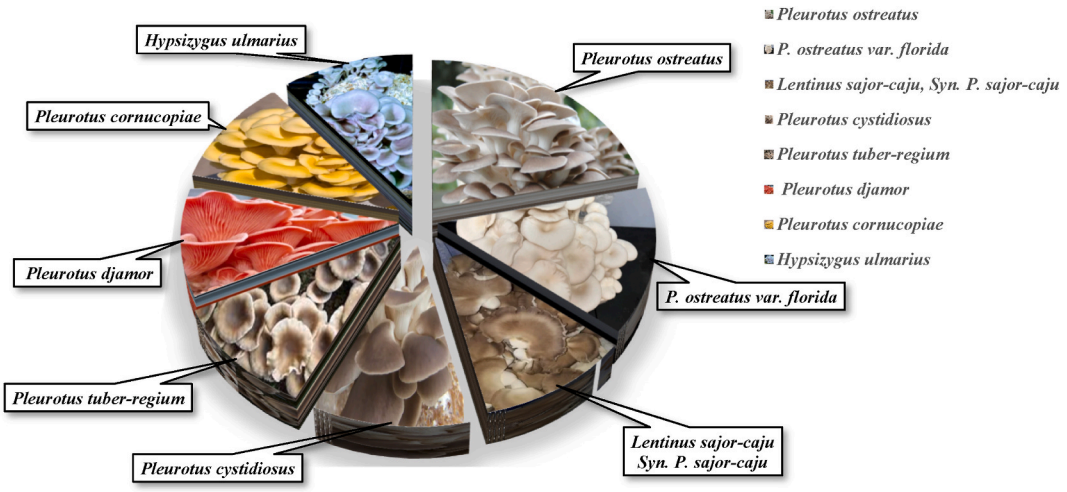

Fig. 7. Different oyster mushroom species cultivated in India.

mushrooms grew faster when the spawn rate was higher, but the total amount of mushrooms that grew was not significantly different. This suggests that there is an optimal spawn rate for growing mushrooms, and that increasing the spawn rate beyond this point does not result in a significant increase in yield. Pardeep et al. [98] conducted a study to assess the performance of different spawn grains (maize, bajra, paddy and wheat) at two spawning rates (5.0 and 6.0 %) for the production of *P. florida* on paddy straw and found that the maximum yield (550.0 g/kg of the dry substrate) with a biological efficiency of 55.65 percent was achieved with a 6.0 percent spawn rate using maize grain spawn. Similar spawn rates of bajra, paddy and wheat also resulted in decent yields, although slightly lower than maize grain spawns. Aditya et al. [99] in their study on *H. ulmarius* also substantiated that out of five spawn doses i.e., 1.0, 2.0, 3.0, 4.0 and 5.0 percent tested for yield parameters on wheat straw substrate, minimum time (12.62 d) for spawn run, the maximum number of sporocarps in first flush (42.33) and maximum yield (794.0 g/0.6 kg dry substrate) exhibiting highest biological efficiency (132.33 %) was recorded at 5.0 percent spawn dose. Maximum time (22.67 d), the minimum number of sporocarps in first flush (25.33) and lesser yield (582.80 g/0.6 kg dry substrate) with the lowest biological efficiency of 97.13 percent was recorded at 1.0 percent spawn dose. Many scientific studies have documented the utilization of diverse grain substrates to enhance the production of high-quality spawn. These studies have also explored varying spawning rates aiming for increased yield and enhanced biological efficiency [Table 3].

2.5. Utilization of various growing substrates influencing morphology, nutrition, yield and biological efficiency of different oyster mushroom species

Researchers from around the world have extensively utilized various agricultural, industrial and forest wastes, as well as by-products, for cultivating different species of *Pleurotus* mushrooms. These studies have been conducted by several researchers, including Mane et al. [2]; Suman and Jarial [101]; Sobal et al. [102]; Dey et al. [103]; Gupta et al. [104]; Oseni et al. [105]; Mungekar [106]; Fatriasari et al. [107]; Masevhe et al. [108]; Singh et al. [109]; Ritota and Manzi [110]; Neeraj et al. [111]. Oyster mushrooms can grow on wide agricultural wastes. The cultivation of oyster mushrooms has been successfully achieved using various agricultural wastes as substrates. These include rice and wheat straw [87], date palm leaves [112], palm date fibers [113], empty fruit branches [114], olive cake [115], tomato waste [116,117] and sugarcane bagasse [118]. Globally mushroom production and consumption are on the rise but India witnesses a lukewarm response in its growth, though India has incredible potential, immense assets and variety of climatic conditions for its cultivation. The recent production data showing that the different species of oyster mushrooms *viz*., *P. ostreatus, P. florida, P. sajor-caju, P. cystidiosus, P. tuber-regium, P. djamor* and *H. ulmarius* are commonly cultivated in India [Fig. 7].

Experiments conducted at different centers of All India Coordinated Research Project on Mushroom [51] assessed the growth and yield of *H. ulmarius* on various types of growing substrates and it was observed that short spawn run and highest biological efficiency (148.0 %) was recorded on paddy straw at Coimbatore center. Wheat straw ranked second with a biological efficiency of 134 percent [119]. Kulshreshtha et al. [120] investigated the potential of cultivating oyster mushrooms using solid sludge and effluent from cardboard and handmade paper industries. They discovered that when 50 percent of the waste from paper industries was mixed with 50 percent of wheat straw, there was a significant increase of 96.38 percent in biological efficiency compared to using wheat straw alone. Sethi et al. [60] studied three different substrates, wheat straw, paddy straw and a mixture of wheat straw and paddy straw (1:1) for cultivating *H. ulmarius*. Among these substrates, the shortest spawn run (24 d) period was observed in wheat straw and the mixture of wheat straw and paddy straw, while paddy straw took 36 days. Biswas and Kuiry [90] evaluated various species of *Pleurotus*, including *P. sajor-caju*, *P. flabellatus*, *P. florida*, *P. eous*, *P. ostreatus* and *H. ulmarius*, for their growth on the paddy straw under controlled conditions in the Lateritic zone of West Bengal. *Hypsizygus ulmarius* had the shortest spawn run period of 15 days, followed by *P. ostreatus* (18 d), *P. sajor-caju* (19 d) and *P. florida* (20 d). *Pleurotus eous* took the longest time, requiring 24 days to complete the spawn run. Kushal and Thakur [121] studied the effect of paddy straw quality and its supplements on the growth and yield of *H. ulmarius* and revealed that non-scented varieties of paddy straw took minimum days for spawn run (18–20 d) and produced higher biological efficiency (68.6–77.4 %) whereas, scented rice varieties showed no spawn run. However, the Kasturi rice variety gave minimum biological efficiency (52.6 %). Mishra et al. [53] tested the yield performances of different species of *Pleurotus viz., P. fossulatus, P. citrinopileatus, P. sajor-caju, P. sapidus, P. florida, P. flabellatus, P. ostreatus, P. djamor, P. platypus* and *H. ulmarius* on wheat straw. Their results indicated that *H. ulmarius* gave a higher yield (975 g/kg of substrates) than other tested species. Usha and Suguna [122] used paddy straw for the cultivation of *H. ulmarius* and recorded a biological efficiency of 46.22 percent in 42 days of crop duration. Sumi and Geetha [78] examined the performance of two species of oyster i.e., *H. ulmarius* and *P. florida* on paddy straw substrate. *Hypsizygus ulmarius* completed the spawn run in 22.4 days while *P. florida* took less time for the spawn run (17 d). *Hypsizygus ulmarius* recorded more yield and higher biological efficiency (109.7 %) than that of *P. florida* (97.6 %) under the favorable climatic conditions.

Several researchers, Atila [15]; Sharma [79]; Mandeel et al. [123]; Rezania et al. [124]; Pereria et al. [125]; Postemsky et al. [126]; Hoa et al. [127]; Sardar et al. [128]; Adebayo et al. [129]; De et al. [130]; Subedi et al. [131] have also conducted studies on cultivating oyster mushrooms using different lignocellulosic materials. Khanagoudhar and Mallesha [132] evaluated different substrates for the growth of *H. ulmarius* and found maximum yield on paddy straw (688.0 g) and maize sheath + paddy straw (400.0 g). The lowest yield was recorded on maize straw (235.0 g). Baghel [55] evaluated various substrates to understand their impact on the growth and yield of

Table 4
Influence of various substrates on biological efficiency of oyster mushroom species.

Sr. No.	Mushroom species	Substrate	Biological efficiency (%)	Reference
1.	*P. sajor-caju*	Sugarcane bagasse	56.00	[147]
		Newspaper	45.50	
		Paddy straw	80.30	
		Banana leaves	72.40	
		Wheat straw	60.10	
		Sesame leaves	43.00	
		Maize stalk	26.00	
		Wheat straw	63.85	[53]
		Paddy straw	96.00	[137]
		Cotton waste	115.00	
		Pearl millet	39.60	
		Banana waste	71.00	
		Maize straw	37.0	
		Corn cobs	137.40	
		Sesame waste	0.00	
		Sugarcane bagasse	91.60	
		Sugarcane trash	85.40	
		Spent compost	34.10	
		Gram seed husk	118.00	
		Wheat straw	56.20	
		Cotton stalk + wheat straw	73.60	[2]
		Soyabean straw + wheat straw	66.80	
		Pigeonpea stalk + leaves	46.30	
		Groundnut haulms	36.50	
		Soyabean straw	72.90	
		Wheat straw	44.70	
2.	*P. eous*	Tapioca leaves	11.36	[139]
		Cotton stalks	73.80	
		Groundnut haulms	64.66	
		Sugarcane bagasse	62.05	
		Cyperus rotundus	78.65	
		Soyabean straw	52.76	
		Paddy straw	96.36	
		Sugarcane trash	19.46	
		Groundnut shells	7.29	

(*continued on next page*)

Table 4 (*continued*)

Sr. No.	Mushroom species	Substrate	Biological efficiency (%)	Reference
			36.00	
		Pearl millet stalks	82.00	[148]
		Soyabean straw	61.50	
		Sunflower stalk	75.10	
		Wheat straw	73.20	
		Sorghum straw	71.60	
		Pearl millet straw	79.80	
		Paddy straw		
3.	*P. sapidus*	Wheat straw	50.12	[53]
			72.90	[148]
		Soyabean straw	45.90	
		Sunflower stalk	62.20	
		Wheat straw	50.30	
		Sorghum straw	46.70	
		Pearl millet straw	64.70	
		Paddy straw	44.20	[149]
		Hazelnut husk + wheat bran + wheat straw		
4.	*P. platypus*	Wheat straw	39.00	[53]
5.	*P. cystidiosus*	Corn cob	50.10	[150]
			49.50	
		Sugarcane bagasse	44.10	
		Saw dust + sugarcane bagasse	43.60	
		Saw dust + corn cob	36.30	
		Saw dust		
6.	*P. djamor*	Oak saw dust	62.50	[15]
			77.80	
		Safflower hay	78.20	
		Stem of phaseolus	45.50	
		Sunflower head residue	77.00	[151]
		Paddy straw	68.68	
		Wheat straw	46.21	
		Apple leaves	45.56	
		Popular leaves	29.20	
		Chinar leaves	75.50	[53]
		Wheat straw		
7.	*P. flabellatus*	Mango leaves	–	[152]
			–	
		Jack fruit	–	
		Coconut	–	
		Jam	–	
		Kadom	–	
		Mannogony		

(*continued on next page*)

Table 4 (*continued*)

Sr. No.	Mushroom species	Substrate	Biological efficiency (%)	Reference
			–	
		Shiris	53.87	[53]
		Wheat straw	45.71	[153]
8.	*P. florida*	Mango leaves	34.67	
		Neem leaves	41.14	
		Acacia leaves	27.41	
		Coconut leaves	75.20	[154]
		Coir pith +4 percent $CaSO_4$	52.20	
		Coir pith +6 percent $MgSO_4$	27.50	
		Coir pith +0.4 percent $FeSO_4$	22.70	
		Coir pith +0.2 percent $ZnSO_4$	53.70	[53]
		Wheat straw	96.38	[120]
		Wheat straw + paper waste	81.30	[155]
		Teak + paddy straw (PS)	77.00	
		Bamboo + PS	77.34	
		Eucyptus + PS	81.30	
		Popular + PS	94.00	
		Paddy straw	71.56	[128]
9.	*P. eryngii*	Cotton waste	51.80	
		Corn cobs	41.31	
		Sugarcane bagasse	48.24	
		Wheat straw	45.99	
		Rice straw	35.47	
		Saw dust	66.60	[15]
		Oak saw dust	73.10	
		Safflower hay	67.00	
		Stem of phaseolus	46.80	
		Sunflower head residue	38.41	[156]
		Wheat straw	48.19	
		Grape marc + wheat straw	42.19	
		Olive leaves + two-phase olive meal waste	87.50	[157]
		Wheat straw	68.52	[53]
10.	*P. citrinopileatus*	Wheat straw	73.90	[15]
		Oak saw dust	42.50	
		Safflower hay	43.00	
		Stem of phaseolus	54.10	
		Sunflower head residue		

(*continued on next page*)

Table 4 (*continued*)

Sr. No.	Mushroom species	Substrate	Biological efficiency (%)	Reference
			94.30	[158]
		Pea pod + paddy straw	92.30	
		Brassica straw + paddy straw	90.80	
		Cauliflower leaves + paddy straw	90.00	
		Paddy straw		
11.	*P. fossulatus*	Wheat straw	27.00	[53]
12.	*P. pulmonarius*	Wheat straw	42.15	[97]
			99.70	[157]
		Wheat straw		
13.	*P. ostreatus*	Sawdust (SD)	64.69	[138]
			44.72	
		Wheat straw (WS)	43.59	
		SD + WS	62.09	
		SD + leaves	57.85	
		WS + leaves	95.46	[140]
		Rice straw (RS)	77.32	
		RS + wheat straw	74.89	
		RS + paper	61.96	
		Sawdust	67.04	
		Sugarcane bagasse	75.55	[53]
		Wheat straw	68.16	[142]
		Wheat straw	66.20	
		Sinar straw	65.82	
		Barley straw	66.31	
		Saw dust	54.33	[159]
		Wheat straw + apple pomace	70.45	[141]
		Cardboard waste + wheat straw	74.17	[160]
		Cotton seed	34.22	
		Paper waste	35.88	
		Wheat straw	9.73	
		Sawdust	64.64	[161]
		Waste paper + corn stalk	36.01	[162]
		Sawdust (SD)	51.94	
		Faba bean stalk (FS)	70.87	
		Maize stalk	64.70	
		Wheat straw (WS)	32.44	
		Teff straw (TS)	74.59	
		WS + TS + SD	53.72	
		SD + FS		

(*continued on next page*)

Table 4 (*continued*)

Sr. No.	Mushroom species	Substrate	Biological efficiency (%)	Reference
			106.60	[163]
		Sugarcane trash	70.01	
		Sugarcane bagasse	114.90	
		Wheat straw	106.18	[156]
		Wheat straw	98.03	
		Grape marc + wheat straw	26.95	
		Olive leaves + two-phase olive meal waste	82.70	[164]
		Paddy straw	58.60	
		Banana leaves	41.80	[165]
		Maize stover		
14.	*P. cornucopiae*	Paddy straw	90.55	[109]
			82.67	[166]
		Wheat straw	80.00	
		Rice straw	71.66	
		Sugarcane bagasse	64.66	
		Maize cobs	30.83	
		Sawdust		
15.	*P. tuber-regium*	Maize cob	80.70	[83]
			80.50	
		Cassava peelings	54.47	[167]
		Plantgin leaves	62.05	
		Water hyacinth	99.65	
		Millet stalks		
16.	*P. nebrodensis*	Wheat straw	35.90	[156]
		Grape marc + wheat straw	60.80	
		Olive leaves + two-phase olive meal waste	11.90	
17.	*H. ulmarius*	Wheat straw	97.50	[53]
			109.00	[78]
		Paddy straw	68.10	[79]
		Wheat straw	84.03	[56]
		Wheat straw	81.90	
		Rice straw	95.55	
		Soyabean straw	80.85	
		Maize straw	69.77	
		Sorghum husk	60.03	
		Sugarcane bagasse	63.26	
		Cotton stalk	61.25	
		Pigeon peas	86.26	
		Pearl millet straw	48.23	
		Saw dust	98.12	[55]
		Wheat straw		

(*continued on next page*)

Table 4 (*continued*)

Sr. No.	Mushroom species	Substrate	Biological efficiency (%)	Reference
			84.75	
		Paddy straw	64.47	
		Pigeon pea	70.62	
		Mustard	66.52	
		Sesamum	124.00	[146,168]
		Wheat straw	113.20	
		Maize stalk and leaves	96.00	
		Pine needles	94.47	
		Lantana leaves	86.27	
		Saw dust	77.07	
		Curry plant leaves	72.80	
		Wood chips		

H. ulmarius. The substrates examined included paddy straw, pigeon pea straw, wheat straw, mustard straw and sesamum straw. The results indicated that wheat straw had the highest yield and biological efficiency for mushroom production, followed by paddy straw. On the other hand, the lowest mushroom yield was obtained from the use of pigeon pea straw. Sharma [79] also corroborated the above findings and reported that wheat straw is the best substrate for *H. ulmarius* growth and development as maximum growth took place after 20 days of spawning. Shendge [56] evaluated different growing substrates *viz.,* sorghum husk, wheat straw, maize straw, paddy straw, soyabean straw, sugarcane bagasse, cotton stalks, pigeon pea straw, bajra straw and sawdust as a substrate for *H. ulmarius* cultivation. The findings indicated that the maximum size and yield of sporophore, fruit bodies and biological efficiency (96.15 %) was recorded in the soyabean straw followed by maize straw (89.85 %). Minimum yield and biological efficiency were recorded on sawdust substrate.

Jain and Vyas [133] evaluated the yield performance of *P. florida* on wheat straw in combination with groundnut shell, bamboo leaves, paddy straw, soyabean straw, grasses, used tea leaves, ashoka leaves, sawdust and pine needles. Out of the nine combinations only two combinations i.e., wheat straw + soyabean straw (1:1) and wheat straw + used tea leaves (1:1) were reported as the best substrate for cultivation of *P. florida* with higher biological efficiency. Chandrashekhar and Savalgi [134] conducted experiments to assess whether it was possible to cultivate *P. sajor-caju* using by-products from sugarcane instead of paddy straw. The results showed that the highest level of biological efficiency was achieved when using paddy straw, reaching 88.35 percent. The combination of sugarcane trash and milled bagasse in a 1:1 ratio yielded a biological efficiency of 73.20 percent. When used individually, milled bagasse and sugarcane trash exhibited biological efficiencies of 72.23 and 71.36 percent, respectively. Haque [135]; Iqbal et al. [136] and Bhatia [137] in their studies also corroborated the above findings. Shah et al. [138], recommended the utilization of sawdust as a substrate for cultivating *P. ostreatus* due to its superior performance in terms of biological efficiency. The results showed that sawdust alone achieved the highest biological efficiency of 64.69 percent, followed by a combination of sawdust and leaves at 62.09 percent. Wheat straw combined with leaves yielded a biological efficiency of 57.85 percent, while wheat straw alone achieved 44.72 percent biological efficiency. The combination of sawdust and wheat straw resulted in a biological efficiency of 43.59 percent and using leaves alone yielded the lowest efficiency of 21.0 percent.

Jarial et al. [139] used six locally available plant materials *viz.,* fallen and dried leaves of *Lactuca sericola, Poplus ciliate, Iris* spp., *Rubinia* spp., *Pathenium hysterophorus* and *Hordeum* spp. with standard check i.e., wheat straw for the production of *P. florida, P. djamor and P. sajor-caju* and reported that wheat straw gave the highest yield and biological efficiency followed by *Hordeum* spp. and poplar under the dry temperate zone of Himachal Pradesh. Sharma et al. [140] investigated the five different types of substrates to determine the growth and yield of *P. ostreatus.* Paddy straw proved the best substrate for mushroom cultivation in all areas, with the highest yield (381.85 g) and biological efficiency (95.46 %), followed by rice + wheat straw and rice straw + paper waste. The nutritional content of mushroom fruit produced on rice straw was also significantly superior. Owaid et al. [141] showed the successful use of cardboard, wheat straw and their combinations to cultivate *P. ostreatus* mushroom in Iraq. The biological efficiency of blue oyster mushroom was higher in cardboard substrates and their combinations as cellulosic wastes than wheat straw. Tesfaw et al. [142], indicated that using waste paper and gobi waste alone or in combination with sawdust resulted in a higher yield of *P. ostreatus* compared to wheat, barley and sinar straw. Neupane et al. [143] conducted a study to examine the growth of *P. florida* using various substrates *viz.*, banana leaves, rice straw, wheat straw, a mixture of rice and wheat straw and sawdust. Their findings indicated that banana leaves were the most effective substrate followed by rice straw for cultivating *P. florida*, resulting in the highest biological efficiency. In contrast, sawdust produced the lowest yield, possibly due to the presence of phenolic compounds in this substrate. Yamauchi et al. [144], studied the feasibility of using moso bamboo sawdust as a replacement for conventional substrates in the cultivation of *P. ostreatus* in Japan. The

researchers utilized bamboo sawdust that had undergone a two-month fermentation process and combined it with rice bran and sweet potato shochu lees to enhance its nutritional value. The results demonstrated that mushrooms cultivated on the bamboo media exhibited faster growth, with a shorter cultivation period of 3–7 days compared to traditional media. Additionally, the bamboo media supplemented with rice bran yielded better results, producing a higher quantity of fruiting bodies. Moreover, the inclusion of sweet potato shochu lees in the bamboo sawdust increased the protein content of the fruit bodies while reducing the carbohydrate level. Furthermore, the sporocarps obtained from the bamboo substrate exhibited 1.5 times higher levels of free amino acids compared to those grown on conventional media, thereby potentially enhancing their value relative to regular mushrooms. Dubey et al. [145], investigated the effect of different substrates on the performance of *P. sajor-caju* and concluded that the highest yield, stipe length and cap diameter were obtained from rice straw compared to other substrates. Aditya et al. [146], compared the yield and biological efficiency of *H. ulmarius* grown on seven different locally available substrates. They found that wheat straw substrate gave the highest yield and biological efficiency, followed by maize straw substrate. The yield and biological efficiency were low in the case of pine needles, curry leaves and sawdust. The wheat straw substrate also had the shortest spawn run time (14.66 d) and first flush time (20.66 d), as well as the highest number of sporocarps produced during the first flush (37.33). The pine needles substrate had the longest stipe length (6.46 cm), while the maize straw substrate had the largest cap diameter (10.13 cm). The wood chips substrate had the longest spawn run time (22.33 d), first flush time (34.0 d), shortest stipe length (3.36 cm) and minimum yield (436.79 g/0.6 kg dry substrate), but it still exhibited a biological efficiency of 72.80 percent.

In commercial cultivation of mushrooms, the quality and abundance of suitable substrate play a pivotal role in dictating both the rate of mushroom growth and the quality of the resulting yield. The expense associated with mushrooms is intrinsically tied to the accessibility of appropriate substrate and the mushroom species ability to effectively utilize it. Among mushroom varieties, *Pleurotus* species stand out for their capacity to thrive on a diverse range of agricultural and forest waste. Various agricultural waste materials have been effectively utilized in the cultivation of oyster mushrooms, demonstrating promising results by significantly boosting the yield. *Pleurotus* species are also known to produce a wide variety of polysaccharides and lignin-degrading enzymes which are capable of degrading lignocellulosic materials, Table 4 shows the results of different workers regarding the cultivation of oyster mushrooms on different agro-industrial based wastes.

2.6. Addition of various supplements influencing nutrition, yield and biological efficiency of different oyster mushroom species

Supplements are substances that enhance the growth of mycelium and increase mushroom yield by providing specific nutrients [169,170]. However, these supplements also increase the risk of contamination by 25 percent or more since they also provide nutrients to other microorganisms [171]. Different researchers have experimented with various organic amendments or supplements to increase the C:N ratio and achieve higher yields of *Pleurotus* spp.

In a study conducted by Baghel [55], the performance of *H. ulmarius* was assessed by supplementing it with different levels of wheat and rice bran. The results showed significant differences in the fresh yield of *H. ulmarius* depending on the specific supplements used. A significantly higher yield of *H. ulmarius* was recorded in 2.0 percent wheat bran and 2.0 percent rice bran as well as 5.0 percent wheat bran while, it was low in control and 5.0 percent rice bran supplements. Sharma [79] cultivated *H. ulmarius* on paddy and wheat straw supplemented with wheat bran and gram flour at 2.5 and 5.0 percent and maximum growth was achieved when wheat straw was supplemented with gram flour at 5.0 percent.

Kolsulkar [172] conducted a study to evaluate the effectiveness of different supplements amended in paddy straw substrate to evaluate yield performance of *P. sapidus*. He concluded that, rice bran and wheat bran were added at a rate of 10 percent each, while cotton seed cake, maize grain, groundnut cake and gram dal powder were added at a rate of 5 percent each (based on the weight of the substrate). The highest yield of *P. sapidus* was observed in paddy straw amended with cotton seed cake, followed by rice bran and wheat bran. Yadav [58] evaluated eight substrates for the growth of *H. ulmarius* and recorded the maximum average mushroom yield of *H. ulmarius* in sawdust (80.0 %) + wheat bran (20.0 %) followed by wheat straw + termatorium soil (5.0 %). Further, mushroom yield in wheat straw + cotton linter (10.0 %), wheat straw + wheat bran (10.0 %), wheat straw + cotton linter (5.0 %) and wheat straw + wheat bran (5.0 %) had more or less similar yield of harvested mushroom. Moreover, wheat straw alone gave the lowest yield. Khare et al. [173] reported that wheat straw supplemented with gram flour at the rate of 5.0 percent (w/w) was an ideal substrate for growing *P. sajor-caju.* Narian et al. [174] evaluated *P. florida* on corn cob with different supplements such as urea, cotton seed cake, ammonium sulphate, soyabean meal, gram flour, groundnut cake and molasses at the rate of 2.0 percent. Corn cob-cotton seed cake combination was recorded best for cultivation. Nagothkar [175] determined the effect of various supplements *viz.,* rice bran, soyabean flour, wheat bran, maize grain flour and groundnut seed cake in combination with paddy straw substrate for cultivation of *P. sajor-caju.* Among all the substrate supplement combinations, paddy straw supplemented with wheat bran was found suitable substrate for its cultivation. Musakhail et al. [176] determined the effect of gram flour powder on the yield of *P. ostreatus.* Maximum biological efficiency (70.17 %) was recorded at 2.5 percent amendment of gram powder followed by 2.0 percent (52.56 %). Patil et al. [177] conducted a study to explore how different supplements affected the growth and yield of *P. sajor-caju* and *P. florida* on paddy straw. The findings indicated that the combinations of paddy straw + wheat bran at 10 percent and paddy straw + rice bran at 10 percent had a significant impact, resulting in 76.8 percent and 71.0 percent biological efficiency, respectively. Chauhan and Gupta [178] conducted

a study to explore the impact of different combinations of organic supplements derived from forest and agricultural wastes and found that a mixture of wheat straw and wheat bran in a ratio of 9:1 had the shortest incubation time, taking only 10.33 days. Another combination that yielded a relatively quick incubation time was wheat straw and cotton seed meal in the same ratio. On the other hand, the slowest spawn run occurred when wheat straw was combined with urea at a concentration of 1.0 percent. Among the treatments tested, the combination of wheat straw and wheat bran in a ratio of 9:1 demonstrated the highest yield and biological efficiency. Conversely, the lowest yield and biological efficiency were observed in the treatment where wheat straw was combined with CAN (calcium ammonium nitrate) at a concentration of 0.5 percent. Kinge et al. [179] analyzed the effects of various supplemented substrates on the growth and yield performance of *P. ostreatus*. Among the different combinations, the eucalyptus-corn flour combination yielded the highest biological yield (0.47 kg/packet), followed by corn-cobs-corn flour (0.45 kg/packet) and iroko-rice bran (0.37 kg/packet). Pathania et al. [159] investigated the cultivation of *P. ostreatus* mushrooms using horticultural waste, specifically apple pomace and wheat straw, in different ratios. Their findings showed an increase in mushroom yield when apple pomace was mixed with wheat straw.

Bhatta and Bist [180], investigated the feasibility of utilizing rice straw, which underwent treatment with four distinct organic additives (rice bran, wheat bran, gram flour and crushed maize cobs), as a means to enhance the nutrient content for the cultivation of *P. florida* mushroom. The results revealed that the most favorable outcomes were observed when rice straw was supplemented with wheat bran. This particular combination resulted in the highest yield and improved the overall growth of *P. florida* mushroom. In a similar way, Mkhize et al. [181] conducted a study to investigate the performance of *P. pulmonarius* mushroom grown on maize stalks with varying amounts of wheat bran and maize flour as supplements and they found that higher levels of supplementation with wheat bran and maize flour led to the highest yield and biological efficiency of *P. pulmonarius* mushroom. Both studies demonstrated the significance of using organic additives, such as wheat bran, to enhance the cultivation of different types of mushrooms. The supplementation with wheat bran proved to be particularly effective in promoting optimal growth and maximizing the yield of mushrooms. These findings contribute to understanding mushroom cultivation techniques and highlight the potential benefits of using specific organic additives as nutrient supplements in mushroom farming. However, the yield and biological efficiency declined when supplementation levels exceeded 12.0 percent wheat bran and 14.0 percent maize flour. Lower supplementation levels led to a faster colonization period and improved growth rate, while higher supplementation levels resulted in better yield and biological efficiency. Therefore, to achieve maximum production, it was recommended to use 12.0 percent wheat bran and 14.0 percent maize flour, whereas, for a faster production time, 2.0 percent maize flour and 2.0 percent wheat bran were recommended.

Tadesse [182] used different substrate combinations i.e., cotton seeds that were left over and spent coffee ground for the cultivation of *P. sajor-caju* and *P. ostreatus* and reported that substrates and their combinations were more suitable for *P. ostreatus* than for *P. sajor-caju* in terms of growth and nutritional value. However, the khat left over and spent coffee ground alone showed the lowest results while, their supplementation with cotton seed exhibited better results in terms of fruiting bodies, nutritional value and biological efficiency as well. Tesfay et al. [161], investigated the potential utilization of a mixture comprising discarded paper, corn stalks and wheat bran as a medium for cultivating *P. ostreatus*. The study discovered that by supplementing waste paper with corn stalk and wheat bran, they achieved a remarkable increase in both biological efficiency and overall yield of the cultivated mushrooms. Therefore, the utilization of waste paper, along with other additives, showed promise as an alternative method for cultivating oyster mushrooms. Similarly, Nguyen and Ranamukhaarachchi [42] recently explored the possibility of using recyclable materials such as cardboard and spent coffee grounds as substrates for cultivating *Pleurotus* mushrooms. They discovered that supplementing wheat straw with spent coffee grounds improved the growth of mycelium. Additionally, a substrate composed of 50 percent wheat straw and 50 percent cardboard was found to be the most favorable for both mycelium growth and primordia formation in *P. eryngii* and *P. ostreatus*. Aditya [183] conducted a series of experiments to determine the best methods for cultivating *H. ulmarius*. He found that bajra (pearl millet) grains were proved to be a good substrate for spawn preparation, as it resulted in faster mycelial growth, higher yield and biological efficiency. A spawn dose of 5.0 percent based on the wet weight of bajra grains spawn on wheat straw led to a shorter spawn period, increased fruit body production and higher yield and biological efficiency. Wheat straw was found to be the best substrate overall, while wood chips had the lowest yield and took more days to spawn run. Furthermore, recently conducted a commercial trial for the cultivation of *H. ulmarius* by using identified substrates, supplements and spawn doses. He documented that incorporating a 10 percent proportion of cotton seed hull into the wheat straw substrate, along with a 5.0 percent spawn of bajra grains, resulted in the most substantial yield (8944.0 g/4 kg of dry substrate) and highest biological efficiency (294.44 %). Conversely, employing wheat straw alone, devoid of any supplementation, produced the least yield (6538.0 g/4 kg of dry substrate) and biological efficiency (163.30 %) [184]. Supplementing with nitrogen can boost the productivity of the crop up to a specific threshold. Excessive nitrogen levels, however, can hinder the fruiting of mushrooms. Wheat bran, soyabean flour, cotton seed hull, rice bran, gram flour, maize flour, urea and their combinations were used as a supplement to enhance the yield of oyster mushrooms however, the amount and type of bran can differ depending on the species or strain. Different types of supplements were tried by various works to increase C: N ratio and to obtain higher yield and biological efficiency [Table 5].

Table 5
Influence of various supplementations on biological efficiency of *Pleurotus* species.

Sr. No.	Mushroom species	Substrate	Supplement	Dose (%)	Biological efficiency (%)	Reference
1.	*P. pulmonarius*	Wheat straw	Saw dust	5.0	60.85	[97]
				5.0	24.15	
			Ammonium nitrate			
				5.0	77.65	
			Cotton seed meal			
				5.0	31.85	
			CAN			
			Maize flour	14.0	132.0	[181]
		Maize stalk		12.0	113.0	
			Wheat bran			
2.	*P. sajor-caju*	Wheat straw	Wheat bran	5.0	70.40	[100]
				5.0	77.20	
			Soyabean flour			
				5.0	45.10	
			Cow dung			
3.	*P. florida*	Wheat straw	Wheat bran	5.0	68.00	[100]
				5.0	72.50	
			Soyabean flour			
				5.0	40.05	
			Cow dung			
4.	*P. ostreatus*	Waste paper	Corn stalk	50.0	62.00	[161]
				25.0	48.44	
			Corn stalk			
				25.0	52.28	
			Wheat bran			
				25.0 + 25.0	64.44	
			Corn stalk + wheat bran			
			Cardboard	50.0	68.10	[141]
		Wheat straw		70.0	49.50	
			Cardboard			
			Apple pomace	25.0	54.23	[159]
		Wheat straw				
			Rice bran	10.0	95.46	[61]
		Wheat straw				
5.	*H. ulmarius*	Wheat straw	Termatorium soil	5.0	80.07	[58]
				5.0	75.86	
			Wheat bran			
				5.0	76.66	
			Cotton linter			
			Wheat bran	2.0	90.46	[55]
		Wheat straw		2.0	66.23	
			Rice bran			
				5.0	85.66	
			Wheat bran			
				5.0	83.56	
			Rice bran			
			Rice husk	2.0	75.78	[185]
		Wheat straw		2.0	79.77	
			Krang cake			
				2.0	84.11	
			Neem cake			
				2.0	73.56	
			Gram flour			
				2.0	78.76	
			Wheat bran			
				2.0	32.00	
			Soyabean flour			
				2.0	71.48	
			Maize flour			
			Gossypium hirsutum seed waste	10.0	176.87	[184]
		Wheat straw		10.0	168.93	
			Cicer arietinum flour			
				10.0	162.00	
			Rice bran			
				10.0	158.20	
			Chokar			
				10.0	154.53	
			Maize powder			

(*continued on next page*)

Table 5 (*continued*)

Sr. No.	Mushroom species	Substrate	Supplement	Dose (%)	Biological efficiency (%)	Reference
				9.0	162.93	
			Gossypium hirsutum seed waste	9.0	159.93	
			Cicer arietinum flour	9.0	154.27	
			Rice bran	9.0	152.53	
			Chokar	9.0	147.93	
			Maize powder	8.0	153.13	
			Gossypium hirsutum seed waste	8.0	150.27	
			Cicer arietinum flour	8.0	147.33	
			Rice bran	8.0	144.53	
			Chokar	8.0	141.60	
			Maize powder	7.0	149.07	
			Gossypium hirsutum seed waste	7.0	147.07	
			Cicer arietinum flour	7.0	143.80	
			Rice bran	7.0	139.60	
			Chokar	7.0	137.47	
			Maize powder	6.0	145.73	
			Gossypium hirsutum seed waste	6.0	144.07	
			Cicer arietinum flour	6.0	138.93	
			Rice bran	6.0	138.00	
			Chokar	6.0	134.73	
			Maize powder	5.0	138.87	
			Gossypium hirsutum seed waste	5.0	134.40	
			Cicer arietinum flour	5.0	131.47	
			Rice bran	5.0	130.47	
			Chokar	5.0	128.95	
			Maize powder			

3. F uture aspects

The *Pleurotus* genus has gained extensive research attention worldwide due to its outstanding ability to break down lignin. This type of fungi, known for its edible mushrooms and rich in bioactive compounds, belongs to the group of Basidiomycetes. When it comes to Basidiomycetes fungi, their lignocellulolytic enzymes are influenced by various factors typically encountered during fermentation, including factors like the composition of the growth medium, the ratio of carbon to nitrogen, pH levels, temperature and the composition of the surrounding air. These factors can either individually affect enzyme activity or interact with one another to create combined effects. Achieving the ideal combination of air temperature, C:N ratio, water-holding capacity of the growth medium and other variables results in a synergistic effect that optimizes mushroom production. Therefore, a comprehensive understanding of both the intrinsic and extrinsic factors is crucial for achieving efficient and effective *Pleurotus* species cultivation. However, it is worth noting that such information is often lacking in the available scientific literature. Consequently, the following are some of the prospective focal points that warrant exploration in the times ahead.

1. Oyster mushrooms hold great promise in the future of sustainable waste management and agriculture. Their ability to efficiently convert organic waste into nutrient-rich biomass not only addresses environmental challenges but also provides valuable resources

for agriculture. As awareness of sustainable practices grows, integrating oyster mushrooms into waste utilization strategies may become mainstream, contributing to a circular economy. Moreover, oyster mushrooms play a role in environmental remediation by absorbing and degrading pollutants in soil and water, making contaminated sites safer. Beyond waste utilization, their exceptional nutritional profile and adaptability position them as a key player in the future of food, offering a sustainable and versatile protein source that aligns with the increasing demand for eco-friendly nutrition.

2. Spawn serves as the essential foundation and plays a pivotal role in the prosperous cultivation of mushrooms. However, in many countries, the spawn industry operates without proper organization and requires substantial research backing in the future. This support is necessary to elevate its quality standards and enhance its competitiveness to match that of multinational corporations. It is imperative for each country to establish and enforce stringent spawn standards to benefit mushroom cultivators.
3. Standard design infrastructure and technology should be developed for all types of mushrooms suitable for seasonal and commercial cultivation. Greater emphasis may be given to mechanization and indigenous machinery may be developed to reduce the cost of cultivation.
4. To boost productivity, it is essential to have adequate harvesting facilities that can improve the longevity and appeal of mushrooms in the market. Mushrooms are quite fragile and prone to spoilage, so it is important to focus on developing cost-effective drying methods, adopting modified atmospheric packaging, employing eco-friendly and recyclable packaging materials, implementing strategies to reduce losses during the blanching process in canning and creating affordable freeze-drying and individual quick freezing (IQF) technologies.
5. Further research is also required to determine the optimum level of UV radiation required to produce a nutritionally useful amount of Vitamin D_2 in mushrooms along with optimal storage conditions and cooking methods.
6. A comprehensive examination is required to explore the therapeutic and biotechnological potential of mushrooms, in order to fully harness the abundant, yet largely unexplored, food resource on our planet. Genomics, proteomics and metabolomics are valuable tools that can significantly enhance the study of the bioactive compounds within mushrooms, ultimately advancing our understanding and utilization of these remarkable organisms. The future trajectory of oyster mushrooms as a medicinal powerhouse appears promising and impactful. The ongoing revelation of their diverse health benefits, including anti-inflammatory, anti-viral and immune-modulating properties, hints at a significant role in supporting human health and potentially mitigating various diseases. As scientific comprehension advances, the integration of oyster mushrooms into both dietary and pharmaceutical realms holds the promise of a holistic well-being approach and need of the hour because of their dual properties they possesses. This not only underscores their potential preventive and therapeutic applications but also paves the way for innovative strategies that leverage the inherent medicinal prowess of these fungi, marking a noteworthy advancement in the field of natural health solutions.
7. Oyster mushrooms have promising applications in internet of things (IoT) and artificial intelligence (AI). Internet of things sensors can optimize mushroom farming by monitoring conditions and AI can suggest adjustments for optimal growth. Predictive maintenance ensures equipment efficiency. Artificial intelligence-based quality control and sorting enhance mushroom grading. The Internet of things aids supply chain tracking and AI analyzes data for logistics optimization. Nutritional analysis and smart packaging help consumers make informed choices. Artificial intelligence accelerates genetic improvement. Sustainability is improved through resource optimization and waste repurposing. Integrating IoT and AI can boost efficiency, quality and sustainability in the mushroom industry, benefiting producers and consumers while advancing smart agriculture and food technology.

Certainly, we have made significant strides in ensuring food security by generating millions of tons of various agricultural crops. Nevertheless, the challenge of attaining nutritional security remains an ongoing endeavor. Looking ahead, we anticipate formidable challenges, including population growth, diminishing land resources, global warming and the increasing demand for high-quality food products at competitive prices, all of which may have far-reaching consequences. In this context, the advancement of mushroom cultivation presents an opportunity to address dietary concerns and reduce malnutrition by providing more nutritious diets. The technological progress in mushroom production offers the potential to bridge the gap in food scarcity and nutritional deficiencies without exerting additional pressure on land and the environment.

4. Conclusion

This review provides valuable insights into the physiological requirements, spawn preparation, cultivation substrates, supplements affecting yield, nutritional and medicinal properties of various *Pleurotus* species and *H. ulmarius*. Mushrooms have been traditionally used not only for their taste and nutrition but also for their medicinal properties. The information presented here suggests that *Pleurotus* species can be upgraded from functional food to holistic mushroom medicine. These mushrooms are popular for their taste, medicinal benefits and ease of cultivation on diverse agroforestry by-products and wastes. Sustainable food waste management can be achieved through mushroom cultivation, making it suitable and profitable in various climatic conditions. It also plays a crucial role in recycling agricultural waste and enhancing forest ecosystems. Mushroom cultivation offers income generation and livelihood opportunities, particularly in developing nations. Cultivation techniques for *Pleurotus* species are straight forward, cost-effective and highly profitable compared to other mushroom species. Moreover, they contribute to converting waste materials into valuable compounds and addressing environmental pollution. *Pleurotus* species are rich in nutrition and possess various medicinal properties, including antioxidant, anticancer, antimicrobial and cardiovascular benefits. The review also highlights *H. ulmarius* as a novel oyster mushroom species with high biological efficiency and significant medicinal and nutritive value. Overall, this review article is a valuable resource for academic purposes, covering commercial cultivation and the nutritional benefits of oyster mushroom species.

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Data availability

The data that was collected and analyzed during this study is contained in this published article and the data that was used to support the findings of this review are listed in the references at the end of the article.

Consent to publish

All authors read and approved the manuscript and agree with its publication.

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

CRediT authorship contribution statement

Aditya: Conceptualization, Visualization & Methodology; Writing – original draft; Writing – review & editing. **Neeraj:** Writing – review & editing, Supervision, Project administration. **R.S. Jarial:** Literature compilation and resources. **Kumud Jarial:** Data collection and formal analysis. **J.N. Bhatia:** Writing – review & editing, Validation, Supervision, Project administration.

Declaration of competing interest

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

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