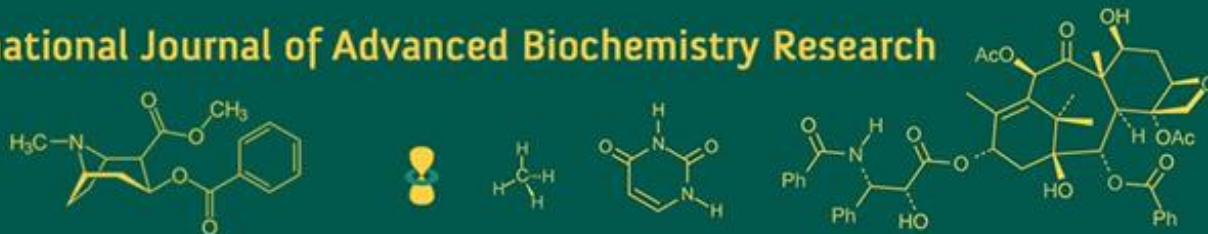


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Economic cultivation of medicinal mushrooms: A Comprehensive review

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Abstract

Medicinal mushrooms have gained substantial global attention owing to their nutritional value, therapeutic potential, and increasing commercial demand in the pharmaceutical, nutraceutical, functional food, and cosmetic industries. Species such as *Ganoderma lucidum*, *Lentinula edodes*, *Hericium erinaceus*, *Cordyceps militaris*, *Grifola frondosa* and *Trametes versicolor* are recognized for their diverse bioactive compounds, including polysaccharides, β -glucans, triterpenoids, phenolics, lectins, terpenes and peptides, which exhibit antioxidant, immunomodulatory, anticancer, antimicrobial, anti-inflammatory, hepatoprotective, neuroprotective, and antidiabetic activities. The expanding global preference for natural healthpromoting products has accelerated investment in medicinal mushroom cultivation, creating promising opportunities for sustainable entrepreneurship and rural livelihood development. Economic cultivation of medicinal mushrooms depends on the integration of appropriate species selection, high-quality spawn production, efficient substrate utilization, environmental control, disease management, post-harvest processing, and value addition. Agricultural residues such as wheat straw, paddy straw, sawdust, sugarcane bagasse, maize cobs, cotton waste, and other lignocellulosic by-products provide inexpensive and environmentally sustainable substrates that significantly reduce production costs while contributing to agricultural waste recycling and the circular bioeconomy. Recent technological innovations, including climate-controlled cultivation systems, precision farming, IoT-enabled environmental monitoring, artificial intelligence-based crop management, and improved substrate sterilization techniques, have enhanced production efficiency, product quality, and profitability. This review comprehensively synthesizes current knowledge on the biology, cultivation technologies, substrate management, environmental requirements, harvesting practices, processing techniques, bioactive constituents, medicinal properties, economic feasibility, and commercial potential of major medicinal mushrooms. Particular emphasis is placed on cost-effective production systems, enterprise economics, market trends, export opportunities, and value-added product development. The review also discusses major production constraints, including contamination, inconsistent spawn quality, limited mechanization, post-harvest losses, regulatory challenges, and market standardization issues. Furthermore, emerging research directions involving biotechnology, molecular breeding, omics technologies, and digital agriculture are critically examined to improve productivity and sustainability. By integrating scientific advances with practical cultivation strategies and economic analyses, this review provides a comprehensive resource for researchers, extension professionals, entrepreneurs, policymakers, and commercial growers seeking to promote economically viable and environmentally sustainable medicinal mushroom production.

Keywords: Medicinal mushrooms, economic cultivation, agricultural residues, bioactive compounds, functional foods, nutraceuticals, value addition, circular bioeconomy

1. Introduction

Medicinal mushrooms have been recognized for their nutritional and therapeutic properties for thousands of years and have occupied a prominent place in traditional healthcare systems, particularly in China, Japan, Korea, India, and other Asian countries. Ancient medical texts documented the use of mushrooms such as *Ganoderma lucidum* (Reishi), *Lentinula edodes* (Shiitake), *Cordyceps sinensis*, and *Hericium erinaceus* (Lion's Mane) for promoting longevity, enhancing immunity, improving vitality, and treating various chronic diseases. Over the past three decades, scientific research has validated many of these traditional claims by identifying numerous bioactive compounds possessing antioxidant, immunomodulatory, anticancer, antimicrobial, antiviral, anti-inflammatory, hypoglycemic, hepatoprotective, cardioprotective, and neuroprotective activities (Aditya et al., 2025a)^[1, 2]. The increasing consumer preference for natural products, functional foods, and nutraceuticals has significantly expanded the global medicinal mushroom industry^[3].

Unlike edible mushrooms that are primarily consumed as food, medicinal mushrooms are cultivated specifically for their therapeutic compounds, including polysaccharides, β -glucans, triterpenoids, phenolic compounds, lectins, sterols, proteins, peptides, alkaloids, and terpenes. These secondary metabolites have attracted considerable attention from pharmaceutical companies because of their potential applications in developing novel therapeutic agents against cancer, diabetes, cardiovascular diseases, Alzheimer's disease, Parkinson's disease, obesity, and immune disorders. The economic significance of medicinal mushroom cultivation extends beyond healthcare. Mushroom farming provides an attractive enterprise for small-scale farmers, women entrepreneurs, rural youth, and agribusiness startups due to its relatively low land requirement, short production cycle, efficient utilization of agricultural wastes, and high market value. Cultivation can be carried out using inexpensive lignocellulosic substrates such as wheat straw, rice straw, maize stalks, sugarcane bagasse, sawdust, cotton waste, coffee husks, tea residues, and other agroindustrial by-products, thereby converting agricultural waste into high-value products while supporting environmental sustainability and the circular bioeconomy. Medicinal mushroom cultivation contributes significantly to sustainable agriculture through waste recycling, carbon sequestration, reduced environmental pollution, and the generation of nutrient-rich spent mushroom substrate that can be utilized as organic manure, vermicompost, livestock feed, or biofertilizer. These characteristics make mushroom cultivation an environmentally friendly enterprise aligned with global sustainable development goals. Technological advancements have further enhanced the commercial feasibility of medicinal mushroom production. Controlled environment cultivation, improved spawn production techniques, sterilized substrate preparation, climate-controlled production units, automated humidity and temperature management, molecular breeding, biotechnology, Internet of Things (IoT)-based monitoring systems, artificial intelligence-assisted crop management, and precision mushroom farming have collectively increased biological efficiency, reduced production risks, and improved product quality. Furthermore, advanced extraction techniques have enabled the development of high-value products such as mushroom powders, capsules, tablets, teas, beverages, cosmetics, functional foods, dietary supplements, and pharmaceutical formulations (Aditya and Jarial, 2023) [3-5]. Despite remarkable progress, several challenges continue to constrain the expansion of medicinal mushroom cultivation. These include contamination during spawn production, inconsistent substrate quality, inadequate technical knowledge among growers, high initial investment for environmental control systems, post-harvest deterioration, lack of standardized cultivation protocols for several medicinal species, limited processing infrastructure, regulatory constraints, and market fluctuations. Addressing these issues requires multidisciplinary research integrating mycology, biotechnology, agricultural engineering, economics, food technology, and environmental sciences.

The present review comprehensively summarizes the current knowledge regarding medicinal mushroom cultivation, including taxonomy, biology, cultivation technologies, substrate selection, environmental requirements, spawn production, harvesting, processing, value addition, medicinal properties, economic feasibility, marketing opportunities, and future research priorities. The review emphasizes

economically sustainable cultivation practices that can enhance profitability while promoting environmentally responsible agricultural production systems.

2. Global Status of Medicinal Mushroom Cultivation

The global mushroom industry has experienced remarkable growth over the last two decades, driven by increasing awareness of health-promoting foods, expanding pharmaceutical applications, and rising consumer demand for natural therapeutics. While edible mushrooms such as button (*Agaricus bisporus*), oyster (*Pleurotus* spp.), and paddy straw (*Volvariella volvacea*) dominate overall production, medicinal mushrooms represent one of the fastestgrowing segments of the global mushroom market because of their superior economic value and expanding applications in nutraceuticals, pharmaceuticals, cosmetics, and functional foods. Asia remains the global leader in medicinal mushroom cultivation, accounting for the majority of worldwide production. China dominates global production and consumption, contributing more than 75% of commercially cultivated medicinal mushrooms. The country has developed highly mechanized cultivation systems, advanced spawn production technologies, and extensive processing industries that produce extracts, capsules, beverages, powders, and medicinal formulations. Japan and South Korea have also established sophisticated medicinal mushroom industries focusing on premium-quality *Lentinula edodes*, *Ganoderma lucidum*, *Grifola frondosa*, and *Hericium erinaceus*. These countries emphasize scientific cultivation methods, quality assurance, standardized processing, and international marketing.

North America and Europe have witnessed rapid growth in medicinal mushroom production due to increasing consumer awareness regarding natural health supplements and functional foods. Commercial cultivation has expanded in the United States, Canada, Germany, France, Italy, the Netherlands, and the United Kingdom. Modern cultivation facilities equipped with climate-controlled systems, automation, and strict quality control produce high-quality medicinal mushrooms for domestic consumption and export markets. Regulatory support for nutraceuticals and functional foods has further accelerated industrial growth. India possesses enormous potential for medicinal mushroom cultivation because of its diverse agro-climatic conditions, abundant agricultural residues, low labor costs, and growing domestic demand. Traditionally, commercial mushroom production in India has focused on button, oyster, and milky mushrooms; however, cultivation of medicinal mushrooms such as *Ganoderma lucidum*, *Cordyceps militaris*, *Lentinula edodes*, and *Hericium erinaceus* is increasing rapidly through research institutions, private enterprises, and agricultural startups. Organizations, including ICAR, agricultural universities and state horticulture departments, actively promote mushroom entrepreneurship through training programs, financial assistance, and technology dissemination.

The global medicinal mushroom market is expected to maintain strong growth due to increasing incidences of chronic diseases, aging populations, consumer preference for preventive healthcare, and expanding applications in pharmaceutical research. Products derived from medicinal mushrooms now include dietary supplements, herbal medicines, functional beverages, protein powders, cosmetic formulations, immune boosters, anti-aging products, sports nutrition supplements, and veterinary health products.

Continuous investment in biotechnology, genetic improvement, fermentation technologies, and extraction methods is expected to further expand commercial opportunities.

Several medicinal mushroom species have emerged as commercially important worldwide. *Ganoderma lucidum* remains the most valuable medicinal mushroom because of its immunomodulatory and anticancer properties. *Lentinula edodes* is extensively cultivated for both culinary and medicinal applications due to the presence of lentinan. *Hericium erinaceus* has gained international popularity for its neuroprotective compounds, while *Cordyceps militaris* has become an important commercial species for its production of cordycepin. *Grifola frondosa*, *Trametes versicolor*, *Agaricus blazei* and *Phellinus linteus* have also attracted considerable commercial attention due to their unique pharmacological activities. Government support, increasing research funding, technological innovations, and expanding export markets indicate that medicinal mushroom cultivation will continue to play an increasingly important role in sustainable agriculture, rural development, and the global bioeconomy.

3. Biology and Classification of Major Medicinal Mushrooms

Medicinal mushrooms comprise a diverse group of macrofungi that produce large fruiting bodies and synthesize biologically active secondary metabolites with significant therapeutic value. Most economically important medicinal mushrooms

belong to the phylum Basidiomycota, while a smaller number belong to Ascomycota. These fungi obtain nutrients through saprophytic, parasitic, or symbiotic modes of nutrition and reproduce through microscopic spores that germinate to produce hyphae. Interconnected hyphae form a mycelial network, which colonizes the substrate and ultimately develops into mature fruiting bodies under favourable environmental conditions. The life cycle of medicinal mushrooms begins with spore germination, followed by the formation of monokaryotic mycelium. Fusion of compatible hyphae produces dikaryotic mycelium, which represents the vegetative stage responsible for substrate colonization. Environmental factors such as temperature, humidity, light intensity, carbon dioxide concentration, and substrate composition trigger fruiting body initiation. Mature mushrooms subsequently produce basidiospores or ascospores, completing the reproductive cycle.

Based on nutritional ecology, medicinal mushrooms can be classified into three major groups:

- Saprophytic mushrooms-Grow on dead organic matter and agricultural residues (e.g., *Ganoderma lucidum*, *Lentinula edodes*, *Pleurotus* spp., *Hericium erinaceus*).
- Parasitic mushrooms-Obtain nutrients from living hosts (e.g., *Cordyceps* spp.).
- Mycorrhizal mushrooms-Form symbiotic associations with plant roots (certain medicinal species with limited commercial cultivation).

Table 1: Major Commercially Cultivated Medicinal Mushrooms

Scientific Name	Common Name	Family	Major Bioactive	Principal Medicinal
			Compounds	Properties
<i>Ganoderma lucidum</i>	Reishi/Lingzhi	Ganodermataceae	Triterpenoids, β -glucans, polysaccharides	Immunomodulatory, anticancer, hepatoprotective
<i>Lentinula edodes</i>	Shiitake	Omphalotaceae	Lentinan, eritadenine	Antitumor, cholesterol-lowering, immune enhancement
<i>Hericium erinaceus</i>	Lion's Mane	Hericiaceae	Hericenones, erinacines	Neuroprotective, cognitive enhancement
<i>Cordyceps militaris</i>	Caterpillar Mushroom	Cordycipitaceae	Cordycepin, adenosine	Antioxidant, anti-inflammatory, immunostimulatory
<i>Grifola frondosa</i>	Maitake	Meripilaceae	D-fraction β -glucans	Anticancer, antidiabetic, immunomodulatory
<i>Trametes versicolor</i>	Turkey Tail	Polyporaceae	PSK, PSP	Cancer adjunct therapy, immune stimulation
<i>Agaricus blazei</i>	Brazilian Mushroom	Agaricaceae	β -glucans, polysaccharides	Antioxidant, antitumor, antidiabetic
<i>Phellinus linteus</i>	Black Hoof Mushroom	Hymenochaetaceae	Phenolics, polysaccharides	Anticancer, antimicrobial, hepatoprotective

3.1 Morphological Characteristics

Medicinal mushrooms consist of vegetative and reproductive structures. The vegetative mycelium absorbs nutrients from the substrate, whereas the fruiting body comprises the cap (pileus), stalk (stipe), gills or pores (hymenophore), and spore-producing tissues. Woody medicinal mushrooms such as *Ganoderma* and *Trametes* produce perennial bracket-like basidiocarps, whereas species like *Lentinula*, *Hericium*, and *Cordyceps* develop fleshy annual fruiting bodies.

3.2 Bioactive Constituents

The medicinal value of these mushrooms is attributed to a diverse array of biologically active molecules, including:

- β -glucans and heteropolysaccharides
- Triterpenoids
- Phenolic compounds
- Flavonoids

- Ergosterol
- Lectins
- Glycoproteins
- Terpenes
- Peptides
- Alkaloids
- Sterols
- Vitamins and essential minerals

These compounds exhibit multiple pharmacological activities, including antioxidant, immunomodulatory, anticancer, antiviral, antibacterial, antifungal, anti-inflammatory, hypoglycemic, antihyperlipidemic, hepatoprotective, nephroprotective, cardioprotective, and neuroprotective effects. The concentration of these metabolites varies with species, substrate composition, cultivation method, developmental stage, and environmental conditions, making

optimized cultivation practices critical for maximizing both yield and medicinal quality.

4. Economic Importance of Medicinal Mushrooms

Medicinal mushrooms have emerged as one of the most profitable sectors of modern agriculture due to their high market value, rising consumer demand, and diverse applications across the pharmaceutical, nutraceutical, cosmetic, and functional food industries. Unlike conventional edible mushrooms, medicinal species command premium prices due to the presence of bioactive compounds such as β -glucans, polysaccharides, triterpenoids, lectins, terpenes, sterols, and phenolic compounds. These compounds are extensively utilized in the manufacture of dietary supplements, herbal medicines, immune boosters, protein powders, beverages, cosmetics, and pharmaceutical formulations (Wasser, 2011; El Enshasy *et al.*, 2022) [6, 7]. Medicinal mushroom cultivation provides an attractive livelihood option for small and marginal farmers because it requires relatively little land, can be practiced year-round under controlled conditions, and efficiently utilizes agricultural residues such as wheat straw, rice straw, sawdust, sugarcane bagasse, cotton waste, and maize stalks. This not only reduces production costs but also converts low-value lignocellulosic biomass into high-value products, contributing to waste recycling and the circular bioeconomy (Chang and Wasser, 2017; El Enshasy *et al.*, 2022; Aditya *et al.*, 2023a) [8, 7, 4].

Commercial cultivation generates employment throughout the value chain, including spawn production, substrate preparation, cultivation, harvesting, processing, packaging, transportation, marketing, and export. The industry has created entrepreneurial opportunities for rural youth, women self-help groups, farmer-producer organizations, and agribusiness startups. Furthermore, value-added products such as mushroom extracts, capsules, tablets, teas, coffee blends, nutraceuticals, and cosmetics substantially increase profit margins compared with fresh mushrooms (Royse *et al.*, 2017; Divya *et al.*, 2024) [9]. International demand for medicinal mushrooms continues to grow due to rising awareness of preventive healthcare and natural therapeutics. Species such as *Ganoderma lucidum*, *Cordyceps militaris*, *Hericium erinaceus*, and *Lentinula edodes* are now traded globally as dried fruiting bodies, extracts, powders, and standardized nutraceutical ingredients. Consequently, medicinal mushroom cultivation represents a promising export-oriented enterprise with considerable foreign exchange earning potential (El Enshasy *et al.*, 2022) [7].

5. Cultivation Technologies

Successful cultivation of medicinal mushrooms depends on selecting suitable species, preparing high-quality spawn, using appropriate substrates, maintaining optimum environmental conditions, and adopting effective crop management practices. Over the past four decades, cultivation technologies have evolved from traditional log cultivation to highly sophisticated controlled-environment production systems that maximize yield, quality, and biological efficiency (El Enshasy *et al.*, 2022) [7].

5.1 Log Cultivation

Log cultivation is the oldest technique used for producing medicinal mushrooms, particularly *Lentinula edodes* and *Ganoderma lucidum*. Hardwood logs such as oak, beech, maple, and poplar are inoculated with spawn and incubated

under shaded, humid conditions. Although production requires several months before harvesting begins, this method produces premium-quality fruiting bodies with excellent medicinal properties. The major disadvantages include long incubation periods, seasonal dependence, and comparatively lower productivity (Chang and Wasser, 2017) [8].

5.2 Bag Cultivation

Bag cultivation is the most widely adopted commercial method because of its simplicity, low investment, and efficient utilization of agricultural residues. Sterilized substrates such as sawdust, wheat straw, rice straw, maize cobs, sugarcane bagasse, or cotton waste are filled into polypropylene bags and inoculated with mushroom spawn. After completing mycelial colonization, environmental conditions are modified to induce fruiting. This system provides higher biological efficiency, shorter production cycles, reduced contamination, and improved product uniformity.

5.3 Bottle Cultivation

Bottle cultivation is extensively practiced in Japan, South Korea, and China for species such as *Hericium erinaceus*, *Flammulina velutipes*, and *Ganoderma lucidum*. Sterilized bottles containing formulated sawdust-based substrate are inoculated mechanically, allowing automation of filling, inoculation, incubation, harvesting, and cleaning. This technology is suitable for industrial-scale production requiring consistent quality and high productivity (Royse *et al.*, 2017) [9].

5.4 Controlled Environment Cultivation

Modern medicinal mushroom production increasingly employs environmentally controlled growing chambers equipped with automated systems regulating temperature, humidity, carbon dioxide concentration, ventilation, and illumination. Controlled cultivation minimizes seasonal variability, improves biological efficiency, reduces contamination, and enables year-round production of premium-quality mushrooms. Integration of Internet of Things (IoT), sensor-based monitoring, automation, and artificial intelligence has further improved crop management and production efficiency.

6. Environmental Requirements

Environmental conditions strongly influence mycelial growth, fruiting body initiation, biological efficiency, and the accumulation of medicinal metabolites. Different mushroom species require specific environmental conditions; however, most medicinal mushrooms exhibit similar general requirements.

6.1 Temperature

Temperature is one of the most critical factors affecting mushroom growth. Mycelial colonization generally occurs between 22–28 °C, while fruiting requires comparatively lower temperatures depending on the species. *Ganoderma lucidum* grows optimally at 25–30 °C whereas *Lentinula edodes* requires 15–22 °C during fruiting. Temperature fluctuations outside the optimum range reduce mycelial growth, delay fruiting, and increase contamination risk (Chang and Wasser, 2017; Aditya *et al.*, 2022a; Aditya *et al.*, b) [11, 10].

6.2 Relative Humidity

High relative humidity (85–95%) is essential during fruiting to maintain proper moisture content and prevent drying of

developing fruiting bodies. Low humidity causes cracking, deformation, and reduced yield, whereas excessive moisture promotes bacterial and fungal contamination.

6.3 Carbon Dioxide

Mycelial growth generally benefits from elevated carbon dioxide concentrations, whereas fruiting body formation requires adequate ventilation to reduce CO₂ accumulation. High CO₂ levels during fruiting result in elongated stipes, malformed fruiting bodies, and poor quality. Therefore, fresh air exchange is an essential management practice in commercial production.

6.4 Light

Unlike green plants, mushrooms do not require light for photosynthesis. However, low intensity diffused light (approximately 300-800 lux for several hours daily) acts as an environmental signal that stimulates primordia formation, pigmentation, and normal fruiting body development. Complete darkness often suppresses fruiting in many medicinal species.

6.5 pH

Most medicinal mushrooms grow best on substrates with a slightly acidic pH ranging from 5.5 to 6.5. Maintaining the proper pH promotes efficient nutrient availability, supports vigorous mycelial colonization, and suppresses competing microorganisms.

7. Spawn Production

Spawn serves as the planting material (seed) of mushroom cultivation and is considered the foundation of successful commercial production. High-quality spawn ensures rapid substrate colonization, minimizes contamination, shortens cropping duration, and significantly improves yield and biological efficiency (Chang and Miles, 2004; Aditya *et al.*, b; Raza *et al.*, 2026) ^[12]. Spawn production begins with the isolation of pure fungal cultures from healthy fruiting bodies or tissue cultures under aseptic laboratory conditions. The culture is maintained on Potato Dextrose Agar (PDA) or Malt Extract Agar (MEA), where vigorous mycelial growth is established before multiplication.

The most commonly used commercial spawn is cereal grain spawn prepared from wheat, sorghum, pearl millet, rye, or maize grains. The grains are cleaned, soaked, boiled, drained, and supplemented with calcium carbonate and gypsum to prevent clumping and maintain suitable pH. After filling into autoclavable bottles or polypropylene bags, the grains are sterilized at 121 °C under 15 psi pressure for 1-2 hours. Sterile grain is then inoculated with actively growing mycelium in a laminar airflow cabinet and incubated until complete colonization. Quality spawn should exhibit vigorous, uniform white mycelial growth, absence of contamination, high viability, genetic purity, and rapid colonization ability. Poor-quality spawn often leads to delayed growth, contamination, reduced biological efficiency, and substantial economic losses. Recent studies emphasize that spawn type, spawn rate, and spawn quality are among the most influential determinants of commercial mushroom productivity.

8. Substrate Selection and Preparation

The substrate serves as both the physical support and nutrient source for medicinal mushroom cultivation. Selection of an appropriate substrate is crucial because it directly influences

mycelial colonization, biological efficiency, fruiting body quality, medicinal compound accumulation, and production economics. Most medicinal mushrooms are lignocellulose-degrading fungi capable of converting agricultural and forestry residues into valuable biomass through extracellular enzymatic activity (Chang and Wasser, 2017) ^[8].

8.1 Common substrates include:

- Wheat straw
- Paddy straw
- Sawdust (hardwood)
- Cotton waste
- Sugarcane bagasse
- Maize cobs
- Corn stalks
- Coffee husks
- Tea waste
- Bamboo leaves
- Coconut coir
- Hardwood chips

Supplementation with wheat bran, rice bran, soybean meal, gypsum, and calcium carbonate enhances nitrogen availability and improves mushroom yield. The substrate is adjusted to approximately 60-65% moisture, filled into cultivation bags or bottles, and sterilized or pasteurized before inoculation. Sterilization at 121 °C effectively eliminates competing microorganisms and ensures successful spawn establishment, particularly for medicinal mushrooms requiring prolonged incubation periods.

Proper substrate preparation includes chopping (where required), soaking, moisture adjustment, pH correction, supplementation, bag filling, sterilization, cooling, inoculation under aseptic conditions, and incubation. High-quality substrates should possess adequate porosity, balanced carbon-to-nitrogen ratio, good water-holding capacity, and freedom from contaminants. Optimized substrate formulations not only improve biological efficiency but also enhance the concentration of therapeutically important bioactive compounds, thereby increasing the commercial value of medicinal mushrooms.

9. Substrate Selection and Preparation

The substrate serves as the primary nutrient source and physical support for the growth of medicinal mushrooms. Selection of an appropriate substrate is one of the most critical determinants of mycelial colonization, fruiting body development, biological efficiency, and the production of bioactive compounds. Most medicinal mushrooms are lignocellulolytic fungi capable of degrading cellulose, hemicellulose, and lignin through extracellular enzymes such as cellulases, xylanases, laccases, lignin peroxidases, and manganese peroxidases, enabling the utilization of a wide range of agricultural and forestry residues (Chang and Miles, 2004; Sánchez, 2010; El Enshasy *et al.*, 2022) ^[12, 13, 7].

The use of agricultural wastes as cultivation substrates significantly reduces production costs while promoting environmental sustainability through biomass recycling. Common substrates include wheat straw, rice straw, sawdust, sugarcane bagasse, maize stalks, cotton waste, coffee husks, tea waste, coconut coir, bamboo leaves, hardwood chips, sunflower stalks, and corn cobs. Hardwood sawdust remains

the preferred substrate for species such as *Ganoderma lucidum*, *Lentinula edodes*, and *Hericium erinaceus*, whereas straw-based substrates are commonly used for *Pleurotus* spp. and several medicinal mushrooms under commercial cultivation (Royse et al., 2017; Grimm and Wösten, 2018)^[9, 14]. To improve productivity, substrates are supplemented with nitrogen-rich materials such as wheat bran, rice bran, soybean meal, maize flour, gypsum (CaSO₄), and calcium carbonate (CaCO₃). These supplements improve the carbon-to-nitrogen ratio, enhance mycelial growth, and increase fruiting body yield. However, excessive supplementation may encourage contamination by competitor microorganisms; therefore, balanced substrate formulation is essential (Sánchez, 2010)^[13]. Substrate preparation involves several sequential steps. Initially, raw materials are cleaned and chopped into small pieces to improve handling and colonization. The substrate is then soaked in water to achieve an optimum moisture content of approximately 60-65%, followed by draining excess water. The pH is adjusted to 5.5-6.5 using calcium carbonate or gypsum where necessary. Supplementary nutrients are mixed thoroughly before filling the substrate into polypropylene bags or cultivation bottles (Chang and Miles, 2004)^[12]. Sterilization or pasteurization is essential for eliminating competing microorganisms. For medicinal mushrooms, sterilization is generally preferred because of the long incubation period. Substrate-filled bags are sterilized in an autoclave at 121 °C and 15 psi for 1-2 hours depending on bag size. After cooling to room temperature, inoculation is performed under aseptic conditions using high-quality grain spawn in a laminar airflow cabinet. Proper substrate preparation ensures rapid mycelial colonization, minimizes contamination, and enhances both yield and medicinal quality (El Enshasy et al., 2022)^[7].

10. Crop Management

Efficient crop management is essential for maximizing biological efficiency, improving fruiting body quality, and minimizing crop losses due to contamination and environmental stress. Successful medicinal mushroom cultivation requires continuous monitoring of temperature, humidity, ventilation, light intensity, carbon dioxide concentration, sanitation, and crop health throughout the production cycle (Royse et al., 2017)^[9].

Following inoculation, cultivation bags are transferred to incubation rooms maintained under optimum environmental conditions suitable for mycelial growth. During this phase, temperatures ranging between 22-28 °C, relative humidity of 70-80%, and minimal light are maintained depending on the species. Complete substrate colonization generally requires 20-

60 days, although the duration varies with mushroom species, substrate composition, and spawn quality (Chang and Miles, 2004)^[12].

After complete mycelial colonization, environmental conditions are modified to induce fruiting body formation. Relative humidity is increased to 85-95%, while fresh air exchange is enhanced to reduce carbon dioxide concentration. Diffused light (approximately 300-800 lux) is provided for several hours daily to stimulate primordia initiation. Regular monitoring of environmental parameters ensures uniform fruiting and minimizes physiological disorders such as malformed fruiting bodies, elongated stipes, or reduced cap development (Grimm and Wösten, 2018)^[14].

Sanitation is a critical component of crop management. Cultivation rooms, equipment, and workers should maintain strict hygiene practices to prevent contamination from molds such as *Trichoderma*, *Penicillium* and *Aspergillus*, as well as bacterial pathogens. Infected bags should be removed immediately to prevent disease spread. Integrated pest management strategies involving physical sanitation, biological control, and proper environmental regulation are preferred over chemical pesticides because medicinal mushrooms are consumed as healthpromoting products (Sánchez, 2010)^[13]. Modern commercial mushroom farms increasingly employ automated environmental control systems integrated with sensors, programmable controllers, IoT platforms, and artificial intelligence. These technologies enable real-time monitoring of temperature, humidity, carbon dioxide concentration, and ventilation, thereby improving crop uniformity, reducing labor costs, and increasing production efficiency (El Enshasy et al., 2022)^[7].

11. Harvesting and Post-harvest Management

Harvesting at the appropriate stage is essential to maximize yield, medicinal quality, and market value. The optimum harvesting stage varies among species. *Ganoderma lucidum* is generally harvested after complete maturation and spore formation, whereas *Lentinula edodes* and *Hericium erinaceus* are harvested before excessive cap expansion or spine elongation to preserve texture and bioactive compound concentration (Chang and Wasser, 2017)^[8]. Harvesting is performed manually using sterile knives or by gently twisting the fruiting body from the substrate without damaging the remaining mycelium. Careful handling reduces mechanical injuries and minimizes microbial contamination. After harvesting, residual substrate adhering to the mushroom base is removed before grading and packaging.

Fresh medicinal mushrooms contain 85-95% moisture, making them highly perishable. Consequently, immediate post-harvest management is necessary to preserve quality. Fresh mushrooms intended for local markets are stored at 2-4 °C with high relative humidity, extending shelf life to approximately one week depending on the species (Royse et al., 2017)^[9].

For long-term preservation, mushrooms are dehydrated using hot-air drying, vacuum drying, freeze-drying, solar drying, or microwave-assisted drying. Freeze-drying is considered the best technique because it preserves polysaccharides, antioxidants, vitamins, aroma, and medicinal compounds more effectively than conventional drying methods. Properly dried mushrooms containing less than 10% moisture can be stored for several months without significant deterioration (El Enshasy et al., 2022; Bhatia et al., 2025b)^[7, 15, 16]. Packaging materials such as vacuum-sealed laminated pouches, polyethylene bags, moisture-proof containers, and modified atmosphere packaging protect dried products from moisture absorption, oxidation, and microbial contamination during storage and transportation.

12. Processing and Value Addition

Value addition substantially enhances the profitability of medicinal mushroom enterprises by converting fresh mushrooms into diversified commercial products with extended shelf life and higher market value. The pharmaceutical and nutraceutical industries increasingly utilize mushroom-derived bioactive compounds for manufacturing functional foods, dietary supplements, cosmetics, and herbal

medicines (Wasser, 2011; Aditya *et al.*, 2024b) [6, 17, 18]. The simplest value-added products include dried whole mushrooms, mushroom powder, tea formulations, instant soups, seasoning mixes, coffee blends, noodles, biscuits, chocolates, beverages, capsules, and tablets. Drying and pulverization facilitate convenient storage, transportation, and incorporation into various food formulations while retaining most medicinal constituents (Patel and Goyal, 2012; Bhatia *et al.*, 2024) [19, 20].

Advanced processing technologies involve solvent extraction, hot-water extraction, supercritical carbon dioxide extraction, ultrasonic extraction, and enzymatic extraction to obtain concentrated polysaccharides, β -glucans, triterpenoids, phenolics, and other bioactive compounds. These extracts are standardized and incorporated into pharmaceutical formulations targeting immune enhancement, cancer therapy, diabetes management, liver protection, cognitive health, and cardiovascular wellness (El Enshasy *et al.*, 2022) [7]. Mushroom-derived ingredients are also widely utilized in cosmetic products such as anti-aging creams, moisturizers, facial masks, shampoos, and skin serums because of their antioxidant, antiinflammatory, and skin-regenerating properties. Furthermore, spent mushroom substrate has commercial applications as organic manure, vermicompost, livestock feed, enzyme production substrate, biofertilizer, and bioenergy feedstock, thereby increasing resource-use efficiency and supporting circular agriculture (Sánchez, 2010) [13].

13. Bioactive Compounds and Therapeutic Properties

The medicinal value of mushrooms is attributed to their diverse array of biologically active compounds synthesized during mycelial growth and fruiting body development. These compounds exhibit multiple pharmacological activities that have been scientifically validated through *in vitro*, animal, and clinical investigations (Wasser, 2011) [6]. Polysaccharides, particularly β -glucans, represent the most extensively studied medicinal constituents. β -glucans stimulate macrophages, dendritic cells, natural killer cells, and T lymphocytes, thereby enhancing innate and adaptive immune responses. Numerous studies have demonstrated their immunomodulatory and anticancer properties (Boh *et al.*, 2007; Aditya *et al.*, a; Aditya *et al.*, b) [21].

Triterpenoids, predominantly found in *Ganoderma lucidum*, possess anti-inflammatory, hepatoprotective, antihypertensive, antiviral, antioxidant, and cholesterol-lowering activities. These compounds also exhibit promising anticancer effects through apoptosis induction and inhibition of tumor angiogenesis (Paterson, 2006; Bhatia *et al.*, a) [22]. Other important bioactive constituents include phenolic compounds, flavonoids, sterols (ergosterol), lectins, peptides, terpenes, glycoproteins, nucleosides (cordycepin), hericenones, erinacines, and eritadenine. These compounds exhibit antioxidant, antimicrobial, antiviral, neuroprotective, antidiabetic, cardioprotective, hepatoprotective, nephroprotective, and cholesterol-lowering effects (Patel and Goyal, 2012) [19].

Species-specific bioactive compounds include lentinan from *Lentinula edodes*, cordycepin from *Cordyceps militaris*, hericenones and erinacines from *Hericium erinaceus*, PSK and PSP from *Trametes versicolor*, and D-fraction polysaccharides from *Grifola frondosa*. These compounds are widely investigated as adjunct therapies for cancer, neurodegenerative diseases, diabetes, obesity, and immune dysfunction (El Enshasy *et al.*, 2022) [7].

14. Cost of Cultivation and Economic Analysis

Economic viability is one of the primary factors determining the commercial success of medicinal mushroom cultivation. Compared with many horticultural enterprises, medicinal mushrooms require relatively limited land resources while generating high-value products with substantial profit margins. Production costs vary according to mushroom species, cultivation technology, substrate availability, scale of operation, labor charges, and level of mechanization (Royse *et al.*, 2017) [9]. The major cost components include infrastructure development, spawn procurement or production, substrate materials, supplements, sterilization, labor, environmental control systems, packaging, transportation, marketing, and electricity. In commercial production units, infrastructure and environmental control generally account for the highest initial investment, whereas substrate and spawn constitute the major recurring production costs (Chang and Miles, 2004; Aditya and Bhatia, 2020) [12, 23].

The use of locally available agricultural residues substantially reduces production costs while improving profitability. Farmers utilizing wheat straw, rice straw, sugarcane bagasse, sawdust, or other locally available lignocellulosic materials achieve lower input costs than those relying on commercially formulated substrates. Additionally, on-farm spawn production can further decrease operational expenses, provided adequate laboratory facilities and technical expertise are available (Sánchez, 2010) [13]. Value addition significantly enhances economic returns. Fresh mushrooms generally command lower market prices than processed products such as dried mushrooms, standardized extracts, capsules, nutraceutical formulations, herbal teas, and medicinal powders. Processing also extends shelf life, reduces post-harvest losses, and facilitates export, thereby increasing overall profitability (Patel and Goyal, 2012) [19].

Economic analyses from commercial farms indicate that well-managed medicinal mushroom enterprises can achieve favourable benefit-cost (B:C) ratios, particularly when integrated with value addition and direct marketing strategies. Premium medicinal species such as *Ganoderma lucidum*, *Cordyceps militaris*, and *Hericium erinaceus* generally provide substantially higher net returns than common edible mushrooms because of their higher market prices and expanding demand in pharmaceutical and nutraceutical industries (El Enshasy *et al.*, 2022) [7].

15. Marketing and Export Opportunities

Medicinal mushrooms have emerged as high-value agricultural commodities owing to their expanding applications in nutraceuticals, pharmaceuticals, functional foods, cosmetics, and dietary supplements. The growing consumer preference for natural and plant-based healthcare products has substantially increased the global demand for medicinal mushrooms such as *Ganoderma lucidum*, *Lentinula edodes*, *Cordyceps militaris*, *Hericium erinaceus*, *Grifola frondosa*, and *Trametes versicolor* (Royse *et al.*, 2017; El Enshasy *et al.*, 2022) [9, 7]. The global medicinal mushroom market has witnessed remarkable growth due to increasing awareness of preventive healthcare, aging populations, and the rising prevalence of chronic diseases. Consumers are increasingly seeking products with scientifically validated health benefits, creating substantial market opportunities for mushroom-based nutraceuticals and functional foods (Wasser, 2011; Patel and Goyal, 2012) [6, 19]. Dried mushrooms, powdered formulations, aqueous and alcoholic extracts,

capsules, tablets, herbal teas, coffee blends, functional beverages, cosmetics, and immune-enhancing supplements constitute the major commercial products traded in domestic and international markets (Kalač, 2016)^[24].

Commercial marketing of medicinal mushrooms follows multiple channels, including direct farm sales, wholesalers, supermarkets, pharmacies, health food stores, online marketplaces, nutraceutical companies, pharmaceutical manufacturers, and export agencies. Digital marketing and e-commerce platforms have significantly expanded market accessibility by enabling producers to reach consumers directly while reducing dependence on intermediaries. Branding, quality certification, attractive packaging, traceability, and compliance with food safety standards play crucial roles in improving consumer confidence and product competitiveness (Royse et al., 2017)^[9]. International trade in medicinal mushrooms has expanded considerably during the last two decades. China remains the world's largest producer and exporter, followed by Japan, South Korea, Taiwan, the United States, and several European countries. These nations have established advanced cultivation technologies, standardized processing industries, and well-developed export infrastructure that ensure consistent product quality (Chang and Wasser, 2017)^[8].

India possesses significant export potential due to favourable agro-climatic conditions, abundant agricultural residues, comparatively lower production costs, and increasing investments in mushroom cultivation. The export of dried mushrooms, mushroom powders, extracts, and nutraceutical products is gradually increasing, particularly to markets in North America, Europe, Southeast Asia, Australia, and the Middle East. However, successful international marketing requires adherence to Good Agricultural Practices (GAP), Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Point (HACCP), ISO quality standards, organic certification, and international phytosanitary regulations (FAO, 2021).

The commercialization of value-added products significantly enhances profitability compared to the sale of fresh mushrooms alone. Processing medicinal mushrooms into standardized extracts, pharmaceutical ingredients, nutraceutical capsules, herbal beverages, protein supplements, and cosmetic products provides substantially higher returns while reducing postharvest losses and extending shelf life (El Enshasy et al., 2022)^[7]. Future growth of the medicinal mushroom industry will depend on market diversification, consumer education, quality assurance, and international certification systems.

16. Government Schemes and Entrepreneurship

Medicinal mushroom cultivation has become an important component of agricultural diversification, rural development, and agri-entrepreneurship. Governments across the world increasingly recognize mushroom farming as a sustainable enterprise capable of generating employment, enhancing farmers' income, utilizing agricultural wastes, and promoting environmentally friendly agricultural production systems (FAO, 2021). In India, several government organizations actively support mushroom cultivation through financial assistance, technical training, research, infrastructure development, and entrepreneurship promotion. The Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs), Krishi Vigyan Kendras (KVKs), National Horticulture Board (NHB), Mission for Integrated

Development of Horticulture (MIDH), Agricultural and Processed Food Products Export Development Authority (APEDA), and various State Horticulture Departments regularly organize training programmes, demonstrations, and capacity-building activities for prospective mushroom entrepreneurs (ICAR-DMR, 2023)^[25].

Government financial assistance includes subsidies for mushroom production units, spawn laboratories, environmental control systems, processing facilities, cold storage, and postharvest infrastructure. Credit facilities are available through NABARD-supported schemes, commercial banks, cooperative institutions, and various startup promotion programmes. Young entrepreneurs, women self-help groups, farmer-producer organizations (FPOs), and rural youth are increasingly encouraged to establish commercial mushroom enterprises through entrepreneurship development initiatives (NABARD, 2022). The Government of India also promotes organic farming, sustainable agriculture, and waste recycling through various national programmes, creating favorable conditions for medicinal mushroom cultivation. Since mushrooms efficiently utilize agricultural residues and generate valuable organic manure through spent mushroom substrate, they contribute directly to circular agriculture and climatesmart farming systems (Sánchez, 2010)^[13]. Entrepreneurship opportunities extend beyond fresh mushroom production. Commercial ventures include spawn production laboratories, mushroom processing industries, nutraceutical manufacturing, medicinal extract production, functional food development, organic fertilizer production from spent substrate, mushroom training centres, consultancy services, and export-oriented businesses. These diversified enterprises create multiple income streams while reducing production risks (Chang and Miles, 2004)^[12]. Future government policies should emphasize improved access to credit, quality certification, export facilitation, incubation centres, startup support, and public-private partnerships to accelerate the commercialization of medicinal mushroom technologies and strengthen the rural bioeconomy.

17. Constraints and Challenges

Despite significant commercial potential, medicinal mushroom cultivation faces numerous technical, economic, environmental, and institutional challenges that limit its widespread adoption and industrial growth. Addressing these constraints is essential for achieving sustainable and profitable production systems (Royse et al., 2017)^[9]. One of the most critical challenges is contamination by competing fungi, bacteria, and insects during spawn production and substrate colonization. Species such as *Trichoderma*, *Aspergillus*, *Penicillium*, and bacterial contaminants frequently reduce biological efficiency and cause substantial economic losses. Maintenance of strict aseptic conditions and quality spawn production remains essential for successful cultivation (Chang and Miles, 2004)^[12]. Availability of genetically superior, disease-free, and high-quality spawn is another major limitation, particularly in developing countries. Inadequate laboratory infrastructure, limited technical expertise, and insufficient quality control frequently result in poor spawn performance and inconsistent crop yields (ICAR-DMR, 2023)^[25].

Environmental control constitutes another significant challenge. Many medicinal mushroom species require precise regulation of temperature, humidity, carbon dioxide concentration, and ventilation. Maintaining these conditions

throughout the year often necessitates expensive environmental control systems and continuous electricity supply, increasing production costs (Grimm and Wösten, 2018)^[14]. Market-related constraints include fluctuating prices, inadequate consumer awareness, absence of standardized quality grading systems, limited processing infrastructure, and insufficient market linkages. Small-scale farmers frequently depend on local markets where demand for medicinal mushrooms remains relatively limited compared to conventional edible mushrooms (Patel and Goyal, 2012)^[19].

Post-harvest deterioration presents another important challenge because fresh mushrooms possess high moisture content and limited shelf life. Lack of cold chain facilities, drying units, and processing industries contributes to considerable post-harvest losses and reduced profitability (Kalač, 2016)^[24]. Regulatory issues also affect commercialization. Variations in international regulations governing nutraceuticals, herbal medicines, food supplements, and pharmaceutical products complicate export procedures. Scientific validation, standardization of bioactive compounds, traceability, and quality certification remain important prerequisites for accessing premium international markets (FAO, 2021). Climate change poses emerging challenges by influencing substrate availability, energy requirements, and environmental control costs. Sustainable production systems integrating renewable energy, improved waste management, and climate-resilient technologies will become increasingly important for future medicinal mushroom industries.

18. Recent Advances (AI, IoT, Automation, and Precision Mushroom Farming)

Recent technological innovations have transformed medicinal mushroom cultivation from traditional manual practices into highly sophisticated precision production systems. Integration of digital technologies, automation, artificial intelligence (AI), Internet of Things (IoT), robotics, biotechnology, and data analytics has significantly improved production efficiency, crop monitoring, quality control, and economic profitability (El Enshasy *et al.*, 2022)^[7]. IoT-based environmental monitoring systems employ wireless sensors to continuously measure temperature, humidity, carbon dioxide concentration, substrate moisture, light intensity, and ventilation. Real-time monitoring enables automatic adjustment of environmental conditions, minimizing human error while improving biological efficiency and reducing production costs (Grimm and Wösten, 2018)^[14]. Artificial intelligence has emerged as an important tool for intelligent crop management. Machine learning algorithms analyze environmental data to optimize irrigation schedules, ventilation rates, humidity management, and harvesting time. AI-assisted image analysis also facilitates early detection of contamination, diseases, and physiological disorders before visible symptoms become severe, thereby reducing production losses (Li *et al.*, 2023)^[26].

Automation technologies have significantly reduced labor requirements in commercial mushroom farms. Automated substrate mixing, bag filling, sterilization, inoculation, bottle cultivation, harvesting, grading, packaging, and environmental control systems improve productivity while maintaining consistent product quality. Robotic harvesting systems are currently under development for industrial-scale mushroom production (Royse *et al.*, 2017)^[9]. Precision mushroom farming integrates sensor networks, cloud computing, mobile applications, geographic information systems (GIS), artificial intelligence, and decision support systems to optimize

resource utilization. These technologies enable growers to maximize yield while minimizing energy consumption, water use, and production costs. Smart cultivation facilities equipped with remote monitoring and automated climate control have become increasingly common in developed countries. Biotechnological advances including molecular breeding, genomic sequencing, CRISPR-based genome editing, marker-assisted selection, metabolomics, transcriptomics, and proteomics are providing new opportunities for developing high-yielding strains with improved medicinal properties, enhanced disease resistance, and superior environmental adaptability (Money, 2016)^[27].

19. Future Research Priorities

Although substantial progress has been achieved in medicinal mushroom research, several scientific and technological challenges remain unresolved. Future investigations should emphasize multidisciplinary approaches integrating mycology, biotechnology, molecular biology, agricultural engineering, food science, pharmacology, and economics. Development of genetically improved mushroom strains possessing higher biological efficiency, enhanced bioactive compound production, disease resistance, and environmental tolerance should remain a major research priority. Modern molecular breeding techniques including genome sequencing, gene editing, marker-assisted selection, and genomic prediction offer promising opportunities for accelerating strain improvement (Money, 2016)^[27].

Optimization of substrate formulations using locally available agricultural residues should receive greater research attention. Studies investigating carbon-to-nitrogen ratio, supplementation strategies, microbial interactions, and enzyme activities may substantially improve production efficiency while reducing cultivation costs (Sánchez, 2010)^[13]. Further investigations are required to standardize extraction technologies for medicinal compounds and establish internationally accepted quality standards for nutraceutical products. Comprehensive clinical trials evaluating safety, efficacy, pharmacokinetics, dosage, and therapeutic mechanisms are necessary to strengthen scientific evidence supporting medicinal mushroom applications (Patel and Goyal, 2012)^[19].

Digital agriculture will play an increasingly important role in future mushroom cultivation. Research should focus on AI-assisted decision support systems, predictive modeling, autonomous cultivation systems, smart sensors, blockchain-based traceability, digital twins, and precision environmental management. These innovations will contribute to sustainable, resource-efficient, and climate-resilient mushroom production systems. Greater emphasis should also be placed on life-cycle assessment, carbon footprint analysis, renewable energy integration, waste valorization, and circular bioeconomy approaches to improve environmental sustainability. International collaboration among research institutions, industries, governments, and policymakers will be essential for accelerating commercialization and global adoption of advanced medicinal mushroom technologies.

20. Conclusion

Medicinal mushrooms represent one of the most promising sectors of modern sustainable agriculture because of their exceptional nutritional, medicinal, environmental, and economic importance. Their rich diversity of bioactive compounds, including β -glucans, polysaccharides,

triterpenoids, phenolics, lectins, and peptides, has established them as valuable raw materials for pharmaceutical, nutraceutical, cosmetic, and functional food industries. Increasing global demand for natural healthcare products continues to stimulate commercial cultivation and international trade. Economic cultivation of medicinal mushrooms relies on scientific management of spawn production, substrate preparation, environmental control, crop management, harvesting, post-harvest handling, processing, and marketing. Utilization of agricultural residues as cultivation substrates not only reduces production costs but also promotes waste recycling, environmental conservation, and circular agriculture. Value-added processing into extracts, capsules, powders, beverages, and cosmetics further enhances profitability while extending product shelf life.

Technological innovations including artificial intelligence, Internet of Things, automation, precision farming, biotechnology, and molecular breeding are transforming medicinal mushroom cultivation into an efficient, data-driven agricultural enterprise. Nevertheless, challenges related to contamination, quality spawn production, environmental control, processing infrastructure, quality certification, and market access continue to limit industrial expansion. Future growth of the medicinal mushroom sector will depend on multidisciplinary research, government support, entrepreneurship development, international quality standards, advanced cultivation technologies, and sustainable production practices. By integrating scientific innovation with commercial entrepreneurship, medicinal mushroom cultivation has immense potential to enhance farmers' income, strengthen rural economies, promote environmental sustainability, and contribute significantly to global health and food security.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this review article.

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