The Nutritional And Medicinal Benefits Of Mushroom Cultivation: A Sustainable Approach To Food Security

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Abstract
Mushroom cultivation offers a sustainable and multidimensional approach to strengthening food security under increasing demographic, environmental, and resource pressures. This review evaluates the nutritional, medicinal, environmental, and socioeconomic contributions of mushroom farming within sustainable food systems. Mushrooms provide high-quality proteins, essential amino acids, dietary fiber, B-complex vitamins, vitamin D2, minerals, and antioxidant compounds, supporting dietary diversification and nutritional improvement. Their bioactive constituents, including polysaccharides, β-glucans, triterpenoids, lectins, ergothioneine, and glutathione, contribute to antimicrobial, antiviral, immunomodulatory, anticancer, cardiovascular, neuroprotective, and antidiabetic effects. Mushroom cultivation also supports environmental sustainability by requiring limited land and water, enabling indoor and vertical production, utilizing agricultural and food-processing wastes, reducing landfill burdens, and promoting circular economy practices. Mycelial systems further contribute to organic matter transformation, nutrient cycling, and the development of biodegradable materials. Socioeconomically, mushroom farming offers low-cost livelihood opportunities, supports smallholder participation, encourages rural entrepreneurship, and contributes to women's empowerment. Despite these advantages, wider adoption is constrained by strict cultivation requirements, contamination risks, limited strain improvement, short shelf life, and post-harvest losses. Advances in biotechnology, preservation technologies, value-added products, and supportive policy frameworks can improve scalability and market integration. Overall, mushroom cultivation represents a viable strategy for linking nutrition, health promotion, environmental sustainability, and rural development in future food security programs.

Keywords: Mushroom cultivation, Food security, Functional foods, Circular economy, Medicinal mushrooms

Introduction

Ensuring access to adequate, safe and nutritious food for a growing population is a persistent challenge for many countries around the world, and food security is a key concern. The concept is not confined to food production, but also includes food availability, accessibility, utilization and stability. Although agriculture has seen significant progress in productivity, millions of people are still hungry and malnourished because of environmental, demographic and socio-economic stressors. These challenges have further fueled the quest for sustainable food production systems that can ensure food security without putting excessive strain on natural resources. Mushroom cultivation is a promising method due to its nutritional benefits, efficient use of resources, and sustainable production practices, which can help meet the food security needs of the future (Mc Carthy et al., 2018).

Population growth is continuing to exert strong pressure on the world food system. As food demand continues to grow, the limited availability of agricultural resources has led to concerns over how well traditional farming and production methods will be able to satisfy future food demand in an environmentally sustainable way. Climate change also exacerbates these issues, including current increasing temperatures, irregular precipitation patterns, longer periods of drought and floods, and other extreme weather events, which negatively impact agricultural productivity and food supply stability (Prosekov and Ivanova, 2018). Environmental shocks that affect agricultural production and animal husbandry also exacerbate the vulnerabilities of food systems, thereby raising the chances of food insecurity in many areas (Baum et al., 2016). There has been a decrease in the availability of arable land and freshwater resources as a result of urbanization, land degradation, industrial expansion and unsustainable resource use. The limited availability of land for agriculture and intensified water resource competition are becoming factors limiting agricultural production. These restrictions underscore the importance of novel food production systems that can achieve high food output with low input use (Pandey et al., 2018). Food insecurity is also attributed to unequal food distribution as a significant contributor. While there is enough food available worldwide, low infrastructure, access to the economy, storage facilities and distribution channels make this food not available to those who need it, and many populations suffer from hunger and malnutrition (Sharma, 2018). Conventional farming has its drawbacks, which have been driving increased demand for alternative food systems as a way to improve food system resilience and sustainability. However, alternative protein sources and sustainable foods are gaining attention as key elements in future food security plans, as they can complement traditional food production methods and mitigate environmental impacts. Diversification of food sources can help to increase the stability and adaptability of food systems in the face of changing environmental and economic conditions (Thakur, 2014).

Mushrooms are attractive options among the alternatives, due to their high nutritional content and efficient production process. They can be grown on various agricultural wastes and food wastes, utilising low-value biomass as a source for high-value food. They can be grown under relatively low resource requirements and can be developed to overcome food security issues in resource-poor areas (Patel, 2014).
Mushroom farming has various benefits that make it a good choice for sustainable farming. Edible mushrooms are rich in protein, dietary fibre, vitamins, minerals and bioactive compounds, which augment the nutritional value of the diet and nutritional security. The nutrients they possess contribute to the increasing awareness of mushrooms as functional foods in human health and well-being (Gupta et al., 2018). Besides the nutritional values, mushroom cultivation also has a relatively low impact on the environment and can be based on the use of agricultural and agro-industrial residues as growth substrates. This ability to turn organic wastes into valuable foods means resource recycling, lower levels of environmental pollution, and a contribution to implementing the principles of a circular economy (Grimm and Wösten, 2018). In addition, the growing interest in the edible and medicinal mushroom market and their rapid growth rate increase their economic potential, generating income, jobs and rural development, and promoting food security and sustainable agriculture. The nutritional, medicinal, environmental and economic benefits and potential of mushroom cultivation and how this fits into food security in relation to sustainable agriculture are reviewed.

Nutritional Benefits of Mushrooms

Macronutrient Composition

Mushrooms have been recognized as foods rich in nutrients and containing a well-balanced macronutrient profile, making them an increasingly important food in human nutrition. One of the most important nutritional values of mushrooms is protein, which represents about 20-35% of the dry matter of the mushroom, depending on the mushroom species and growing conditions. Mushroom proteins are a good source of all essential amino acids for human growth and development, tissue repair and metabolism, which makes them an alternative protein source, especially for vegetarian and vegan diets (Kalač, 2013). The protein content of mushrooms has a high biological value, with the digestibility of the protein in mushrooms further improving its value as a potential source of animal protein (Baars, 2017). Carbohydrates are another significant portion of mushroom biomass, which mostly comprises glycolic polysaccharides, glycogen, and chitin. Carbohydrates are important for providing energy and other physiological functions. This is because mushrooms are composed of a unique carbohydrate fraction, which is not found in many conventional food sources and which acts to impart nutrients and functional characteristics to mushrooms (Meghalatha et al., 2014). A second characteristic of mushrooms is the low total amount of fat in the mushroom, and the lipids usually make up a small percentage of dry matter. The lipid fraction is mainly composed of polyunsaturated fatty acids, which have been related to the health benefits of mushrooms for the cardiovascular system and are part of the nutritional value of edible mushrooms (Wang et al., 2014).

Essential Vitamins and Minerals

Mushrooms are a valuable food source for a number of vitamins and are a good source of vitamins that have a normal physiological role. They are also a good source of B-complex vitamins, such as riboflavin (vitamin B2), niacin (vitamin B3), pantothenic acid (vitamin B5), and folate (vitamin B9), which are essential for energy metabolism, nerve function, and cellular growth. Mushrooms are an important source of these vitamins, and their contribution to a balanced diet is important (El-Sayed et al., 2013). One of the few forms of food that can provide this essential nutrient, mushrooms are a unique nutritional feature because they are able to produce vitamin D2 when exposed to UV radiation (Cardwell et al., 2018). Mushrooms' mineral content adds to their nutritional significance. Edible species are rich in minerals such as potassium, phosphorus, copper and other minerals which are essential for metabolic and physiological processes. Potassium is important for fluid balance and cardiovascular health, while phosphorus and copper are crucial for bone development and metabolism (Mallikarjuna et al., 2013). Mushrooms can also absorb trace elements like selenium, an effective antioxidant and immune stimulator. Selenium-enriched mushrooms have attracted a lot of interest as a functional food with an improved nutritional value (Rzymski et al., 2017). Macro- and trace-mineral elements are an important part of the nutritional value of mushrooms, but their concentrations can differ between species and growing conditions (Falandysz and Borovička, 2013).

Dietary Fiber and Gut Health

Mushrooms are an essential nutritional component of dietary fiber and chitin, and β-glucans are the major polysaccharides found in the cell wall of mushrooms. Of particular interest are the prebiotic properties of these compounds, which also have the ability to promote beneficial populations of gut bacteria, favouring digestive health and nutrient use, while β-glucans have been singled out for their prebiotic properties and their capacity to stimulate beneficial gut microbiota populations (Barros et al., 2016; Sari et al., 2017). Mushrooms are a source of fibre, which helps with digestion, promotes a healthy gut microbial community and maintains blood glucose levels. The immune supportive properties of mushroom fibers, with the mechanism of gut microbiome and immune system interaction, extend the physiological roles of these bioactive polysaccharides as well (Vitak et al. 2015).

Antioxidants and Health

The health-promoting characteristics of mushrooms are due to a range of antioxidants. One of the most significant of these is the presence of polyphenols, flavonoids, ergothioneine and glutathione, which all help neutralize the reactive oxygen species and decrease oxidative stress. These compounds have emerged as having a significant role in antioxidant protection of cell components against the oxidative process involved in the ageing and chronic disease process (Kozarski et al., 2015). Two compounds, ergothioneine and glutathione, are especially high in many mushroom varieties and are considered to be unique dietary antioxidants. These antioxidants have been associated with decreased inflammation, a strengthened immune system and protection against neurodegenerative diseases. All these compounds are responsible for the mushroom's increasing number of roles as a functional food in disease prevention and health maintenance (Kalaras et al., 2017).

Nutritional Comparison with Traditional Food Sources

Mushrooms have a number of nutritional properties that set them apart from other foods like meat, milk, and vegetables. While the protein content of mushrooms is normally less than that of other animal foods, they contain good-quality proteins that are easily digested and have an excellent amino acid profile. In addition, they have nutritional benefits because they contain bioactive compounds and dietary fibres, which are almost not found in meat products (Barroetaveña and Toledo, 2016). Mushrooms also have more minerals than most of the vegetables, including selenium and potassium and are a natural source of vitamin D2 after exposure to UV. They are low in calories and rich in nutrients, making them an ideal choice for weight loss and a healthy diet. The anti-obesity and anti-metabolic disease effect was further supported by mushroom consumption, which has been linked to increased satiety and decreased energy intake (Hess et al., 2017). Lactose-free also makes them a good food alternative for those who cannot eat dairy products. Major Nutrients, physiological effects and health benefits of mushrooms are summarised in Table 1.

Table 1. Major nutritional components of mushrooms and their associated health benefits

Nutritional Component	Major Constituents	Nutritional Significance	Health Benefits	Representative Studies
Macronutrients	Proteins (20–35% dry weight), essential amino acids, digestible carbohydrates, polyunsaturated fatty acids	Alternative source of high-quality nutrients	Supports growth, tissue repair, energy metabolism, and cardiovascular health	Kalač (2013); Baars (2017); Meghalatha et al. (2014); Wang et al. (2014)
Vitamins	Riboflavin (B2), niacin (B3), pantothenic acid (B5), folate (B9), vitamin D2	Essential cofactors in metabolic processes	Supports nervous system function, cellular growth, bone health, and immunity	El-Sayed et al. (2013); Cardwell et al. (2018)
Minerals	Potassium, phosphorus, copper, selenium	Important for physiological and metabolic functions	Maintains electrolyte balance, antioxidant defense, and bone health	Mallikarjuna et al. (2013); Rzymski et al. (2017); Falandysz and Borovička (2013)
Dietary Fiber	Chitin and β-glucans	Functional dietary fiber and prebiotic compounds	Improves digestion, gut microbiota composition, immune function, and glycemic regulation	Sari et al. (2017); Barros et al. (2016); Vitak et al. (2015)
Antioxidants and Functional Compounds	Ergothioneine, glutathione, polyphenols, flavonoids	Protects against oxidative damage	Reduces oxidative stress, inflammation, and risk of chronic diseases	Kozarski et al. (2015); Kalaras et al. (2017)
Comparative Nutritional Advantages	High nutrient density, low calories, lactose-free composition	Suitable for diverse dietary patterns	Supports weight management, satiety, and dietary diversification	Barroetaveña and Toledo (2016); Hess et al. (2017)

Mushrooms are rich in quality proteins, dietary fibre, essential vitamins, minerals and bioactive components in a low-calorie food matrix. The specific nutritional profile also highlights their possible use as functional foods in the context of human nutrition, as well as in sustainable food systems to alleviate nutritional deficiencies and enhance overall health. More consumption of mushrooms in human diets could be beneficial for nutrition and potentially help to move towards more sustainable food systems.

Medicinal Properties of Mushrooms

Antimicrobial and Antiviral Properties

Mushrooms are rich in bioactive compounds, which have been proven to have antimicrobial and antiviral properties, offering potential sources of natural therapeutics. Polysaccharides, terpenoids, peptides, phenolics, and glycoproteins are among the most significant compounds with inhibitory activity against different bacterial, fungal, and viral pathogens. The compounds work in various ways, such as disrupting the cell wall of microbes, inhibiting the growth of the microbes and altering the immune response of the host (Sharma et al., 2014). Medicinal mushrooms are a source of interest for researchers because of their antiviral properties, which involve interfering with the virus's ability to replicate and boosting the body's defenses. Polysaccharides and other secondary metabolites have been shown to have antiviral activity by several species of Agaricomycetes, which act as stimulators of antiviral immunity (Teplyakova and Kosogova, 2016). The medicinal mushrooms *Trametes versicolor* (TurkeyTail) and *Ganoderma lucidum* (Reishi) are especially known for their antimicrobial and antiviral properties, due to their high levels of bioactive compounds that play a role in these defense mechanisms (Benkeblia, 2015).

Immunomodulatory Effects

One of the most well-researched medicinal properties of mushrooms is their immunomodulatory effects. The bioactive molecules like β-glucans, triterpenoids, lectins, and polysaccharide-protein complexes are able to interact with the immune cells and modulate both innate and adaptive immune responses. These compounds are able to boost immune competence by stimulating macrophages, dendritic cells, natural killer cells and lymphocytes that recognize pathogens and eliminate them (El Enshasy and Hatti-Kaul, 2013). Immunomodulators derived from mushrooms induce the production of cytokines, enhance the interaction between cells of the immune system, and enhance host defense mechanisms. The improved immune surveillance helps identify and eliminate abnormal or infected cells, promoting disease prevention and boosting immunity. These biological activities have enabled the mushroom components to be used as functional ingredients in the management of immune health (Vitak et al., 2017).

Anticancer Potential

The mushroom has a high anticancer activity because of the presence of bioactive compounds that act on various pathways associated with the formation and advancement of tumors. The polysaccharides, β-glucans, triterpenoids and protein-bound complexes have been found to induce apoptosis, inhibit tumoral cell proliferation, and inhibit the growth of new blood vessels, which are associated with limiting the growth of cancer and metastasis. All of these mechanisms play a role in the protective effect of mushrooms from various types of cancers (Oana et al., 2018). Ganoderma lucidum has garnered special attention as a medicinal species with anticancer properties. Polysaccharides and triterpenoids in Reishi mushrooms have cytotoxic activity against tumor cells and also aid in boosting immune-mediated suppression of tumors. The dual function suggests mushrooms could serve as complementary agents for cancer prevention and therapy (Benkeblia, 2015).

Cardiovascular Benefits

Medicinal mushroom consumption has been linked to several cardiovascular benefits, which are mainly attributed to their role in lipid metabolism, vascular function and oxidative balance. The bioactive compounds in mushrooms may help lower the level of cholesterol in the blood and maintain normal blood pressure. These effects are especially significant in preventing cardiovascular diseases and atherosclerosis risk factors (Abidin et al., 2017). Besides lipid-lowering properties, mushrooms also possess antioxidant properties that help shield the tissues in the vascular system from oxidative stress and inflammation. The enhanced endothelial function and improved circulation also play a role in heart health, making mushrooms a good part of heart-healthy eating (Rathore et al., 2017).

Neuroprotective Effects

Mushrooms possess intriguing neuroprotective benefits, particularly in maintaining cognitive health and preventing neurodegenerative diseases. Hericium erinaceus (Lion's Mane) is especially interesting due to its effect on the production of a protein called nerve growth factor (NGF), which regulates neuronal survival, differentiation and regeneration. Experimental research has shown that Lion's Mane extracts have been beneficial for memory, learning, and cognitive function (Spelman et al., 2017). Ganoderma lucidum also has neuroprotective properties due to its anti-inflammatory and antioxidant properties. Reishi bioactive oligosaccharides and polysaccharides have been found to have protective properties against oxidative stress and neuroinflammation, which are associated with neuronal damage. The mechanisms indicate possible applications of medicinal mushrooms in the prevention and treatment of neurological diseases (Aguirre-Moreno et al., 2013).

Diabetes Management

The medicinal mushrooms have shown potential in managing diabetes, affecting glucose metabolism and regulating insulin, which are crucial in managing diabetes. Polysaccharides from mushrooms promote insulin sensitivity and increase glucose uptake by peripheral tissues, which promotes better glycemic control. These effects help maintain blood glucose control and may contribute to lowering the risk for diabetes-related complications (Vitak et al., 2017). Other advantages are the capacity of mushroom bioactive components to inhibit carbohydrate digestion and absorption, therefore decreasing postprandial hyperglycaemia. Anti-inflammatory properties further contribute to metabolic health by alleviating chronic inflammation, a key factor associated with insulin resistance and type 2 diabetes. The synergic mechanisms indicate the therapeutic value of mushrooms as functional foods in diabetes prevention and treatment (El Enshasy and Hatti-Kaul, 2013). Medicinal mushrooms offer a wide range of bioactive compounds that are beneficial for antimicrobial, antiviral, immunomodulatory, anticancer, cardiovascular, neuroprotective and antidiabetic effects. They possess a multifunctional therapeutic action, thus reflecting the mushroom's increasing value as a functional food and natural health-promoting agent with great potential in the field of preventive and complementary medicine. The key medicinal attributes of mushrooms and the main bioactive compounds that contribute to mushrooms' health-promoting effects are summarized in Figure 1.

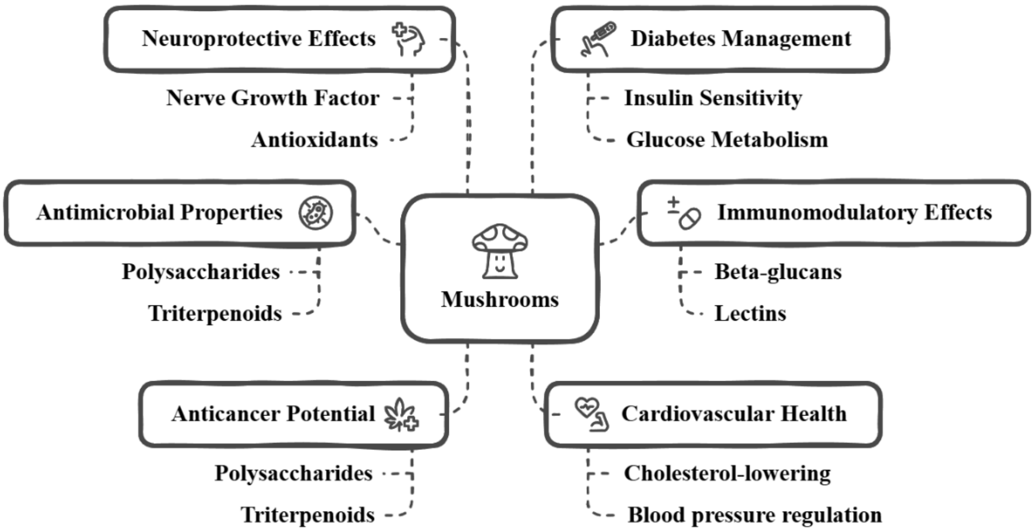

Figure 1. Major medicinal properties of mushrooms and their associated bioactive compounds and physiological effects

Sustainable Aspects of Mushroom Cultivation

Low Resource Requirements

The mushroom farming process is also considered a resource-efficient agriculture as it consumes less land area, less water and less energy as compared to many conventional crops. Mushrooms can be grown in vertical systems of agriculture or indoor production, as opposed to outdoor farming methods, thereby achieving high productivity in a limited space. These models of cultivation are especially well-suited for urban and peri-urban settings where there is limited land for agriculture and the growing season is limited (Higgins et al., 2017). Mushroom production uses relatively little water since mushrooms get most of their moisture needs from the substrate and from the humidity conditions that they need to grow. Optimizing environmental control systems and effective production management can also be a way of optimizing energy demands. Research with commercial mushroom production has shown that careful monitoring of energy inputs can increase the efficiency and sustainability of the production process, and the use of renewable energy technologies can provide further potential reductions in operating costs and environmental impacts (Qasemi-Kordkheili et al., 2013).

Use of Agricultural and Food Waste

The use of agricultural and food-processing wastes for growing mushrooms is one of the greatest sustainability benefits of this practice. Wheat straw, sawdust, coffee grounds, banana leaves and sugarcane bagasse are suitable lignocellulosic materials for fungal growth. The mushrooms use biological conversion processes to convert these low-value material residues to high-value food products, improving resource utilization efficiency (Barshteyn and Krupodorova, 2016). Organic waste materials used in mushroom cultivation promote waste recycling and save a considerable amount of biomass going to the landfill. This practice helps in minimizing environmental pollution and promotes circular economy models focusing on resource recovery and reuse. After the mushroom picking, spent substrates can be further processed to be used in agriculture, thus utilizing the value chain of organic resources and avoiding waste generation (Dittrich, 2016).

Carbon Footprint Reduction

In addition to economic benefits, mushroom production is environmentally beneficial due to its relatively low carbon footprint and reliance on fewer synthetic agricultural chemicals and fertilizers. It has been reported that GHG emissions from food production systems can be substantially reduced through environmental assessments of commercial mushroom production, which involve assessing the substrate management, energy efficiency and waste management of the mushroom production system (Leiva et al., 2017). Fungal mycelium is also important in the decomposition of organic matter and the stabilization of carbon in biological systems. Mycelia networks help in recycling nutrients and sequestration of carbon, and also help to lower the accumulation of agricultural wastes through mycoremediation and organic matter transformation processes. Furthermore, mushroom production does not necessarily involve the use of higher concentrations of pesticides and chemical fertilizer compared to many other crops, thus reducing the risk of contamination of the environment and promoting more sustainable farming methods (Kulshreshtha et al., 2014).

Integration into Agroecological Systems

Agroecological systems that focus on closed-loop production and resource efficiency are suitable for mushroom production. Bio-integrated farming systems offer potential for integrating mushrooms into composting, greenhouse production, aquaponics, and livestock production to promote nutrient cycling and farm sustainability. This integration can be realized in such a way that waste from one part of the system is utilized as a useful resource in another part of the system, which increases productivity and reduces losses of resources (Jadrnicek and Jadrnicek, 2016). The role of mushrooms in the circular economy concepts is not limited to food production. In addition, spent mushroom substrates can be recycled as compost and soil amendment, thereby contributing to waste reuse and avoiding reliance on external agricultural resources (Picornell-Buendía et al., 2016). In addition, mycelium is now being used to make biomaterials as a sustainable alternative to petroleum-based materials. In summary, mycelium-based biodegradable packaging materials hold significant promise for mitigating plastic waste and promoting sustainable packaging solutions. Overall, mycelium-based materials for biodegradable packaging have emerged as a promising solution for reducing plastic waste and fostering more sustainable packaging practices (Abhijith et al., 2018).

Socio-Economic Benefits

The mushroom industry has the potential to contribute to rural development and poverty alleviation due to its low start-up cost, short production period and high profits. These are the reasons why mushroom farming is fit for the smallholder farmers, landless households and rural entrepreneurs who are looking for extra income-generating opportunities. In addition, mushroom growing technologies are adaptable to local conditions, further increasing their potential to be used in community-based agricultural development (Higgins et al., 2017). In addition to income generation, mushroom production can also help in job creation, empowerment of women and entrepreneurship development in rural communities. The value chain of mushroom production, processing, marketing and value-added mushroom products creates opportunities at multiple stages. Beyond that, mushroom-related practices can bring wider socioeconomic effects, both in the sense of local enterprise development and mycotourism, which can boost rural livelihoods and contribute to sustainable community development (Büntgen et al., 2017). In this sense, mushroom growing is a good example of a sustainable practice in agriculture that can be used for both environmental and socio-economic purposes. It utilizes inputs with efficiency, can incorporate organic waste into its system and can support systems of the circular economy and create rural livelihoods, which make it a key element for sustainable food production and resilient agricultural systems. Figure 2 shows that mushroom farming has several key sustainability features and that mushrooms contribute to environmental and socio-economic resilience.

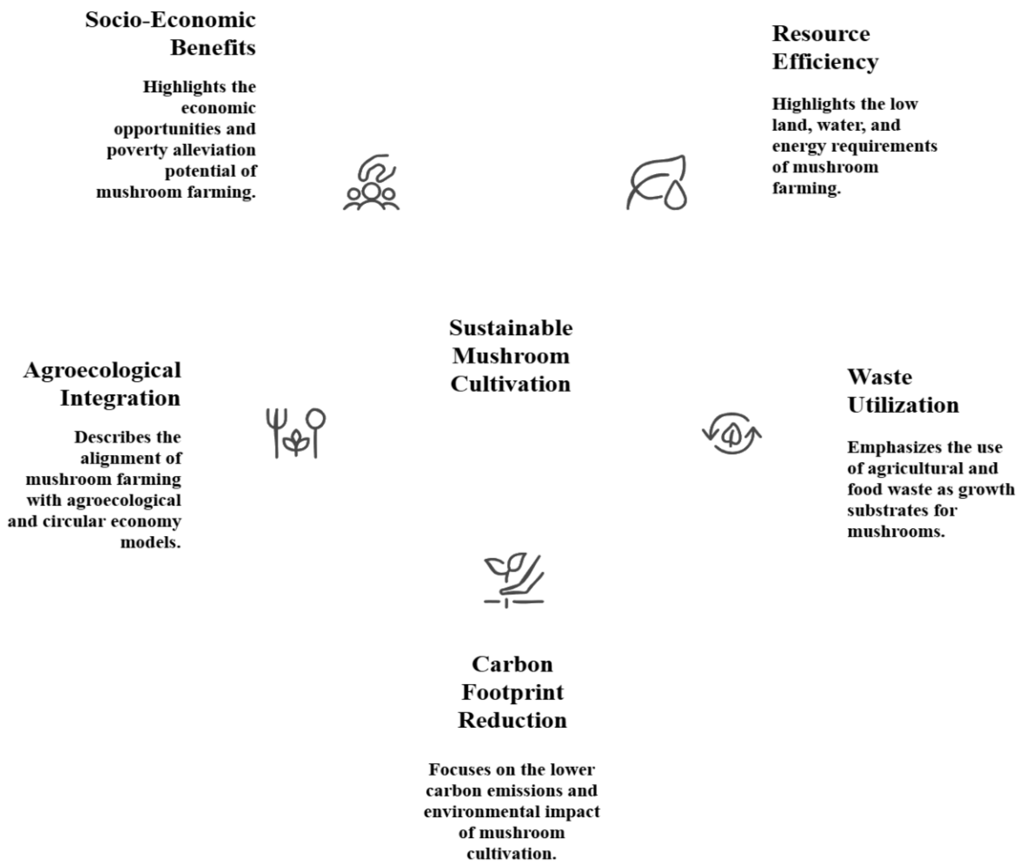

Figure 2. Key sustainability dimensions of mushroom cultivation and their contributions to resource efficiency, environmental protection, and socioeconomic development

Challenges and Future Prospects

Although mushroom cultivation has significant potential to be a sustainable food production system, there are several technical, biological and economic challenges that prevent the widespread adoption and success of mushroom farming on a large scale. Growing conditions should be carefully monitored, such as temperature, humidity, ventilation, and lighting. Mycelial growth, yield and product quality may be seriously affected by even minor deviations from the optimum growing conditions. Increased sensitivity to the environment raises production expenses and can be troublesome for growers with limited resources (Chang and Wasser, 2015). Disease outbreaks and contamination from competing fungi, bacteria, insects, and pests continue to be significant problems in mushroom production systems. Contamination can happen at the substrate preparation period, spawning stage, incubation stage, or fruiting stage, and can cause significant loss of yield and lack of profitability. To manage diseases effectively, good hygiene practices and regular monitoring should be followed, and this may be difficult for small-scale producers (Chang and Wasser, 2015).

Limited research is also a challenge to mushroom cultivation. Research on mushroom genetics, breeding and strain improvement has been relatively minimal, as compared to major food crops. The relatively small number of genetically enhanced strains available limits the possibilities for breeding for greater productivity, disease resistance, adaptability to the environment and nutritional content. Therefore, increased investment in research and development of mushrooms, in the field of fungal biotechnology and breeding, is needed in order to encourage the future mushroom industry (Wasser, 2014). Another challenge is post-harvest management due to the short shelf-life and high moisture content of mushrooms. During storage and transport, fresh mushrooms are very vulnerable to microbial spoilage, enzymatic browning, texture breakdown and moisture loss. The above traits pose challenges in ensuring quality, extending shelf-life and minimizing post-harvest losses, especially in areas lacking cold-chain facilities (Thakur, 2018).

The use of biotechnology has great potential to enhance mushroom production and to increase its role in food security. New techniques like genome editing, molecular breeding and strain selection can aid in the production of better mushrooms that are more resistant to diseases and stress, and have higher productivity and nutritional values. These innovations could contribute to more efficient cultivation and sustainable growth of mushroom production systems (Wasser, 2014). Enhanced preservation technologies are also likely to be very important in overcoming post-harvest constraints. The application of modified atmosphere packaging, freeze drying and edible coatings is an important tool that can provide good extension of shelf life without compromising the nutritional quality and sensory properties. There will be further innovation in post-harvest processing and value addition, which will help to improve the market accessibility and minimize the economic loss due to spoilage (Thakur, 2018).

From a market standpoint, the commercial potential of functional foods, nutraceuticals and medicinal mushroom food products is great. As the awareness of the health benefits of mushrooms has grown, mushroom supplementation, mushroom extracts with beneficial bioactive compounds, and value-added food products are garnering more interest from consumers. Further, product development and commercialization in the mushroom industry will be facilitated by standardization of the nutritional quality and biological activity evaluation procedure (Balan et al., 2018). Sustainable development and food security will require policy support in order to maximise the contribution of mushroom cultivation. Promoting mushroom cultivation at the smallholder level and among vulnerable groups of farmers could be promoted through mushroom farming in food security programmes, rural development projects and sustainable agriculture practices. Training, financial support, infrastructure development and extension support provided by the government can enhance production systems and provide opportunities for job creation and entrepreneurship (Shahi et al., 2018). Table 2 summarizes some of the major challenges and future opportunities in mushroom cultivation.

Table 2. Major challenges and future opportunities in mushroom cultivation.

Category	**Key Aspect**	**Major Issues/Developments**	**Expected Impact**	**Representative Studies**
Production Challenges	Environmental requirements and contamination	Strict control of temperature, humidity, aeration, and disease management	Improved productivity and reduced crop losses	Chang and Wasser (2015)
Research Challenges	Genetic improvement and strain development	Limited breeding programs and availability of improved strains	Enhanced yield, disease resistance, and adaptability	Wasser (2014)
Post-Harvest Challenges	Shelf-life and storage limitations	High moisture content, spoilage, browning, and quality deterioration	Reduced post-harvest losses and improved marketability	Thakur (2018)
Biotechnological Opportunities	Genome editing and molecular breeding	Development of superior cultivars with improved traits	Increased cultivation efficiency and sustainability	Wasser (2014)
Market and Policy Opportunities	Functional foods, nutraceuticals, and policy support	Expansion of value-added products and integration into food security initiatives	Greater commercial growth and rural development	Balan et al. (2018); Shahi et al. (2018)

The future of mushroom farming is about developing scientific innovations, post-harvest technology, diversifying markets and supporting policy mechanisms. To realize the potential of mushrooms as a sustainable food, health and livelihood source in future food systems, existing production limitations need to be overcome and new mushroom technologies need to be tapped.

Conclusion

Relying on the mushroom industry provides a robust sustainable approach to food security, with health and resilience to the environment. Mushrooms contain high-quality protein, dietary fiber, essential vitamins, minerals and bioactive compounds which not only contribute to dietary diversity but also the nutrition deficiency issues as well. The medicinal use, which is associated to antimicrobial, immunomodulatory, anticancer, cardiovascular, neuroprotective and antidiabetic effects further enhance their status as functional foods. In addition to nutrition and health, mushroom cultivation fosters the adoption of resource efficient farming practices, including minimum land and water needs, utilization of agricultural wastes, reduction of environmental impacts and circular economy. It also provides concrete economic benefits such as job creation, small businesses, and rural living. Biotechnology, preservation techniques, development of value added products, and policy support can help enhance scalability and commercial viability, although cultivation control and contamination issues, as well as limited strain improvement and post harvest losses, are challenges. The potential to improve nutrition, health promotion, environmental protection and socioeconomic development through integrating mushroom cultivation into sustainable agriculture and food security programs is important.

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