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# Mushrooms as a Climate Change Solution: Expanding Production and Consumption in a Warming World

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## Abstract

Climate change is increasingly destabilizing global agricultural systems through rising temperatures, water scarcity, extreme weather events, and declining soil productivity. These pressures threaten global food security and intensify the need for sustainable, climate-resilient food production systems. Edible mushrooms represent a promising solution because of their high biological efficiency, low land and water requirements, adaptability to controlled cultivation environments, and capacity to convert agricultural and agro-industrial residues into nutrient-rich food biomass. This mini review examines the emerging role of mushrooms in sustainable agriculture and climate adaptation strategies. Recent advances in cultivation technologies, substrate innovation, waste valorization, post-harvest preservation, and mushroom-based functional foods are reviewed. The article also discusses major economic, technological, and sociocultural barriers limiting the expansion of mushroom production and consumption. In addition, the role of mushrooms in circular bioeconomy systems, alternative protein development, and rural economic resilience is highlighted. Strengthening research, infrastructure, producer training, and supportive policy frameworks will be essential for integrating mushroom production into future climate-smart agricultural systems. Mushrooms have the potential to transition from a specialty crop to an increasingly important component of sustainable global food systems.

## Keywords

Mushrooms, Climate Change, Sustainable Agriculture, Food Security, Circular Economy, Waste Valorization, Functional Foods, Alternative Proteins, Controlled-Environment Agriculture

## 1. Introduction

Climate change is exerting increasing pressure on global agricultural systems and food supply chains. Rising temperatures, prolonged droughts, unpredictable rainfall patterns, flooding events, and soil degradation are reducing agricultural productivity in many regions of the world (IPCC Climate Change, 2022). At the same time, the global population continues to grow, increasing demand for food, water, land, and energy resources (FAO, 2021). These combined pressures are intensifying the search for sustainable and climate-resilient food production systems capable of maintaining productivity while minimizing environmental impacts.

Conventional livestock and crop production systems are associated with substantial greenhouse gas emissions, high water consumption, land degradation, and biodiversity loss. Consequently, considerable attention has shifted toward alternative food systems that can improve resource-use efficiency and reduce environmental footprints. Among these alternatives, edible mushrooms have emerged as a particularly promising agricultural commodity because of their unique biological and ecological characteristics.

Unlike conventional field crops, mushrooms can be cultivated indoors under controlled environmental conditions, making production less dependent on seasonal variability and adverse climatic conditions (Chang & Wasser, 2017). Mushroom cultivation requires relatively small land areas and comparatively low water inputs while achieving high biological conversion efficiencies. In addition, mushrooms can utilize lignocellulosic agricultural residues and agro-industrial byproducts as cultivation substrates, thereby transforming low-value organic waste streams into high-value nutritional products (Grimm & Wösten, 2018).

Global demand for edible mushrooms has increased steadily during the past two decades due to growing consumer interest in healthy diets, sustainable foods, and plant-based protein alternatives. Mushrooms are recognized not only for their nutritional value but also for their bioactive compounds with antioxidant, anti-inflammatory, immunomodulatory, and medicinal properties (Valverde et al., 2015; Sharma et al., 2024; Pawde et al., 2026). Recent advances in mushroom cultivation technologies, automation, substrate optimization, and food processing are further expanding the economic and industrial potential of the sector.

This mini-review examines the role of edible mushrooms as a climate-resilient food source and evaluates their contribution to sustainable agriculture, circular bioeconomy systems, and food security. The review focuses on recent developments in production technologies, waste valorization, post-harvest management, nutritional applications, consumer trends, and policy considerations relevant to expanding mushroom production and consumption in a warming world. To evaluate the existing knowledge in these fields, databases of scientific/professional publications were searched and examined.

## 2. Mushrooms as Climate-Resilient Food Systems

Edible mushrooms possess several characteristics that make them highly suitable for climate-resilient agriculture. Unlike conventional crops that depend heavily on soil quality, rainfall, and seasonal climatic conditions, mushrooms are cultivated in controlled indoor environments where temperature, humidity, ventilation, and light can be regulated with precision (Chang & Wasser, 2017). This controlled-environment production system substantially reduces vulnerability to droughts, heatwaves, flooding, and other climate-related disruptions that increasingly affect open-field agriculture. For these reasons, mushroom cultivation allows adaptation to (adversely) changing climate conditions and therefore can be considered as climate resilient food production systems.

The ratio between output and input in a biological system is considered as biological efficiency. Mushroom production demonstrates high values of biological efficiency because the use of the main inputs in agriculture: land and water for their production, is minimal (Levanon & Danai, 2026). Many cultivated mushroom species can convert agricultural residues into protein rich edible biomass with remarkable efficiency compared to traditional livestock production systems. As mentioned above, mushrooms production requires significantly less land and water than animal protein sources, contributing to lower environmental impacts and improved resource-use efficiency (Francis et al., 2026).

The short production cycle of mushrooms represents another important advantage. Depending on the species and cultivation system, harvest cycles may range from several weeks to a few months, allowing rapid adaptation to market demand and production planning. Such flexibility may become increasingly important under unstable climatic and economic conditions (Marshall & Nair, 2009).

Nevertheless, climate change may also affect mushroom cultivation systems indirectly through increased energy requirements for cooling and environmental control, fluctuations in substrate availability, and the emergence of pests and diseases. Temperature instability and altered humidity conditions can negatively influence mushroom yield and quality, particularly in regions lacking advanced environmental control technologies (Karunarathna et al., 2026). Consequently, future research should focus on the development of climate-resilient mushroom strains, improved cultivation technologies, and energy-efficient production systems.

## 3. Circular Economy and Agricultural Waste Valorization

The most important sustainability advantage of mushroom cultivation is its compatibility with circular economy principles. Mushrooms can grow on a wide range of lignocellulosic agricultural waste materials, including wheat straw, rice straw, corn cobs, sawdust, cotton waste, sugarcane bagasse, olive mill solid waste (OMSW), coffee residues, and other agricultural byproducts that are often underutilized or discarded. Recent study revealed that OMSW, which is an environmentally polluting recycling resource, when used as a substrate for fungi, acts as a modulator of health-promoting compounds synthesis by the fungus *P. eryngii*. (Ezov et al., 2025). Therefore, mushrooms cultivation is minimizing/avoiding the need for these wastes' disposal (Sánchez, 2010). Another important contribution to sustainability is the minimum land and water needed for mushroom cultivation compared to other crops (Levanon & Danai, 2026).

The bioconversion of agricultural waste into edible biomass provides multiple environmental benefits. First, it reduces the accumulation and disposal of organic residues that may otherwise contribute to environmental pollution or greenhouse gas emissions through decomposition or open burning. Second, it increases the economic value of agricultural waste streams by transforming them into marketable food products. Third, it improves resource efficiency by recycling nutrients within agricultural systems (Jasińska, 2023).

Recent studies have emphasized the integration of mushroom cultivation into broader circular bioeconomy frameworks in which agricultural residues are sequentially utilized for food production, animal feed, composting, biofertilizers, and bioenergy generation. Such integrated systems can contribute significantly to sustainable rural development and climate mitigation strategies (Ezov et al., 2025).

Spent mushroom substrate (SMS), the residual material remaining after mushroom harvest, represents an additional opportunity for waste recycling and nutrient recovery. SMS contains organic matter, microbial biomass, and residual nutrients that may be reused as soil amendments, organic fertilizers, livestock feed supplements, or substrates for additional agricultural and industrial applications (Grimm & Wösten, 2018). The development of efficient recycling strategies for SMS could further enhance the environmental sustainability of mushroom production systems.

## 4. Advances in Substrate Innovation

Substrate composition plays a critical role in determining mushroom productivity, biological efficiency, nutritional quality, and production economics. Traditional substrates such as straw and sawdust remain widely used; however, increasing attention has focused on alternative and locally available waste materials that may reduce production costs and improve sustainability.

Recent research has explored the use of agro-industrial residues, food-processing wastes, olive mill wastewater byproducts, brewery wastes, paper residues, and urban organic wastes as alternative substrate components (Zhou et al., 2025). Such diversification can improve substrate availability while simultaneously reducing environmental burdens associated with waste disposal.

The use of region-specific agricultural residues may be particularly important for expanding mushroom production in developing regions and peripheral agricultural areas. Locally adapted substrate formulations can reduce transportation costs, increase sustainability, and support regional circular economy systems.

Despite these advantages, substrate diversification also presents technical and safety challenges. Variability in chemical composition, contamination risks, heavy metals, pesticide residues, and inconsistent physical properties may affect mushroom growth and food safety. Therefore, careful substrate characterization, sterilization protocols, and quality-control measures remain essential for commercial production systems.

Future research should focus on optimizing substrate formulations, improving microbial management, and developing standardized methodologies for evaluating alternative waste-based substrates.

## 5. Post-Harvest Technologies and Supply Chain Challenges

Fresh mushrooms are highly perishable because of their high moisture content, rapid respiration rates, and delicate tissue structure. Consequently, post-harvest deterioration represents a major constraint limiting market expansion and increasing economic losses throughout the supply chain (Singh et al., 2010).

Quality deterioration during storage includes discoloration, texture softening, microbial contamination, moisture loss, and nutrient degradation. Effective post-harvest management is therefore essential for maintaining product quality and extending self-life.

Recent technological advances in packaging systems, modified-atmosphere storage, refrigeration technologies, edible coatings, and dehydration methods have improved the preservation and transportation of fresh mushrooms. In addition, value-added processing technologies such as drying, powder production, extraction of bioactive compounds, and development of mushroom-based food ingredients are expanding commercial opportunities and reducing post-harvest losses.

Processing technologies are especially important in regions lacking advanced cold-chain infrastructure. Dried and powdered mushroom products possess longer shelf life, reduced transportation costs, and broader applicability in food formulations, dietary supplements, and functional foods.

Further improvements in logistics, packaging materials, cold storage infrastructure, and decentralized processing systems will be critical for supporting large-scale market growth and international distribution.

## 6. Nutritional and Functional Food Potential

Edible mushrooms are increasingly recognized as valuable functional foods because of their nutritional composition and bioactive properties. Mushrooms contain high-quality proteins, dietary fiber, essential amino acids, vitamins, minerals, and relatively low-fat levels (Valverde et al., 2015). They are particularly rich in B vitamins, potassium, selenium, copper, and bioactive polysaccharides such as beta-glucans.

Numerous studies have demonstrated antioxidant, anti-inflammatory, antimicrobial, cholesterol-lowering, immunomodulatory, and anticancer activities associated with mushroom-derived compounds (Sharma et al., 2024). These properties have stimulated growing interest in mushrooms as nutraceuticals and health-promoting dietary ingredients.

The global expansion of plant-based diets has further increased interest in mushrooms as alternative protein sources and meat substitutes. Mushrooms possess desirable umami flavor characteristics and fibrous textures that make them suitable ingredients for meat analogs, blended foods, and functional snack products (Pawde et al., 2026).

Advances in breeding, strain selection, cultivation management, and post-harvest processing may further improve the nutritional quality and functional properties of edible mushrooms. Future research should focus on enhancing bioactive compound production, improving digestibility, and optimizing mushroom-based food formulations.

## 7. Consumer Acceptance and Market Development

Global mushroom consumption has increased steadily in response to growing interest in healthy foods, vegetarian and flexitarian diets, and environmentally sustainable agricultural products. Nevertheless, substantial regional differences in mushroom consumption patterns remain due to cultural preferences, culinary traditions, consumer awareness, and product availability.

In many countries, mushroom consumption remains limited by insufficient product diversity, high retail prices, inconsistent quality, and limited consumer familiarity with specialty mushroom species. Consumer education regarding the nutritional and environmental benefits of mushrooms may therefore play an important role in market expansion.

Recent innovations in mushroom-based foods, including meat alternatives, beverages, nutritional supplements, snack products, and functional ingredients, are diversifying market opportunities and attracting new consumer groups (Pawde et al., 2026). The incorporation of mushrooms into mainstream food products may help increase acceptance among consumers unfamiliar with traditional mushroom cuisine.

Marketing strategies emphasizing sustainability, health benefits, and climate-friendly food production may further support consumption growth, particularly among younger and environmentally conscious consumers.

## 8. Economic and Technological Barriers

Despite growing interest in mushroom cultivation, several economic and technological barriers continue to limit industry expansion. Commercial mushroom production often requires substantial investments in infrastructure, environmental control systems, sterilization equipment, and cold storage facilities (Marshall & Nair, 2009). Energy costs associated with temperature regulation and ventilation may be particularly significant in warm climates.

Technical expertise also represents an important limitation. Successful mushroom cultivation requires specialized knowledge regarding substrate preparation, environmental management, contamination control, harvesting, and post-harvest handling. Limited access to training and extension services may constrain adoption, particularly among small-scale producers.

Automation and smart farming technologies are increasingly improving production efficiency, labor management, and environmental control (Badoni &

Siddiqui, 2025). However, these technologies remain unevenly distributed and are often inaccessible to small and medium-sized producers because of high capital costs.

Research gaps also remain regarding climate adaptation, low-energy cultivation systems, decentralized production models, and region-specific technological solutions. Expanding research collaborations between academic institutions, industry, and regional innovation centers may accelerate technological development and improve accessibility.

There is a significant difference in consumption of mushrooms and their cultivation methods between different species of edible mushrooms. These differences are based on different traditional consumption habits between regions/continents of the world. In general, in Western countries (mainly Europe the US), most of the cultivated and consumed mushrooms are of the species *Agaricus bisporus*, known as "White button mushrooms", while in Asian countries (China, Japan etc.), the most popular species are *Pleurotus ostreatus* known as "Oyster mushrooms" and *Lentinula edodes* known as "Shii Take". The cultivation of these different species is of course done, using different methods adapted to each of them (Chang & Hayes, 2013). However, everything that has been mentioned so far about the advantages of mushrooms cultivation, compared to other agricultural crops, is true for these three species and other edible mushroom species.

## 9. Policy and Rural Development Implications

Mushroom production has important implications for sustainable rural development, particularly in peripheral agricultural regions facing limitations in land, water availability, and economic diversification. Because mushroom cultivation requires relatively small production areas and can utilize locally available agricultural residues, it may provide valuable opportunities for small-scale farmers and rural entrepreneurs.

Supportive public policies can significantly accelerate the development of mushroom-based agricultural systems. Investments in research infrastructure, vocational training, extension programs, renewable energy integration, and post-harvest logistics may strengthen regional mushroom industries and improve economic resilience.

Mushroom cultivation may also contribute to climate-smart agricultural policies by reducing agricultural waste, lowering greenhouse gas emissions, and promoting circular bioeconomy systems. Integrating mushrooms into broader food security and sustainability strategies could therefore support national and international climate adaptation goals (Mishra & Shankar, 2025).

Experiences from regional development initiatives, including the Galilee mushroom industry in northern Israel, demonstrate the importance of institutional coordination, applied research, technology transfer, and producer support systems in building successful mushroom industries in peripheral regions (Levanon & Danai, 2026).

## 10. Conclusion

Edible mushrooms represent a highly promising component of future climate-resilient food systems. Their ability to grow on agricultural waste streams, low environmental footprint, adaptability to controlled-environment agriculture, and substantial nutritional value position them as an increasingly important agricultural commodity in a warming world (Ezov et al., 2025).

Mushroom cultivation aligns closely with the principles of sustainable agriculture and circular bioeconomy systems by promoting waste valorization, nutrient recycling, and efficient resource utilization. In addition, the growing demand for healthy foods, alternative proteins and health-promoting materials, is creating new opportunities for expanding mushroom production and consumption globally.

However, achieving the full potential of mushroom-based food systems will require overcoming significant technological, economic, and socio-cultural barriers. Future progress depends on continued advances in cultivation technologies, energy-efficient production systems, post-harvest preservation, substrate innovation, and market development.

Coordinated efforts among researchers, policymakers, industry stakeholders, and agricultural extension systems will be essential for integrating mushrooms into mainstream climate-smart agriculture strategies. With appropriate investment, innovation, and policy support, mushrooms can evolve from a specialty agricultural product into a major contributor to sustainable food security and rural economic resilience in the twenty-first century.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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