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Valorization of agricultural waste for sustainable mushroom cultivation: A comprehensive review with special reference to India and Punjab

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Abstract

Mushroom growing is a great way to be environmentally friendly and to grow food that is both high-value and nutritious. There are many types of waste produced from agriculture, such as paddy straw, wheat straw, maize, and sugarcane bagasse, that can all be used as material for growing mushrooms; they are inexpensive, plentiful, and contain high amounts of both cellulose and lignin. Using waste this way not only produces food for edible biomass but increases the amount of use that can be used from these resources and helps both with waste management and with reducing pollution in the environment. The yield, biological efficiency, and nutritional quality of mushrooms are all greatly affected by the type of waste used for substrate as well as by environmental factors and methods used for growing mushrooms. This document provides a detailed evaluation of how agro-waste material has been used to grow mushrooms, how they were grown, factors that affect productivity, and whether or not there is any sustainable value in mushroom production, focusing primarily on the Punjab area in India. In addition, this report reviews the potential use of mushroom production both economically and environmentally, as well as the potential growth of mushroom production in the future. It has been shown that, if the substrate materials are optimally managed, and successful growing methods used, mushroom production can produce biological efficiencies greater than 100%. Consequently, mushroom production is a good method to promote sustainable practices within agriculture and to develop a circular economy in production of food within agriculture.

Keywords: Agro-waste, biological efficiency, mushroom cultivation, sustainability.

1. Introduction

As the world's agricultural industry has been experiencing significant growth over the past few decades, the resultant increase in agricultural residual (crop) material is creating a rapidly expanding management problem. In countries like India, many farmers still commonly practice the open burning of crop residuals. This method produces significant amounts of air pollution from smoke and toxins, increases greenhouse gas emissions, and reduces the availability of soil nutrients. Thus, there is an urgent necessity for the development of sustainable and environmentally responsible alternatives to managing agricultural waste. The use of lignocellulosic (plant-based) agricultural residuals as a growth medium for the cultivation of edible mushrooms has been identified as one viable option for managing agricultural wastes ^[1, 2].

Mushrooms are one of the most nutritious food sources available, having an array of protein, vitamin and mineral nutrients present and other bioactive substances which are known to have healing properties ^[12, 18]. There are numerous varieties of cultivated mushrooms; however, oyster mushrooms (*Pleurotus* spp.) and button mushrooms (*Agaricus bisporus*) make up nearly 98% of global production in the mushroom industry. This high output level is due to their adaptability to various growing environments; their rapid production cycle (i.e., from planting to harvest/market ready in 3-8 weeks), and high levels of

consumer demand for both products ^[8].

Additionally, these fungi produce enzymes which enable the breakdown of complex organic material such as cellulose, hemicellulose, and lignin; thus, these fungi are capable of growing rapidly on multiple sources of agricultural waste ^[13, 14]. The cultivation of mushrooms is a key component of sustainable agriculture: recycling agro-residues, reducing pollution, and creating additional income for farmers. The circular economy concept promotes this type of operation by converting low-value waste products into high-value food items. With increasing consumer demand for nutritional and functional foods, mushroom cultivation will become increasingly popular as an alternative to traditional farming practices.

Around the world, mushrooms are becoming more popular in terms of production, increasing from less than 5 million mt in the 1980s to now producing over 40 million mt ^[27]. Of the nearly 40 mt produced across the world, China produces more than 70% of them and ranks first in terms of volume produced, with other countries such as the USA, the Netherlands, and India contributing to the remaining volumes produced. While India has a number of environmental advantages such as climatic and availability of agricultural by-products that would lead to the growth of the mushroom industry, the amount produced in India is relatively low compared to world production; therefore, there is considerable room for growth in the mushroom

industry in India [8].

The increased demand for plant-based protein as well as functional foods has led to the growing relevance of mushrooms in today's diets and developing the future food systems that will be sustainable. Therefore, this review is focused on examining the agricultural waste valorization possibilities for producing mushrooms sustainably, particularly in India and Punjab.

2. Agro-Waste as Substrate for Mushroom Cultivation

Agricultural residues (waste) provide an excellent substrate for growing mushrooms since most agricultural waste

consists of lignocellulosic materials that contain the required nutrients to support fungal growth. Some of the most common agricultural residues used for growing mushrooms are paddy straw (rice), wheat straw, corn cob, sugarcane bagasse, wood sawdust, and cotton garbage (in pounds) [1], [2]. Plant material also contains three primary components, i.e., cellulose, hemicellulose, and lignin. To grow, fungi release enzymes that help deconstruct the various components of these plant sources into their constituent sugars so that the fungi can obtain energy through both mycelial growth and fruiting body development (i.e., mushrooms).

Table 1: Common agricultural wastes used as substrates for mushroom cultivation and their suitability.

S. No.	Agro-Waste Material	Major Components	Suitability	Remarks
1	Paddy straw	Cellulose, lignin	Excellent	Most widely used in India
2	Wheat straw	Cellulose, hemicellulose	Excellent	High biological efficiency
3	Sugarcane bagasse	Fiber, lignin	Good	Requires supplementation
4	Maize cobs	Hemicellulose	Good	Good aeration
5	Sawdust	Lignin-rich	Moderate	Used for specialty mushrooms
6	Cotton waste	Cellulose	Good	High water retention

In India, the predominant substrates for mushroom production are paddy straw and wheat straw due to the availability of these substrates and their suitability for producing high yields of mushrooms [7]. Many researchers indicate that the composition of a substrate greatly impacts colonization rates of the substrate, yields of mushrooms produced on that substrate, and the biological efficiency of that substrate [6]. Some researchers have demonstrated that wheat straw outperforms other substrate types (when raised under comparative conditions) in terms of yield primarily due to its superior physical characteristics and nutrient concentration.

products from agricultural and industrial sources to enhance agricultural production and allocate waste products more efficiently to create a more sustainable form of food production. The cultivation of mushrooms can also be accomplished through the combined use of substrate types that will increase both the quantity of mushrooms grown and provide a method to better utilize waste materials. In addition, the efficiency of using agro-waste in mushroom cultivation is dependent on how the substrate material is treated before it is inoculated with mycelium and how it is formulated. For example, physical methods of treatment (chop and soak) can help to improve the amount of water absorbed by the substrate; thermal methods of treatment (pasteurization) can lower the number of microorganisms on the substrate, making it more suitable for growth. In addition, having a carbon:nitrogen (C:N) ratio in the substrate of between 25:1 and 30:1 is critical for determining the amount of mycelium produced and yield of mushrooms produced. In order to have an ideal environment for fungiculture, there must be a balance of the nutrients present in the substrate which will allow for optimum use of nutrient resources and maximum biological efficiency in relation to nutrition.

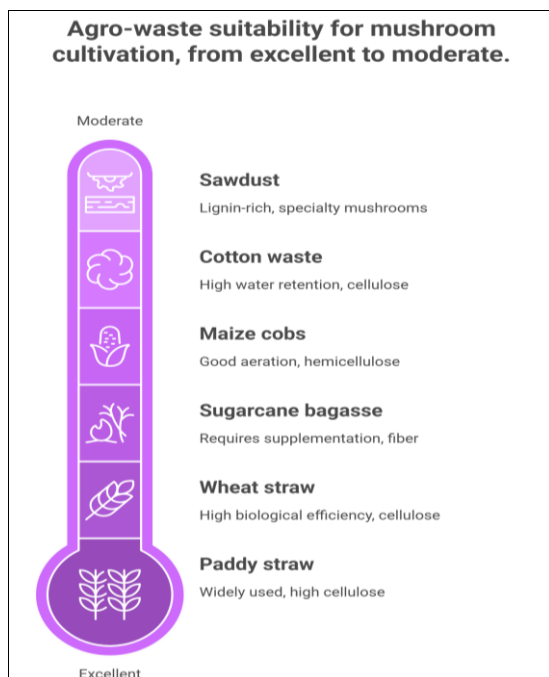


Fig 1: Different Agro-Waste as Substrate for Mushroom Cultivation

Recent studies have explored how to reduce reliance on a single type of substrate by using mixed substrates/waste

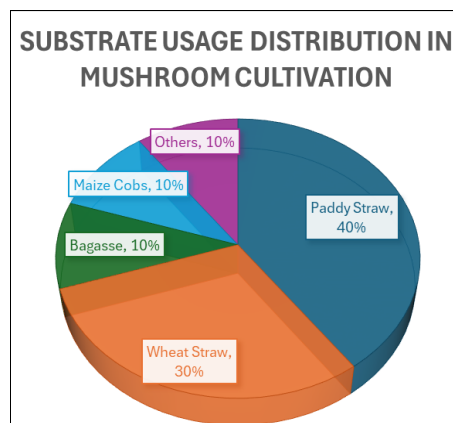


Fig 2: Distribution of commonly used agro-waste substrates in mushroom cultivation.

The substrates used in growing mushrooms typically have 30–50% cellulose, 20–30% hemicellulose, and 10–25% lignin content and provide a source of carbon and energy for the mushrooms to grow. Mushrooms break down these components, demonstrating that they are natural decomposers and proficient recyclers of organic materials.

3. Cultivation Techniques

There are three key areas that play major roles in successful mushroom cultivation: (1) substrate preparation and (2) environmental controls and (3) production management. All methods of treating substrates (pasteurization, sterilization or use of chemicals) must be able to eradicate any

contaminating microorganisms and allow for the optimal development of healthy and rapid growing mycelia ^[1]. The most common method of treating a substrate is to pasteurize it with either steam or hot water, and to disinfect the substrate with a chemical disinfectant (formalin). Mushroom cultivation presents the opportunity to create and/or maintain optimal environmental conditions to produce mushrooms. Temperature, humidity, ventilation and light all impact the development of the mycelium and the fruiting of the mushrooms. The ideal moisture content of the substrate for optimum water/nutrient uptake and fastest growth rate of mushrooms is 60–70%.

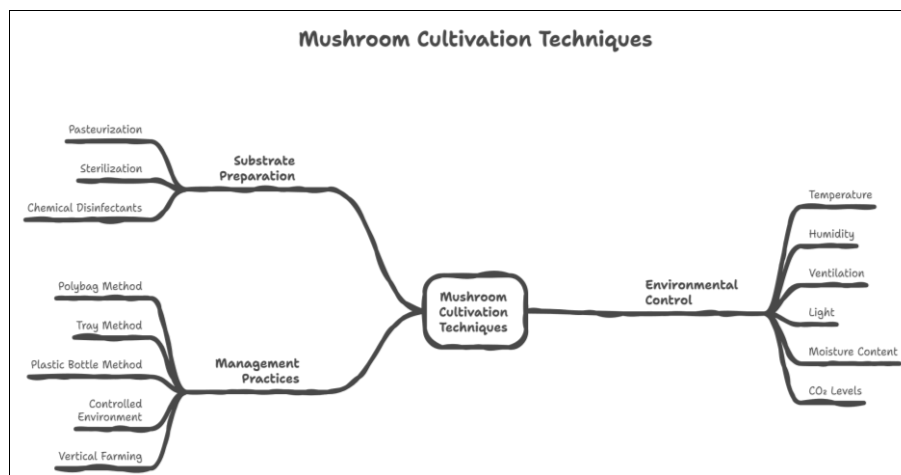


Fig 3: Mushroom cultivation techniques

Advancements in modern mushroom farming have included the use of Controlled Environment Systems, which allow for year-round cultivation and improved yields. The use of controlled environment systems allows for highly controlled conditions (temperature, humidity, and carbon dioxide concentration) when raising mushrooms. During fruiting, levels of Carbon Dioxide (CO₂) can affect the size and shape of the fruiting bodies and should be kept below 1000 ppm for optimal growth; when CO₂ levels are too high, the

resulting fruit bodies will have long stems and small caps. Automated ventilation and misting systems have been added to many commercial operations, which have helped maintain consistent production and high-quality crops. Though more capital investment is required to have installed Controlled Environment Systems and additional technical expertise is needed, the type of mushroom farming used should depend on the volume of expected production as well as available resources.

Table 2: Comparison of different mushroom cultivation methods.

S. No.	Method	Advantages	Limitations
1	Polybag method	Low cost, widely used	Higher contamination risk
2	Tray method	Easy handling	Requires space
3	Plastic bottle method	Better aeration, uniform growth	Initial setup required
4	Controlled environment	High yield, year-round production	High investment

Also, in urban areas where space is limited due to the density of the population, vertical farming systems are becoming increasingly popular. Vertical farming systems use multiple growing layers to produce more crops in less land. Controlled Environment Agriculture (CEA) has also allowed mushroom growers to produce crops year-round, and have eliminated seasonality from producing mushrooms, allowing for consistent mushroom supplies in the marketplace.

4. Biological Efficiency and Yield Performance

Mushroom-growing systems can be evaluated regarding their productivity, as measured by the effectiveness of

mushroom-growing systems for producing mushrooms. One accepted method of defining productivity is the Biological Efficiency (BE) of mushroom-growing systems. Biological Efficiency is determined by the ratio of the weight of a fresh mushroom to the weight of the dry substrate (expressed in percentages) ^[5]. The higher the Biological Efficiency, the better the use and productivity of the substrate material. The Biological Efficiency of mushrooms can range between 70% - 130%, depending on the nature of the growing substrate used, the characteristics of the mushrooms produced, and the growing conditions involved in producing them ^[6]. Wheat straw produces the highest Biological Efficiency among all of the other available substrate

materials, and when wheat straw substrate is combined with other substrate materials or supplemented with nutrients, Biological Efficiency increases further [3]. To obtain maximum yield, other factors such as spawn quality, environmental conditions, and the management of growing

mushrooms must also be considered, as these factors greatly affect yield. When using quality spawn and optimal environmental control, the use of quality spawn will produce higher yields than with poor spawn.

Table 3: Influence of different substrates on biological efficiency of mushroom cultivation.

S. No.	Substrate Type	Mushroom Species	Biological Efficiency (%)	Reference
1	Paddy straw	<i>Pleurotus</i> spp.	70–120	[5]
2	Wheat straw	<i>Pleurotus</i> spp.	90–124	[6]
3	Mixed substrate	<i>Pleurotus</i> spp.	100–130	[3]
4	Sawdust + bran	<i>Pleurotus ostreatus</i>	110–135	[21]

Research has been done that illustrates improvements in Biological Efficiency through supplementing techniques and optimal growing conditions. An example of this is the addition of nitrogen-containing supplements such as wheat bran at 10-20% levels will result in a yield increase of 20-30% [5]. In similar ways, pre-treatment processes such as composting and/or fermentation enhance both the digestibility of the substrate utilized as well as promoting the potential for fungal growth onto those substrates. Research has been directed toward the examination of

enzyme activities: i.e., cellulase, ligninase and xylanase and the influence of such enzymatic activity upon substrate degradation efficiency. There were strong correlations established between the degree of enzyme activity and therefore availability of nutrients created to produce greater yields of mushroom crops. Thus, the findings from this body of research again demonstrate the essential contribution of biochemical processes towards the optimization of production systems for mushrooms.

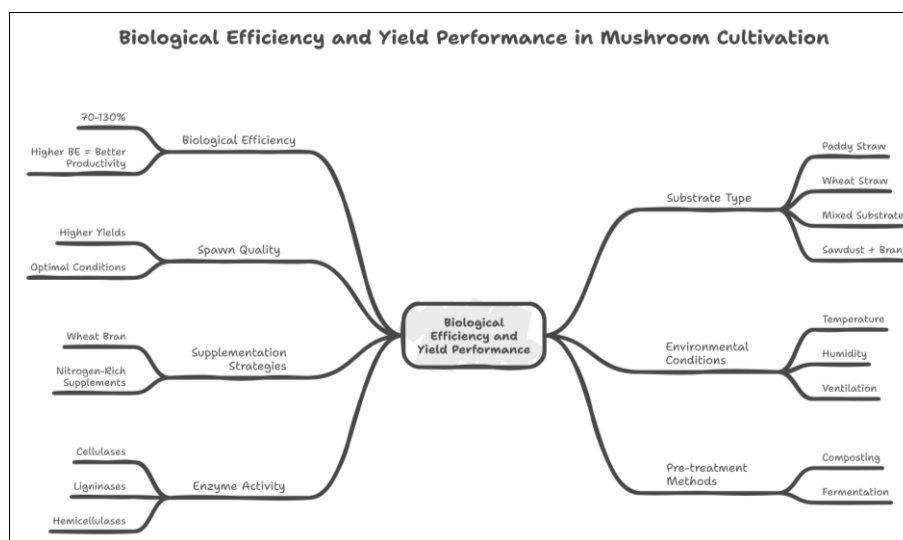


Fig 4: Biological Efficiency and Yield Performance in Mushroom Cultivation

5. Environmental Sustainability

Mushroom production is an important aspect in creating environmentally sustainable alternatives through the reuse of agricultural based waste materials and decreasing pollution caused by burning of agricultural wastes through open burning of agricultural field stubble. The spent mushroom substrate Generated by mushroom farms during harvest can also be utilized to create organic fertilizers, animal feeds (livestock) and soil amendments and improvements. These complementary practices contribute to improving soil quality as well as improving overall physical soil structure and increasing soil microbial stimulation. The integration of mushroom farming activity through the utilization of mushroom substrates into the general agricultural system can positively advance the concept of circular economies where all wastes generated can be degraded and reused to provide useful products. Furthermore, growing mushrooms uses far less water and

land than other types of agriculture which makes this type of farming very efficient as far as resources are concerned. Mushrooms can also help in reducing greenhouse gas emissions from agriculture by keeping crop residues (like paddy straw) from being burned; it is estimated that burning one metric ton of paddy straw can create about 1.5 metric tons of CO₂-equivalent gases when they are released into the environment. Because mushroom farms can divert this kind of biomass into their production systems, greenhouse gas emissions have already been reduced. In addition, recycling agricultural residues back to the soil through the mushroom-growing process is a great example of effective biological processes for waste recovery. Much of the organic carbon contained within the substrate is converted into fungal tissue, while the remaining substrate is enhanced in many nutrients. The spent mushroom substrate now contains increased nitrogen levels and a lower lignin concentration which makes it a very useful product for

improving soil and organic farming.

Lastly, the use of spent mushroom substrates as an organic fertilizer has been shown by many studies to increase the amount of carbon in soils and to increase agricultural

productivity, as well as to increase soil accumulation of moisture and nutrients, which is critical to supporting sustainable agricultural production system.

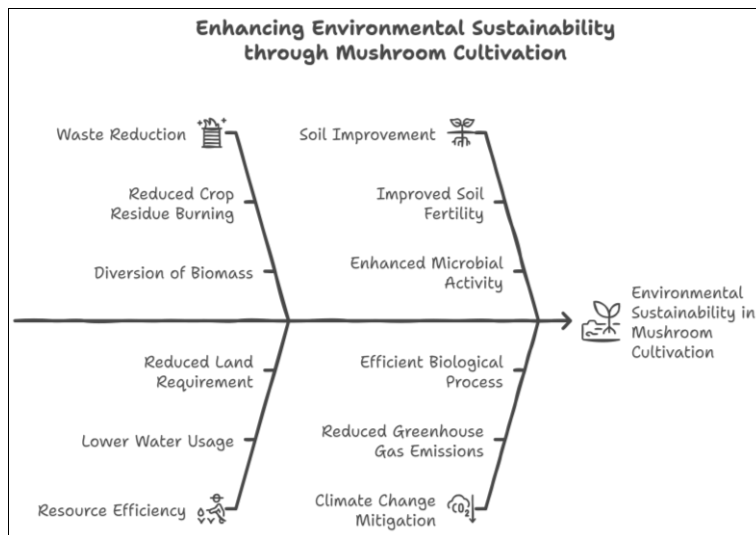


Fig 5: Enhancing Environmental Sustainability through Mushroom Cultivation

6. Status of Mushroom Cultivation in India

Mushroom cultivation in India offers a great business opportunity due to the varied climatic conditions and large quantities of agricultural by-products within our country [8]. Button mushrooms account for the largest share of Indian mushroom production, followed by oyster mushrooms, with numerous other varieties of mushrooms being produced as well. Electricity [18] from mushrooms grown in India has increased approximately 10 to 15% every year since the early 2000's, but whether or not the reported increase is meaningful is debatable because overall production volumes remain considerably below global production numbers. There are numerous reasons why Indian mushroom production is limited, including a lack of knowledge about the various types of mushrooms available for purchase, inadequate infrastructure, and insufficient marketing outlets. The value of the total Indian mushroom industry is around ₹5,000 to 6,000 crore (\$12.5 to 15 million), and continued strong growth is anticipated due to an increase in the demand for all varieties of mushrooms and strong government support. The average annual per capita consumption levels of mushrooms in India are currently very low. In fact, the average Indian consumes less than 100 grams of mushrooms annually compared to over 2 to 3 kg in countries such as China and the US. Thus, on average, per capita mushroom consumption levels show there is significant potential for growth in Indian market for mushrooms to develop.

Government programs, through a number of existing government agencies, agricultural colleges, and agricultural research institutions, are providing numerous programs that provide training, subsidies, and technical assistance for the development of mushroom growers. It is anticipated that these efforts will lead to higher levels of adoption and production in the future.

In addition to methods of growing mushrooms based on agriculture tradition, the trends emerging from the

mushroom industry in India are beginning to change. The most rapid transformations in mushroom agriculture are taking place in climate controlled mushroom producing buildings (indoor farms) and smaller scale indoor mushroom production in urban areas. Start-up companies and agribusinesses are involved in the mushroom industry trying to develop new markets for mushroom production; focusing on organic mushroom production and new ways for delivery of mushrooms to urban areas through direct delivery and e-business. In addition, the integration of mushroom culture with alternative agricultural production, like vermicomposting and dairy cows, is becoming increasingly popular as an environmentally-friendly way to recycle resources and increase sales income. In addition, we are beginning to develop farmer-producer organizations (FPOs) and cooperative marketing efforts, to create better bargaining power for growers, and provide them with improved prices. The overall trend of integrating mushroom culture with other agricultural production in India indicates a significant change in production from subsistence production to a more organized, market-oriented industry.

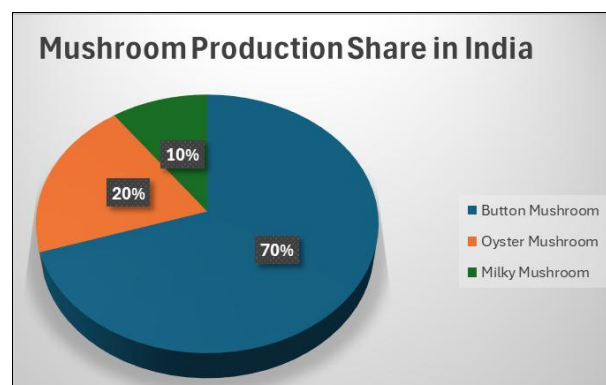


Fig 6: Share of different mushroom types in total production in India.

7. Mushroom Cultivation in Punjab

One of the leading states for mushroom culture in India is Punjab, where there is abundant availability of two primary growing materials, in the way of paddy straw and wheat straw [8]. There are a number of different types of infrastructure available in Punjab that are specifically designed to support mushroom cultivation (e.g., training facilities, research and development facilities, etc.). In Punjab, mushrooms are grown seasonally and under controlled conditions (e.g., using greenhouses), allowing the farmer to use multiple growing periods over a single year. Growing mushrooms can be very beneficial for agricultural producers from an economic standpoint because it improves the farmer's economic condition and allows for better utilization of by-product remaining from other processes. By utilizing leftover rice straw as a source of product input during the mushroom cultivation process, farmers have been able to avoid burning their paddy straw, releasing air pollutants into the atmosphere. For example, with the annual production of 40, 000–50, 000 tonnes in Punjab, it is one of India's largest producing states. To support all levels of farmers in the production and marketing of mushrooms, the state has put in place an integrated system of research, training, and extension services. By providing a use for paddy straw, mushroom growing has decreased the incidence of burning stubble in different parts of Punjab. In addition, the combination of mushrooms with dairy and crop systems has been adopted as an environmentally sound agricultural practice in Punjab. Farmers are increasingly using the spent substrate from mushroom production as feed for their cows and as organic fertilizer, which creates a closed-loop system and improves the efficiency of resources.

The cultivation of fungi has also provided additional job opportunities to rural populations through new economic activity generated in those communities.

Table 4: Seasonal cultivation pattern of mushrooms in Punjab.

Season	Months	Mushroom Type	No. of Crops
Winter	Sept–March	Button mushroom	2 crops
Winter	Sept–March	Oyster mushroom	3 crops
Summer	April–August	Paddy straw mushroom	4 crops
Summer	April–August	Milky mushroom	3 crops

8. Economic Importance

Growing mushrooms as a business is very lucrative because there are minimal investments and the crop has a short growing cycle [4]. Farmers can receive income from 30 to 45 days of planting, and therefore this type of business venture is highly sought after by small and marginal farmers. Many urban markets are presently seeing an increase in demand for mushrooms, and because of their nutritional value and medicinal benefits, there are many additional opportunities for farmers and entrepreneurs within this area. In addition to mushrooms, value-added products such as dried mushrooms, powdered mushrooms, and pickled mushrooms can also add to profitability. Mushroom farming creates job opportunities for rural youth and women, aiding in social and economic development.

As previously mentioned, mushroom farming requires very little investment in the beginning, very little time to grow the crop from seed to market, and has a very high

conversion rate from agricultural waste to a marketable value-added product, therefore creating numerous opportunities for small and marginal farmers to have high returns per square foot compared to many traditional farm crops. The amount of input to produce a crop is relatively minimal compared to traditional crops, as well as using the locally available agricultural waste to create products (agro-residues), further reducing the cost of production and increasing the net profitability of the operation [4].

In addition, mushroom farming can create alternative sources of income for rural families. By growing mushrooms alongside their existing farm operations instead of needing extensive acreage, growers can use smaller areas: a shed, an extra room, or other buildings. Therefore, mushroom farming is highly beneficial for people who do not own land and for very poor families. Different species of mushrooms can be harvested at different times of the year, resulting in the opportunity for year-round earnings and increasing the farmers' financial security [8].

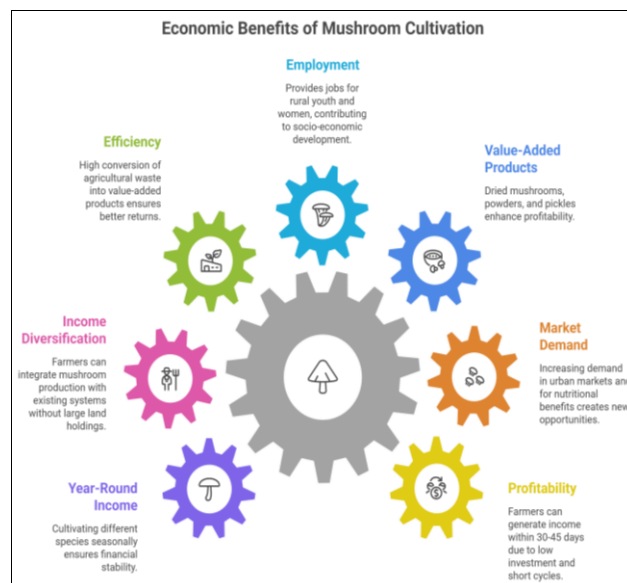


Fig 7: Benefits of Mushroom Cultivation

Mushrooms have additional potential for value-added processing. Dried mushrooms (including noodles), mushroom powder, mushroom pickles and mushroom ready-to-cook products have a longer shelf life than fresh mushrooms and are generally higher in market value. The production of these products creates opportunities for small-scale agro-processing industry and promotion of entrepreneurship (especially for women and youth) in rural areas. The recent trend towards the recognition of mushrooms as health food items has also resulted in a surge of customer interest for these products within urban centres and globally, thus resulting in increased exporting potential and additional income generation opportunities.

In addition to direct economic benefits from mushroom farming, there are indirect benefits resulting from employment generation along the value chain (spawn production; substrate preparation; production; harvesting; processing; packing; marketing). The nature of the agriculture enterprise is labour intensive and therefore provides a source of incomes for many people, which in return will support rural development. Using spent

mushroom substrate as an organic manure substitute will help eliminate the reliance on chemical fertilizers, thus reducing agricultural input costs; and increasing sustainability of future cropping systems.

The mushroom cultivation industry is projected to grow at a rapid pace thanks to government initiatives, information and training, and funding support. Many farmers are being bolstered by subsidization, skill enhancement, and other types of institutional support to pursue mushroom cultivation as a profitable operation at a commercial level. Significant growth has occurred in the market for mushrooms due to greater demand, advances in technology, and improvements in supply chains. Therefore, mushroom cultivation should significantly increase farmers' income and enhance sustainable agricultural development in the near future.

9. Challenges and Constraints

Nevertheless, mushroom production is still constrained by various issues that hinder its widespread adoption. For example, pests and pathogens frequently contaminate crops and lead to significant economic losses (Byers *et al.* 2018) [7 viewed 01 March 2020]; low-quality spawn; and a deficiency of technical knowledge among farmers, which substantially diminish harvests. But postharvest losses are exacerbated by poor infrastructure, such as insufficient cold storage and transportation systems. Other challenges limiting the growth of the mushroom industry are fluctuations in market prices and poor consumer awareness. Providing better training to growers, enhancing infrastructure, and implementing favourable policies will be necessary to solve these issues. Variability in weather conditions and inadequate climate-controlled agriculture facilities will continue as pressing obstacles for many small farmers engaged in mushroom production. Extreme changes in weather conditions (i.e., high or low temperature and/or relative humidity) can substantially decrease yields and affect quality. Farmers have many barriers preventing widespread adoption of mushroom cultivation, including the lack of an organized marketing system and unstable prices. In addition, high-quality spawn is in short supply, which affects production. Improving spawn production facilities and ensuring that spawn is of high quality are critical to improving performance.

10. Future Prospects

There is a growing interest in sustainable agriculture and environmental stewardship, which bodes well for the future of mushroom cultivation. Biotechnology and new cultivation techniques will improve yield and increase production efficiency. High-yield strains, automated cultivation systems, and increased integration with other agricultural practices will further increase productivity. There is also an expansion of export markets and a stronger promotion of value-added products, resulting in higher economic returns from mushroom cultivation. Furthermore, mushroom cultivation has an important role in climate-smart agriculture by reducing waste and increasing resource use efficiency. Organic mushroom production, like biofortification of mushrooms, and therapeutically valuable mushrooms are among the current trends expected to fuel future demand. Medicinal mushrooms (like *Ganoderma* and

Cordyceps) are growing in popularity for their therapeutic benefits and open the door for new opportunities in the pharmaceutical industry. The use of artificial intelligence and machine learning will also drive advances in cultivation practices by making it easier to forecast climate variations and identify pests. These new technologies will increase the efficiency of commercial mushroom production systems and help to mitigate risk.

11. Conclusion

Growing mushrooms by leveraging agricultural waste can be an economically and environmentally sustainable practice of modern agriculture. Converting lignocellulosic residues like paddy and wheat straw and other types of agricultural waste into edible biomass provides a solution to both the problem associated with managing crop residues as well as providing significant contributions to food security and rural income generation. This review article has identified three main factors that determine each growing system's overall biological efficiency and total productivity of mushroom crops grown on waste materials: substrate composition, supplementation, and environmental conditions. Therefore, optimized growing systems may obtain maximum yields when grown under ideal conditions. For example, in India, mushroom cultivation could provide a practical and environmentally sound way for farmers to manage their crop residues rather than burning them. Improved cultivation techniques (like substrate enrichment) and innovative systems (like the use of plastic bottles) could increase the efficiency of production and maximizing resource usage when growing mushrooms on agricultural waste materials. The use of mushrooms as a component of sustainable and climate-resilient agriculture systems has the potential to provide multiple socio-economic benefits, including the diversification of income sources, job creation, and the ability to add value to products. Using spent mushroom substrate as a source of organic manure helps improve soil health and reduces the amount of chemical fertiliser used. Demand for mushrooms is increasing due to growing consumer awareness of their nutritional value; therefore the mushroom industry has great potential to grow both domestically and internationally. Overall, mushroom production represents a comprehensive approach to waste management, environmental sustainability and economic development. Through ongoing research, technological advances and better implementation at the farm level, the use of spent mushroom substrate can help support sustainable agricultural practices and improve the livelihood of farmers, especially in areas such as Punjab, where there are large quantities of agro-residues available.

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