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From production to consumption: Strategies for affordable and diverse edible mushrooms

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ABSTRACT

Edible mushrooms are nutrient-rich foods that can be cultivated using agricultural and other lignocellulosic residues, while requiring relatively little land and water. These characteristics make them promising components of more sustainable and resilient food systems. However, mushrooms are still considered a premium or occasional food in many markets, and production remains concentrated around a limited number of species-particularly the button mushroom (*Agaricus bisporus*) in regions outside East Asia. Production is also unevenly distributed across countries and regions, limiting the availability and diversity of mushrooms in many markets.

This review examines the factors that influence mushroom production costs and prices, as well as the barriers that limit greater species and market diversity. The discussion follows the mushroom value chain, from production inputs to final consumption. Five broad areas of opportunity are identified: (i) reducing input costs through locally available and circular substrate resources and decentralised, quality-controlled spawn production; (ii) improving cultivation efficiency through affordable, modular technologies, better-performing strains and higher biological efficiency; (iii) reducing postharvest losses through improved cooling, packaging and value-added processing; (iv) strengthening market systems through producer aggregation, shorter supply chains and digital marketing platforms; and (v) stimulating demand through consumer awareness, culinary innovation, mushroom-meat blends and nutritional enhancement, including vitamin D enrichment through ultraviolet exposure.

These measures need to be supported by an enabling environment that includes appropriate standards, extension services, access to finance and continued research and development. Based on the evidence reviewed, we propose an integrated framework that links individual interventions to different stages of the mushroom value chain while recognising important trade-offs, including energy requirements, contamination risks, possible market oversupply and food-safety challenges. The review also identifies priorities for future research, particularly the development of low-cost substrate formulations, breeding of species and strains suited to tropical and subtropical conditions, life-cycle and cost assessments of small-scale production systems, and studies of consumer attitudes and acceptance. Overall, making mushrooms more affordable and widely available will require coordinated efforts on both the supply and demand sides, rather than relying on increased production alone.

Keywords: Edible mushrooms, Affordability, Market diversification, Circular economy, Value chain, Food security, Smallholder cultivation

1. Introduction

Mushrooms, the fruiting bodies of macrofungi, have been part of human diets for thousands of years, and their cultivation has expanded considerably in recent decades. This growth reflects not only increasing consumer interest but also the nutritional and environmental value of mushrooms. Royse *et al.* (2017) [1] estimated that global production of cultivated edible and medicinal mushrooms reached approximately 34 million tonnes in 2013. China accounted for nearly 87% of this production, while average global per-capita consumption increased from about 1 kg in 1997 to almost 4.7 kg in 2013. Despite this rapid expansion, global mushroom production remains concentrated among a relatively small number of genera. *Lentinula*, *Pleurotus*, *Auricularia*, *Agaricus*, *Calocybe* and *Flammulina* together account for most of the world's cultivated mushroom supply. In many markets outside East Asia, however, consumer choice remains limited, with *Agaricus bisporus*-the common button mushroom-often dominating sales and being offered in only a few forms.

Mushrooms also have several characteristics that make them particularly relevant to today's food-system challenges. They are naturally low in fat and energy while providing protein, dietary fibre, including β -glucans and chitin, as well as important micronutrients such as B vitamins, potassium and selenium. They also contain ergothioneine, a bioactive compound of growing nutritional interest. In addition, exposure to ultravi-

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olet light can substantially increase their vitamin D content, creating an opportunity to enhance their nutritional value (Kalač, 2013; Reis *et al.*, 2012; Cardwell *et al.*, 2018; Rizzo *et al.*, 2021) [3, 4, 2, 5].

An important advantage of mushroom cultivation is its ability to turn agricultural and forestry residues into edible food. Materials such as straw, sawdust, bagasse, cotton waste and spent coffee grounds can serve as cultivation substrates, allowing resources that might otherwise be discarded or underused to enter the food chain (Philippoussis, 2009; Grimm *et al.*, 2018; Rinker, 2017) [7, 6, 8]. Even after harvesting, the process can continue to generate value because spent mushroom substrate (SMS) can be used as a soil amendment, animal-feed ingredient or potential feedstock for energy production. This gives mushroom cultivation a potentially circular character, in which agricultural residues are converted into food and the remaining biomass is put to further use.

Mushrooms can also be produced with relatively little arable land and are well suited to controlled indoor and vertical production systems. Their cultivation can therefore be adapted to areas where land is scarce or agricultural conditions are less favourable. At the same time, mushroom production is relatively labour-intensive and can create employment opportunities in rural and peri-urban communities. These opportunities may be particularly relevant for women and landless households seeking additional sources of income (Marshall *et al.*, 2009; Zhang *et al.*, 2014; Thakur, 2020) [9, 10, 11]. Taken together, these nutritional, environmental and socioeconomic characteristics position mushrooms as a promising component of more diverse and resource-efficient food systems.

Despite these advantages, mushrooms still face two major challenges that limit their contribution to diets in many countries. The first is affordability. Fresh mushrooms often cost more per kilogram than commonly consumed vegetables and, in some markets, may even be more expensive than pulses or certain animal-based foods. As a result, mushroom consumption tends to be concentrated among higher-income and urban consumers. Several factors contribute to these relatively high prices, including the cost of compost, spawn and energy for climate control, low productivity in poorly managed growing systems, the highly perishable nature of fresh mushrooms, fragmented marketing channels and limited consumer demand.

The second challenge is limited market diversity. In many regions, production and consumption depend heavily on only one or two mushroom species and are dominated by a narrow range of fresh products. Production may also be concentrated among a small number of producers or geographic areas. Such dependence can make markets more vulnerable to disease outbreaks, fluctuations in input prices and supply disruptions, while also limiting opportunities to make greater use of the many mushroom species that can be cultivated under different climatic conditions and on a variety of locally available substrates (Chang *et al.*, 2004; Stamets, 2000) [12, 13].

Although a substantial body of research has examined mushroom cultivation technologies, the use of agricultural residues as growing substrates and the nutritional value of mushrooms, relatively few studies consider these areas together from the perspectives of affordability and market diversity. This paper addresses that gap by examining how production costs, market structures and value-chain conditions influence mushroom prices and accessibility. Specifically, the paper aims to: (a) examine the factors that shape mushroom prices and market concentration across the value chain; (b) synthesise evidence on approaches for reducing production and marketing costs while expanding the range of species, products and consumer groups; (c) develop an integrated framework that connects these strategies; and (d) discuss the associated trade-offs and identify priorities for future research and policy.

2. Methodology

This paper adopts a structured narrative, or integrative, review approach. This approach is well suited to the present topic because the available evidence spans several interconnected fields, including

agronomy, food science, economics, marketing, and public policy, making a quantitative *meta-analysis* difficult. Relevant evidence was identified through searches of *Scopus*, Web of Science, Google Scholar, and the FAO repository. Search terms included combinations of *edible mushroom*, *cultivation*, *cost*, *substrate*, *spent mushroom substrate*, *value chain*, *market*, *consumer*, *postharvest*, and *policy*. Key review papers were also examined through backward citation tracking to identify additional relevant studies.

Studies and other sources were considered for inclusion when they provided evidence on the production costs, productivity, postharvest management, marketing, distribution, or consumption of cultivated or wild edible mushrooms. To bring together evidence from these different areas, the findings were organised around five major stages of the mushroom value chain: inputs, cultivation, postharvest handling, distribution, and consumption. The evidence was further examined through two main outcome dimensions: *affordability* and *market diversity*. Affordability refers to the cost of producing and supplying consumer-ready mushrooms and their price in relation to household food budgets. Market diversity captures the breadth of species, product forms, producers, marketing channels, and consumer groups represented in the market.

The review also recognises two important limitations. First, detailed and reliable data on mushroom production costs are limited and can vary substantially across production systems, locations, scales of operation, and species. For this reason, the analysis focuses primarily on the relative contribution of different cost components and the likely direction of their effects rather than presenting precise cost estimates that may not be broadly comparable. Second, official data on mushroom production and trade remain incomplete in many countries. This is particularly the case for small-scale and informal production and for wild-harvested mushrooms, which are often poorly captured in national statistics (Boa, 2004) [14]. These limitations were taken into account when interpreting and comparing the available evidence.

3. The global production and market landscape

3.1 Concentration of production and species

Mushroom production around the world is concentrated in a relatively small number of countries and species. China is by far the dominant producer, supported by decades of policy development, a large base of small and household-scale growers, well-established supply networks for substrates and spawn, and strong domestic demand for a diverse range of mushroom species (Zhang *et al.*, 2014; Li *et al.*, 2022) [10, 15]. In Europe and North America, production is more strongly oriented towards large, specialised farms, with *Agaricus bisporus* (button mushroom) accounting for a major share of output. These systems generally rely on specialised composts and relatively high levels of capital and environmental control. At the same time, speciality mushrooms such as oyster (*Pleurotus* spp.), shiitake (*Lentinula edodes*), enoki (*Flammulina filiformis*), and king oyster (*Pleurotus eryngii*) have established smaller but expanding market segments.

In India and many other low and middle-income countries, button mushroom has traditionally been an important part of commercial production. However, oyster, milky (*Calocybe indica*) and paddy straw (*Volvariella volvacea*) mushrooms are also important, particularly in warmer regions where their environmental requirements are better suited to local conditions and where small-scale cultivation can make use of locally available agricultural residues (Sharma *et al.*, 2017; Thakur, 2020) [16, 11].

The major cultivated species and the characteristics that influence their production costs and suitability for different production systems are summarised in Table 1. These species vary considerably in their substrate requirements, production cycles, temperature sensitivity, investment needs and post-harvest shelf life. Such differences are important because they allow producers to select species according to local climate, available agricultural residues, production facilities, labour, investment capacity and consumer demand. Matching mushroom species with local resources and market conditions can therefore

provide an important pathway for expanding production beyond the currently dominant species and production regions.

Table 1. Characteristics of major cultivated edible mushrooms relevant to cost and diversification (qualitative synthesis based on Chang & Miles, 2004 [12]; Stamets, 2000 [13]; Sánchez, 2010 [17]; Zied & Pardo-Giménez, 2017).

Species	Typical substrates	Fruiting temperature	Capital intensity	Key cost/market notes
Button (<i>Agaricus bisporus</i>)	Composted straw with manure, gypsum; casing layer	Cool ($\approx 15-18^{\circ}\text{C}$)	High (composting, climate control)	Economies of scale; compost and energy dominate costs; short shelf life
Oyster (<i>Pleurotus</i> spp.)	Pasteurised straw, sawdust, cotton waste, bagasse, coffee residues	Wide range by species/strain ($\approx 10-30^{\circ}\text{C}$)	Low	Easiest entry species; high biological efficiency; very perishable; suits drying
Shiitake (<i>Lentinula edodes</i>)	Supplemented hardwood sawdust blocks or logs	Moderate ($\approx 12-25^{\circ}\text{C}$)	Medium	Longer cycle; premium price; good dried market
Wood ear (<i>Auricularia</i> spp.)	Sawdust, logs, agro-residues	Warm	Low-medium	Dried trade well established; strong in Asian cuisines
Enoki (<i>Flammulina filiformis</i>)	Sawdust/cob mixtures in bottles	Cold	High (industrial bottle systems)	Highly automated; low unit cost at scale
Paddy straw (<i>Volvariella volvacea</i>)	Rice straw, cotton waste	Hot ($\approx 30-35^{\circ}\text{C}$)	Low	Rapid cycle; suited to tropics; very short shelf life
Milky (<i>Calocybe indica</i>)	Pasteurised straw with casing	Hot ($\approx 30-35^{\circ}\text{C}$)	Low	Better shelf life than many tropical species; regional markets
King oyster (<i>Pleurotus eryngii</i>)	Supplemented sawdust in bottles/bags	Cool-moderate	Medium-high	Firm texture, longer shelf life; meat-substitute potential

Note: Temperature ranges are indicative and vary by strain and cultivation system.

3.2 Consumption patterns

Per-capita consumption varies by orders of magnitude between countries. High consumption markets are characterised by long culinary traditions, many species and product forms (fresh, dried, pickled, canned, frozen, in sauces and snacks), and dense retail and food-service channels. Low-consumption markets typically combine limited familiarity, a narrow product range, high prices relative to incomes and, in some regions, cultural hesitancy or confusion with poisonous wild fungi. Wild edible fungi remain important to rural diets and incomes in many parts of the world, but their supply is seasonal, and their safety depends on local knowledge (Boa, 2004) [14].

4. Determinants of mushroom prices and market concentration

The price consumers pay for mushrooms is shaped by several factors along the supply chain. Broadly, it reflects three main components: the cost of producing one kilogram of mushrooms, the losses that occur between harvest and sale, and the marketing costs and margins associated with transport, cold storage, packaging, retailing, and market risks. Understanding how each of these components contributes to the final price helps identify practical opportunities for reducing costs and improving market efficiency (Table 2).

4.1 Production cost and productivity

The cost of producing mushrooms per kilogram depends not only on the price of inputs but also, importantly, on how much mushroom can be produced from those inputs. In simple terms, production cost per kilogram is determined by the total cost of production divided by the yield. For many mushroom species, productivity is measured using biological efficiency (BE), which refers to the fresh weight of mushrooms produced as a percentage of the dry weight of the substrate. BE can vary considerably depending on the mushroom strain, substrate composition, supplementation, quality of pasteurisation, and the level

of environmental control provided during cultivation (Sánchez, 2010; Hoa *et al.*, 2015; Bellettini *et al.*, 2019) [17, 19, 18].

Yield can also be significantly affected by contamination and pest problems. Competing moulds such as *Trichoderma* spp., along with pests such as sciarid and phorid flies and mites, can damage crops and reduce production. Diseases, including dry and wet bubble in *Agaricus*, can have similar effects. These problems are particularly serious in small-scale production units where hygiene and environmental management may be less consistent. In such systems, contamination can become one of the main reasons for higher production costs because it results in wasted substrate, labour and other inputs. The main expenses in mushroom production generally include substrate and supplements, spawn, energy for processes such as pasteurisation, heating, cooling and humidification, and labour, especially during harvesting. In addition, growers must consider the cost of buildings, growing rooms, equipment and other capital investments. Improving productivity, reducing contamination and using inputs efficiently can therefore play an important role in lowering the cost of mushrooms and improving the profitability of cultivation.

4.2 Perishability and postharvest losses

Fresh mushrooms are highly perishable because they contain a large amount of water, have high respiration rates, and lack a protective outer layer. As a result, they can lose quality quickly through browning, softening, moisture loss, and microbial spoilage. Without refrigeration, their shelf life may be limited to just a few days (Singh *et al.*, 2010; Zhang *et al.*, 2018) [20, 21]. In areas where reliable cold-chain facilities are not available, producers are often forced to sell their mushrooms soon after harvest, sometimes at very low or distress prices. Retailers also face the risk of unsold mushrooms deteriorating before they can be sold, and this risk is often reflected in the final price. High perishability therefore limits how far mushrooms can be transported and sold, making producers more dependent on nearby markets and contributing to geographic concentration in production and trade.

4.3 Market structure and information

Small-scale mushroom growers often operate in limited local markets and have relatively little bargaining power compared with traders and intermediaries. They may also have limited access to timely information about prevailing prices, consumer demand, and market opportunities. Collecting and transporting mushrooms can be costly because individual farms usually produce small quantities, while harvesting takes place frequently. This makes it difficult for small producers to achieve the economies of scale needed to reach larger markets.

Larger, integrated farms have an advantage because they can spread production, packaging, transport, and marketing costs over much larger volumes, reducing their costs per unit. However, these operations often focus on a small number of mushroom species and standardised package sizes that suit modern retail systems. While this improves efficiency and consistency, it can also reduce the range of species and product forms available to consumers. In this way, the

structure of the market can simultaneously favour lower-cost large-scale production and limit diversity in the products reaching mainstream retail channels.

4.4 Demand-side constraints

Consumer demand for mushrooms is often limited by a lack of familiarity with species beyond the commonly available button mushroom. Some consumers may also be unsure about how to prepare or cook different varieties. In addition, mushrooms are sometimes viewed as a luxury food or simply as a garnish rather than an important part of everyday meals. Concerns about food safety can further discourage consumption. When demand remains low, producers and distributors have fewer opportunities to benefit from economies of scale, which can keep production and marketing costs high. This can create a cycle in which low demand leads to higher prices, while higher prices in turn make mushrooms less attractive to consumers.

Table 2. Main cost and price drivers along the mushroom value chain and associated levers.

Stage	Principal cost/price drivers	Illustrative levers
Inputs	Substrate purchase and transport; supplements; spawn price and quality; energy	Local agro-residues; circular substrate sharing; decentralised certified spawn labs; renewable energy
Cultivation	Low biological efficiency; contamination losses; climate-control costs; labour intensity	Improved strains; low-energy pasteurisation; hygiene protocols; passive climate design; mechanisation at appropriate scale
Postharvest	Rapid deterioration; distress sales; lack of grading and packaging	Pre-cooling; evaporative or solar cold rooms; MAP; drying, pickling, powders; by-product use
Distribution	Small, dispersed volumes; long intermediary chains; cold-chain gaps	Cooperatives and collection hubs; contract farming; direct and digital sales; shared logistics
Consumption	Low awareness; narrow product range; perceived luxury status	Education and recipes; blended and ready-to-cook products; vitamin D mushrooms; institutional procurement

5.1 Reducing input costs through circular and local substrates

Substrate is often one of the major variable costs in mushroom production, and its quality and composition have a direct effect on yield. Research has shown that edible mushrooms, especially *Pleurotus* species, can grow well on a wide range of locally available agricultural and industrial residues. These include cereal straw, maize stalks and cobs, sugarcane bagasse, cotton waste, sawdust, banana leaves, coffee pulp and spent coffee grounds, as well as tea waste (Philippoussis, 2009; Sánchez, 2010; Kumla *et al.*, 2020; Wan Mahari *et al.*, 2020) [7, 17, 22, 23]. Using residues that are inexpensive, readily available and produced close to the farm can reduce both the cost of purchasing substrate and the cost of transporting it. It can also provide environmental benefits when these materials would otherwise be burned, dumped or sent to landfills (Grimm *et al.*, 2018) [6].

The benefits of using local residues can be increased through three complementary approaches. First, substrate optimisation is important. Combining carbon-rich materials with suitable nitrogen-rich supplements, such as bran or legume residues, can improve biological efficiency (BE) and help create conditions that are less favourable to contamination. Since the availability and cost of residues differ from one region to another, local trials can help identify substrate combinations that provide good yields at the lowest possible cost. Extension services could use these results to develop simple, region-specific substrate recipes for growers (Hoa *et al.*, 2015; Bellettini *et al.*, 2019) [19, 18].

Second, industrial symbiosis can create useful links between mushroom farms and nearby industries. Mushroom producers located close to sawmills, breweries, coffee-processing units, sugar mills or cotton

gins may be able to obtain suitable residues at very low cost, or sometimes even at no cost. In return, the spent mushroom substrate (SMS) can be reused as a soil conditioner, animal-feed ingredient or feedstock for biogas production, creating additional value from what would otherwise be a waste material (Rinker, 2017; Grimm *et al.*, 2018; Grimm *et al.*, 2021) [24, 6, 8].

Third, centralised substrate preparation can help small producers overcome the costs and technical difficulties of preparing substrate individually. In the *A. bisporus* industry, specialised composting facilities already supply growers with phase II or phase III compost, allowing producers to benefit from economies of scale. A similar model could be developed for oyster and shiitake mushrooms, with local hubs preparing, pasteurising and spawning ready-to-use substrate bags. Small-scale growers could then focus mainly on fruiting and marketing rather than investing in specialised substrate-preparation facilities. This could reduce production costs, improve consistency and lower the risk of contamination.

Spawn is another essential input in mushroom production, and its quality can have a major influence on overall productivity. In many developing mushroom-growing sectors, producers often face problems with contaminated, poor-quality, or genetically unstable spawn. Relying on suppliers located far from production areas can also increase costs and cause delays. Establishing decentralised spawn laboratories at universities, research stations, cooperatives, or licensed private facilities could help address these challenges. If these laboratories operate under a certification system that ensures strain identity, purity, and viability, they could reduce production failures and lower the cost of spawn. They could also make a wider range of mushroom species and locally adapted strains more readily available to growers (Marshall *et al.*, 2009; Thakur, 2020) [9, 11].

5.2 Appropriate, low-cost and energy-efficient cultivation technology

Technology choice should match species, climate and scale. For many tropical and sub-tropical regions, species that fruit at ambient temperatures - oyster, paddy straw and milky mushrooms-can be grown in low-cost structures (bamboo, thatch, shade-net or converted buildings) without mechanical cooling, dramatically lowering capital and energy costs. Seasonal scheduling, in which cool-season species (e.g., button mushroom or cold-tolerant oyster strains) alternate with warm-season species in the same structure, raises utilisation and year-round supply (Sharma *et al.*, 2017) [16].

Energy-saving practices include low-energy pasteurisation methods such as hot-water immersion, steam from biomass boilers or solar thermal collectors, and chemical or alkaline treatments of substrate were permitted and appropriately managed (Sánchez, 2010) [17]; passive building design using insulation, evaporative cooling and earth-sheltering; and integration of solar photovoltaics for fans and humidifiers. Life-cycle assessments of *A. bisporus* production indicate that compost production and energy use are major contributors to environmental impacts (Robinson *et al.*, 2019) [25], so energy efficiency simultaneously lowers cost and emissions.

At larger scales, bottle and bag-based systems with automated filling, sterilisation, inoculation and climate control-widely used for enoki, king oyster and shiitake in East Asia-have lowered unit costs and made once-exotic species routine in supermarkets. Modular, container-based or vertical farms can bring some of these efficiencies to peri-urban settings, reducing transport and spoilage, although their capital costs must be justified by high utilisation and reliable markets. Across mushroom production systems of all sizes, following simple and consistent hygiene practices can significantly reduce production losses. Measures such as using filtered air, maintaining positive pressure in spawn-run rooms, keeping clean and dirty areas separate, disinfecting facilities between production cycles, and preventing pest entry are relatively low-cost but highly effective. Since contamination can result in the loss of entire batches, good hygiene directly helps reduce the cost of producing each kilogram of mushrooms.

5.3 Strain improvement and species diversification

Improving mushroom strains can contribute greatly to higher productivity and more reliable production. Breeding and selection can produce strains with better yields, shorter production cycles, greater tolerance to heat and diseases, and improved shelf life. In *A. bisporus*, breeding has traditionally been challenging because of its predominantly secondarily homothallic life cycle and relatively narrow commercial genetic base. However, advances in genomics, marker-assisted selection and the use of wild genetic resources are creating new opportunities for improvement (Sonnenberg *et al.*, 2017) [26]. Modern techniques such as gene editing may offer additional possibilities. For example, a CRISPR-edited white button mushroom with reduced browning was considered outside the scope of US biotechnology regulations in 2016 (Waltz, 2016) [27]. Nevertheless, the acceptance and regulation of gene-edited crops differ between countries, so their wider use will depend on local regulations and consumer attitudes.

For mushroom species that have undergone less intensive domestication, selecting promising strains from local wild populations can be a practical approach. Such strains may be better adapted to local temperatures, available substrates and growing conditions. A better understanding of the environmental conditions that trigger fruiting-such as changes in temperature, light, carbon dioxide and humidity-can also make production more predictable and reduce the need for expensive environmental control (Kües *et al.*, 2000; Sakamoto, 2018) [28, 29].

Growing a wider range of mushroom species can provide several advantages. It can reduce the risks associated with relying on a single crop, allow producers to maintain supply throughout different seasons, make use of a broader range of agricultural and forestry residues, and help farmers reach different types of consumers. For example, shiitake and wood ear mushrooms can be suitable for dried-

product markets, while king oyster mushrooms may appeal to consumers looking for meat-like textures. Lion's mane and nameko can also provide opportunities in speciality food and food-service markets.

Public germplasm collections and culture banks can play an important role in supporting this diversification by preserving useful genetic resources and making them accessible to licensed spawn producers. For ectomycorrhizal mushrooms such as truffles and some boletes, large-scale cultivation on conventional substrates is still difficult. In these cases, managed plantations and sustainable wild harvesting may provide useful longer-term options for diversifying mushroom production (Hall *et al.*, 2003; Boa, 2004) [30, 14].

5.4 Postharvest management and value-added processing

Reducing postharvest losses is an important way to lower the overall cost of mushrooms and make them accessible to wider markets. Since fresh mushrooms are highly perishable, careful handling immediately after harvest can make a significant difference. Mushrooms should be harvested at the appropriate stage of maturity and, where possible, during cooler hours of the day. Rapid pre-cooling, using forced-air or vacuum cooling where feasible, followed by proper temperature and humidity management, can help maintain freshness. Suitable packaging, such as modified-atmosphere or perforated-film packaging, can further reduce moisture loss and spoilage. Gentle handling is also essential to prevent bruising and physical damage. Other approaches, including edible coatings and controlled irradiation, are being explored to extend shelf life (Singh *et al.*, 2010; Zhang *et al.*, 2018) [20, 21]. In areas without reliable electricity or conventional cold-storage facilities, simple technologies such as evaporative-cooling chambers and solar-powered cold rooms can provide practical alternatives for small-scale producers.

Processing is another effective way to deal with the short shelf life of fresh mushrooms while increasing product diversity. Mushrooms can be dried using sunlight, solar dryers or mechanical dryers and then sold as dried mushrooms or powder. Other possibilities include pickling, canning and freezing, as well as using mushrooms in soups, sauces, snacks, pasta, bakery products, seasoning mixes and meat-based products (Pérez-Montes *et al.*, 2021) [31]. These processing options are particularly useful when production is high and fresh mushrooms cannot be sold immediately. Instead of forcing farmers to sell during periods of oversupply, processing can help absorb market surpluses, reduce wastage and prevent sharp price declines. Mushrooms that are broken, misshapen or otherwise unsuitable for fresh retail, including stems, can also be used in processed products rather than being thrown away. Dried and powdered mushrooms have an additional advantage because they can be stored without refrigeration and can reach consumers in rural and lower-income areas at a relatively low cost per serving.

Another promising approach is the use of ultraviolet (UV) treatment to improve the nutritional value of mushrooms. Exposure to UV light converts ergosterol naturally present in mushrooms into vitamin D₂. Studies have shown that short, controlled UV treatments can substantially increase vitamin D₂ levels without requiring expensive processing systems (Cardwell *et al.*, 2018) [2]. Vitamin-D-enriched mushrooms could therefore provide an opportunity to develop higher-value products while also contributing to improved dietary vitamin D intake, particularly in populations where vitamin D deficiency or insufficiency is common.

5.5 Market structure, aggregation and distribution

Working together can help small-scale mushroom producers overcome many of the challenges associated with limited production volumes. Producer cooperatives, farmer producer organisations and self-help groups can jointly purchase inputs, establish shared facilities for substrate preparation and spawn production, and collect and store mushrooms in common centres equipped with basic cold-storage facilities. They can also grade, package and brand their products collectively and negotiate better terms with wholesalers, retailers and food

processors (Marshall *et al.*, 2009; Zhang *et al.*, 2014) [9, 10]. Contract farming and outgrower arrangements with processors or retail chains can further provide producers with more reliable markets, technical guidance and production support. However, such agreements should be transparent and structured so that production and market risks are shared fairly between farmers and buyers.

Reducing the number of intermediaries in the supply chain can also improve returns for producers while making mushrooms more affordable for consumers. Farmers, markets, direct sales to restaurants and institutional kitchens, subscription-based delivery, digital market-places and social-media platforms can provide producers with more direct access to customers. Better access to market information is equally important. Systems that provide regular wholesale price information can help farmers make informed selling decisions, while production forecasting can help them stagger cropping and avoid periods of oversupply and sharp price declines. Greater market diversity also requires retailers to give adequate shelf space to different mushroom species and product forms, supported by consistent grading and clear labels that explain how the products can be used. Together, these measures can create a more efficient, transparent and diverse mushroom market.

5.6 Demand creation and consumer engagement

Reducing production costs is useful only when there is enough demand to absorb the additional mushroom supply. If production increases faster than consumption, prices may fall sharply, leaving growers with lower returns and discouraging future production. For this reason, creating consumer demand should be considered alongside efforts to improve production and marketing. Research highlighting the nutritional and potential health benefits of mushrooms (Feeney *et al.*, 2014; Valverde *et al.*, 2015; Rizzo *et al.*, 2021) [32, 33, 5] can support nutrition education, public-health campaigns and dietary guidance. Consumer awareness can also be increased through simple and practical approaches such as recipe development, cooking demonstrations, tasting events and collaboration with chefs. Clear food-safety information is equally important, particularly in helping consumers distinguish safely cultivated mushrooms from potentially poisonous wild fungi.

Another useful approach is to incorporate mushrooms into familiar everyday foods. For example, chopped mushrooms can be blended with or partly replace meat in burgers, tacos, sauces and other commonly consumed dishes. Studies suggest that this type of substitution can maintain or even improve consumer acceptance while helping to reduce the amount of sodium and fat and lowering the cost of some meals (Myrdal Miller *et al.*, 2014; Pérez-Montes *et al.*, 2021) [34, 31]. At the same time, the expanding market for plant-based and alternative-protein foods provides new opportunities for mushrooms and mycelium-based ingredients. Their natural umami flavour, appealing texture and nutritional value make them useful ingredients in a range of food products. The development of fungal biomass fermentation, including mycoprotein, further demonstrates the potential of fungi as an alternative source of protein (Wiebe, 2002) [35].

Institutional buyers can also play an important role in creating a more reliable market. Schools, hospitals, military establishments and public canteens can provide regular demand for mushrooms in relatively large quantities. This can give producers greater market security, encourage investment in production and distribution, and potentially reduce costs through economies of scale. Introducing mushrooms, either fresh or dried, into selected institutional meal programmes could therefore be explored as a policy option. Such initiatives would need appropriate quality, hygiene and food-safety standards, along with pilot studies to assess consumer acceptance, costs and nutritional benefits.

5.7 Enabling policies and institutions

The strategies discussed above cannot succeed through individual efforts alone. Supportive policies, reliable institutions and better coordination are needed to create an environment in which mushroom pro-

ducers can reduce costs, manage risks and reach wider markets. Several areas deserve particular attention:

Research and extension: Public and private investment in strain improvement, locally available substrates, affordable cultivation technologies and farmer training can help producers adopt better practices. Demonstration farms, training centres and incubation programmes can also support new entrepreneurs and small-scale growers (Thakur, 2020) [11].

Quality and safety standards: Clear and practical standards are important for building consumer confidence and maintaining product quality. These should include certification systems for spawn, grading standards for fresh mushrooms, and guidance on food-safety risks such as pesticide residues, heavy-metal contamination from unsuitable substrates and microbial contamination. Clear labelling requirements are also needed for processed mushroom products (Kalač, 2013) [3].

Finance and risk management: Access to affordable credit can help producers invest in essential facilities such as pasteurisation units, cold storage and improved production structures. Targeted grants or subsidies may be particularly useful for small producers and cooperatives. Since mushroom production can be affected by contamination, disease, climate and market fluctuations, suitable insurance or other risk-sharing mechanisms should also be explored.

Infrastructure: Reliable electricity, roads, storage facilities and market infrastructure are essential for a competitive mushroom industry. Investment in renewable energy and shared cold-storage facilities can be especially valuable in rural areas, where high energy costs and poor postharvest infrastructure can reduce profitability.

Regulatory clarity: Regulations should keep pace with developments in the mushroom sector. Clear and practical guidelines are needed for emerging products such as new mushroom species, mycelium-based ingredients and gene-edited strains. Regulations governing the use and disposal of agricultural residues and spent mushroom substrate (SMS) should also encourage recycling and other circular-economy practices rather than creating unnecessary barriers.

Inclusion: Mushroom cultivation can be particularly suitable for women, young people and landless households because it requires relatively little land and can be carried out using small-scale production units. Training, credit and market-support programmes designed specifically for these groups can help broaden participation and create additional livelihood opportunities (Marshall *et al.*, 2009; Zhang *et al.*, 2014) [9, 10].

Overall, effective policy support should focus not only on increasing production but also on making the entire mushroom value chain more affordable, reliable and inclusive. Stronger links among researchers, extension agencies, producers, financial institutions and markets can help ensure that technical improvements translate into real economic benefits for growers.

5.8 Digitalisation and precision cultivation

Affordable digital tools can make mushroom production more efficient and easier to manage, particularly for small-scale growers. Simple sensors that monitor temperature, humidity and CO₂ levels can help farmers maintain suitable growing conditions and identify problems before they lead to major crop losses. Mobile-based advisory services can further support growers by providing timely information on cultivation practices, pest and disease management, weather conditions and market opportunities.

Digital platforms can also improve coordination across the value chain. Sharing information on production schedules, market prices and consumer demand through cooperatives or public platforms can help producers plan their crops more effectively and connect with buyers. At the industrial level, automation and machine-vision technologies may reduce labour requirements, especially for harvesting *A. bisporus*, where harvesting remains a highly labour-intensive activity. However, these technologies are still developing, and their possible effects on rural employment and smallholder livelihoods need to be considered carefully.

6. An integrated framework

Figure 1. brings together the different strategies discussed above and shows how they are connected across the five main stages of the mushroom value chain. The framework groups these strategies into two broad areas: cost-reducing measures and market-expanding measures. Cost-reducing measures mainly focus on inputs, cultivation and postharvest handling, while market-expanding measures focus on distribution, consumer awareness and demand.

Both areas are supported by an enabling environment that includes research, extension services, infrastructure, standards, finance and sup-

portive policies. Importantly, affordability and market diversity are closely linked rather than being separate goals. Lower production and distribution costs can make mushrooms more affordable and encourage wider consumption. At the same time, stronger and more diverse demand can help producers achieve economies of scale, use facilities more efficiently and reduce price fluctuations. These improvements can then create greater confidence to invest in better technologies and production systems, further reducing costs and strengthening the mushroom value chain.

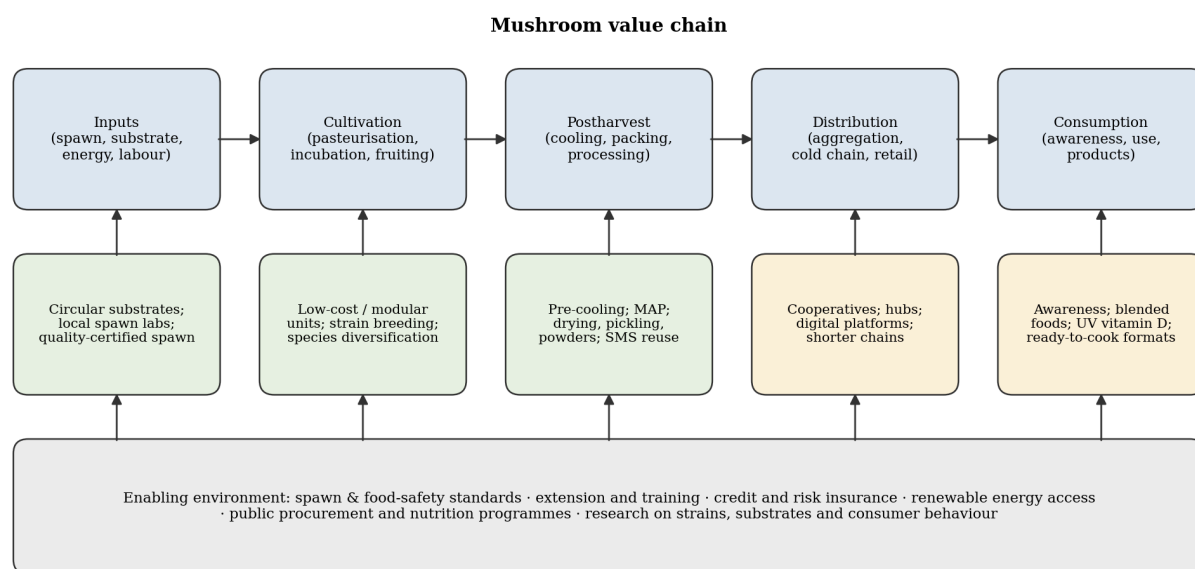


Figure 1. Integrated framework linking value-chain stages to cost-reducing (green) and market-widening (amber) levers, supported by an enabling environment. MAP = modified-atmosphere packaging; SMS = spent mushroom substrate.

Priorities differ by context. Table 3 suggests an indicative sequencing for three stylised settings.

Table 3. Indicative strategic priorities by development context.

Context	Priority affordability strategies	Priority diversity strategies
Emerging sectors (low consumption, mainly smallholders)	Certified local spawn; least-cost residue substrates; low-cost structures for ambient-temperature species; hygiene training	Awareness and recipe campaigns; drying and pickling for rural and low-income markets; cooperative marketing; institutional procurement pilots
Transitional sectors (growing urban demand, mixed scales)	Centralised substrate/spawn hubs; pre-cooling and cold-chain investment; strain improvement for local climates	Multi-species retail ranges; processed and ready-to-cook products; digital and direct sales; grading and branding
Mature sectors (high consumption, industrial production)	Energy efficiency and renewables; automation; circular SMS use; genomics-assisted breeding	Specialty species; functional products (e.g., vitamin D); blended meat products and alternative proteins; export diversification

7.1 Trade-offs and risks

Market saturation and price collapse. Encouraging mushroom cultivation too quickly can create problems if markets do not expand at the same pace. When large quantities of highly perishable mushrooms reach the market at the same time, prices can fall sharply, reducing farmers' incomes and discouraging further production. For this reason, programmes that promote cultivation should also focus on developing markets, improving distribution and expanding processing and storage facilities.

Energy and environmental footprint. Mushroom production can require considerable energy, particularly when climate-controlled growing rooms are used in very hot or cold regions. Sterilisation and other intensive production practices can also increase energy use. The benefits of larger-scale and more efficient production should therefore be balanced against its environmental impact. Life-cycle assessments can help producers and policymakers identify technologies that are

both affordable and environmentally sustainable (Robinson *et al.*, 2019) [25].

Food safety. Food safety is another important concern. Mushrooms may accumulate heavy metals or other contaminants from the materials used as growing substrates, while inappropriate pesticide use can create additional risks (Kalač, 2013) [3]. The use of unconventional agricultural and industrial residues in circular production systems therefore needs to be supported by proper testing and clear safety guidelines. Similar attention is required for postharvest treatments and processed mushroom products, where good hygiene, quality control and accurate labelling are essential.

Equity and labour. Mechanisation and larger production units can improve efficiency and reduce production costs, but they may also reduce employment opportunities or make it harder for small producers to compete. The benefits of technological development should therefore be shared as widely as possible. Cooperatives, producer groups

and inclusive business models can help smallholders and workers participate in growing mushroom markets rather than being left behind.

Biodiversity. Rising demand for wild mushrooms can put pressure on naturally occurring populations, particularly when harvesting is poorly regulated. Excessive collection can reduce wild populations and disturb their habitats. Sustainable harvesting practices, together with the cultivation of species that were previously collected mainly from the wild, can help meet demand while reducing pressure on natural resources (Boa, 2004) [14].

7.2 Research agenda

Future research should focus on practical questions that can help make mushroom cultivation more productive, affordable and sustainable, particularly for small and medium-scale producers. The following areas deserve greater attention:

Cost and economic performance: More transparent and comparable studies are needed to understand the actual costs of production, marketing and delivery for different mushroom species, production scales and regions. Such evidence can help guide investment decisions and the design of effective policies.

Better use of local substrates: Research should explore region-specific substrate combinations and supplementation methods using locally available agricultural residues. At the same time, potential contamination and food-safety risks associated with new or unconventional residues need to be carefully assessed.

Improved strains for changing climates: Greater emphasis is needed on developing and selecting strains that can tolerate high temperatures, resist common diseases and remain fresh for longer after harvest. Research should also support the conservation and responsible use of valuable mushroom genetic resources, particularly in tropical and sub-tropical regions.

Affordable and sustainable technologies: Techno-economic and life-cycle studies can help identify cultivation systems that are both affordable and environmentally sustainable. Particular attention should be given to modular production units, low-energy technologies, renewable energy and efficient cold-chain systems.

Understanding consumer preferences: More research is needed on how consumers respond to different mushroom species, processed products and meat-mushroom blends in different cultural settings. Studies should also examine whether mushrooms can be successfully incorporated into institutional feeding programmes such as schools and community nutrition initiatives.

Measuring the impact of new institutions and digital tools: Future studies should assess whether cooperatives, certified spawn systems and digital marketing platforms actually improve farmers, prices, incomes, market access and overall mushroom consumption. Evidence from such evaluations can help determine which interventions provide lasting benefits.

8. Conclusions

Edible mushrooms have the potential to play an important role in building healthier, more sustainable and inclusive food systems. However, for this potential to be fully realised, mushrooms need to become more affordable and accessible to a wider population, with greater diversity in the species and forms available to consumers.

This review shows that the relatively high cost and limited availability of mushrooms are not caused by a single problem. Instead, they result from a combination of challenges across the value chain, including costly or unreliable inputs, inconsistent yields, short shelf life, fragmented markets and limited consumer demand. Addressing these challenges therefore requires a coordinated approach rather than relying on one intervention alone.

A more practical pathway would combine the use of locally available and circular substrates with reliable, certified spawn production; technologies suited to local climates and different production scales; improved strains and greater species diversity; better postharvest handling and processing; stronger producer groups and shorter supply chains; and efforts to increase consumer awareness and demand.

These measures also need to be supported by appropriate research, quality standards, access to finance and basic infrastructure.

Ultimately, improving affordability and increasing the diversity of mushrooms should be viewed as complementary goals. Developing production and markets together can help reduce costs, improve farmer returns and make mushrooms available to a much wider range of consumers. With the right combination of technology, market development and institutional support, mushrooms could move beyond being a niche or premium food and become a more common part of everyday diets for people around the world.

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