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Original Research Article

Advancing Sustainable Mushroom Production in Developing Countries: A Pathway to Nutritional Security and Economic Growth

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Abstract: Mushroom production represents a promising industry with significant economic and environmental benefits and offers a viable strategy for addressing the nutritional deficits prevalent in these regions. Its low capital requirements make it an accessible tool for poverty alleviation and wealth creation, providing extensive job opportunities and contributing to national economic growth. The utilization of agro-forestry waste as raw material for mushroom cultivation aligns with the waste-to-wealth approach, fostering environmental sustainability. Despite the popularity of mushrooms as a food source, most of the mushrooms consumed in developing countries are gathered from the wild. The commercialization of mushroom production, which has the potential to become a sustainable and profitable agro-industrial sector, remains largely untapped, underexplored, underutilized, underexploited, and underrepresented. Various challenges impede the growth of the mushroom industry in developing countries, including socio-economic and cultural barriers, inadequate technical and scientific expertise, lack of supportive government policies, fluctuating market prices, and inefficient marketing systems. However, increased awareness of the nutritional, health, and economic benefits of mushrooms, coupled with the establishment of mushroom farming enterprises, could significantly enhance the industry's visibility and accelerate its industrial development in a short time. This review examines the development and sustainability of mushroom production for nutritional security and national economic development in developing nations, along with its many opportunities and challenges.

Keyword: Mushrooms, Nutritional Security, Malnutrition, Economic Growth, Agro-Forestry Wastes, Commercialization.

1. INTRODUCTION

Mushrooms are the fruiting bodies of macrofungi, primarily from the Basidiomycota group and some species of Ascomycota (Gupta, *et al*., 2022). For thousands of years, edible mushrooms have been collected and consumed by humans and wildlife, serving as both a food source and a component of traditional medicine in certain cultures (Debnath, *et al*., 2019). With thousands of species found worldwide, mushrooms play essential ecological roles, as they are heterotrophic organisms often used to assess the quality and age of ecosystems (Ngom, *et al*., 2022). Globally, mushrooms are highly valued for their nutritional, medicinal, environmental, and socio-economic significance. They are rich in proteins, vitamins, minerals, fiber, and essential amino acids while being low in calories, sodium-free, cholesterol-free, gluten-free, and fat-free, making them a recognized health food (Sharma, *et al*., 2017). Furthermore, several species of mushrooms contain medicinal and therapeutic compounds, which have been widely documented for their efficacy in preventing and treating various diseases and disorders (Fernandes, *et al*., 2021).

Mushroom production is an environmentally friendly practice that thrives on lignocellulosic materials, many of which are agro-industrial and forestry byproducts such as sawdust, wild grasses, and sugarcane bagasse (Haukongo, *et al*., 2021). In natural forests, mushrooms grow on decaying organic matter or living plant material, contributing to biomass recycling through the secretion of extracellular enzymes that break down

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lignocellulosic compounds into nutrients absorbable by the hyphae (Kumla, *et al*., 2020; Akter, *et al*., 2022). This recycling process reduces environmental pollution and promotes organic matter degradation (Khan, *et al*., 2024). The mushroom industry is one of the most successful examples of traditional biotechnology, offering numerous economic and ecological benefits. Mushroom farming is particularly suited to addressing challenges such as food insecurity, malnutrition, unemployment, and pollution (Niazi & Ghafoor, 2021). It is labor-intensive and provides significant employment opportunities for youth and women, thereby reducing unemployment in developing countries (Raman, *et al*., 2018). Despite these benefits, challenges persist. Some mushroom species produce toxic compounds, and the limited knowledge of mushroom edibility, combined with the biological similarity between edible and poisonous varieties, leads to frequent cases of mushroom poisoning (Bandara, *et al*., 2021). In developing countries, most edible mushrooms are still gathered from the wild by local harvesters—predominantly women and children—making them scarce and expensive (Shivute, 2020). Urbanization, deforestation, bush burning, and overexploitation of forest resources have led to a decline in the availability of wild mushrooms, which were once a delicacy for indigenous communities (Odediran, *et al*., 2020).

The lack of skills and technologies for mushroom cultivation has perpetuated reliance on wild harvesting, posing public health risks due to misidentification of poisonous mushrooms. Although some mushroom species have been successfully cultivated, challenges remain in introducing advanced technologies to breed new strains and cultivate wild species that require specific host plants to sporulate (Chang, 2007; Chakravarty, 2011). In developing countries, mushroom production remains underdeveloped due to ignorance and an overreliance on wild mushrooms. This reliance undermines commercial cultivation despite the availability of raw materials, ultimately limiting the potential for revenue generation and foreign exchange earnings (Okhuoya, *et al*., 2010; Osemwegie, *et al*., 2014).

Advancing scientific research and development in mushroom cultivation could positively impact its propagation and commercialization, promoting mushrooms as a functional food and preserving culturally significant varieties. Mushroom production has the potential to address critical issues such as malnutrition, unemployment, and economic instability while protecting traditional mushroom species from extinction (Khan, *et al*., 2024). This review underscores the need to explore the opportunities and address the constraints in sustainable mushroom production in tropical developing countries, particularly in Africa, as a pathway to nutrition security and economic development.

2. METHODOLOGY

Information and data from scientific investigations and reviews published in peer review journals on different perspectives of mushrooms were compiled and applied in scripting this paper.

3. Mushroom Ecology

Mushrooms are filamentous fungi classified under the phyla Basidiomycota and Ascomycota. They play a critical role in nutrient cycling by degrading lignocellulosic materials that are otherwise resistant to decomposition, making them valuable indicators of an ecosystem's quality and age (Ngom, *et al*., 2022). Nutritionally, mushrooms are heterotrophic organisms that acquire nutrients through three trophic mechanisms: saprotrophic, parasitic, and symbiotic (mycorrhizal) (Perez-Moreno, *et al*., 2021a).

Saprotrophic mushrooms derive nutrients from decomposing organic matter, such as dead plants and animals. Examples include species from genera such as *Afroboletus*, *Agaricus*, *Auricularia*, *Coprinus*, *Ganoderma*, *Lentinus*, *Pleurotus*, *Psathyrella*, and *Volvariella* (Bastos, *et al*., 2023). Some mushrooms, like certain *Armillaria* species, exhibit both saprotrophic and parasitic behaviors (Mlambo & Maphosa, 2022). Parasitic mushrooms obtain nutrients from living organisms, often damaging or killing their hosts in the process. Edible parasitic species include *Laetiporus* spp., while *Hypomyces lactifluotum* parasitizes other mushrooms (Perez-Moreno, *et al*., 2021b). Mycorrhizal mushrooms form symbiotic associations with plants, exchanging water and nutrients from the soil for organic compounds provided by the host plant. Edible ectomycorrhizal mushrooms include species from genera such as *Amanita*, *Boletus*, *Cantharellus*, *Lactarius*, *Russula*, and *Tricholoma*. Additionally, the genus *Termitomyces* has a unique symbiotic relationship with termites, relying on organic matter processed by termites and secreting enzymes that help break down lignocellulosic substrates for termite digestion (Khastini, *et al*., 2023).

Ectomycorrhizal fungi are essential for nutrient cycling, plant protection against pathogens, and the development of underground networks that connect trees and plants, often referred to as the "wood wide web" or the "internet" of forests (Perez-Moreno, *et al*., 2021a). While some edible ectomycorrhizal mushrooms are region-specific, others have been introduced through tree plantations (Boa, 2004). Overall, the ability of mushrooms to decompose lignocellulosic materials and their symbiotic relationships with plants significantly benefit ecosystems, supporting nutrient recycling and fostering biodiversity (Perez-Moreno, *et al*., 2021b).

4. Edible Mushrooms of Tropical Africa

The edibility of mushrooms is determined by their lack of toxic effects on humans and animals, along with their appealing organoleptic and culinary qualities

(Samsudin & Abdullah, 2018). In many African countries, edible mushrooms play a significant role in the livelihoods and diets of rural communities, serving as a basis for ethnic, cultural, religious, and medicinal significance (Bastos, *et al*., 2023). Preparation methods for wild edible mushrooms vary among ethnic groups, depending on their intended use. Mushrooms may be sold for income, used medicinally or mystically, or consumed as food. When used as food, they are typically cooked fresh, added to traditional soups and dishes for flavor or as a meat substitute, or preserved by sun-drying for later use. Annual consumption of wild edible mushrooms per family varies widely across Africa, ranging from 20 kg in Zimbabwe to 30–35 kg in Malawi, 30 kg in the Democratic Republic of Congo, and up to 160 kg in Mozambique (Boa, *et al*., 2000; Hailing, 2006; Degreef and de Kesel, 2017; Bastos, *et al*., 2023).

Traditional knowledge of mushroom edibility and uses has historically been passed down orally through generations, a practice that continues in many parts of tropical Africa. Mushrooms are often identified by vernacular names based on their shape, texture, taste, or ecological associations. For example, in southern Africa, *Lactarius* species growing on the *masuku* tree are known as *chimsuku* or *kamsuku* (Boa, 2004). In southeastern Nigeria, *Termitomyces* species growing on termite nests are referred to as *ero mkpu* (mkpu meaning termite nest). The earwood mushroom (*Auricularia auricular-judae*) is named for its shape, with local translations varying by ethnic group. While local names highlight the cultural importance and traditional uses of mushrooms, they can lead to misidentification between ethnic groups, emphasizing the need for scientific nomenclature for accurate identification.

Globally, thousands of edible mushroom species have been documented. Researchers have identified approximately 2,786 species across 99 countries, with 2,189 deemed edible. Of these, 2,006 are safe for consumption, while 183 require pretreatment (Li, *et al*., 2021). In Africa, 959 mushroom species have been identified, including 801 edible species. The highest number of species is found in Central Africa (477), followed by East Africa (145), West Africa (97), Southern Africa (56), and North Africa (26), figure 1. Sileshi *et al*., (2023) recorded 480 species of wild edible mushrooms in Africa, categorized as mycorrhizal (249 species), termitophilic (28 species), and saprophytic or parasitic (203 species). However, the distribution of wild edible mushrooms has declined due to factors such as climate change, urbanization, chemical pollution, overgrazing, and deforestation (Gizaw, *et al*., 2018). In Africa's Miombo Woodlands, Degreef *et al*., (2020) documented 77 edible mushroom species, while Kamalebo *et al*., (2018) identified 73 species in the Democratic Republic of Congo. Kabacia & Muchane (2023) reported 306 wild edible mushroom species from East Africa, and Bastos *et al*., (2023) listed notable species from Central and Southern Africa. In West Africa, Osemwegie *et al*., (2014) highlighted key edible mushroom species prominent in ethnomycological literature.

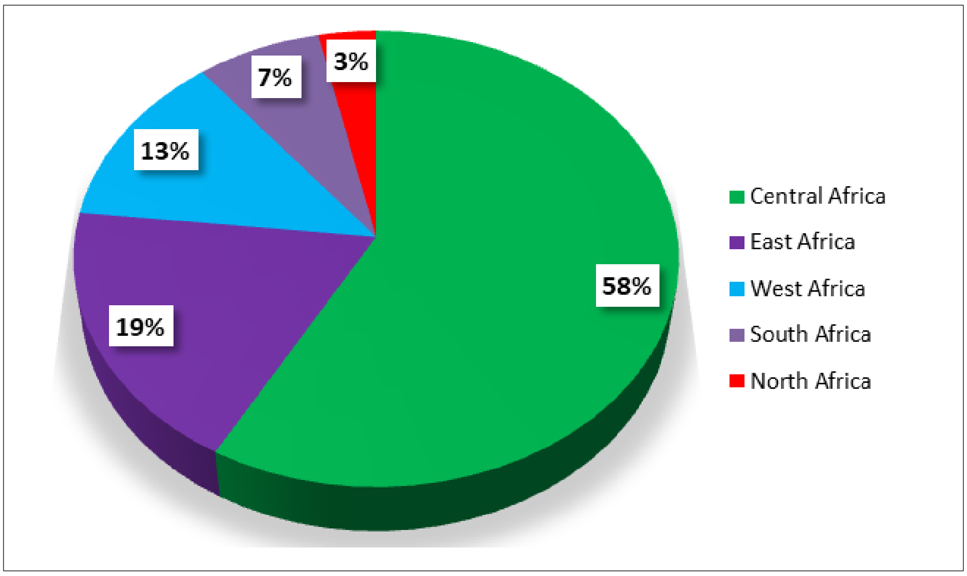

Figure 1: Distribution of edible mushrooms across Africa (Ndifon, 2021)

However, irrespective of rich diversity of mushrooms and woodlands in tropical region of Africa, there are limited account and poor inventory of mushroom taxa and their uses resulting to low perception of this valuable resource (Osemwegie, *et al*., 2014). Edible mushrooms consumed by different ethnic groups across tropical Africa include *Amanita spp., Auricularia auricular-Judae, Calvatia cyathiformis, Cantharellus spp., Coprinus africanus, Lactifluus spp., Lactarius spp., Lentinus spp., Ganoderma lucidum, Pleurotus tuber-regium, Russula spp., Schizophyllum commune, Termitomyces microcarpus, Tricholoma spp.,* *Volvariella volvacea* among others (Kamalebo *et al*., 2018; Degreef *et al*., 2020; Bastos *et al*., 2023; Kabacia & Muchane, 2023).

5. Sources of Edible Mushrooms

The collection of wild edible mushrooms dates back to the Upper Paleolithic period, approximately 18,700 years ago (Power, *et al*., 2015). In Africa, the earliest documented references to mushroom foraging are limited, with notable accounts by Walker (1931), Zoberi (1972), and Oso (1975). Mushroom foraging remains an ancient practice, where edible mushrooms are collected from the wild for food or income (Osemwegie, *et al*., 2014). This method continues to be the primary way of sourcing mushrooms in Africa, significantly contributing to the livelihoods of indigenous populations. However, it is an unsustainable approach that poses challenges to food security and environmental conservation (Miambo & Maphosa, 2022). Wild edible mushrooms are typically harvested at the onset of the rainy season, a period traditionally referred to as the "hunger season," providing critical sustenance for impoverished, mycophilic rural populations. These mushrooms are a vital food resource, predominantly used for subsistence (Boa, 2004). Commercial harvesting is often limited to local trade along busy roads and village markets, with little to no export activity. As awareness of their nutritional and medicinal benefits grows, the societal significance of wild edible mushrooms increases. Rich in bioactive metabolites, they have long been used as natural remedies for various diseases (Dulay, *et al*., 2023). Nutritionally, they are high in protein, carbohydrates, and fiber while being low in fatty acids (Bastos, *et al*., 2023). For rural populations, particularly women and children, mushrooms provide an essential source of income, with excess harvest sold to urban consumers.

Globally, around 2,000 species of wild edible mushrooms have been identified, but only 30 species have been successfully cultivated (Kabacia & Muchane, 2023). In Africa, there is limited information on the domestication of wild mushrooms, including its prospects, challenges, and potential contributions to the mushroom industry. Mushroom domestication remains uncommon in the region, with ignorance and lack of awareness being major factors driving overdependence on wild foraging. This reliance on wild collection hinders the development of mushroom cultivation despite the abundance of raw materials (Okhuoya, *et al*., 2010). Such dependency undermines commercial production and the potential for foreign exchange earnings.

Domestication of mushrooms offers significant benefits, including the commercialization of indigenous species, mitigation of seasonal supply constraints, and reduction of the uncertainties associated with wild harvests (Osemwegie, *et al*., 2014). It also facilitates the cultivation of disease-resistant strains suited to tropical climates. By replicating and optimizing natural growth conditions, it is possible to identify suitable substrates for the production of various mushroom strains (Kabacia & Muchane, 2023). Moreover, domestication helps preserve endangered indigenous species, promoting sustainability. Concerns over the declining availability of certain prized species have prompted policies regulating wild mushroom collection in developed countries (Boa, 2004). While such regulations are largely absent in many developing countries, similar laws could be implemented to control overharvesting and reduce overdependence on wild mycoresources. Domestication and policy interventions hold great potential for addressing the challenges of unsustainable wild mushroom harvesting and fostering the growth of the mushroom industry in Africa.

6. Commercial Mushroom Production

Several species of wild edible mushrooms have been successfully cultivated, with the majority being saprotrophs (Boa, 2004). Saprotrophic mushrooms can be cultivated using a variety of organic substrates, while ectomycorrhizal mushrooms rely heavily on symbiotic relationships with host plants, making their cultivation challenging due to factors such as climatic conditions, seasonal dependency, and low accessibility (Miambo & Maphosa, 2022). Cultivating ectomycorrhizal mushrooms poses significant nutritional, ecological, economic, and socio-cultural challenges. Although there have been notable advancements since the first cultivation of the ectomycorrhizal mushroom *Tuber melanosporium* in 1977 (Guerin-Laguette, 2021), commercial production remains rare.

The cultivation of ectomycorrhizal mushrooms is hindered by their complex symbiotic life cycle, which requires specific interactions with host plants. However, some species can be cultivated without a host plant. For instance, *Lyophyllum shimeji*, a prized mushroom in Japan, has been successfully cultivated commercially without host plants (Yamada, *et al*., 2017). Advances in scientific research have improved the cultivation of ectomycorrhizal mushrooms. Guerin-Laguette (2021) demonstrated in a field trial that *Lactarius deliciosus* produced yields ranging from 0.4 kg/ha to 1,100 kg/ha under *Pinus radiata* and *P. sylvestris* after six and nine years, respectively. Continued research into the domestication of ectomycorrhizal mushrooms, including methods to cultivate them without host plants, is essential for potential commercialization.

Commercial mushroom production requires a steady supply of organic substrates, such as sawdust, cotton waste, oil palm fruit fiber, cassava peels, plantain and banana leaves/pseudostems, corn straw/cobs, wheat straw/bran, and rice straw/husks, which are abundant in tropical Africa (Okhuoya, *et al*., 2010). Despite the availability of raw materials, favorable climatic conditions, and a growing awareness of the nutritional and economic value of mushrooms, commercial mushroom production in Africa remains low.

Additionally, accurate data on the number of commercial and cottage mushroom industries in the region is scarce.

Globally, the gross production value of mushrooms has grown significantly, from USD 2.99 billion in 1991 to USD 46.61 billion in 2021 (FAOSTAT, 2022). Similarly, global mushroom production increased from 2.53 million tons in 1991 to 44.21 million tons in 2021, with China accounting for 93% of the total production at 41.13 million tons (FAOSTAT, 2022). In contrast, Africa produced only 36,922.72 tons in 2021, representing less than 1% of global production. South Africa led the continent with 29,064 tons, accounting for 78% of Africa's total production (FAOSTAT, 2022). This highlights the limited commercialization of mushrooms in Africa.

Globally, commercially cultivated mushrooms belong to genera such as *Agaricus*, *Agrocybe*, *Auricularia*, *Coprinus*, *Flammulina*, *Ganoderma*, *Hericium*, *Lentinula*, *Lentinus*, *Pleurotus*, *Tuber*, and *Volvariella* (Royse, *et al*., 2017; Kumla, *et al.*, 2020; Dulay, *et al*., 2023). Of these, five genera dominate global edible mushroom production, with *Lentinula* being the most prevalent (Figure 2). In Africa, *Pleurotus*, *Agaricus*, and *Lentinus* are the primary genera cultivated commercially, with Ghana leading in the cultivation of five mushroom genera (Miambo & Maphosa, 2022). Among these, *Pleurotus* species are the most widely cultivated, and Tanzania ranks highest in the diversity of mushroom species grown (Figure 3).

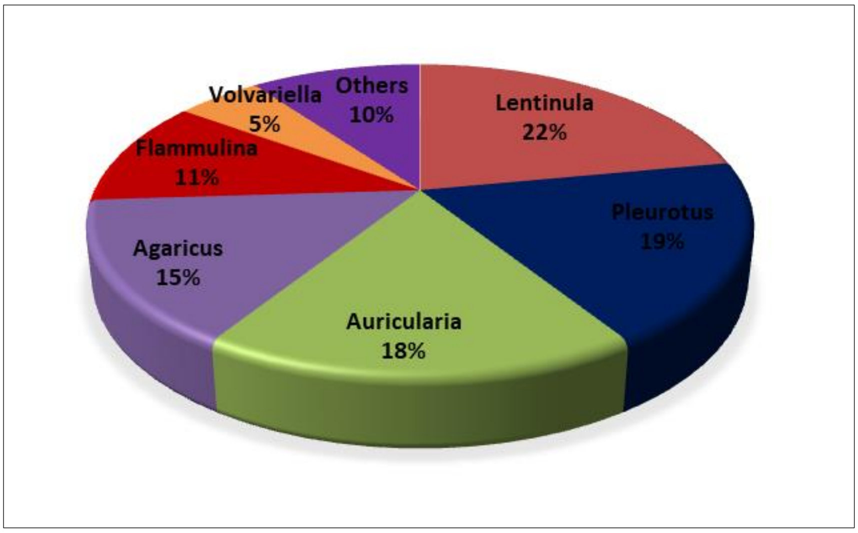

Figure 2: Global production of edible mushroom by genera (Data source: Royse *et al.*, 2017)

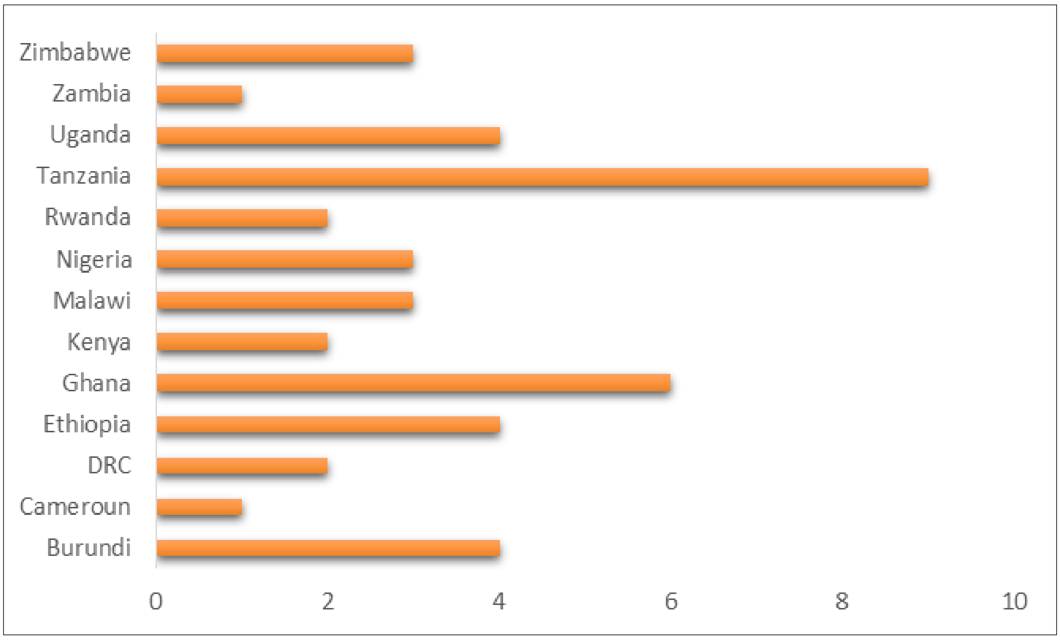

Figure 3: Number of mushroom species commercially produced in some African countries (Data source: Mlambo & Maphosa, 2022)

7. Scope of Mushroom Market

Mushroom consumption is widely popular and holds cultural significance among various ethnic groups worldwide. In Africa, the majority of mushrooms consumed are harvested from the wild, particularly during the rainy season. These mushrooms are sold by local harvesters in fresh or dried forms at rural markets, roadside outlets, or through door-to-door sales. However, in many developing countries, commercial mushroom production remains limited and grows at a pace slower than the increasing demand (Kinge, *et al*., 2014). Challenges such as short shelf life, inadequate packaging, poor handling, and insufficient storage infrastructure further hinder the mushroom market (Raut, 2019). Growing awareness of the nutritional and health benefits of mushrooms, along with shifting dietary preferences toward organic and health-conscious foods, has significantly increased global demand. In developed industrial nations, this demand is effectively met through large-scale commercial mushroom production. In contrast, many developing countries, with limited industrial and biotechnological capacity, struggle to meet the growing demand, resulting in a significant supply gap.

The global trade of wild edible mushrooms has grown considerably, with transactions increasing from $181,599 in 2002 to $769,162 in 2017 (De Frutos, 2020). Wild mushrooms account for approximately 8% of total global mushroom production, with a market value estimated at USD 5 billion (Royse, *et al*., 2017). China leads in both the diversity and commercialization of wild edible mushrooms, providing livelihoods for many communities, where 15–90% of annual income is derived from mushroom-related activities. China also earns approximately USD 100 million annually from the export of wild mushrooms (Perez-Moreno, *et al*., 2021a). Despite Africa's significant forest resources and human populations reliant on ecosystem services, its contribution to the global wild mushroom trade remains negligible. This underrepresentation highlights a missed opportunity to capitalize on the economic benefits of wild mushrooms. Globally, wild mushroom markets are dominated by species from genera such as *Agaricus*, *Pleurotus*, *Tricholoma*, *Termitomyces*, *Russula*, *Cantharellus*, *Boletus*, *Lactarius*, and *Tuber* (Boa, 2004; Wang, *et al*., 2004).

The global market for cultivated mushrooms has experienced substantial growth over the past three decades. Mushroom export volumes have risen from 101,790 tons in 1991 to 784,517.61 tons in 2021, with a value of USD 2.43 billion. The top five mushroom exporters are Poland, the Netherlands, China, Ireland, and Belgium (FAOSTAT, 2022). Global mushroom imports were valued at USD 2.28 billion in 2021, with Europe accounting for more than 35% of the global import market (Raman, *et al*., 2018; FAOSTAT, 2022). In contrast, Africa's contribution to the global mushroom market remains minimal. Between 1991 and 2021, Africa's mushroom export volumes ranged from 338 tons to 1,846.78 tons, with a total export value of just USD 8,096 in 2021 (FAOSTAT, 2022). These figures underscore Africa's low adoption of commercial mushroom production and its limited participation in the global market. This lack of development presents a missed opportunity for leveraging mushroom production as a driver of economic growth and development in the region.

8. Technology of Mushroom Cultivation

Mushroom cultivation is a meticulous process that requires precision and a series of sequential steps or unit operations to ensure success. Any failure or neglect in these steps can lead to adverse outcomes such as contamination, low yields, or substantial losses (Chang, 2007). Each mushroom species has specific cultivation requirements, including distinct methods and suitable growth substrates (Haukongo, *et al*., 2021). Despite the abundance of naturally occurring edible mushrooms, only a few species have been successfully cultivated to date (Chakravarty, 2011).

Maintaining aseptic practices is critical for achieving optimal yields in mushroom cultivation. Sterile techniques help prevent contamination, particularly from toxin-producing microorganisms, which can compromise the integrity of the cultivated mushrooms and jeopardize production (Mishra, *et al*., 2019). While the fundamental principles of mushroom cultivation are consistent across species, practical methods must be tailored and adjusted to accommodate local climatic conditions, available substrates, and the specific varieties of mushrooms being cultivated (Mlambo & Maphosa, 2022).

For effective production of high-quality mushrooms with strong market potential, several essential parameters must be carefully managed. These include:

8.1. Identification and Selection of Mushroom Strain

Selecting an appropriate mushroom strain is a critical factor often overlooked in mushroom cultivation. The choice of strain must align with the availability of substrates, prevailing climatic conditions, and market demand. A key initial step in effective mushroom production is obtaining a pure mycelial culture of the desired mushroom strain (Riaz, *et al*., 2022).

Mycelium serves as the foundation for mushroom cultivation, acting as the seed that initiates growth and fosters nutritional development (Sullivan, *et al*., 2020). Pure cultures can be developed through various methods, including single or multi-spore cultures, tissue culture from high-yielding and vigorous strains, or acquired from culture collections or research laboratories (Chang, 2007). Cultures sourced from established laboratories or collections offer the advantage of being pre-tested for production efficiency and guaranteed for purity and safety. Potato Dextrose Agar, Malt Extract Agar, Oat Meal Agar, Barley Extract Agar, Yeast Mannitol Agar, Wheat Extract Agar are commonly used media for cultivating mushroom mycelia, providing the necessary nutrients for robust mycelial growth and development (Aditya, *et al*., 2024).

8.2. Spawn Production

Mycelium propagated on any naturally supporting medium under aseptic conditions to obtain inoculum required for faster colonization of growth substrate in mushroom production is known as spawn (Jarial, *et al*., 2020; Riaz, *et al*., 2022). Mycelium from pure culture of selected mushroom strain is often inoculated onto a steam sterilized grain after which mycelium completely colonizes the entire grain. Cereal grain is popularly used in spawn production because it serves a nutritive role for mycelia and activates their vigor to quick colonization of the mushroom substrate (Aditya, *et al*., 2024). Spawn production is a fermentation process that increases the growth of mushroom mycelia through a solid organic matrix under controlled environment (Tabish, *et al*., 2022). The quantity of spawn used in spawning a given substrate is not directly proportional to the yield, although the use of more spawn may reduce the effect of competitive organisms present and allows for faster colonization of the substrate (Sullivan, *et al*., 2020). Different types of substrates successfully used in spawn production include walnut shells, almond chips, chicken peas, wheat grains, maize grains, maize cobs, barley grains, oat grains, paddy grains, bajra (pearl millet) grains and sorghum grains (Kumari & Suman, 2020; Tabish, *et al*., 2022, Aditya, *et al*., 2022).

Spawn quality is an important parameter in successful mushroom cultivation. Aseptic practice in spawn production reduces bacteria and mold contamination of mycelia growth in the substrate which often produces patches of slimy fluids or coloured mycelia on the substrate other than the unblemished white colour characteristic of a good/quality spawn (Borah, *et al*., 2019). Bad quality grains, improper sterilization, contamination, excess moisture and high storage temperature are some factors responsible for spoilage of spawn during storage. Shelf life of spawn spans between 30days (for storage at room temperature) up to 6months (for storage under refrigerator condition) however, duration of storage affects the yield of mushrooms (Borah, *et al*., 2019).

Spawn production is a complex task of primary concern in mushroom cultivation and require high level of expertise, specific knowledge and technology advancement (Aditya, *et al*., 2022). In some developing countries where there are no suppliers of mycelium, spawn importation is inevitable with its concomitant cost and local mushroom farmers who often lack expertise, cost-effective and sustainable method of producing spawn faces difficulties because keeping a culture alive require electricity for refrigeration which is usually inaccessible due to financial constraint (Sullivan, *et al*., 2020).

8.3. Substrates for Mushroom Cultivation

Organic matter containing lignocellulose (cellulose, hemicellulose and/or lignin) are commonly used as substrates in mushroom cultivation. These substrates usually agro-industrial or forestry wastes are converted to low molecular weight compounds (required for nutrient to promote mycelia growth) through the actions of lignocellulosic enzymes secreted by mushrooms (Kumla, *et al*., 2020; Abena, *et al*., 2023). Different substrates are used as growth medium for different mushroom species (Table 1) and the use of appropriate substrate suitable for a given mushroom specie influences their nutritional content, bio-efficiency and cost (Haukongo, *et al*., 2021). Also, combination of different substrates has proven to increase chemical composition of mushrooms and enhance mycelia growth as well as quality fruit body production (Siwulski, *et al*., 2019). Lignocellulosic substrates usually have low nitrogen content, minerals, etc. and addition of supplements in a desirable proportion can increase the biological efficiency of the mushroom (Rahman, *et al.*, 2022). Nutritional demand differ depending on mushroom species, *Agaricus bisporus* require enhanced nitrogen content, requiring carbon/nitrogen (C:N) ratio of about 17:1 for mycelial running and grows on fermented compost of wheat straw with horse manure while *Volvariella volvacea*, *Lentinula edodes* and *Pleurotus* species require low nitrogen content and grow on raw or less composted lignocellulosic materials with C:N ratio of about 80:1, implying that they can metabolize large amount of carbohydrates in the presence of a very small amount of nitrogen (Chang, 2009; Ndem & Martha, 2016).

Combination of lignocellulosic substrate is necessary to augment its nutrient content for increased mushroom yield. According to Stamets (2000), 100kg sawdust plus supplement can produce 80kg fresh weight of mushrooms, with even higher yields regularly possible. Yang *et al*., (2013) reported that the supplementation of wheat bran and cotton seed hull to rice straw or wheat straw could shorten mushroom stipe length and enlarge mushroom diameter, which may result from the supplement changing the physical properties and C: N ratio of rice straw substrate. Thus, they concluded that supplementation of cotton seed hull to rice straw (or wheat straw) substrate can increase *Pleurotus* marketable qualities. Fanadzo *et al*., (2010) reported that 25% supplementation with maize bran could reduce mushroom yields significantly. Sailaja & Radhika (2020) observed that supplementation of mushroom substrate with medicinal plants enhanced their bioactive/phytochemical properties with increased added value. Ejigu *et al.*, (2022) reported that water hyacinth supplemented with wheat or teff straw improved the growth, yield and biological efficiency of oyster mushroom.

Table 1: Variety of agro wastes used as substrates for mushroom cultivation

Mushroom	Substrates	Substrate Preparation	References
Agaricus spp.	Straws of wheat, barley, oat, rice, maize, soyabean meal, coffee pulp, groundnut hull, poultry manure, horse/donkey manure.	Composting, sterilization, supplementation and spawning	Toker, *et al*., 2007; De Andrade, *et al*., 2008; Weil, *et al*., 2013; Thongklang & Luangharn, 2016; Kumla, *et al*., 2020; Mlambo & Maphosa, 2022.
Auricularia spp.	Sawdust, oil palm fronds, empty fruit palm bunch	Soaking, draining, bagging, supplementation with rice/wheat bran, calcium carbonate, sterilization and spawning	Razak, 2013; Priya, *et al*., 2016; Liang, *et al*., 2019; Thongklang, *et al*., 2020.
	Logs of wood	Drilling of hole, spawning, cover with bark and seal with wax.	
Calocybe indica	Paddy straw, coconut leaf, coco peat, sawdust	Composting, sterilization and spawning	Jose, 2020
Lentinula edodes	Straws of wheat, oat, rice, millet, barley, rice bran, wheat bran, tea leaves, corn cobs, sawdust, sugarcane bagasse, sugarcane filter cake, cotton seed hulls, chicken manure, horse manure, cow dung	Soaking, draining, bagging, supplementation with rice/wheat bran or chicken/horse manure/cow dung, calcium carbonate, gypsum, sterilization and spawning	Gaitan-Hernandez, *et al*., 2014; Kamthan, *et al*., 2017; Meta, *et al*., 2018; Gao, *et al*., 2020; Desisa, *et al*., 2023
Lentinus spp.	Wheat straw/bran, coconut fruit fiber, rice straw soya stalk, sunflower stalk	Soaking, draining, bagging, sterilization and spawning	Fasidi & Kadiri, 1993; Okhuoya, *et al*., 2010; Kumla, *et al*., 2020
Pleurotus spp.	Paddy straw, nut grass, sawdust, newspaper, banana leaves, cottonseed hull, cassava peel, yam peel, groundnut pod, cocoa pod, popcorn cob, teff straw, wheat straw, barley straw, lawn grass, coconut fruit fiber, oil palm fiber and cake, waste papers, rice husk, corn husk, elephant grass, sesame stalk, dried plantain leaves.	Soaking, draining, bagging, supplementation with rice/wheat bran, calcium carbonate, gypsum, sterilization and spawning	Osemwegie, *et al*., 2002; Obodai, *et al*., 2003; Shah, *et al*., 2004; Adebayo, *et al*., 2009; Onuoha, *et al*., 2009; Okhuoya, *et al*., 2010; Peter, *et al*., 2019; Melisha, *et al*., 2020; Tekeste, *et al*., 2020; Wabali & Favour, 2021; Hakizimana, *et al*., 2022.
Volvariella volvacea	Rice straw, maize husk, oil palm empty fruit bunch, cassava peels coconut fiber, tea leaves, water hyacinth, cotton waste, sugarcane bagasse	Soaking, draining, bagging, supplementation with calcium carbonate, sterilization and spawning	Ahlawat, *et al*., 2005; Fasola, et al., 2007; Haq, *et al*., 2011; Adedokun & Akuma, 2013; Biwas & Layak, 2014; Apetorgbor & Apetorgbor, 2015; Kamthan, *et al*., 2017; Tryono, *et al*., 2019; Rahman, *et al*., 2022
Psathyrella spp.	Corn straw/cob, oil palm empty fruit fiber, rice straw, banana leaves	Soaking, draining, bagging, sterilization and spawning	Ayodele & Okhuoya, 2007, Okhuoya, *et al*., 2010.

The preparation of substrates for mushroom cultivation varies depending on the type of mushroom being grown. Common methods include composting and partial/non-composting techniques. Composting involves a biological process where microorganisms break down substrates into more digestible forms for mycelial growth (Jibrin, *et al*., 2017). The raw materials for the substrate undergo fermentation for 9-12 days, with periodic turning and watering. After fermentation, the substrates are sterilized, and additives are incorporated before spawning. Mushrooms cultivated on composted substrates include *Agaricus* spp., *Calocybe* spp., *Clitocybe* spp., *Tremella fuciformis*, *Ustilago maydis*, and *Phallus indusiatus* (Mlambo & Maphosa, 2022). In contrast, for partial/non-composted substrates, the raw materials are soaked in water, drained, pasteurized, and additives are added before spawning (Mlambo & Maphosa, 2022). Mushrooms like *Pleurotus* spp., *Lentinus* spp., *Lentinula edodes*, *Volvariella volvacea*, and *Auricularia* spp. are cultivated using this method (Rahman, *et al*., 2022). Sterilization of the substrate is a critical step in mushroom production. A sterile substrate provides an ideal environment for mushroom growth and often requires pretreatments to minimize competing microorganisms (Jibrin, *et al*., 2017). Various pests and diseases can affect mushroom substrates, especially if aseptic techniques and sterilization protocols are not followed, which can negatively impact both yield and quality (Ralph & Kurtzman, 2010).

The quantity of spawn used to inoculate a substrate largely depends on the grower's preference, as various studies report differing spawn quantities for optimal efficiency. Subramanian *et al*., (2014) recommended sprinkling one handful of spawn (about 30g) over 250g of paddy straw. Sardar *et al*., (2020) applied 5% spawn to a mixture of 4kg cotton stalk and cotton seed hulls in varying ratios. Fanadzo *et al*., (2010) used 4% spawn. After inoculation, the substrate bags are incubated in the dark at room temperature for 21-45 days for full mycelium colonization.

Globally, a wide range of waste materials are utilized as substrates for mushroom cultivation, although the types of available waste vary by region (Sofi, *et al*., 2014; Rahman, *et al*., 2022). In Africa, resources for commercial mushroom cultivation are abundant, particularly for saprophytic or wood-rotting mushrooms, as many regions are rich in forest resources and agriculture. Agroforestry by-products such as maize husks, corn cobs, cottonseed hulls, rice straw, banana leaves, groundnut pod shells, sawdust, sugarcane bagasse, coconut fiber, oil palm waste, and wild grasses are plentiful and have been successfully used in mushroom cultivation (Megersa, *et al*., 2013; Majamanda, *et al*., 2023).

8.4. Fruiting and Harvesting

To ensure successful mushroom fruiting, the environmental conditions—temperature, humidity, light, and aeration—must be optimally controlled. Key techniques to induce fruit body formation include increasing aeration (by perforating substrate bags), applying cold water shocks to the substrate, and raising the relative humidity of the environment (Megersa, *et al*., 2013). Due to variability in strains and substrates, it is challenging to define precise fruiting periods. Typically, pinheads (seed flush) appear 2-3 weeks after substrate colonization and are ready for harvest within 5-6 days (Ceasar, *et al*., 2020; Boruah, *et al*., 2021). Pinheads develop first and then mature into fruiting bodies. Ideal growth conditions include an ambient temperature of 28°C, relative humidity above 80%, and light intensity around 100 lux (Yang, *et al*., 2013). Strict control of microbiological contamination is crucial, and while pesticides, particularly fungicides, may be used, they should be avoided if the mushrooms are intended for consumption as nutraceutical powders (Chang, 2007).

The timing of mushroom harvest depends on the species, consumer preferences, and market demand (Chang, 2009). Mushrooms are typically ready for harvest 30-50 days after spawning, with cultivation cycles lasting 6-8 weeks (Mishurov, *et al*., 2021). Harvesting involves gently pulling or twisting the mushrooms from the substrate, and the process can continue as long as the mycelium remains white and firm. Generally, three to four flushes can be harvested during a single cycle (Kanaujiya, *et al*., 2023).

9. Mushroom Products and Value Addition

Value addition involves transforming a product from its original state into a more valuable and desirable form. In the case of mushrooms, this process increases availability to consumers, meets demand, and enhances the economic value of the product (Ogbo, *et al*., 2023). However, the commercialization of mushrooms often leads to increased output, and due to their high perishability, significant postharvest losses occur, especially during peak harvest seasons (Mensah & Archeampong, (2023). Adequate postharvest processing and preservation methods of mushrooms are necessary for sustaining their nutritional and organoleptic qualities (Sangeeta, *et al*., 2024). While the mushroom industry primarily focuses on marketing fresh or dried mushrooms, value addition remains underutilized (Ganeshkumar, *et al*., 2020).

Value addition and processing are essential for sustaining mushroom production, reducing postharvest losses, and boosting consumption (Huchchannanavar, *et al*., 2020; Khadka, 2023). These practices significantly impact farmers, processors, consumer satisfaction, marketability, and the overall sustainability of the enterprise. They also improve farmers' net income by addressing spoilage challenges (Al Hinai, *et al*., 2022). Mushrooms are highly nutritious, and their incorporation into value-added products enhances the nutritional quality and health benefits of processed foods (Archana & Neetu, 2016). Several novel value-added products have been successfully developed from various mushroom species worldwide (Table 2).

Effective processing techniques for value-added mushroom products can transform consumption patterns, extend shelf life, and increase profitability for farmers (Ganeshkumar, *et al*., 2020). With the emerging innovative processing methods, modern mushroom processing uses automated equipment unlike the traditional methods. Innovative techniques such as high pressure processing, electrofluidic drying, cold plasma treatment as well as advanced packaging-coating technology and quality detection methods including spectroscopy, imaging technology and nuclear magnetic have been developed for effective processing and rapid detection in contemporary mushroom processing (Huo, *et al*., 2023; Sangeeta, *et al*., 2024).

In Africa, value-added mushroom products are scarce due to limited commercial production, low consumer awareness, and insufficient knowledge of processing technologies. Marketing channels are often short, and farmers frequently lack cold storage or drying facilities for preservation. Despite these challenges, Africa holds immense market potential for value-added mushroom products. Developing mushroom-based products that align with indigenous and staple foods widely consumed by local populations could harness this potential, particularly as many ethnic groups in the region are mycophilic. Value addition to mushrooms could play a critical role in alleviating hunger and food shortages across the continent (Khan, *et al*., 2024).

Table 2: Value-added products from some mushroom species

Mushroom species	Products	References
Auricularia auricular	Biscuits	Tu, *et al*., 2022
Agaricus spp.	Pasta, cake, beef patties, taco filling, frankfurter, liver pate, ketchup, egg-patties, fish patties, beef burger, cookies, bread.	Nayak, *et al*., 2015; Lu, *et al*., 2016; Kumar & Ray, 2016; Liu, *et al*., 2018; Wong, *et al*., 2019; Ceron-Guevara, *et al*., 2020b; Ceron-Guevara, *et al*., 2021; Du, *et al*., 2021; Patinho, *et al*., 2021; Al-zamani, *et al*., 2022; Slawinska, *et al*., 2022; Sham, *et al*., 2023.
Calocybe indica	Cookies	Pathore, *et al*., 2019; Banerjee, *et al*., 2020.
Flammulina velutipes	Goat meat nuggets, chicken sausage, ground ham	Jo, *et al*., 2018; Banerjee, *et al*., 2020; Jo, *et al*., 2020.
Lentinula edodes	Sausage, muffins, pasta, beef/pork patties, noodles	Heo, *et al*., 2014; Lu, *et al*., 2016; Arora, *et al*., 2017; Lu, *et al*., 2018; Mattar, *et al*., 2018; Wang, *et al*., 2019; Olawuyi & Lee, 2019; Chun, *et al*., 2020
Pleurotus spp.	Sausage, chicken patties, frankfurter, beef burger, liver pate, steamed buns, cookies, biscuits, noodles, jam, ketchup, instant soup powder premix	Wan Rosli & Solihah, 2011; Wan Rosli & Solihah, 2012; Prodhan, *et al*., 2015; Wan Rosli, *et al*., 2015; Ng, *et al*., 2017; Wan-Mohtar, *et al*., 2018; Arora, *et al*., 2018; Wang, *et al*., 2019; Wan-Mohtar, *et al*., 2020; Ceron-Guevara, *et al*., 2020a; Parvin, *et al*., 2020; Shushuma, *et al*., 2021; Ceron-Guevara, *et al*., 2021; Kurnianto, *et al*., 2022; Ogbo, *et al*., 2023.
Volvariella volvacea	Extruded snacks	Tepsongkroh, *et al*., 2019; Tepsongkroh, *et al*., 2020

10. Economics of Mushroom Production

Investing in commercial mushroom production is highly profitable and has significant potential to contribute to the economic development of developing countries. Economic analyses of mushroom production help assess the efficiency and viability of commercialization by determining optimal output levels and benefit-cost ratios (Rawat, *et al*., 2020). These analyses evaluate production costs, profitability, and economic implications, which ultimately influence the feasibility of mushroom farming enterprises (Acharya & Dhungel, 2021).

Over the years, various studies have highlighted the economic potential of mushroom production, providing valuable insights for investors to estimate costs, profit margins, and market share. For instance, Chitra *et al*., (2018) reported a net profit of ₹14,240 from oyster mushroom cultivation over three months, with a total expenditure of ₹5,760. Similarly, Ofodile & Yusuf (2010) documented a gross profit of ₦103,400 from a two-month oyster mushroom cultivation, with expenses totaling ₦21,600. In Zimbabwe, Mutema *et al*., (2019) evaluated oyster mushroom production profitability, reporting impressive figures: a Net Present Value (NPV) of 13036.46%, a Benefit-Cost Ratio (BCR) of 15.75, and an Internal Rate of Return (IRR) of 141.42% for 2014–2017. Kharbikar *et al*., (2020) highlighted an efficient benefit-cost ratio and break-even point in mushroom enterprises, with profits of ₹0.61 per rupee invested and a maximum net profit of ₹10,324.6. Kumari *et al*., (2022) reported a gross income of ¥1,785.34 against a production cost of ¥80.60, resulting in a BCR of 1.31 for oyster mushroom cultivation. Rawat *et al*., (2020) compared oyster and button mushroom production, revealing gross returns of ₹17,400 and ₹70,335, respective production costs of ₹11,850 and ₹59,550, and BCRs of 1.47:1 and 1.18:1.

In developing countries, limited investment in mushroom farming compared to other crops is partly due to a lack of knowledge about the venture's benefits and risks. Despite this, the mushroom industry has the potential to become a lucrative business, as it faces minimal competition with other farming ventures and offers significant economic prospects (Gupta, *et al*., 2022). The profitability demonstrated in various studies suggests that commercial mushroom farming can serve as an ideal opportunity for self-employment, particularly in Africa, where unemployment rates are high. Mushroom farming requires relatively low startup costs in terms of space and capital, making it accessible and sustainable for aspiring entrepreneurs.

11. Prospects of Mushroom Production in Developing Countries

Mushroom production is a promising industry with significant economic, environmental, and nutritional benefits (Jayaraman, *et al*., 2024), making it a valuable strategy for addressing food security challenges in developing countries. It offers an affordable and high-quality protein source to combat hidden hunger and malnutrition (Kazige, *et al*., 2022). Unlike wild mushrooms, commercial production ensures a year-round supply, reduces seasonal limitations, and helps preserve endangered species through sustainable cultivation practices (Osemwegie, *et al*., 2014). Furthermore, mushroom processing into value-added products enhances consumer acceptability, prolongs shelf life, and addresses post-harvest losses (Ganeshkumar, *et al*., 2020).

Expanding mushroom production offers vast opportunities to attract investments and develop innovative value-added products. Many mushroom species have pharmacological properties, contributing to the production of antimicrobial agents and medicinal products (Wasser, 2014). Their bioaccumulation capabilities can be leveraged through bio-fortification, introducing health-enhancing properties into diets and reducing the risk of certain diseases (Pattanayak & Das, 2022). Moreover, commercial cultivation, which uses pre-identified strains, mitigates the risk of poisoning commonly associated with foraged wild mushrooms (Mishra, *et al*., 2019).

Environmentally, mushroom farming supports sustainability through the bioconversion of organic waste into growth substrates (Mensah & Acheampong, 2023). Agro-industrial wastes, often considered environmental hazards, are effectively recycled, aiding waste management and pollution control while aligning with global initiatives to transform waste into wealth (Osuafor, *et al*., 2023). The spent substrates from mushroom farming have additional applications in animal feed, soil conditioning, and biogas production (Niazi & Ghafoor, 2021), demonstrating the circular economic potential of mushroom production.

Economically, mushroom farming generates employment, improves farmer livelihoods, and reduces poverty. Its rapid growth cycle and short production timeframe provide quick returns, making it a profitable enterprise for smallholder farmers (Tekeste, *et al*., 2020). The labor-intensive nature of mushroom farming creates job opportunities, particularly for women and youth, promoting self-employment and reducing unemployment in regions like Africa (Raman, *et al*., 2018). Setting up mushroom cottage industries is cost-effective, requiring minimal space, infrastructure, and maintenance (Bajpai, *et al*., 2021). Additionally, mushroom farming utilizes crop residues, overcoming land scarcity challenges and enabling year-round production (Khadka, 2023). Favorable climatic conditions in tropical regions further support cultivation (Sullivan, *et al*., 2020).

Globally, the demand for mushrooms exceeds current production levels, leading to importation in many countries (Picornell-Buendia, *et al*., 2016). Africa, with its abundant wood and non-wood forest resources, has the potential to become a hub for diverse mushroom species by scaling up production. Commercial cultivation of traditional mushrooms with culinary, medicinal, and economic value can drive market growth, meet local and global demand, and generate foreign exchange revenue. Adopting a small-scale approach to mushroom farming can raise awareness and establish a foundation for sustainable large-scale production (Grimm, *et al*., 2022). This cost-effective strategy allows rural farmers to market mushrooms without significant losses from post-harvest storage issues. In developing countries, small-scale production can improve income for rural communities, reducing poverty at the grassroots level. With rising food costs, increasing poverty, and widespread protein deficiencies, mushroom production offers a pathway to national food security and economic resilience.

12. Challenges of Mushroom Production in Developing Countries

Mushroom production is widely recognized as an economically viable venture, yet its adoption and successful commercialization in developing countries face numerous challenges. These obstacles persist despite the industry's potential to address issues such as increasing populations, unemployment, and food shortages. While progress has been made, mushroom commercialization remains limited, with minimal motivation for widespread adoption (Mensah & Acheampong, 2023).

One significant constraint is the lack of affordable and sustainable methods for culture or spawn maintenance and preservation. Grain spawn, which is sensitive to heat and light, typically has a short lifespan of 2–3 weeks without refrigeration. Unfortunately, the cost and limited availability of electricity or alternative power sources for refrigeration hinder efficient spawn preservation in many regions (Sullivan, *et al*., 2020). This challenge extends to post-harvest preservation, where the high perishability of mushrooms often leads to substantial losses. Additionally, spores from mature mushrooms can pose health risks and environmental hazards if not properly managed. Issues such as respiratory disorders, equipment contamination, genetic diversity loss, and broader environmental concerns have been linked to the dispersal of spores during cultivation (Nishida & Yatera, 2022). Poor sanitation practices and inadequate facilities further exacerbate the risk of contamination, leading to reduced yields and financial losses (Grimm, *et al*., 2022).

Financial and institutional barriers also impede the development of the mushroom industry. The absence of financial assistance, poor policy support, weak political will, and the lack of trade and quality control mechanisms have slowed progress (Azeez, *et al*., 2019; Khadka, 2023). Farmers often depend on wild mushrooms, face price fluctuations, and lack information about the export and import potential of mushrooms, limiting their integration into the broader agricultural sector (Osemwegie & Dania, 2016). Moreover, inadequate post-harvest processing options, transportation facilities, and poorly regulated marketing channels further hinder the commercialization of mushrooms (Gupta, *et al*., 2022).

Technological gaps, insufficient harvest management practices, and unfavorable environmental conditions present additional challenges (Riaz, *et al*., 2022). Mensah & Acheampong (2023) highlight institutional and personal weaknesses, market uncertainties, and value chain issues as significant barriers to commercialization. Furthermore, widespread poverty in developing countries results in limited funding for scientific research and inadequate laboratory facilities, curtailing efforts to advance mushroom production techniques (Osemwegie, *et al*., 2014; Kinge, *et al*., 2014).

In many developing countries, there is a lack of documented data on commercial or cottage mushroom industries and their contributions to national income. In Nigeria, for example, the status of mushroom diversity, composition, and utilization remains underrepresented due to insufficient research (Okhuoya, *et al*., 2010). Socio-economic and cultural factors also contribute to the slow development of mushroom cultivation. In some ethnic groups, mushrooms are associated with superstitions or negative occurrences, leading to a poor market image and reluctance to adopt mushroom farming. Compared to other agricultural activities such as fisheries and livestock farming, mushroom cultivation remains relatively unpopular, further hindering its development.

13. CONCLUSION

Mushroom production offers significant nutritional and economic benefits, making it a viable solution to address hidden hunger, malnutrition, and poverty in developing countries. Advancing mushroom cultivation is critical to ensuring a sustainable and consistent supply and preserve prized mushrooms from extinction, especially as natural habitats for wild edible mushrooms continue to decline. Establishing mushroom farms requires minimal investment, utilizing small spaces, simple equipment, and agro-industrial waste as raw material, which aligns with the principles of waste-to-wealth and sustainable development with consequent economic growth. Developing value-added mushroom products promotes shelf life extension and quality preservation while avoiding postharvest losses. To ensure the growth and sustainability of the industry in developing countries, governments must establish supportive national policies, provide financial incentives such as grants or loans, and offer training programs for farmers. These initiatives can help expand profitable mushroom farming ventures while raising awareness and facilitating technology adoption. By increasing awareness of the nutritional, health, and economic benefits of mushrooms and establishing well-supported farming ventures, the mushroom industry can gain prominence in developing countries. With strategic efforts, its industrial development can be achieved in a relatively short period, contributing to improved food security and economic growth.

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Authors' Contribution

Calista O. Itubochi: Original draft manuscript preparation, Methodology, Review design, Data curation, Resources Writing – Review and Editing. **Jerry O. Ugwuanyi**: Supervision, Conceptualization, Detailed manuscript preparation, Validation, Writing – Review and Editing. **Ifeanyi B. Ezea**: Acquisition of data, Visualization, manuscript revision. All authors read and approved the manuscript.

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