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Sustainability perspectives for future continuity of mushroom production: The bright and dark sides

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Mushrooms are now well-known as healthy food ingredients that contain dietary fiber, vitamin D and compounds with numerous health benefits. Its procurement was initially based on the collection of naturally occurring wild mushrooms in the field, which depended on the region. Modern established cultivation techniques have contributed to environmental sustainability through the recycling of forestry and agricultural by-products and have successfully developed into a global industry. Such development of global mushroom production is the "bright" side as circular agriculture. However, the potential environmental and economic benefits in the sustainability of mushroom production have not yet been widely recognized, and its global production trend has stagnated in recent years. Therefore, dissemination activities through international mutual cooperation centered on education including ecology, cultivation science, and nutrition science of mushrooms are indispensable for the development of mushroom production in the future. On the other hand, we also need to urgently identify and address the challenges associated with negative sustainability impacts, or "dark" side, of mushroom production. The adverse effects of spores derived from cultivated mushrooms on the surrounding environment and disposal methods such as used heat-resistant bags and spent mushroom substrates are often neglected. Clarifying such the positive and negative aspects of sustainability in mushroom production and presenting their future prospects should contribute to improving international perceived value and the continuity of mushroom production.

KEYWORDS
circular agriculture, environmental sustainability, food production, global cooperation, mushroom industry, waste management

Introduction

Mushrooms are roughly classified into saprophytes that decompose the remains of organisms as a source of nutrients, symbionts that live in symbiosis with plants, and parasites that parasitize plants and insects. Saprophytes are indispensable as decomposers in ecosystems. Among saprophytic mushrooms, white rot fungi, which comprise many edible fungi (=mushrooms), are the only organisms on earth that can completely decompose wood components including cellulose, hemicellulose, and lignin (Chang and Miles, 2004). Historically, mushrooms were procured by gathering naturally occurring mushrooms. The establishment of various cultivation methods using wooden logs, bags, bottles and beds (Figures 1A–D), which all exploit the characteristics of mushrooms as decomposers in ecosystems, has solidified the important role that mushrooms play as food (Dhar, 2017). Mushroom cultivation currently utilizes wooden logs and sawdust, which forestry by-products, and agricultural by-products (Grimm and Wösten, 2018). Also, since no pesticides or chemical fertilizers are typically used in mushroom cultivation, the burden on the surrounding environment caused by mushroom cultivation is small and such activities can be regarded as a good example of circular agriculture.

Global mushroom production has increased 13.8-fold to 42.8 million tons over the 30 years from 1990 to 2020 (FAOSTAT, 2022). Production quantities of the main mushrooms are considered to be highest for shiitake mushroom (*Lentinula edodes*), followed by oyster mushrooms (*Pleurotus* spp.), wood-ear mushrooms (*Auricularia* spp.) and button mushroom (*Agaricus bisporus*) (Royse et al., 2017). China accounts for more than 93% of global mushroom production, including these species. Despite the continued increase in the world's population and the "apparent" increase in global mushroom production over the last 30 years, total mushroom production in countries other than China has experienced a marked decline after peaking in 2012, and production has subsequently stagnated (FAOSTAT, 2022). This stagnation is also seen in Japan, the world's second largest mushroom producer, where production has plateaued for 10 years (MAFF, 2021). Such trends are a concern for current mushroom production, and the author proposes the need to internationally promote the future continuity of the mushroom production in light of its contribution to the environmental sustainability and attending global demand. In addition, the author will clarify the often neglected, but significant pressures on the environment, such as adverse effects of the spores and waste management (Figure 2) that occur in the shadow of mushroom production. Recognizing the contribution of mushroom production to sustainability and attending these agendas and issues should help ensure the future continuity of mushroom production.

Mushroom production with sustainability: The bright sides

Mushroom cultivation differs significantly from other types of crop production, as it can utilize low-economic value trees, sawdust, thinning and branches, which are by-products associated with sustainable forest management, as cultivation materials (Figures 1A,C,D). Their use in mushroom cultivation can serve as a valuable resource leading to economic growth instead of causing environmental pollution and subsequent health hazards due to incineration (Chang and Wasser, 2017). For example, in Japan, mushrooms account for 44% of the production value generated in the forestry industry, which utilizes forests that occupy nearly 70% of the country's land (MAFF, 2020). Mushrooms also account for over 80% of the value of non-wood forest products including edible nuts, edible wild plants, Japanese lacquer, bamboo, charcoal, and firewood. Appropriate forest management for mushroom production can improve water storage and suppress landslides by keeping the roots of trees firmly in the soil and preventing the outflow of sediment. In addition, the increased capacity of soil to store water and organic matter as nutrient supports the ecological and hydrological functions of a wide range of natural environments by providing food for organisms in soils, water, and even in the sea (Forest agency, 2019). Therefore, forest management centered on mushroom production is not only an economic source, but also important for maintaining soil and aquatic ecosystems connected to forests. Agricultural by-products as well as forest by-products can be resources for mushroom cultivation. Various agricultural activities in different regions produce many agricultural by-products such as cottonseed hulls, corncob meal, straw, bagasse, rice bran, and wheat bran (Grimm and Wösten, 2018; Figures 1A–D). Especially in intensive agriculture in low-income regions, these tend to be incinerated, which has a negative impact on the environment. Several studies show mushroom production using such low-value agricultural and forestry by-products, rather than incinerating them, can be a profitable business (Pavlík and Halaj, 2019; Odediran et al., 2020; Nanje Gowda and Chennappa, 2021). Also, unsustainable agriculture, such as pesticide use and overly intensive production activities, can cause soil pollution and land degradation (Hu et al., 2021), whereas mushroom cultivation does not use pesticides and chemical fertilizers, and has a low environmental impact. These environmental and economic benefits show that mushroom cultivation fits into the UN Sustainable Development Goals (SDGs) such as "11: Sustainable cities and communities," "12: Responsible consumption and production," "13: Climate action," "14: Life below water," and "15: Life on land" and is a model of sustainable circular agriculture.

Despite these benefits global mushroom production is declining or stagnating, except in China. These trends can be improved by one key factor: education. In developing countries that are trying to expand mushroom production, it is important to accumulate basic knowledge and experience, as well as to install and maintain industrial scale sterilization and cultivation facilities in mushroom cultivation. The Japan International Cooperation Agency (JICA) improved local mushroom production in Bhutan as part of the JICA Partnership Program (2016–2019), "Livelihood Improvement of Mushroom Farmers in Western Bhutan" (Figures 1E,F). In addition, the Netherlands University Foundations for International

FIGURE 1
"Bright" sides of mushroom production in sustainability. **(A–D)** Examples of mushroom cultivation using by-products of forestry and agriculture that contribute to environmental sustainability. Bag cultivation is currently the most commonly used cultivation method in global mushroom production. **(A)** Bag cultivation of wood-ear mushroom using broadleaved tree sawdust and wheat bran. **(B)** Bed cultivation of button mushroom using horse manure and paddy straw. **(C)** Log cultivation of shiitake mushroom using broadleaved tree logs. **(D)** Bottle cultivation of king trumpet mushroom using conifer tree sawdust and wheat bran. **(E,F)** Examples of educational and technical assistance to developing countries (As part of the Japan International Cooperation Agency Partnership Program "Livelihood Improvement of Mushroom Farmers in Western Bhutan," at the Tottori Mycological Institute, 2018). **(E)** Training for sterile technique on clean bench. **(F)** Inspection of log cultivation of shiitake mushroom.

Cooperation (NUFFIC) for Tanzania (Mshandete and Cuff, 2008), the Korean International Cooperation Agency (KOICA) for Sri Lanka (Dairy News, 2017), and the China International Development Cooperation Agency (CIDCA) for Papua New Guinea and the Central African Republic (CIDCA, 2021), had provided mushroom related facilities and technical support for the economic strengthening of the rural areas. The projected decrease in China's population after 2040 will cause a decrease in domestic food demand (Zhao et al., 2021), including mushrooms, which will likely result in an increase in mushroom exports from China. Although it is not known whether China's advanced mushroom production technology will be transferred to other countries, technology transfer from China is expected to have a significant impact on the future development of the global mushroom production. However, considering the more realistic need for food production in the world, international support for mushroom production will be required new efforts in addition to aforementioned international partnership programs, rather than waiting for 2040. So far, the training programs have mainly been one-on-one between public organizations of each country, which may be inefficient in expanding mushroom production globally. Therefore, the development of an international forum involving not only public organizations, but also private companies will lead to the establishment of a more profitable business. The establishment and application of the sustainability certification programs can also help maximize the contribution of mushroom production to sustainability, and also return profits to forestry and agriculture stakeholders who provide materials for mushroom production.

Recent production trends should also be considered within the context of the nutritional value of mushrooms. Mushrooms contain less of the three major nutrients (proteins, fats and carbohydrates excluding dietary fiber) than crops that are staple food. For example, while protein is considered to be relatively high in mushrooms, levels in wheat (10.8 g/100 g), rice (6.8 g/100 g), and corn (8.6 g/100 g) are higher than shiitake (3.1 g/100 g), oyster (3.3 g/100 g), and button (2.9 g/100 g) mushrooms (MEXT, 2015). Mushrooms are rich in dietary fiber, compounds with numerous health benefits, and some vitamins, especially vitamin D (El-Ramady et al., 2022). Therefore, they play a role in providing healthy food ingredients and/or dietary supplements, as well as being a valuable source of vitamin D for people with specific dietary requirements and preferences due to religious or philosophical factors. Nevertheless, in developing countries where the production of foodstuffs containing the three major nutrients, especially high carbohydrates, is

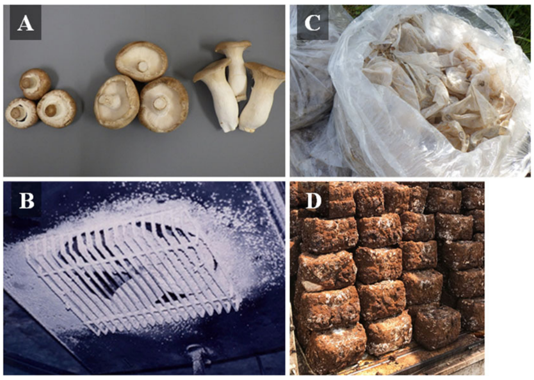

FIGURE 2
"Dark" sides of mushroom production in sustainability. **(A)** An example of mushrooms commercially available in Japan (Tottori prefecture). Left, button mushrooms; middle, shiitake mushrooms; right, king trumpet mushrooms. Button mushrooms can be harvested before their pileuses (caps) expand, but shiitake and oyster mushrooms including king trumpet mushroom are morphologically difficult to harvest before their hymeniums (lamellas) that spores form are exposed. **(B)** A contaminated ventilation fan with spores derived from king trumpet mushroom. Photo by Yasushi Obatake. **(C,D)** Waste derived from bag cultivation. **(C)** Heat-resistant bags made of polypropylene or high-density polyethylene. Alternative bags composed of polylactic acid have been developed, but their use is not widespread due to their relatively high cost and limited biodegradability. **(D)** Spent mushroom substrate contains various materials depending on the region. It is expected that a more efficient and environmentally friendly disposal method will be established.

prioritized the need to expand mushroom production may be considered less pressing compared to growing other crops. Eating habits that relies solely on the calorie content from high carbohydrates may lead to social problems such as obesity in the future. The international community needs to counter this negative impact by actively disseminating information about usefulness of mushrooms, such as rich dietary fiber with low calories and health functionalities. Unexpectedly and ironically, the protracted nature of the COVID-19 pandemic may have had a positive effect on dietary education, increasing the importance of health consciousness and consumers' desire to improve their immunity by consuming mushrooms.

Sustainability challenges facing the mushroom production: The dark sides

The mushroom production faces a few, but significant, environmental challenges that have traditionally been overlooked when formulating development goals. The oldest problem is the adverse effects that the enormous number of spores that are produced by mature mushrooms has on the surrounding environment (Figures 2A,B). It has been suggested that spores derived from mushrooms naturally occurring outdoors form droplets and promote rainfall (Hassett et al., 2015), but spores from modern mushroom cultivation in closed-room environments can cause various problems including health hazards to mushroom producers (Nishida and Yatera, 2022), pollution to cultivation facilities (Okuda et al., 2013) and depletion of genetic diversity in wild populations (Hibbett and Donoghue, 1996: Obatake et al., 2003). For some mushroom species, including button mushroom, this problem can be controlled by harvesting before expansion of the spore-dispersing pileus (cap) and hymenium (lamella) by adjusting harvest timing through temperature and humidity controls during the cultivation. However, many mushroom species such as shiitake and oyster mushrooms are difficult to control for the morphological reasons (Figure 2A). As a typical example, the spores derived from cultivars have been reported to cause severe respiratory disorders such as asthma and hypersensitivity pneumonitis in 3.5–29.0% of mushroom producers who inhale the spores (Nishida and Yatera, 2022). Although spore-induced decreases in the Quality of Working Life (QWL) were first reported in the 1970s, these are still recognized as a threat to QWL and have yet to be resolved (Schulz et al., 1974; Nishida and Yatera, 2022). Other problems include the pollution to cultivation facilities (Okuda et al., 2013; Figure 2B) and erosion of genetic diversity in natural population when spores of cultivars are dispersed outside production facilities (Hibbett and Donoghue, 1996; Obatake et al., 2003). This problem can be resolved using cultivars with sporulation deficient (sporeless) mutations. To the author's knowledge, only four such varieties have been developed to date; three were developed in Japan for *Agrocybe cylindracea*, *Pholiota adipose*, and king trumpet mushroom (*Pl. eryngii*), and one was developed in the Netherlands for the oyster mushroom (*Pl. ostreatus*). In recent years, the *MSH4* homolog, which is involved in meiosis, has been identified as the gene responsible for the sporeless trait in multiple species, and the possible application of this gene to molecular breeding has already been clarified (Okuda et al., 2013; Lavrijssen et al., 2020). The introduction of sporulation deficiency in major mushroom species (e.g., shiitake mushroom and other oyster mushrooms) using genome editing techniques is expected to make a positive contribution to improving both natural and working environments.

Post-production waste management in bag cultivation, which is currently the most common practice in mushroom cultivation, is another global issue in the mushroom production. Used culture bags consist of heat-resistant bags and their contents, i.e., spent mushroom substrate (SMS), which consist of the ingredients mentioned in the previous section of this article. The heat-resistant bags are made of polypropylene or high-density polyethylene (HDPE) and are non-biodegradable and disposable, which means that they are a major cause of environmental pollution in mushroom production (Figure 2C).

In the author's experience, for every 900 g of shiitake mushroom yield, ∼15 g of HDPE bags become waste. This means that if the global production of shiitake mushroom is 10 million tons based on past literature (Royse et al., 2017), then more than 160,000 tons of waste is produced annually. Similarly, producing 450 g of oyster mushrooms generates 18 g of waste (Panjikkaran and Mathew, 2012). Consequently, the use of almost 1 million tons of polypropylene and HDPE bags to cultivate the major mushroom species annually has a major negative impact on the environment. Although the quantity of waste produced by the mushroom production may seem less than that in other industries, the quantities produced are roughly equivalent to 1,000 times the weight of the one billion plastic straws that were used annually by Starbucks before their use was abolished in 2020 (Starbucks Corporation, 2018). As an alternative to polypropylene and HDPE, bags made of polylactic acid (PLA), which is a biodegradable plastic, have already been produced. However, since PLA is difficult to decompose except under hot and humid conditions such as composting (Poulin et al., 2021) and is more expensive than polypropylene and HDPE, their use is not widespread. Preparation of bag cultivation has a process of sterilization at temperatures as high as 120°C, making heat resistance an essential property of the bags. There are other promising biodegradable plastics such as PBS (polybutylene succinate) and PHBH [poly (3-hydroxy-butyrate-co-3-hydroxyhexanoate)], but the former has low heat resistance. Therefore, cost reduction and improvement of the biodegradability of materials such as PLA and PHBH will be the future focus in developing biodegradable heat-resistant bags for mushroom cultivation.

More than 100 million tons of SMS is generated annually, placing a significant burden on the environment (Figure 2D). Studies on processes such as composting, conversion to fuel and feed, and reuse as a mushroom cultivation substrate have been conducted in an attempt to minimize the waste generated by the mushroom industry (Phan and Sabaratnam, 2012; Grimm and Wösten, 2018). The easiest way to process SMS without special techniques is by composting or burning; the former is promising, but has clear limits in terms of the time required and the amounts that can be composted efficiently, and the latter is not eco-friendly due to the high ash content and creates new environmental problems (Phan and Sabaratnam, 2012; Grimm and Wösten, 2018). Actual mushroom cultivation is carried out in many different regions using a variety of different materials. Thus, processing the SMS requires careful consideration of the conditions in each region, including differences in the chemical constituents of the materials that comprise SMS, the agricultural landscape, and the construction costs of industrial-level composting systems. The range of these factors means that one-dimensional research outcomes will not be a magic bullet. It should be noted that the establishment of waste management methods for treating heat-resistant bags and SMS will be a common problem for the disposal of all biodegradable plastics in the future. While a variety of biodegradable plastics are being developed, the establishment of effective post-consumption treatment methods is typically neglected. Currently, the most ideal disposal method for PLA and other biodegradable plastics is by composting under high temperature and humidity, which is similar to the waste disposal method used to treat bags in the mushroom production. The enormous amount of biodegradable plastics requires the construction and operation of large-scale composting facilities, and is likely to be incinerated like general waste. Given the possibility that non-biodegradable plastics will be regulated in the future (UNEP, 2022), it is clear that disposal methods such as incineration will not be accepted internationally. Therefore, the development of more effective and efficient composting systems that can be used to process wastes derived from the mushroom production, as well as non-durable consumer goods produced using biodegradable plastics, will be central to solving serious environmental problems in the future.

Recently, the strength of fungal mycelium, especially of mushrooms, has attracted attention, and the cutting-edge technology that utilizes the mycelium have been developed as leather substitutes (Jones et al., 2021), packaging, building materials, paper, and textiles (Grimm and Wösten, 2018). Using these materials reduces our dependency on petroleum products and is beneficial for animal welfare. In addition, using these materials promotes upcycling and these materials are both renewable and biodegradable. Companies involved in the development of leather alternatives have formed a consortium with apparel companies, such as ADIDAS and KERING, and companies involved in developing packaging materials have formed a partnership with home furnishing companies, such as IKEA. Both of these applications of fungus-derived materials have already been put into practical use. These are not necessarily SMS-based, but SMS is likely to be adopted as a cheaper material for them in the near future. Thus, mushroom production has the potential to become sources of specific materials and food, and wipe out its "dark" side in ways that exceed their ecological role as decomposers in the natural ecosystem.

Conclusions

Mushroom production can utilize various low economic value by-products generated in forestry and agriculture as resources instead of incineration. Therefore, it is suggested that mushroom production is a profitable business, especially for developing countries. In addition, mushroom production is a model of circular agriculture that contributes to the sustainability of forests and the surrounding environment because it does not cause soil degradation. Mushroom production needs to address both its "bright" aspects that contribute to sustainability as well as the "dark" aspects contravening such impacts. Unfortunately, despite its contribution to sustainability, global awareness is low and global mushroom production trends are stagnating. Active dissemination of information on the contribution to sustainability and health functionality of mushrooms, and sharing basic knowledge and experience with mushroom-related facilities through the strengthening of international mutual cooperation may help break this logjam. Introducing sustainability certification programs is also a good way to recognize and promote the environmental contributions of mushroom production. On the "dark" sides, the enormous number of spores from mushrooms cultivated in the closed environment cause health hazards to the producers, pollution to the facilities, and erosion of the natural genetic diversity. The identification and exploitation of genes involved in sporulation will be useful for developing more efficient and versatile sporeless breeding. The development of materials with improved biodegradability help improve the disposal method of used heat-resistant bags and SMS, thus reducing the burden on the environment. SMS will be in the spotlight for its role as materials in the near future. In this way, although mushroom production has both a "bright" and "dark" side, trends and recent discoveries appear to be moving this sector toward greater environmental sustainability. Economic sustainability, however, is also an important issue. The author is continually told by mushroom producers in Japan, "The profit of one pack of mushrooms is less than a penny." The notion of profits only covers a small part of the mushroom production of a country. Nonetheless, excessive price competition means that the working environment in this industry may not be sustainable. In order for mushroom production to pursue sustainability, the working environment also needs to be addressed. Although this kind of problem may be too general, it should not be taken lightly and should be recognized as a common challenge in many fields, not just mushroom production. Early resolution of sustainability issues related to the mushroom production is an effective means of increasing the international perceived value of mushrooms and ensuring the viability of mushroom production as a marketing strategy.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

YO is the sole author of this manuscript and wholly accountable for its contents.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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