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RESEARCH ARTICLE

Agricultural Waste–Derived Biofertilizers for Sustainable Mushroom Cultivation: A Case Study Using Banana Peel

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Abstract Mushrooms are not only a nutritious and versatile food source but also have the potential to contribute to sustainable agriculture via the use of biofertilizers. Following Agenda 2030, biofertilizers can be selected from the widely available food and agricultural wastes to increase circularity. Food and agricultural wastes serve as optimal candidates for biofertilizers, offering a wealth of plant-growth-promoting nutrients and microorganisms. Primarily rich in essential macro-elements like nitrogen, phosphorus, and potassium, these wastes directly contribute to plant growth. The diverse array of plant-growth-promoting bacteria within biofertilizers enhances soil fertility, promotes plant growth, improves nutrient absorption, and provides valuable attributes such as antifungal properties and nutrient solubilization. This review seeks to underscore the significance of employing biofertilizers in mushroom cultivation for enhancing circularity in future food production, specifically focusing on banana peels as an illustrative example.

Keywords: Food waste, banana peel, sustainability, future food, beneficial microorganism, macro-elements.

Introduction

Mushrooms play a pivotal role in sustainable food systems as they offer a nutrient-rich and environmentally friendly food source. Mushrooms grow fast while requiring minimal land clearing, water, light, and resources compared to traditional livestock or crops [1]. Their cultivation requires minimal resources and can be achieved using various organic waste materials, contributing to waste reduction and recycling [2,3]. With high protein content, essential vitamins, and minerals, mushrooms serve as an excellent meat substitute for plant-based diets [4].

Addressing food loss and waste offers a threefold benefit: it aids climate change mitigation, bolsters food security, and promotes sustainability in the agrifood sector. The 2019 State of Food and Agriculture report by the Food and Agriculture Organization (FAO) underscores that 14% of the world's food, worth an annual $400 billion, is lost between the post-harvest and retail stages. The Food Waste Index Report by the United Nations Environment Programme (UNEP) discloses an additional 17% of waste at retail and consumer stages, including households. This food loss and waste account for 8-10% of global greenhouse gas emissions, thereby intensifying climate instability and extreme weather events [5].

Circular practices can provide viable solutions. Food that is lost or wasted can be transformed into compost or biogas through anaerobic digestion, which curtails harmful methane emissions and recycles nutrients back into nature [6]. The goal for 2030 is to cut global food waste per capita by half at the retail and consumer stages and to curtail food losses across production and supply chains, as per Sustainable

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Development Goal (SDG) target 12.3. The FAO's report titled "Food Wastage Footprints: Impacts on Natural Resources" interestingly highlights the potential of home composting in diverting up to 150 kg of food waste per household per year from municipal waste [7].

To achieve total circularity, biofertilizers can be applied to highly sustainable crops such as mushrooms. Biofertilizers, made from natural and renewable organic materials, are less likely to pollute soil, water, or air. They can enhance soil health by increasing the population of beneficial soil microorganisms. This leads to improved soil structure and fertility, and better nutrient availability for plants. In less affluent regions, biofertilizers can boost crop yields, particularly in developing countries where farmers may lack access to or the means to purchase chemical fertilizers. Often, biofertilizers are more cost-effective than chemical fertilizers, especially when considering the long-term benefits to soil health and the reduced need for chemical inputs over time [8].

Some common food waste that can be used as biofertilizers for mushroom cultivation include spent mushroom substrate (SMS), coir pith, rice straw, and banana peels [9–11]. This review will focus on recent literature exploring the application of biofertilizers in mushroom cultivation. The objective of this review is to examine the current state of research in this area and provide suggestions for future improvements in biofertilizer applications, using banana peels as an example, for mushroom cultivation. An example of the use of banana peel as a biofertilizer for mushroom cultivation is depicted in Figure 1.

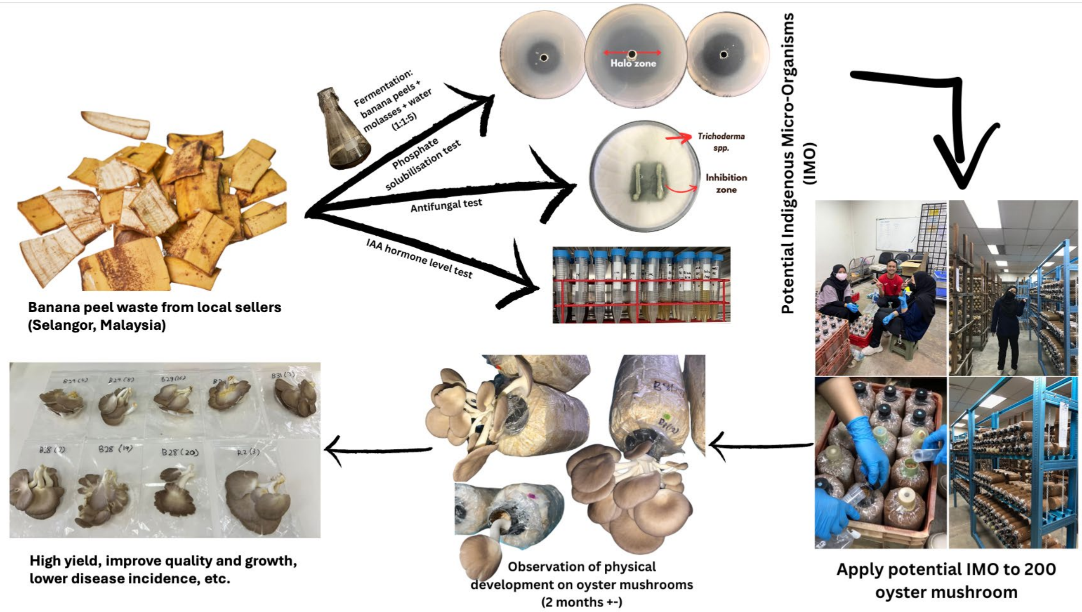

Figure 1. The authors at Universiti Putra Malaysia's mushroom house applied banana peel as a biofertilizer in oyster mushroom cultivation. The preliminary results showed promise, with significant growth enhancement observed both *in vitro* and *in vivo* across treatments involving banana peels

An Introduction to Mushrooms

The global market for mushrooms has been witnessing a consistent growth trajectory, propelled by an escalating consumer preference for exotic and gourmet food products. Using oyster mushrooms as an example, its market was valued at USD 50.3 billion in 2021 and is projected to reach a valuation of USD 87.73 billion by 2029. This projection corresponds to a Compound Annual Growth Rate (CAGR) of 7.20% during the forecast period of 2022-2029 [12].

Several factors have been instrumental in shaping the market dynamics of mushrooms. A primary driver is the burgeoning demand for mushrooms from individual consumers and the food service industry, attributable to their delicate flavor, meaty texture, and versatility in culinary applications. They are gaining recognition as a valuable source of future protein, offering a sustainable alternative to animal-based meat products [13]. With an average protein value exceeding 20% of dry weight, mushrooms are protein-rich and provide a complete profile of essential amino acids necessary for meeting dietary requirements [14]. Moreover, mushroom proteins offer economic advantages compared to proteins derived from animal and plant sources. The consumption of animal-based meat is associated with several drawbacks, including significant environmental impact, contribution to greenhouse gas emissions, extensive land and water usage, and ethical concerns related to animal welfare [15]. By choosing alternative protein sources like mushrooms, individuals can promote responsible consumption and production (SDG 12), reduce their carbon footprint (SDG 13), and support sustainable food systems (SDG 2).

Nutritionally, mushrooms are low in calories and fat, yet abundant in vitamins, minerals, and antioxidants. Different mushroom species exhibit diverse nutritional compositions and profiles, but they often possess excellent amounts of crude protein, essential minerals, complex polysaccharides, and healthy plant-based fats such as unsaturated fatty acids. Furthermore, they are rich in various B vitamins such as B2 riboflavin, B9 folate, B1 thiamine, B5 pantothenic acid, and B3 niacin, as well as secondary metabolites or bioactive compounds, such as polysaccharides, polyphenols, terpenoids, lectins, alkaloids, sterols, glucoproteins, ergosterols, sesquiterpenes, and lactones. Consequently, mushrooms are recognized as a potent source of therapeutic benefits, including medicinal and biological properties like antioxidant, anti-diabetic, immunomodulatory, and anti-cancer effects [16–18]. As a plant source, they are also rich in plant-based compounds such as phenolics, carotenoids, and other bioactive compounds [17,19].

There is a wide range of edible mushrooms, each offering unique characteristics and flavors (which also include the truffle family). Unlike plants, mushrooms are heterotrophic organisms that cannot carry out photosynthesis. They reproduce through both sexual and asexual methods, producing specialized cells called spores, which have the remarkable ability to generate up to one billion offspring in a single day. As saprophytes, mushrooms rely on their enzymes to decompose and absorb complex organic compounds from various environmental sources since they cannot produce their own organic matter [20].

Medium for Mushroom Cultivation

Mushroom farming aligns seamlessly with the principles of sustainability and the objectives outlined in Agenda 2030, specifically the Sustainable Development Goals (SDGs). This form of agriculture embraces sustainable practices by utilizing locally available substrates, such as agricultural waste and by-products [21]. This not only contributes to efficient resource management but also aids in waste reduction. By repurposing these materials, which would otherwise contribute to environmental pollution, mushroom farming supports the targets of SDG 12, which promotes responsible consumption and production. Meanwhile, the use of agricultural waste substrates in mushroom cultivation encourages the efficient utilization of resources. This practice also contributes to climate action (SDG 13) by mitigating greenhouse gas emissions associated with waste decomposition. Furthermore, mushroom cultivation can stimulate economic growth, especially in rural areas, by providing income-generating opportunities. This aligns with SDG 8, which advocates for decent work and economic growth.

Mushrooms, like other bio-based organisms, rely on essential nutrients such as carbon and nitrogen for their growth. Various substrates can be used in mushroom cultivation, preferably those that are locally sourced agricultural by-products and have a high carbon content, containing lignocellulosic substances such as lignin, hemicellulose, and cellulose [22]. Currently, wood husk is a commonly used substrate for oyster mushroom cultivation [23,24]. Its porous structure allows for air circulation and moisture retention, creating an optimal environment for mushroom growth [25]. Additionally, the husk can be supplemented with other materials such as bran or gypsum to enhance its nutritional value and water-holding capacity. These substrates should also provide essential nutrients like nitrogen, iron, potassium, and phosphorus while maintaining a sterile environment. They also require specific environmental conditions, including oxygen levels and optimal pH [26].

Mushroom cultivation involves a solid fermentation process during the initial phase, where the mycelium grows under controlled, aseptic conditions before fructification. Two substrate formulas are commonly employed: composted materials achieved through fermentation and pasteurization, suitable for *Agaricus bisporus* and *Pleurotus ostreatus*, and non-composted materials, involving steam sterilization, suitable for species like *Lentinula edodes* and *Auricularia* sp. [26]. Once sterilized, the husk is mixed with oyster mushroom spawn, which contains the mycelium, the vegetative part of the fungus. The mycelium then colonizes the husk, forming a network of thread-like structures [24]. Recent research highlights the importance of mushroom growth-promoting microorganisms for stimulating mycelium growth and enhancing mushroom fructification. These microorganisms act as reservoirs for nitrogen and vitamins, potentially serving as supplementary resources to increase crop yield, either alone or in combination with nutritional supplements [26].

The Use of Food and Agricultural Waste-derived Biofertilizers on Mushroom Growth

Crop residues, such as crop stalks, straw, and husks, are valuable sources of organic matter that can be transformed into biofertilizers. Through composting or vermicomposting, these residues break down and release nutrients, enriching the soil and improving its structure. Some biofertilizers can help to control harmful microorganisms in the growing environment, improving the overall health and disease resistance of the mushroom crop. In general, the use of biofertilizers can provide several benefits to the mushroom growing process, including improved growth and yields, reduced dependence on chemical fertilizers, and improved sustainability of the growing process [27].

The recent review by Carrasco *et al*. (2018) highlighted the importance of agricultural waste in mushroom cultivation, emphasizing the crucial role of the Carbon-to-Nitrogen (C/N) ratio in achieving optimal yields for various species [26]. Conventional supplements, incorporating defatted vegetable meals like soybean meal and organic protein sources such as cereal bran, are widely used in phase II (spawning) and phase III (casing) substrate production for *Agaricus bisporus* cultivation. While these commercial supplements are prevalent, there is a growing trend towards utilizing low-cost agricultural by-products in productive regions. Cereal meals, brans, chicken manure, cottonseed meal, urea, superphosphate, ammonium sulfate, grape pomace, feather flour, and defatted meals from dry nuts are recognized as effective ingredients for mushroom substrate supplementation in Brazil and Europe. Noteworthy trials in Greece demonstrate the potential of substrates supplemented with olive mill waste ("alperujo") for cultivating *Pleurotus* spp. and *Agrocybe cylindracea*. In Spain, substrates incorporating grapeseed meal, defatted pistachio meal, or defatted almond meal exhibit comparable performance to commercial additives for *Agaricus bisporus* and *Pleurotus ostreatus* cultivation [26]. Other examples of agricultural and food waste-derived biofertilizers for mushroom cultivation are summarised in Table 1.

Table 1. Examples of agricultural and food waste-derived biofertilizers for mushroom cultivation

Biofertiliser	Mushroom	Outcome(s)	Reference(s)
Wheat grain with *rhizobia*	*Pleurotus ostreatus*	Increased minerals, protein, biological efficiency, and dry matter by 30%, and decreased primordial initiation	[28]
Agricultural wastes with *Pseudomonas putida* and *Bacillus megaterium*	*Agaricus bisporus*	Improved yield, fruiting bodies, pinhead initiation, and mycelium run	[29]
Palm kernel shells	*Pleurotus ostreatus*	The shells were processed using microwave vacuum pyrolysis, resulting in biochar, which was then used as a biofertilizer in mushroom cultivation	[30]
Rice straws, wheat straw, coffee pulp, and cotton seed hulls	*Pleurotus ostreatus*	The best crop yield was achieved with a 1.5 kg capacity bag containing wheat straw	[31]
Rubber sawdust with either rice straw, rice husk, or corn cob	*Pleurotus ostreatus*	Rubber sawdust and rice husk produced the best yield of 40-day cultivation cycle	[32]
Palm oil by-products	*Vovariella volvacea*	Shredded empty food bunchs can be pressed into mushroom blocks	[33]
Agricultural wastes rich in hemicellulose (cotton, wheat straw, baobab fruit shell	*Pleurotus ostreatus*	Increase mycelial colonisation rate, developmental stages, yield and biological efficiency	[34]
Paddy Straw	*Pleurotus ostreatus*	*Pleurotus ostreatus* grown on paddy straw with different de-oiled cakes maximizes yield and antioxidant properties	[35]
Defatted pistachio meal and defatted almond meal	*Agaricus bisporus*	Improved quality for white button and oyster mushrooms yielding larger, firmer mushrooms with higher dry weight and protein content	[36]
Sawdust supplemented with varying levels of wheat bran, rice bran, or maize powder	*Lentinula edodes*	The optimal rates identified as 25% wheat bran for maximum yield and 40% wheat bran for superior quality	[37]
Grape marc or olive mill wastes	*Pleurotus* species	Exhibited higher levels of bioactive compounds and productivity comparable to wheat-based substrates	[38]
Kepok banana peels into wood powder media	*Pleurotus ostreatus*	Kepok banana peels improved fresh weight, dry weight, and the number of oyster mushroom fruit bodies	[39]

Royse *et al*. (2017) estimated the annual production of spent mushroom waste (SMS) to be approximately 170–204 billion kg in 2013. To effectively manage this substantial waste, Pardo-Giménez et al. (2018) [36] propose recycling SMS through supplementation with nutritional additives for further mushroom cultivation. When SMS from *Pleurotus ostreatus* is supplemented with specific commercial protein-rich products, there is a notable increase in total nitrogen content, leading to elevated crude protein and neutral detergent-soluble fraction values. This supplementation results in mushrooms with higher protein and ash content. The supplemented SMS formulations exhibit good biological efficiency, a high quantity of mushrooms, and excellent fruiting body weight during the regrowth of *Pleurotus ostreatus*, highlighting the potential of protein-enhanced SMS as a cost-effective base material for cultivation. This approach aligns with circular economy principles by addressing waste management comprehensively [26].

The mechanisms of biofertilizers on mushroom growth can be broadly categorized into two main categories: nutrient supplementation or substrate amendment (direct) by the waste itself, and plant-growth-promoting microbial interactions (indirect) derived from the waste (Figure 2). Certain bacteria can help to improve the quality of the substrate used to grow mushrooms by breaking down complex sugars and converting them into simpler sugars, which are more easily metabolized by the mushroom. This can lead to improved growth and yields. They can also release nutrients from the substrate, making them more available to the growing mushrooms. This can help to improve the overall health and vitality of the mushroom mycelium. Some strains can help to control other harmful microorganisms, acting as biocontrol agents in the growing environment, thereby improving the overall health and disease resistance of the mushroom crop [41]. Certain microbiota, including bacteria from *Lactobacillus*, *Azotobacter*, *Bacillus*, *Paenibacillus*, and *Pseudomonas* genera, have shown promise in enhancing mycelial growth in cultivated species and exhibiting antagonism against competing molds, making them attractive candidates for alternative nutritional supplements and biofertilizers. Bacteria from *Bacillus*, *Pseudomonas*, or *Bradyrhizobium* genera have demonstrated the ability to stimulate mycelial growth in various cultivated species, both in compost and in vitro [42,43]. Some *Pseudomonas* genus members have been identified as contributors to enhanced mushroom fructification during casing. Furthermore, the presence of the thermophilic fungus *Mycothermus thermophilus* in the conditioning stage of phase II composting has been recognized for its role in stimulating the growth, development, and yield of *Agaricus bisporus* while improving substrate selectivity [26].

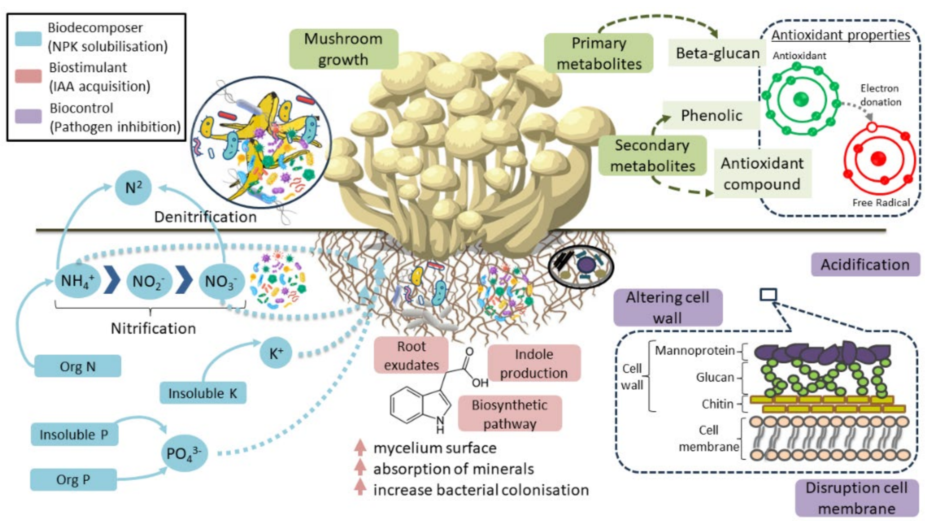

Figure 2. A diagram showing how microbial biofertilizer enhances mushroom growth. The biofertilizer contains microorganisms that can decompose organic matter, stimulate plant growth, and control pests and diseases. These effects can increase the yield and quality of mushrooms, as well as their production of bioactive compounds

Banana Peel as Biofertilizer

Fruit and vegetable peels, scraps, and other waste materials can be composted to create nutrient-rich organic matter. This compost can then be used as a natural fertilizer for mushroom cultivation, providing essential nutrients for their growth and development. Implementing circular strategies for the effective utilization of by-products through recycling and upcycling offers a valuable opportunity to extract value from food waste. In the United States, the highest rates of food wastage are attributed to fresh fruits and vegetables, accounting for 22%, closely followed by dairy products at 19% [44]. Bananas, cultivated in over 130 countries, rank as the second most produced fruit globally (16% of total production). Bananas hold significant agricultural importance in developing countries and serve as a major income source for numerous rural households [45]. Despite the widespread consumption of ripe bananas, a substantial amount undergoes industrial processing to produce items like banana chips. Notably, banana peels constitute around 40% of the total weight of fresh banana fruit [46]. Currently, the banana sector generates an annual production of banana peel exceeding 57.6 million metric tonnes [47]. However, these peels are often discarded without proper treatment, leading to adverse environmental impacts and economic losses. The high content of N, P, and K in banana peels makes their careless disposal a potential environmental concern, as it may result in the leaching of these minerals and environmental pollution [48].

Numerous studies have highlighted the efficacy of banana peels as a growth enhancer for mushrooms. Risnawati *et al*. (2021) observed a significant increase in the number of fruit bodies of white oyster mushrooms when Kepok banana peels were added to the growth medium [39]. Another investigation found that composting green banana peels for 15 days resulted in superior mycelial growth and pin-head development for *Vovariella volvacea* compared to 0-day and 30-day composting [49]. Additionally, banana peel supplementation led to thicker mycelial growth [50] and extension [51]. Mushrooms cultivated on various fruit peels, including bananas, tend to yield higher production and exhibit elevated levels of bioactive and phenolic compounds [52]. The valorisation of a certain structure of banana peels, such as cellulose, can be developed for biofertilizer application. In a recent study, a novel hybrid nanocomposite hydrogel, composed of Banana Peel Cellulose and Layered double hydroxides nanosheets led to the slow release of N and P fertilizers as well as enhanced water retention in loamy sand soil, making it a promising controlled-release fertilizer [53].

Lignocellulosic materials are of great importance as substrates for mushroom cultivation. These materials, which include components like cellulose, hemicellulose, and lignin, are commonly used as base substrates for mushroom production [54]. Mushrooms can degrade lignocellulosic substrates through the production of lignocellulosic enzymes, and they utilize the degraded products to produce their fruiting bodies [55]. Therefore, mushroom cultivation can be considered a prominent biotechnological process for the reduction and valorization of agro-industrial waste, such as banana peels, which are typically rich in lignocellulosic biomass. In a study, the lignocellulosic composition of raw banana peels includes 20.7% cellulose, 17.3% hemicellulose, and 31.6% lignin [56].

Macro-elements in Banana Peel for Mushroom Growth

It could be argued that Nitrogen (N), Phosphorus (P), and Potassium (K) are the three most crucial macro-elements for crop growth. Taking mushrooms as an example, N is involved in protein synthesis, crucial for mushroom growth. P aids in fruit and root development. K, along with other macro-elements, fulfills structural and energy requirements. Various studies on oyster mushroom cultivation showed significant growth enhancement with the application of NPK [57,58].

N is an essential requirement for mushroom growth. However, studies on the N content of banana peels indicate a low presence of N, with notable macro-elements being potassium, phosphorus, and calcium [59–61]. Similarly, Jariwala & Syed (2016) [62] found that acidic-based fruit peels such as orange and lime contain greater N content, while banana peel tends to be higher in P and K instead. Nevertheless, the supplementation of banana peel in compost or as biofertilizer can still lead to significant improvements in N content of the biofertilizer [63,64]. While banana peels may not serve as a main source of N compared to other organic materials, it is important to note that N content can vary based on analysis methods, samples, and applications.

Conversely, banana peels are a known source of K [59,65,66]. A study by Hussein *et al*. (2019) repurposed banana peels for the extraction of a mixed nano bio-stimulant fertilizer, which exhibited constituents like chelated K, chelated iron, tryptophan, urea, amino acids, protein, and citric acid. The application of this nano-fertilizer resulted in increased germination percentages. In a study by Islam *et al.* (2019) [66], banana peel biochar was produced via slow pyrolysis and incorporated into agricultural soil and sand medium to assess its impact on plant growth. In soil, *Ipomoea aquatica* plants exhibited increased height, leaf number, and biomass, while in sand, it mitigated potassium deficiency in *Cucurbita moschata*. This impact as a result of rich P was also observed in other plant models, such as eggplant [67] and soybean [68]. This K can be extracted or enhanced from banana peels through various methods, including hydrothermal, catalytic, and biochar productions [65,69,70].

Several studies have reported the utilization of banana peels for biofertilizer production due to their high P content. For example, Teshome (2022) [60] investigated the available phosphorus content in banana peels through the composting process, finding ranges from 5.77 to 5.91 mg/kg. The P content in banana peels, recorded at 37% in an analysis conducted by Mustapha *et al*. (2021), significantly surpasses the levels of N and K, highlighting the abundant availability of phosphorus in banana peels [71]. Kadir *et al*. (2016) demonstrated that the addition of banana peels increased P content from 195.83 mg/L to 471 mg/L in fertilizer production. Integration with other agricultural waste can improve the dissolution of particulate P and lead to a sustained release for fertilizer application [72]. This makes banana peels a valuable resource for biofertilizer production in mushroom cultivation, providing an environmentally friendly and economically viable option to meet the phosphorus needs of the mushrooms.

Banana peels can also contain other essential plant elements like calcium, iron, magnesium, and sodium [73]. Additionally, many other studies showed the presence of other microelements such as magnesium, sulfur, iron, copper, zinc, and manganese in banana peels [61,74]. These microelements, including copper and zinc, play a crucial role in supporting the mushroom during various stages of growth, such as the development of fruiting bodies, robust mycelial growth, and enhanced structural integrity [26].

Microorganisms in Banana Peel for Mushroom Growth

The cultivation of mushrooms can be significantly enhanced by the use of biofertilizers, which are often composed of various bacterial genera. For instance, Kumari and Naraian (2020) reported that *Azotobacter*, *Bacillus*, *Paenibacillus*, and *Pseudomonas* may contribute to biofertilizers in mushroom cultivation [75]. Similarly, Saubenova *et al*. (2023) found that the bacterial phyla *Bacillota*, *Pseudomonadota*, and *Actinomycetota* play a crucial role in mushroom cultivation [76]. Moreover, specific bacteria have been identified as mushroom growth-promoting bacteria (MGPB). Chen *et al*. (2022) identified *B. cereus* as one such MGPB [77]. Eyini *et al*. (2005) highlighted that *Azotobacter* sp. contributes to the growth of oyster mushrooms [78]. Furthermore, the growth of edible oyster mushrooms in bottle cultures was found to increase due to the presence of *Pseudomonas* sp. P7014, as reported by Kim *et al*. (2008) [79]. *Pseudomonas sp.* has been shown to improve the growth of the mushroom, as it promotes the growth of its mycelia. [77,80,81].

In addition to these bacteria, studies have shown that banana peels harbor a diverse group of microorganisms that could potentially contribute to biofertilizer production. Abdullah & Amalia (2023) and Ngouénam *et al*. (2021) reported that banana peel has the potential to serve as a biofertilizer due to the occurrence of *Lactobacillus plantarum* [82, 83]. These bacteria can promote the acid fermentation process, a crucial step for biofertilizer production in mushroom cultivation. Budiari *et al*. (2019) reported that banana peels contribute to 55.84% of the lactic acid contribution during the fermentation process, indicating that banana peels contain high amounts of lactic acid bacteria along the fermentation process [84].

Banana peel residues are inherently rich in carbohydrates (cellulose, hemicellulose, and simple sugars), minerals (notably potassium, phosphorus, and calcium), and micronutrients—all of which serve as excellent substrates for heterotrophic microorganisms. When banana peels are co-composted or incorporated into mushroom growing media, they rapidly undergo microbial-driven decomposition, leading to the proliferation of beneficial bacterial and fungal taxa (e.g., *Bacillus spp.*, *Pseudomonas spp*., and various saprophytic fungi). These microbes secrete cellulolytic and pectinolytic enzymes that break down complex polysaccharides into simpler sugars and organic acids, effectively “pre-digesting” the substrate into forms more readily assimilable by mushroom mycelia. In addition, certain bacteria within these consortia produce plant- and fungus-growth–promoting phytohormones (such as indole-3-acetic acid) and siderophores that enhance nutrient solubilization and uptake. Studies on banana-peel–derived biofertilizers have documented dense, functionally diverse microbial communities that not only recycle organic waste but also enrich substrates with bioavailable nutrients and growth-stimulatory metabolites [85, 86].

In the context of mushroom cultivation, these enriched microbial consortia create a more hospitable microenvironment for fungal colonization. For instance, *Pleurotus ostreatus* grown on substrates amended with banana peel powders exhibited accelerated mycelial run and higher fruiting-body yields compared to unamended controls; while direct attribution to microbial activity was not always quantified, the accelerated breakdown of lignocellulosic components and improved nutrient release strongly implicate the underlying microbiome as a key driver of enhanced productivity [39, 86]. Additionally, the microbial metabolites produced during banana peel degradation, such as volatile organic compounds (VOCs) and organic acids, can inhibit opportunistic pathogens (e.g., *Trichoderma* overgrowth) and modulate pH in ways that favor mushroom mycelium. Ultimately, leveraging banana peels as a biofertilizer in mushroom substrates aligns with circular-economy principles: it valorizes an abundant agrowaste while establishing a dynamic microbial consortium that synergistically enhances substrate fertility and supports robust fungal growth.

Future Directions

The use of biofertilizers in mushroom cultivation is gaining significant attention, presenting substantial potential for future advancements. As our understanding of the crucial role of microorganisms in mushroom growth and substrate decomposition deepens, a promising pathway for the development of customized biofertilizers, optimized for mushroom cultivation, emerges.

Advanced characterization techniques, such as Next-Generation Sequencing technology, provide invaluable insights into the dynamics of substrate microbiota and microbial functions. The application of the Omics approach, encompassing metagenomics, metatranscriptomics, and metabolomics, holds great promise in creating industry-specific bioinoculants derived from banana peels. Additionally, the use of big data can play a vital role in enhancing the efficiency, precision, and overall success of biofertilizer applications in mushroom cultivation by providing valuable insights, monitoring environmental conditions, and supporting informed decision-making. These sophisticated methodologies not only yield comprehensive data but also enable precise application points throughout the crop cycle.

With the emergence of precision agriculture technologies, there is potential for a more targeted and controlled use of biofertilizers. This allows for the optimization of their application for maximum benefit while minimizing any negative impacts. The standardization of using banana peels as a biofertilizer involves determining key parameters such as species, maturity, composition, and sourcing. Industrial waste from large-scale banana chip production lines offers an efficient source. Enrichment processes, such as fermentation, can be designed to enhance microbial diversity and abundance and stabilize the C:N ratio. Further research into optimized application methods, whether through foliar application or direct application to mushroom substrates, is warranted to maximize yield.

Conclusions

Incorporating banana peels into biofertilizers offers a sustainable and organic solution, promoting circular agricultural practices while improving soil properties. The organic matter in banana peels acts as a natural soil conditioner, enhancing structure, water retention, and nutrient availability. Furthermore, banana peels introduce beneficial microorganisms, fostering a balanced and resilient soil ecosystem. As they decompose, banana peels release essential elements such as potassium, phosphorus, and calcium, providing a gradual and sustained nutrient supply for healthy plant growth.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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