

Review

Investigating the Potential of Polypore Fungi as Eco-Friendly Materials in Food Industry Applications

Tomasz Pawłowicz , Karolina Anna Gabrysiak  and Konrad Wilamowski 

Institute of Forest Sciences, Faculty of Civil Engineering and Environmental Sciences, Białystok University of Technology, Ul. Wiejska 45E, 15-351 Białystok, Poland; karolina.gabrysiak@pb.edu.pl (K.A.G.); k.wilamowski@pb.edu.pl (K.W.)

* Correspondence: tomasz.pawlowicz@pb.edu.pl

Abstract: Polyporoid fungi represent an untapped resource in the ancillary use of forests, traditionally utilized in both historic and contemporary medicine for their diverse bioactive properties, yet their potential for creating materials within the food industry remains largely unexplored. This article delves into the polyporoid fungi as a promising, yet underutilized, biomaterial resource for eco-friendly applications in the food sector. Despite their widespread use in traditional and modern medicine, the exploration of these fungi for industrial applications, particularly in food storage solutions and utensils, is in its nascent stages. The Białowieża Primeval Forest, characterized by its abundant deadwood and minimal human intervention, offers a rich repository of polyporoid fungi. This study aims to illuminate the ecological significance and potential industrial applications of polyporoid fungi. By reviewing existing research and synthesizing insights into the genetic diversity, biochemical capabilities, and ecological roles of polyporoid species such as *Fomes fomentarius*, *Fomitopsis pinicola*, and *Trametes versicolor*, this article proposes a novel approach to leveraging polyporoid fungi in developing sustainable solutions that meet current environmental and health-conscious trends. The investigation not only underscores the potential of polyporoid fungi in advancing green technologies but also highlights the importance of utilizing renewable resources in material science, fostering a shift towards more sustainable industrial practices.

Keywords: polypore fungi; biomaterials; non-wood resources; sustainable materials



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1. Introduction

Polypore fungi, known for their ecological roles and distinctive wood-decaying abilities, encompass a diverse group of Basidiomycetes. Characterized by their porous undersides, which host spore-bearing structures, these fungi exhibit significant ecological diversity, inhabiting various natural habitats and playing crucial roles in nutrient cycling and wood decomposition. Notable examples include *Fomes fomentarius*, *Trametes versicolor*, *Fomitopsis pinicola*, *Laetiporus sulphureus*, *Fomitopsis betulina*, *Ganoderma applanatum*, and *Ganoderma lucidum*. These species, among others, demonstrate the group's adaptation to a wide range of ecological niches, from dense forests to urban woodlands, each contributing uniquely to their ecosystems' dynamics. The genetic and mycelial characteristics of several medicinal polypore mushrooms, including *Fomes fomentarius*, *Fomitopsis pinicola*, and *Ganoderma* species, have been extensively studied, revealing their adaptability and the biochemical diversity underlying their ecological success and potential industrial applications [1].

Polypore fungi offer untapped potential for the development of sustainable materials due to their antimicrobial properties. These fungi possess a robust structure, making them suitable for applications in the food industry as eco-friendly alternatives to conventional materials. Their bioactive compounds not only ensure durability and resistance to external factors but also could provide a safer interaction with food by reducing microbial contamination [2].

Furthermore, the investigation into the utilization of polypore fungi as a substrate for material innovation remains nascent. The spectrum of bioactivities demonstrated by these fungi underscores their viability as a reservoir of natural additives or coatings within the realm of food packaging solutions, wherein their inherent antimicrobial attributes could significantly augment food safety and extend product shelf life. Such a strategy is congruent with the escalating requisition for materials that not only adhere to principles of environmental sustainability but also confer advantages pertinent to human health, particularly noted in the context of edible fungi, which are believed by many, especially the Chinese population, to possess significant health benefits. Following appropriate processing and sterilization procedures (involving the use of an autoclave where hot steam under pressure is applied), polypore fungi emerge as viable substitutes for conventional materials prevalent in the food industry, such as wine corks. This method ensures the elimination of microbial contaminants, making the fungi safe for direct contact with food products.

The inherent durability and resilience of these fungi against various external conditions, when allied with their significant bioactive properties, forge a pathway towards the fabrication of sustainable, eco-conscious products. The resilience and biochemical properties of polypore fungi make them ideal candidates for crafting biodegradable products, pioneering new methodologies in the production of food-related items such as containers and utensils. Notably, the application of polypore fungi in creating sustainable solutions is supported by their lignocellulolytic enzyme activity, which facilitates the breakdown of lignocellulosic biomass into valuable, environmentally friendly materials [3]. Moreover, the exploration of polypore fungi for environmental applications underscores a broader commitment to sustainability, exemplified by their potential in bioremediation and waste management efforts, further reinforcing their role in advancing green technologies within and beyond the food industry [4].

This article aims to review existing research on the application of polypore fungi as biomaterials within the food industry. By synthesizing insights from various studies, the article seeks to elucidate the scope of polypore fungi's utility, emphasizing their potential in creating sustainable solutions that align with current environmental and health-conscious trends. The investigation of polypore fungi not only contributes to the advancement of green technologies but also promotes the utilization of renewable resources in material science, thereby supporting the transition towards more sustainable industrial practices.

Research into sustainable materials is of paramount importance in the context of global environmental protection. The exploration of polypore fungi as alternative resources underscores a commitment to reducing reliance on non-renewable materials, mitigating environmental impact, and fostering ecological balance. Polypore fungi embody a promising avenue for developing biodegradable and eco-friendly products, which could have profound implications for waste management, resource conservation, and overall environmental sustainability. As such, continued research and development in this area are crucial for advancing sustainable solutions that benefit both the planet and its inhabitants.

2. Characteristics of Polyporoid Fungi

Polypore fungi, encompassing a broad spectrum of species within the *Basidiomycota* phylum, exhibit a remarkable array of biological and morphological characteristics that underscore their pivotal role in terrestrial ecosystems. These fungi are predominantly wood-decomposing organisms, with a distinct preference for lignin, cellulose, and hemicelluloses, pivotal components of wood, thereby playing a crucial role in nutrient cycling and forest ecology. Morphologically, polypore fungi are characterized by their hard, woody basidiocarps (fruiting bodies), which are primarily perennial, although some species exhibit annual growth patterns. The fruiting bodies are distinguished by their poroid surfaces, from which spores are released, facilitating their dispersion across varied environmental settings [5].

The structural integrity of polypore fruiting bodies, ranging from shelf-like to bracket formations, not only aids in their ecological functions but also reflects their adaptive strate-

gies to different environmental conditions. This morphological diversity is a response to their substrate preferences, with some species specializing in decomposing hardwoods, while others target coniferous woods. The ability of these fungi to thrive in diverse environments, from the dense, moist forests of the Białowieża Primeval Forest to more arid regions, is indicative of their extensive adaptive capacity. Their presence is particularly noted in old-growth forests where the accumulation of dead wood provides ample substrates for colonization and growth. In these settings, polypore fungi contribute to the decomposition of wood, thereby facilitating the recycling of nutrients back into the ecosystem [6].

The ecological role of polypore fungi within forest ecosystems is multifaceted, significantly influencing wood degradation processes and engaging in complex interactions with other organisms. These fungi are key agents in the decomposition of wood, thereby facilitating nutrient cycling and contributing to the health and sustainability of forest ecosystems [7]. By breaking down the lignin, cellulose, and hemicelluloses in wood, polypore fungi convert dead wood into organic matter that enriches the soil, supporting the growth of plants and the myriad of organisms dependent on them [5].

Polypore fungi's ability to decompose wood is not only crucial for forest regeneration but also for maintaining biodiversity. Their decomposing activity creates a plethora of niches for other species, including insects, birds, and small mammals, which find shelter and food within the decaying wood. For example, certain bird species rely on the soft, decomposed wood to create nesting sites, while numerous insect species use these environments for both habitation and reproduction [6].

The interactions between polypore fungi and other organisms extend beyond mere cohabitation. In some instances, polypore fungi engage in symbiotic relationships with tree species, contributing to the trees' nutrient uptake. Conversely, some polypore species can act as pathogens, affecting tree health and longevity. These dual roles highlight the complex dynamics within forest ecosystems, where polypore fungi can be both beneficial and detrimental to their host trees, depending on various ecological factors [5]. Moreover, polypore fungi play a pivotal role in the forest carbon cycle. By decomposing dead wood, these fungi release carbon dioxide back into the atmosphere, a process integral to the global carbon cycle. This role underscores the importance of polypore fungi in regulating atmospheric carbon levels and combating climate change [7].

Polypore fungi, beyond their ecological significance, present a substantial economic value and potential applications across various industrial sectors. Their unique biological properties have been harnessed in fields such as medicine, environmental management, biotechnology, and materials science, leading to innovative applications and products.

Biotechnological Applications of Polypores

The substantial morphological and chemical diversity of polypore fungi underpins their extensive use across a wide spectrum of biotechnological applications, thanks to their rich array of bioactive compounds and structural features. This versatility facilitates their deployment in fields ranging from pharmaceutical development to environmental sustainability and beyond [8].

Polypore fungi, already recognized for their therapeutic applications in immunology and oncology, also play significant roles in biodegradation processes and have been studied extensively in scientific research [9]. These attributes make them excellent resources for developing health-oriented and eco-friendly food packaging solutions, paving the way for diverse applications in the following areas:

- (a) **Medicine and pharmacy:** polypore fungi have been historically valued for their medicinal properties, with several species known for their immune-boosting and anticancer effects. Compounds extracted from polypore species like *Ganoderma lucidum* (Reishi) and *Trametes versicolor* (Turkey Tail) are currently utilized in supplements and as adjuncts in cancer therapy due to their polysaccharide content, which has been shown to enhance immune system function [10,11].;

- (b) Biodegradation and bioremediation: leveraging their wood-degrading capabilities, polypore fungi have been applied in bioremediation projects to break down pollutants, including hydrocarbons and heavy metals in contaminated soils and water. Their enzymatic systems, particularly lignin-degrading enzymes, are effective in decomposing complex organic pollutants, offering a sustainable alternative to chemical treatments [1,12].;
- (c) Biotechnology and scientific research: In biotechnological research, polypore fungi contribute to the detection of novel enzymes for industrial processes, such as biofuel production. The enzymes produced by these fungi, capable of breaking down plant biomass into fermentable sugars, are pivotal in advancing biofuel technologies and reducing reliance on fossil fuels [13,14].;
- (d) Production of biomaterials and biocomposites: The structural and chemical resilience of polypore fungi is explored in the creation of biomaterials and biocomposites. Innovations include the development of fungal mycelium-based materials that offer sustainable alternatives to plastics and leathers. These fungal biocomposites, noted for their durability and capacity for decomposition, are applied not only in food storage solutions but also in sectors such as fashion and construction. This underscores the broad applicability and innovative potential of polypore fungi for sustainable material solutions [15–17].

3. Polyporoid Fungal Species Suitable as Materials for Use in the Food Industry

In identifying fungi suitable for the food industry from northeastern Poland and the Białowieża Forest, emphasis was placed on species with significant regional prevalence and beneficial health impacts. Factors such as the size of the fungi also influenced the selection, with larger species preferred over smaller ones like corticioid fungi or those from the genus *Postia*. This focus ensures the use of the most common and abundant types from the Białowieża area for detailed examination and application.

However, not all fungal species are viable for use in the food industry as packaging materials due to various limitations. For example, *Inonotus radiatus*, while common, does not meet the criteria for widespread prevalence necessary for sustainable harvesting. Similarly, certain species are subject to conservation efforts and legal protection, such as *Inonotus obliquus* and *Fistulina hepatica*, which are recognized for their unique bioactive properties but are protected to ensure biodiversity and ecological balance. These limitations underscore the importance of selecting fungi not only for their potential industrial applications but also for their availability and ecological sustainability, ensuring that their use does not compromise forest ecosystems or violate conservation laws. The analysis of the occurrence and characteristics of various polypore fungi species allowed for the identification of several species that would be suitable for use as materials in food production. This careful selection aims to utilize the most promising fungi while adhering to sustainable harvesting practices and environmental conservation efforts.

3.1. *Fomes fomentarius* (L.) Fr.

Fomes fomentarius is characterized by its tough, woody basidiocarps, commonly referred to as conks or polypores (Figure 1). These fruiting bodies are perennial, adding layers each year, and have a hoof-like shape with a gray to almost black outer surface. The underside contains pores where spores are released. As a saprotroph, this fungus primarily decomposes dead hardwood, although it can also act as a parasite on weakened trees, contributing to heartwood rot [11]. The spores are ellipsoid, smooth, and have dimensions of $15\text{--}20 \times 5\text{--}7 \mu\text{m}$ [14].

F. fomentarius is commonly found on dead or dying trees in forests across the Northern Hemisphere, including deciduous woods in Europe and North America. Its prevalence is particularly noted in old-growth forests where it plays a vital role in wood decomposition and nutrient cycling [18]. While *F. fomentarius* contributes to forest ecosystem health by decomposing dead wood, it can also cause economic losses in forestry by inducing white

rot in living trees, leading to timber decay. Its presence indicates compromised wood quality, affecting the lumber industry [2].



Figure 1. *Fomes fomentarius* on a dead tree.

Historically, *F. fomentarius* was utilized for its amadou—a felt-like material derived from its fruiting body. Amadou was also used as tinder for fire-starting, evidenced by the approximately 5000-year-old corpse of the Iceman Ötzi, discovered in 1991 in the Ötztal Alps in Italy, who carried pieces of *Fomitopsis betulina* and presumably *Fomes fomentarius* for making fire. Additionally, amadou was employed in traditional medicine for its hemostatic properties and as a styptic [2]. The inherent properties of *F. fomentarius*, despite its rigid structure rendering it not directly consumable, are of significant interest for food industry applications, particularly in the development of food-contact materials such as packaging and corks. The bioactive compounds found in *F. fomentarius*, notably polysaccharides and phenolic compounds, possess antimicrobial and antioxidative properties. These characteristics make it an excellent candidate for creating food-contact materials that could potentially offer health benefits or extend the shelf life of food products by reducing microbial growth and oxidative spoilage. Furthermore, the historical use of *F. fomentarius* in traditional medicine and its recognized safety profile underscore its suitability for incorporation into materials that come into direct contact with food. The absence of known adverse health effects from its use underscores the potential for developing innovative solutions for food containment and preservation that leverage the positive health attributes of this fungus, contributing to the overall safety and quality of food products [2,14].

3.2. *Fomitopsis pinicola* (Sw.) P. Karst.

Fomitopsis pinicola, commonly known as the red-belted conk, exhibits a tough, woody basidiocarp typically found on both coniferous and deciduous trees (Figure 2). As a saprotrophic organism, it plays a critical role in the decomposition of wood, contributing to nutrient recycling within forest ecosystems. The fungus can act both as a saprotroph, decomposing dead wood, and as a weak parasite on living trees [19]. Spores of *F. pinicola* are cylindrical, with dimensions of $5\text{--}7 \times 1.5\text{--}2 \mu\text{m}$ [19]. This species is prevalent in temperate forests across the Northern Hemisphere, indicating its significant ecological role and adaptability [2].

Economically, while *F. pinicola* contributes positively to forest ecosystems through wood decomposition, it can also cause wood rot in timber structures, leading to potential economic losses. Its dual role underscores the importance of managing its presence in commercial forestry and timber preservation [20]. Bioactive compounds of *F. pinicola*, including polysaccharides and phenolic compounds, present opportunities for development into

functional food ingredients or natural preservatives. These compounds have been shown to exhibit antioxidant and antimicrobial properties, which could be beneficial in extending the shelf life of food products and enhancing their nutritional value. The safety profile and historical use of *F. pinicola* suggest its potential for application in food-contact materials, contributing positively to human health without adverse effects [9,20].



Figure 2. *Fomitopsis pinicola* growing on a fallen *Picea abies* trunk.

3.3. *Trametes versicolor* (L.) Lloyd

Trametes versicolor, commonly known as Turkey Tail, has colorful, fan-shaped, multi-zoned basidiocarps (Figure 3). This fungus operates primarily as a saprotroph, decomposing lignocellulosic material in dead wood, which plays a crucial role in forest ecosystems by recycling nutrients. It can be found worldwide, and is especially prevalent in temperate forests [21].

The spores of *T. versicolor* are cylindrical, measuring $5\text{--}7 \times 1.5\text{--}2 \mu\text{m}$ [22]. *Trametes versicolor* is significant both ecologically, as a primary decomposer, and economically. While it aids in the breakdown of wood and nutrient cycling, it can also contribute to wood rot in forest industries. However, its potential negative economic impact is overshadowed by its medicinal value and application in biotechnology [23]. Extracts from the mushroom, particularly polysaccharopeptide (PSP) and polysaccharide-K (PSK), have been utilized in cancer therapy as immune system boosters [22,23].

The bioactive compounds of *T. versicolor*, such as polysaccharides, phenolic compounds, and enzymes like laccase, offer promising applications in the food industry. These compounds have been shown to have antimicrobial and antioxidant properties, making *T. versicolor* a valuable source for developing natural food preservatives or functional food ingredients. The historical application of *T. versicolor* in traditional medicine, coupled with the documented positive health impacts of its bioactive constituents, indicates that this fungus can be safely utilized as a material in direct contact with food items. This application may not only contribute to the enhancement of food safety and nutritional quality but also achieve these outcomes devoid of detrimental health consequences [21].



Figure 3. *Trametes versicolor* colonizing a decaying log.

3.4. *Ganoderma applanatum* (Pers.) Pat.

Ganoderma applanatum is a wood-decaying fungus that forms large, flat, perennial fruiting bodies on the trunks of trees. It is characterized by its brown to dark-brown color, a hard, woody texture, and a white pore surface that darkens when touched (Figure 4). It feeds primarily as a saprotroph, decomposing the heartwood of both dead and living trees, which can lead to the development of heart rot [24]. Spores are brown, oval to cylindrical, and measure approximately $8\text{--}11 \times 6\text{--}7 \mu\text{m}$. [25]. This species is widely distributed, found in forests across North America, Europe, Asia, and other regions, reflecting its significant ecological role in decomposing wood and recycling forest nutrients [25,26].

G. applanatum impacts the forestry and timber industry by causing white rot and reducing wood quality. Despite this, it has historical uses in traditional medicine, exploiting its bioactive compounds for their health benefits [10]. The significance of *G. applanatum* within the food industry emerges not from its consumption in raw form but from leveraging its bioactive components—namely polysaccharides, triterpenoids, and phenolic acids. Importantly, the application of *G. applanatum* in food products is aimed at ensuring contact with food that either maintains a neutral stance or, in some instances, exerts a beneficial effect, thereby enhancing food safety and nutritive value without compromising the quality of the food product. This approach is underscored by the fungus's long standing use in medicinal contexts and its associated health benefits, affirming its suitability for integration into food items with no adverse health repercussions [10].



Figure 4. *Ganoderma applanatum* sporocarp growing on decaying log.

3.5. *Laetiporus sulphureus* (Bull.) Murrill

Laetiporus sulphureus (sulphur shelf fungus) is distinguished by its large, bright yellow to orange fruiting bodies that grow in shelf-like clusters on trees (Figure 5). This polypore fungus primarily acts as a saprotroph, decomposing dead or dying hardwood, but it can also live as a weak parasite on living trees. The fruiting bodies are soft when young, becoming tougher with age. The spores are white to yellowish, elliptical, and measure 5–6 μm in length [12]. Widely distributed, *L. sulphureus* is found in many parts of the world, thriving in both temperate and subtropical forests. It frequently causes brown rot in host trees, leading to significant economic impact in forestry and arboriculture by compromising wood quality and tree health [27]. This mushroom has been utilized both as a culinary delicacy, given its meat-like taste and texture, and medicinally for its purported health benefits, including anti-inflammatory and antimicrobial properties [28].

L. sulphureus presents an innovative material for food-contact surfaces such as wrappings and corks. Its natural bioactive compounds, particularly those with antimicrobial properties, make it a candidate for developing bio-based packaging solutions that could potentially reduce food spoilage and extend shelf life. Moreover, its edibility and safety profile suggest that materials derived from *L. sulphureus* would not have adverse health effects upon contact with food, making it a sustainable alternative to conventional food packaging materials. The fungus's ability to inhibit the growth of undesirable microorganisms further underscores its potential utility in food preservation [12,27].



Figure 5. *Laetiporus sulphureus* growing on dying *Salix* tree.

3.6. *Fomitopsis betulina* (Bull.) B.K. Cui, M.L. Han and Y.C. Dai

Fomitopsis betulina, formerly known as *Piptoporus betulinus*, has robust, annual fruiting bodies that predominantly colonize birch trees (Figure 6). The fruiting bodies are white to brownish, signaling its phase of development, and are rich in bioactive compounds recognized for their antimicrobial, anticancer, and anti-inflammatory properties [13]. The spores are smooth, ellipsoid, and typically measure 3–6 μm in length, with a light coloration [2]. This species has a wide distribution in the northern hemisphere, thriving in both North America and Eurasia, where it plays a pivotal role in decomposing dead wood and facilitating forest nutrient cycling [24].

Fomitopsis betulina embodies a dual functionality, contributing both to the natural decomposition vital for forest health and, conversely, to wood decay, affecting the timber

industry negatively. However, its utilization in traditional medicine for antimicrobial and wound-healing purposes underscores its value beyond mere ecological considerations [13,24]. Within the food industry, *F. betulina* offers a novel application not as a direct food ingredient but as a foundational element for eco-conscious wrapping solutions. The antiseptic properties of *F. betulina*, deriving from its bioactive constituents, suggest its capability to innovate packaging that inherently resists bacterial proliferation, thus prolonging food shelf life. Furthermore, the historical medicinal applications of this fungus suggest that its derived materials would be inherently non-toxic and potentially beneficial to human health, presenting a viable, eco-friendly alternative to traditional containment options for food products [13,29].

Critical to the adoption of *F. betulina*-based materials for food packaging is the imperative to thoroughly investigate their long-term interaction with various food types, including those containing alcohol or bacterial cultures. Ensuring that prolonged contact does not result in the leaching of harmful substances from the fungal material into food products is essential. This further examination will solidify *F. betulina*'s suitability as a safe, sustainable packaging resource, aligning with both health safety standards and environmental sustainability goals.



Figure 6. *Fomitopsis betulina* fruiting body.

4. Polypore Fungi as Innovative Sustainable Material

The exploration of polypore fungi for developing biomaterials has significantly advanced the search for sustainable alternatives to traditional food containment materials, emphasizing ecological benefits and reduced environmental impacts. These fungi, rich in bioactive compounds like polysaccharides, triterpenoids, and phenolic acids, not only fortify their structural resilience but also deliver biofunctional benefits, including antioxidative, antimicrobial, and antitumor effects [4]. As products of renewable and biodegradable resources, biomaterials derived from polypore fungi present an eco-friendly solution that harmonizes with conservation efforts. Their origin from forestry by-products underscores a commitment to a sustainable material lifecycle, effectively minimizing the waste and ecological footprints typically associated with packaging processes [15,30].

The application strategies for polypore fungi in material science are twofold. One method involves the direct use of large fungal bodies, like those from *Fomes fomentarius*, as replacements for materials such as cork. Another approach encompasses processing these fungi through sterilization and grinding, followed by solidification with natural or food-grade resins, yielding sturdy, environmentally considerate wrapping options. This adaptability facilitates the exploitation of polypore fungi's natural attributes across a spectrum of uses, ranging from unaltered applications to refined biomaterials, thereby providing the food packaging industry with innovative and sustainable alternatives.

The production of materials from polypore fungi includes products like amadou, an ecological leather substitute utilized in fashion, primarily for crafting hats and caps. Furthermore, the utilization of fungi has predominantly been confined to employing the mycelium of specific species for various applications, including the creation of bricks, packaging, and even outerwear (Myco-Tex), showcasing the fungi's versatility beyond traditional applications. This expanded use of fungal materials not only underscores their potential in replacing more ecologically taxing resources but also highlights the innovative strides being made towards fully harnessing the sustainability and utility of polypore fungi in material development.

A critical advantage of polypore fungi is their biodegradability, especially notable in compost or soil, where they efficiently break down complex organic polymers. This ability is vital for reducing environmental pollution. Research on the fungal degradation of synthetic polymers, such as poly(l-lactide) (PLLA) and poly(butylene adipate-co-terephthalate) (PBAT), has shown that temperature significantly affects the degradation process, with fungi and bacteria working together to enhance biodegradation rates [31,32].

The role of polypore fungi in biodegradation highlights their importance in promoting environmental sustainability and offering practical waste management solutions. Their capacity to degrade or transform pollutants is particularly valuable in creating sustainable materials for the food industry, leading to the development of eco-friendly wrappings for food products that significantly reduce the environmental footprint of waste associated with food containment [15,33].

Application in Food Industry

The utilization of polypore fungi for biomaterials affords a greener alternative to conventional food storage materials, notably in terms of sustainability and environmental preservation. These fungi are a treasure trove of bioactive compounds, including polysaccharides, triterpenoids, and phenolic acids. Such chemical diversity bolsters their structural robustness [4]. Derived from renewable and biodegradable sources, polypore fungi-based biomaterials represent an environmentally benign choice, resonating with the principles of ecological stewardship. Their derivation from forestry by-products promotes a circular economy, markedly diminishing the waste and environmental detriment traditionally associated with packaging. Due to the current lack of developed strategies for large-scale harvesting and the limited availability of these fungi, the use of such biomaterials is presently intended for local scales or small ecological enterprises. This focus not only makes their adoption by large corporations currently impractical or significantly restricted, but also offers small enterprises the unique opportunity to enhance the prestige of their products. Utilizing these eco-friendly biomaterials can differentiate their offerings in the market, potentially elevating consumer perception and adding value to their brand [15,30].

Innovatively, the application of polypore fungi in the industry can be realized through the direct use of substantial fungal sections, such as those from *Fomes fomentarius*, as a substitute for materials like cork. Alternatively, these fungi can undergo processing—sterilization and pulverization—followed by reinforcement with natural or food-grade resins to create robust, eco-conscious packaging solutions. This dual approach enables the leverage of polypore fungi's inherent properties for varied applications, from intact use in their natural form to processed biomaterials, providing versatile and sustainable storage solutions for the food industry's needs.

These fungi have been used to develop sustainable insulating materials and other wrapping solutions that demonstrate their potential to replace environmentally harmful traditional materials. The unique structural, thermal, and moisture-regulating properties of fungal biomaterials provide both environmental and functional advantages for the food industry [3,30]. Fungal biomaterials, particularly those derived from polypores, are distinguished by their low carbon emissions and renewable nature, making them an economically viable option for reducing industrial ecological footprints.

Advancements in fungal-derived fuels and chemicals, particularly through the use of yeasts in industrial fermentation, underscore the significant role of fungal biotechnology in promoting a bio-based circular economy across various sectors, including food and construction [34,35]. Exergetic analysis has shown the efficiency and environmental benefits of using fungal biomaterials in energy production, highlighting their contribution to sustainable energy systems [17]. Moreover, the capability of fungal biomaterials in water purification processes through biosorption emphasizes their environmental advantages, demonstrating their effectiveness, versatility, and cost-efficiency in removing pollutants [36]. The potential of fungi in bioremediation, capable of breaking down environmental toxins and addressing hazards from heavy metals, metalloids, and radionuclides, presents eco-friendly alternatives to conventional methods [37].

5. Conclusions and Future Research Directions

This manuscript underscores a significant gap in the existing body of research, setting the stage for these comprehensive studies by emphasizing the need for this foundational exploration. It concentrates on emphasizing the lack of prior research on the resilience of fungi to physicochemical factors, their impact on food products, and the technological possibilities of processing. The forthcoming research is poised to embark on a comprehensive exploration into the sustainable harvesting of polypore fungi, examining their chemical compositions and physical properties in detail. This initial phase of research serves as an introduction to the broader capabilities of these fungi within the food industry, particularly focusing on their potential applications in food containment and as active elements in extending shelf life or providing antimicrobial benefits. A vital aspect of this study will be assessing the ecological sustainability of these harvesting practices, with a particular focus on their impact on environments such as the Białowieża Forest. The research aims to ensure that such activities do not adversely affect biodiversity or disrupt ecological balance. Furthermore, this investigation will strive to develop scalable and economically feasible methods for processing polypore fungi into practical biomaterials, tackling the current technological, logistical, and regulatory hurdles that currently limit their wider use.

In addition to these objectives, forthcoming studies will rigorously test the durability and safety of materials derived from polypore fungi, specifically their structural integrity and their safety in prolonged contact with certain food types, notably those containing alcohol or bacterial cultures. This aspect of the research is crucial to ascertain that materials obtained from polypore fungi remain safe and effective over long periods, ensuring they do not release harmful substances when in contact with various food products. Moreover, it is imperative to acknowledge that the biological activity of these fungi on timber substrates frequently presents a more substantial risk compared to their extraction processes. This affirmation will further substantiate the credentials of polypore fungi as a source of sustainable, safe, and durable materials for the food industry, reinforcing their role in advancing eco-friendly solutions.

The exploration of polypore fungi for biomaterial production in the food industry underscores the imperative for broader research initiatives. Future studies are expected to conduct comprehensive analyses of the chemical, physical, and practical applications of polypore fungi, particularly those from ecologically rich areas like the Białowieża Primeval Forest, a notable reservoir of diverse fungi due to its abundant deadwood. Significant challenges include optimizing fungal cultivation for better biomass yield and quality, addressing biomaterial property variability, and creating efficient extraction and processing

techniques. Innovative approaches, such as co-cultivation, offer low-energy, chemical-free solutions that could reduce production costs [38]. Establishing a consistent fungal biomass supply chain, given fungal growth's unpredictability and specific environmental needs, is critical. Complying with strict food safety and regulations adds complexity to introducing fungal biomaterial-based products, necessitating thorough testing for consumer safety [35].

This research agenda aims to harness the ecological and economic benefits of fungal biomaterials fully. Offering a sustainable alternative to conventional packaging materials, which often come from non-renewable sources and significantly pollute, fungal biomaterials are poised to revolutionize the food industry. These innovations hold the promise of contributing to global sustainability efforts while providing biodegradable, renewable packaging solutions with potential food preservation and safety benefits.

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References

1. Badalyan, S.M.; Shnyreva, A.V.; Iotti, M.; Zambonelli, A. Genetic resources and mycelial characteristics of several medicinal polypore mushrooms (Polyporales, Basidiomycetes). *Int. J. Med. Mushrooms* **2015**, *17*, 371–384. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Dresch, P.; D'Aguanno, M.N.; Rosam, K.; Grienke, U.; Rollinger, J.M.; Peintner, U. Fungal strain matters: Colony growth and bioactivity of the European medicinal polypores *Fomes fomentarius*, *Fomitopsis pinicola* and *Piptoporus betulinus*. *Amb Express* **2015**, *5*, 4. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Nguyen, K.; Wikee, S.; Lumyong, S. Brief review: Lignocellulolytic enzymes from polypores for efficient utilization of biomass. *Mycosphere* **2018**, *9*, 1073–1088. [\[CrossRef\]](#)
4. Zjawiony, J.K. Biologically active compounds from Aphyllophorales (polypore) fungi. *J. Nat. Prod.* **2004**, *67*, 300–310. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Karasiński, D.; Wołkowycki, M. An annotated and illustrated catalogue of polypores (Agaricomycetes) of the Białowieża Forest (NE Poland). *Pol. Bot. J.* **2015**, *60*, 217–292. [\[CrossRef\]](#)
6. Junninen, K.; Komonen, A. Conservation ecology of boreal polypores: A review. *Biol. Conserv.* **2011**, *144*, 11–20. [\[CrossRef\]](#)
7. Penttilä, R.; Siitonen, J.; Kuusinen, M. Polypore diversity in managed and old-growth boreal *Picea abies* forests in southern Finland. *Biol. Conserv.* **2004**, *117*, 271–283. [\[CrossRef\]](#)
8. Raghukumar, C. Marine fungal biotechnology: An ecological perspective. *Fungal Divers.* **2008**, *31*, 19–35.
9. Dai, Y.C. Polypore diversity in China with an annotated checklist of Chinese polypores. *Mycoscience* **2012**, *53*, 49–80. [\[CrossRef\]](#)
10. Elkhateeb, W.A.; Zaghlol, G.M.; El-Garawani, I.M.; Ahmed, E.F.; Rateb, M.E.; Moneim, A.E.A. *Ganoderma applanatum* secondary metabolites induced apoptosis through different pathways: In vivo and in vitro anticancer studies. *Biomed. Pharmacother.* **2018**, *101*, 264–277. [\[CrossRef\]](#)
11. Gáper, J.; Gáperová, S.; Pristas, P.; Naplavova, K. Medicinal value and taxonomy of the tinder polypore, *Fomes fomentarius* (Agaricomycetes): A review. *Int. J. Med. Mushrooms* **2016**, *18*, 851–859. [\[CrossRef\]](#)
12. Adamska, I. The possibility of using sulphur shelf fungus (*Laetiporus sulphureus*) in the food industry and in medicine—A review. *Foods* **2023**, *12*, 1539. [\[CrossRef\]](#)
13. Pleszczyńska, M.; Lemieszek, M.K.; Siwulski, M.; Wiater, A.; Rzeski, W.; Szczodrak, J. *Fomitopsis betulina* (formerly *Piptoporus betulinus*): The Iceman's polypore fungus with modern biotechnological potential. *World J. Microbiol. Biotechnol.* **2017**, *33*, 83. [\[CrossRef\]](#)
14. Kalitukha, L.; Galiano, A.; Harrison, F. Medicinal potential of the insoluble extracted fibers isolated from the *Fomes fomentarius* (Agaricomycetes) fruiting bodies: A review. *Int. J. Med. Mushrooms* **2023**, *25*, 21–35. [\[CrossRef\]](#)
15. Gandia, A.; van den Brandhof, J.G.; Appels, F.V.; Jones, M.P. Flexible fungal materials: Shaping the future. *Trends Biotechnol.* **2021**, *39*, 1321–1331. [\[CrossRef\]](#)
16. Sierra, L.A.B.; Mendes-Pereira, T.; García, G.J.Y.; Werkhaizer, C.Q.; de Rezende, J.B.; Rodrigues, T.A.B.; Badotti, F.; de Carvalho Cardoso, E.S.; da Costa, A.M.; Uetanabaro, A.P.; et al. Current situation and future perspectives for the use of fungi in the biomaterial industry and proposal for a new classification of fungal-derived materials. *PeerJ Mater. Sci.* **2023**, *5*, e31. [\[CrossRef\]](#)

17. Kim, H.J.; Kyritsis, D.C. Exergetic analysis of power plants operating on biomaterials. In Proceedings of the IEEE Power and Energy Conference at Illinois (PECI), Urbana, IL, USA, 22–23 February 2013; pp. 18–22.
18. Wang, H.; Zhao, C. Fomes (Polyporales, Basidiomycota): Medicinal, economic and ecological importance. *Fungal Biotech* **2021**, *1*, 1–9.
19. Shnyreva, A.V.; Badalyan, S.M.; Shnyreva, A.A. Analysis of intraspecies genetic variability among collections of medicinal red belt conk mushroom, *Fomitopsis pinicola* (Agaricomycetes). *Int. J. Med. Mushrooms* **2019**, *21*, 291–300. [\[CrossRef\]](#)
20. Angelini, P.; Tirillini, B.; Bistocchi, G.; Arcangeli, A.; Rubini, A.; Pellegrino, R.M.; Fabiani, R.; Cruciani, G.; Venanzoni, R.; Rosignoli, P. Overview of the biological activities of a methanol extract from wild red belt conk, *Fomitopsis pinicola* (Agaricomycetes), fruiting bodies from Central Italy. *Int. J. Med. Mushrooms* **2018**, *20*, 1047–1063. [\[PubMed\]](#)
21. Tišma, M.; Žnidaršič-Plazl, P.; Šelo, G.; Tolj, I.; Šperanda, M.; Bucić-Kojić, A.; Planinić, M. Trametes versicolor in lignocellulose-based bioeconomy: State of the art, challenges and opportunities. *Bioresour. Technol.* **2021**, *330*, 124997. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Habtemariam, S. *Trametes versicolor* (Synn. *Coriolus versicolor*) polysaccharides in cancer therapy: Targets and efficacy. *Biomedicines* **2020**, *8*, 135. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Hobbs, C. Medicinal value of turkey tail fungus *Trametes versicolor* (L.: Fr.) Pilat (Aphyllphoromycetidae). *Int. J. Med. Mushrooms* **2005**, *7*, 346–347. [\[CrossRef\]](#)
24. Minter, D.; Soliman, G. *Ganoderma applanatum*. In *Descriptions of Fungi and Bacteria*; CABI: Wallingford, UK, 2021.
25. Leonard, A.C. Two *Ganoderma* species compared. *Mycologist* **1998**, *2*, 65–68. [\[CrossRef\]](#)
26. Grinn-Gofroń, A.; Bogawski, P.; Bosiacka, B.; Nowosad, J.; Camacho, I.; Sadyś, M.; Skjøth, C.A.; Pashley, C.H.; Rodinkova, V.; Çeter, T.; et al. Abundance of *Ganoderma* sp. in Europe and SW Asia: Modelling the pathogen infection levels in local trees using the proxy of airborne fungal spore concentrations. *Sci. Total. Environ.* **2021**, *793*, 148509. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Petrović, J.; Glamočlija, J.; Stojković, D.S.; Ćirić, A.; Nikolić, M.; Bukvički, D.; Guerzoni, M.E.; Soković, M.D. *Laetiporus sulphureus*, edible mushroom from Serbia: Investigation on volatile compounds, in vitro antimicrobial activity and in situ control of *Aspergillus flavus* in tomato paste. *Food Chem. Toxicol.* **2013**, *59*, 297–302. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Bulam, S.; Üstün, N.Ş.; Pekşen, A. Nutraceutical and food preserving importance of *Laetiporus sulphureus*. *Turk. J. Agric.-Food Sci. Technol.* **2019**, *7*, 94–100. [\[CrossRef\]](#)
29. Grosse, M.; Wu, S.; Krings, U.; Berger, R.G. Formation of decatrienones with a pineapple-like aroma from 1-13c-acetate by cell cultures of the birch polypore, *Fomitopsis betulina*. *J. Agric. Food Chem.* **2020**, *68*, 1678–1683. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Charpentier-Alfaro, C.; Benavides-Hernández, J.; Poggerini, M.; Crisci, A.; Mele, G.; Della Rocca, G.; Emiliani, G.; Frascella, A.; Torrigiani, T.; Palanti, S. Wood-decaying fungi: From timber degradation to sustainable insulating biomaterials production. *Materials* **2023**, *16*, 3547. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Saadi, Z.; Rasmont, A.; Cesar, G.; Bewa, H.; Benguigui, L. Fungal degradation of poly (l-lactide) in soil and in compost. *J. Polym. Environ.* **2012**, *20*, 273–282. [\[CrossRef\]](#)
32. Saadi, Z.; Cesar, G.; Bewa, H.; Benguigui, L. Fungal degradation of poly (butylene adipate-co-terephthalate) in soil and in compost. *J. Polym. Environ.* **2013**, *21*, 893–901. [\[CrossRef\]](#)
33. Jones, M.; Gandia, A.; John, S.; Bismarck, A. Leather-like material biofabrication using fungi. *Nat. Sustain.* **2021**, *4*, 9–16. [\[CrossRef\]](#)
34. Ekas, H.; Deaner, M.; Alper, H.S. Recent advancements in fungal-derived fuel and chemical production and commercialization. *Curr. Opin. Biotechnol.* **2019**, *57*, 1–9. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Meyer, V.; Basenko, E.Y.; Benz, J.P.; Braus, G.H.; Caddick, M.X.; Csukai, M.; De Vries, R.P.; Endy, D.; Frisvad, J.C.; Gunde-Cimerman, N.; et al. Growing a circular economy with fungal biotechnology: A white paper. *Fungal Biol. Biotechnol.* **2020**, *7*, 5. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Legorreta-Castañeda, A.J.; Lucho-Constantino, C.A.; Beltrán-Hernández, R.I.; Coronel-Olivares, C.; Vázquez-Rodríguez, G.A. Biosorption of water pollutants by fungal pellets. *Water* **2020**, *12*, 1155. [\[CrossRef\]](#)
37. Harms, H.; Schlosser, D.; Wick, L.Y. Untapped potential: Exploiting fungi in bioremediation of hazardous chemicals. *Nat. Rev. Microbiol.* **2011**, *9*, 177–192. [\[CrossRef\]](#)
38. Wrede, D.; Taha, M.; Miranda, A.F.; Kadali, K.; Stevenson, T.; Ball, A.S.; Mouradov, A. Co-cultivation of fungal and microalgal cells as an efficient system for harvesting microalgal cells, lipid production and wastewater treatment. *PLoS ONE* **2014**, *9*, e113497. [\[CrossRef\]](#)

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