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Perspective

Environmentally Conscious Technologies Using Fungi in a Climate-Changing World

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Abstract: Fungi are a diverse and fascinating group of organisms that play an important role in various ecosystems, e.g., in the decomposition of organic matter and nutrient cycling. However, climate change poses a significant threat to these ecosystems and the organisms that inhabit them. Fluctuations in temperature and humidity can cause shifts in the distribution of fungi and negatively impact the ecosystems they inhabit. Yet fungi have the potential to play a role in mitigating the effects of climate change. With the use of biotechnology, fungi can help meet the United Nations Sustainable Development Goals, and their properties make them useful organisms in addressing the urgent challenges that humanity faces. For example, industrial biotechnology using fungi can lead to the production of goods that are more biodegradable, use less energy and produce less waste. Fungi have long been used in the production of enzymes, alkaloids, detergents, acids, and biosurfactants on an industrial scale. Recent research in the field of white biotechnology has made significant progress, and further advances are expected in the near future, especially in agricultural and environmental biotechnology. With this in mind, it is crucial to explore the use of fungi in novel and environmentally conscious technologies, as well as in mitigating the effects of climate change.

Keywords: circular bioeconomy; climate change; fungal biotechnology; planetary health; SDGs

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1. The Biodiversity of Fungi and Its Importance

Fungi are a diverse group of eukaryotic organisms that play important roles in various ecosystems, including organic matter decomposition and nutrient cycling [1]. Fungi recycle nutrients from nearly all organic matter, which are then used by other organisms. Some fungi are generalists, decomposing a wide range of organic material, while others are more selective. In recent years, there has been increasing interest in the potential impacts of climate change on fungi and the role that fungi can play in mitigating the effects of climate change [2]. Climate change is a global environmental crisis caused by increasing levels of greenhouse gases in the atmosphere, leading to rising temperatures, more frequent and severe weather events, and other impacts on the Earth's climate system. Fungi are likely to be affected by several aspects of climate change, including changes in temperature and moisture levels, resulting in shifts in their distribution and causing impacts on the ecosystems in which they live [3,4]. At the same time, fungi also have the potential to play a role in mitigating the effects of climate change. For example, certain fungi are capable of decomposing and sequestering carbon and could thus serve as a means of carbon sequestration and storage [5,6]. Fungi are also being explored for their potential to produce biofuels, bioplastics, and other bio-based products that can help reduce greenhouse gas emissions and contribute to a more sustainable and low-carbon economy [7–10].

The term "Great Acceleration" was coined in 2005 by a work group at the Dahlem Conference to describe the impact of human activities on the environment. The human-environment system is depicted as a network of interactions between knowledge, science, and technology, and feedbacks through population dynamics, energy, institutions, and politics [11]. Humanity has proven to be the dominant force in shaping the Earth's climate. Anthropogenic activities generate millions of tons of plastic waste every year, which is a widespread and serious global problem. Man-made mass, also known as anthropogenic mass (man-made objects that are still in use: buildings, roads, machinery, etc.), exceeded global living biomass in 2020 (±6 years) [12]. The steady increase in human population, the degradation of agricultural land, the accumulation of CO_2 in the atmosphere due to the burning of fossil fuels, the gradual increase in the concentration of many man-made pollutants and various contaminants, and global warming are all contributing to drastic changes in our climate [13].

In the face of widespread environmental damage and rapid climate change, biodiversity is a largely untapped tool for sustaining our planet. It has the potential to improve our lives in the face of environmental threats. Fungi have very high diversity, so fungal biotechnology has the potential to accelerate the transition from our petroleum-based economy to a bio-based circular economy by producing, for example, resilient sources of food, medicine, energy, fiber, building materials, packaging, carbon storage, erosion control, pollution mitigation, urban noise reduction, and a host of other benefits to people and ecosystems [14,15]. Several fungi species are already employed in numerous industrial sectors. Important species include *Aspergillus niger*, *Aspergillus flavus*, *Trichoderma reesei*, and *Thermothelomyces thermophilus* from the phylum *Ascomycota*, and *Ganoderma lucidum*, *Pleurotus ostreatus*, *Trametes versicolor*, and *Bjerkandela adusta* from the phylum Basidiomycota, some of which are already significant commercially. Fungi have 144,000 species classified to date. In 2017, over 70 new species from 38 genera of bracket and crust fungi were described, including eight new species of brown rot fungi in the genus *Antrodia*, white rot polypores in the genera *Polyporus*, *Fomitiporia* and *Fomitiporella*, and crust fungi in the genus *Lyomyces* [4]. Recent estimates put the total number of fungal species on Earth at between 2.2 and 3.8 million, with some sources putting the number as high as 5.1 million [16]. This is more than six times the estimated number of plants [4,17]. It is estimated that the vast majority of fungal species (more than 93%) are currently still unknown to science. Global knowledge of fungal diversity and its applications is incomplete and fragmented [18]. Most have never been cultured and studied for their growth characteristics and physiology, so their potential applications are virtually untapped. Technological use of fungal resources can help incentivize their conservation at a time when biodiversity loss is accelerating [19,20].

2. Fungi Potential for a Sustainable Future

Before the loss of fungal biodiversity becomes a major global problem, it is crucial to take action to discover more species of fungi and to conserve and protect fungi and the ecosystems of which they are part. Failure to do so can have serious consequences for the environment, human health, and well-being. The use of fungi in biotechnology has the potential to contribute to the achievement of the United Nations Sustainable Development Goals (SDGs) and can provide an overarching view of the properties that make them useful for addressing the urgent challenges that all humans face [15,21]. The 2030 Agenda for Sustainable Development [22], which was adopted by all United Nations (UN) Member States in 2015, is a shared approach to social, economic, and environmental sustainability for people and the planet. The 17 Sustainable Development Goals (SDGs) with 169 targets are at the heart of it, and they are an urgent call for action by all countries—developed and developing—in a global partnership to end poverty, protect the planet, and ensure that all people live in peace and prosperity by 2030.

Faced with limited resources and the pressures of a growing world population, we need a strategy to drive action in critical areas for humanity and the planet. Biologists, chemists, bioinformaticians, bioengineers, process engineers, and materials scientists have recently collaborated to develop direct applications that support many of the SDGs. A number of patents can be used to assess innovations and show the commercial potential of fungal biodiversity. The proportion of fungal species named in patents is most likely less than 0.4% [23], indicating that the fungal research community has a large scope for innovation and a higher level of development, ensuring that inter- and transdisciplinary science on fungi will create a pathway for innovative breakthroughs. Table 1 shows that fungi undoubtedly offer numerous potential applications to achieve the SDGs, but that many of the applications have not yet been used industrially or are not receiving the attention they deserve [24].

Table 1. Biotechnology using fungi has great potential to make a significant contribution to 10 of the 17 United Nations Sustainable Development Goals (SDGs). The table shows which SDGs benefit from fungi-based technologies, the number of targets and indicators, and the applications of these technologies.

SDG Number	Goal Title	Number of Targets	Number of Indicators	Application
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	8	14	Affordable food production.
3	Ensure healthy lives and promote wellbeing for all at all ages	13	28	Excellent quality and healthy food production.
6	Ensure availability and sustainable management of water and sanitation for all	8	11	Sanitation and water treatment processes. Reduction of water consumption.
7	Ensure access to affordable, reliable, sustainable, and modern energy for all	5	6	Renewable energies.
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	8	12	Technological developments.
11	Make cities and human settlements inclusive, safe, resilient, and sustainable	10	15	Good quality, affordable and sustainable housing. Waste management.
12	Ensure sustainable consumption and production patterns	11	13	Technologies to mitigate climate changing consequences.
13	Take urgent action to combat climate change and its impacts	5	8	Sustainable production, recycle and reuse of products
15	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	12	14	Genetic resources. Sustainable management of forests.
17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	19	24	Revitalize global economy and creation of new partnerships.

3. The Role of Fungal Biotechnology in Circular Bioeconomy

Industrial biotechnology, commonly referred to as white biotechnology, is the use of living cells and/or their enzymes to produce industrial goods that are more readily biodegradable, consume less energy, produce less waste, and occasionally outperform goods produced by conventional chemical processes [25]. In the twentieth century, technology was developed to use fungi to protect human health (through antibiotics, antimicrobials, immunosuppressants, value-added products, etc.), and paved the way for the production of enzymes, alkaloids, detergents, acids, and biosurfactants on an industrial scale. Research in the field of white biotechnology has made significant progress in the last decade and further significant scientific and technological advances are expected soon, particularly in agricultural and environmental biotechnology [26,27].

One of the most important ways in which fungi can contribute to environmentally conscious technologies is their ability to break down and decompose organic materials. Many fungi are capable of decomposing a variety of organic materials, including wood, paper, and textiles, through a process known as biodegradation. This process plays a crucial role in the natural recycling of nutrients in ecosystems and has the potential to be used in waste management and recycling systems to reduce the environmental impact of waste. Fungi have been used in biotechnology for over a hundred years. Materials made from mycelium have the potential to replace leather, textiles, and some plastics. Replacing petroleum-derived materials with mycelium-based materials can help significantly reduce plastic pollution. Plastic-degrading fungi have also been isolated and used to degrade plastics in the laboratory. In addition, basidiomycete enzymes have been identified and used for the degradation of plastic [28–30]. In recent years, scientists from a variety of disciplines have collaborated to develop composite materials from agricultural and forestry by-products and waste [31–34]. Fungi are able to digest plant biomass, and produce enzymes and metabolites, making them invaluable to the food, feed, detergent, pulp and paper, fuel, pharmaceutical and chemical industries (Figure 1). Fungi are also used to produce organic acids, chemicals, antibiotics, proteins, meat alternatives, vitamins, and polyunsaturated fatty acids, as well as composite materials and vegan leather [31]. For example, *Pleurotus ostreatus* and *Phanerodontia chrysosporium* have been used to produce enzymes such as ligninases, which are used to break down lignin and other recalcitrant organic compounds and to clean contaminated soil and water [35–38]. In addition to their role in waste management, fungi have also been explored as a source of renewable energy. The oleaginous fungi (e.g., *Aspergillus fumigatus*, *Umbelopsis isabelline*, *Thermothelomyces thermophilus*, *Thermothielavioides terrestris*) [39–44], that produce lipids, can grow on various carbon sources, including organic waste or low-grade biomass through fermentation, and have been researched and used for the production of biofuels such as ethanol [45,46]. This process is known as biodiesel production and has the potential to provide a sustainable alternative to conventional fossil fuel sources. Fungi can also be used to produce biogas, a mixture of methane and carbon dioxide, through anaerobic digestion of lignocellulosic waste. Biogas production is an important source of renewable energy in many parts of the world and has the potential to significantly reduce greenhouse gas emissions [47,48].

Chemical fertilizers are used indiscriminately and excessively, posing risks to human health and the environment, and having a significant negative impact on agricultural production. Alternative approaches are crucial for sustainability and environmental protection if chemical fertilizers are to be avoided [27,49]. Although bacteria and mycorrhizal fungi are the focus of most research on plant growth-promoting microbes [50,51], fungi nevertheless have some unique properties that are far superior to those of bacteria [27]. For example, fungi can tolerate acidic conditions better than bacteria and are even much more effective than bacteria in mobilizing bound phosphates [51,52]. Fungi have also been shown to produce phytohormones such as indole-3-acetic acid (IAA), gibberellins, and siderophores [51,53]. Although this is an old technology, the use of fungi as biological control agents has taken off tremendously in recent years [54,55]. White biotechnology is moving towards the use of these organisms due to growing concerns about mitigating of the environmental impact of agricultural activities in nature and the search for better food that is free of harmful chemicals [26].

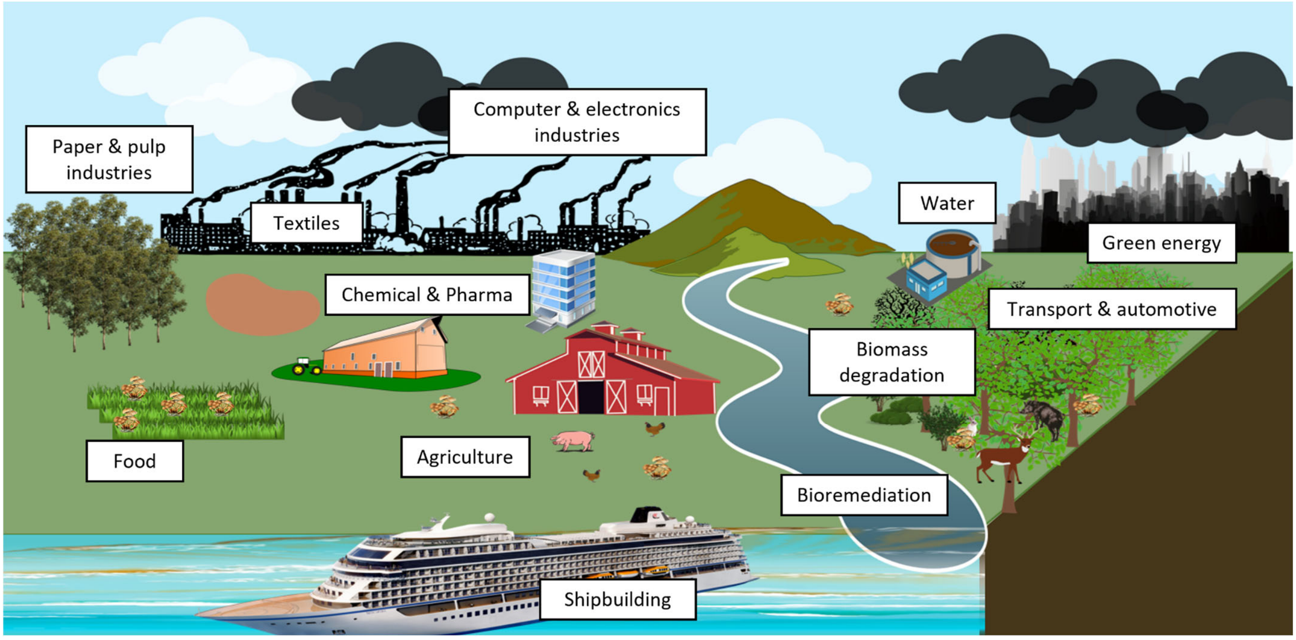

Figure 1. There are numerous applications of fungi in biotechnology with widespread applications that contribute to achieving a sustainable economy. The figure shows examples of industries that benefit from the capabilities of fungi.

Fungi are also commonly used in wastewater treatment because of their ability to break down and remove a variety of pollutants from wastewater. The production of the enzymes amylase and lipase by *Aspergillus niger* has been used to degrade organic matter in wastewater [56,57]. Other species such as *Trichoderma reesei*, *Schizophyllum commune*, and *Phanerodontia chrysosporium* have been used in the degradation of organic matter during wastewater treatment, including pharmaceuticals and persistent pollutants [58–60].

The bioeconomy, as defined at the 2015 Global Bioeconomy Summit, is the knowledge-based production and use of biological resources, innovative biological processes, and principles for the sustainable provision of goods and services across all sectors of the economy [61]. The circular bioeconomy has the potential to reduce emissions, accelerate the transition to clean energy, and improve adaptation to climate change [62]. By reducing waste and pollution, we can reduce greenhouse gas emissions throughout the value chain. In addition, circular bioeconomy strategies can help reduce the extraction and processing of material resources, which are responsible for ninety percent of terrestrial biodiversity loss and water stress. Finally, a circular bioeconomy approach can be used to improve resource efficiency while reducing inputs and emissions, making it an effective strategy to combat climate change [63–65]. An important application of fungi in the circular bioeconomy is waste management and recycling.

Another potential application of fungi in the circular economy is the production of biodegradable plastics. Many conventional plastics are made from fossil fuels and are not biodegradable, contributing to pollution and waste. Fungi, on the other hand, can be used to produce biodegradable plastics that are made from renewable resources and can be degraded in the environment [45,46].

One challenge in using fungi in a circular bioeconomy model is the lack of understanding of the mechanisms of biodegradation and bioproduction processes. To fully realize the potential of fungi in the circular bioeconomy, more research is needed to understand how these processes work at the molecular level. Another challenge is the scalability of fungal processes. Many of the current applications of fungi in the circular bioeconomy are at the laboratory or pilot scale, and there is a need to further develop and optimize these processes to make them more viable at a larger scale. Despite these challenges, the unique capabilities of fungi make them valuable players in the circular bioeconomy. From their role in waste management and renewable energy production to their potential as indicators of ecosystem health, fungi offer numerous opportunities to promote sustainable resource use and minimize waste [34,63,65].

4. Conclusions and Future Research Needs

As the impacts of climate change become more severe, there is a growing need for environmentally conscious technologies that can help mitigate these impacts and promote sustainable resource use. Fungi are a group of organisms that have the potential to play an important role in this. Through a process known as biodegradation, many fungi can decompose a wide range of organic materials. This process is important for the natural recycling of nutrients in ecosystems and has the potential to be used in waste management and recycling systems to reduce the environmental impact of waste. In addition to their role in waste management, some fungi are capable of producing biofuels and have the potential to provide a sustainable alternative to traditional fossil fuel sources. The idea of creating a biobased economy is very interesting for the sectors that produce materials, goods, and products. It promises to develop new process technologies in industrial biotechnology to deliver solutions for a green, sustainable, and circular economy [61].

The SDGs emphasize the importance of national, regional, and international cooperation to achieve lasting solutions by 2030, which are urgently needed. According to a 2022 report prepared by an independent group of academics commissioned by the UN Secretary-General, the world has stopped making progress on the SDGs for the second year in a row in 2022 [47]. Achieving such goals under current political landscapes and governance structures is a tall order. However, if scientists can work quickly to decode the messages stored in collected and wild specimens, and provide policymakers with evidence that could trigger action, we will be better placed to create a sustainable future for all [18,48]. For this reason, it is crucial to identify the fungal species that are most likely to have the chemicals, properties, and characteristics that will be of use. The major challenges defined in the SDGs can be addressed in part by unlocking the many useful properties of fungi by improving and accelerating our access to the fungal cultures available in global collections [48]. Biodiversity on our planet is one of the greatest resources we must support our planet and improve our lives in an age of widespread environmental degradation and rapid climate change. Finally, the overall use of biomass could be optimized through new biorefinery concepts. Despite progress, more research is needed to realize the potential of sustainable environmental fungal biotechnology. The biodiversity research community can indirectly support the Sustainable Development Goals. In this way, we will achieve a truly global perspective on the key issues around fungal diversity research for the benefit of all humanity and our planet.

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