Journal of Microbial Ecology and Function
https://ojs.ukscip.com/index.php/jmef

Review

Ecological Adaptations, Functional Traits, and Biotechnological Potential of Mangrove-Associated Fungi for Sustainable Materials under Climate Change

Juliana Britto Martins de Oliveira

Laboratório de Biofísica de Fungos, Instituto de Biofísica Carlos Chagas Filho, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-902, Brazil; julianamartins@biof.ufrj.br

Received: 9 August 2025; **Revised:** 23 October 2025; **Accepted:** 24 November 2025; **Published:** 17 December 2025

Abstract: Mangrove ecosystems are known for carbon sequestration, nutrient cycling, and coastal protection, and they host diverse fungal communities shaped by salinity, tides, hypoxia, and physicochemical gradients. Mangrove-associated fungi are often cited as sources of enzymes, biopolymers, biosurfactants, and bioactive metabolites, yet proposed applications frequently overlook ecological, physiological, and molecular constraints outside native habitats. This review critically examines when mangrove fungal adaptations translate into industrially relevant traits. We synthesize evidence on taxonomic diversity, lignocellulose degradation, symbioses, and stress responses, while noting methodological biases, limited omics characterization, and overgeneralization of fungal "uniqueness." We evaluate their potential as biofactories for green materials in bioremediation, waste valorization, mycelium biocomposites, and circular bioeconomy models, emphasizing the gap between proof of concept and scalable bioprocesses. We also assess how climate change stressors warming, sea level rise, and salinity shifts may restructure communities, influencing ecosystem functions and trait reliability. Integrating microbial ecology, systems biology, materials science, and environmental governance, we identify gaps in functional validation, strain domestication, reproducibility, scalability, and regulation. The promise of mangrove fungi depends on advancing from description to mechanistic understanding and responsible innovation aligned with conservation in a changing climate.

Keywords: Mangrove-Associated Fungi; Sustainable Biomaterials; Fungal Biofactories; Biopolymers; Circular Bioeconomy; Climate Change Impacts

1. Introduction

Mangrove ecosystems, extensively described as highly efficient carbon sinks and providers of essential coastal services [1,2], are increasingly recognized not only for their ecological relevance but also as reservoirs of poorly understood microbial diversity. Despite the growing number of reports highlighting the biotechnological promise of mangrove-associated fungi, there is still limited mechanistic understanding of how their ecological adaptations translate into traits of industrial relevance [1]. Much of the current literature emphasizes potential applications while offering comparatively little critical analysis of the physiological, molecular, and ecological constraints that govern the performance of these organisms outside their native environments [1,2] (as summarized in **Figure 1**).

The complex root architecture of mangrove plants promotes sediment deposition and organic matter retention, creating heterogeneous niches that sustain highly diverse microbial consortia [3,4]. Within these communities, fungi act as decomposers, symbionts, and producers of bioactive metabolites [5]. However, describing mangrove fungi as ecologically or metabolically "unique" compared to terrestrial counterparts may be an overgeneralization.

https://doi.org/10.54963/jmef.v1i1.2346

Several traits often attributed to mangrove isolates, such as stress tolerance and secondary metabolite diversity, are also observed in terrestrial extremophilic or endophytic fungi. Therefore, understanding what is truly distinctive about mangrove fungal communities requires moving beyond descriptive accounts toward mechanistic and comparative analyses of metabolites [5].

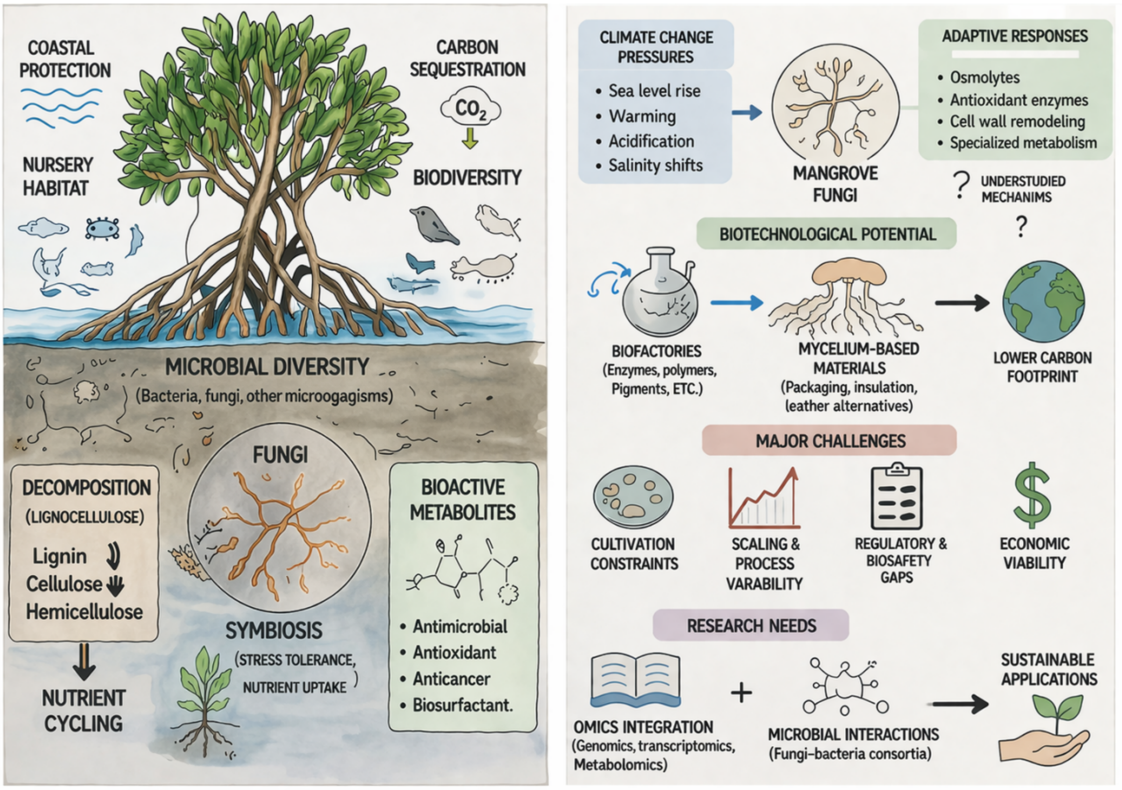

Figure 1. Integration of mangrove functions, fungal roles, and climate change shaping their biotechnological potential.

Note: Mangroves sustain protection, biodiversity, and carbon storage, while fungi drive decomposition and metabolite production. Climate stress induces adaptations with biotechnological promise, despite limits in scalability and application.

Recent comparative studies suggest that many physiological and metabolic traits attributed to mangrove-associated fungi, including halotolerance, oxidative stress resistance, and secondary metabolite diversity, are not exclusive to these environments but are also widely observed in terrestrial extremophilic and endophytic fungi. For instance, species of *Aspergillus*, *Penicillium*, and *Trichoderma* isolated from saline soils, arid ecosystems, and plant tissues exhibit comparable enzymatic plasticity and stress-response mechanisms, including osmolyte accumulation and antioxidant regulation [6–8]. Moreover, lignocellulolytic performance under controlled conditions does not consistently demonstrate superior efficiency of mangrove-derived fungi over well-characterized terrestrial strains, particularly in terms of enzyme yield and catalytic stability [9,10]. These findings indicate that the distinctiveness of mangrove fungi may lie less in unique metabolic capabilities and more in their ecological context and functional plasticity under fluctuating environmental conditions.

Similarly, the role of fungi in lignocellulose degradation within mangrove ecosystems should be interpreted within the framework of complex microbial interactions rather than as a predominantly fungal-driven process. Recent studies highlight that bacteria and archaea contribute significantly to polymer breakdown, particularly under anoxic or fluctuating redox conditions where fungal metabolism may be constrained [9,11,12]. In such environments, synergistic interactions between fungi and prokaryotes enhance the efficiency of carbon turnover through complementary enzymatic systems and metabolic cross-feeding. This perspective challenges simplified assumptions of fungal dominance and emphasizes the need for integrative approaches that consider community-level processes when evaluating both ecological functions and biotechnological potential [9,11].

Environmental conditions in mangroves include high salinity, periodic submersion, hypoxia, temperature fluctuations, and intense UV radiation, which impose strong selective pressures [13,14]. Adaptation to these stressors likely involves well-defined physiological mechanisms, including osmolyte accumulation, ion transport regulation, reinforced cell wall structures, activation of antioxidant systems such as superoxide dismutase and catalase, and shifts toward fermentative or alternative respiratory pathways under hypoxic conditions [15]. Nevertheless, such mechanisms remain largely inferred rather than experimentally characterized for most mangrove fungi, limiting the rational exploration of their biotechnological potential.

From an ecological perspective, fungi are frequently described as primary agents of lignocellulose degradation in mangrove litter [16,17]. While fungal ligninolytic systems are indeed central to this process, increasing evidence indicates that bacteria and complex microbial consortia contribute substantially to polymer breakdown in these dynamic environments [9,18]. Thus, attributing lignocellulose degradation predominantly to fungi oversimplifies the synergistic interactions that drive nutrient cycling in mangrove sediments.

Interest in mangrove-associated fungi has also been driven by reports of novel secondary metabolites with antimicrobial, antioxidant, anticancer, and biosurfactant properties [19,20]. While this metabolic diversity is often linked to environmental pressures and ecological competition, the biosynthetic pathways responsible for these compounds are rarely elucidated. The presence of polyketide synthase (PKS) and non-ribosomal peptide synthetase (NRPS) gene clusters is assumed but insufficiently mapped, highlighting the need for omics-based investigations to connect genotype, metabolism, and ecological function [19].

In industrial biotechnology, fungi are widely recognized as cell factories capable of converting renewable substrates into enzymes, organic acids, pigments, biopolymers, and other value-added products [21,22]. The assumption that fungi from extreme environments, such as mangroves, are inherently more robust under industrial conditions is appealing but not yet systematically validated. Traits such as halotolerance, pH resilience, or inhibitor resistance require controlled evaluation to determine whether they indeed translate into advantages in bioreactors [8,13].

The growing field of mycelium-based materials has further intensified interest in fungal biotechnology as a source of sustainable alternatives to petroleum-derived products [13,23]. These materials show promising biodegradability and low carbon footprints according to life cycle assessments [24,25]. However, challenges such as mechanical variability, moisture sensitivity, lack of standardized production protocols, and scalability remain significant bottlenecks. Most studies rely on terrestrial model genera such as *Aspergillus*, *Trichoderma*, and *Ganoderma* [8,22], while the potential of mangrove fungi for biomaterial production remains largely speculative and underexplored.

Climate change adds another layer of complexity to this scenario. Rising sea levels, temperature shifts, ocean acidification, and salinity changes can reshape mangrove fungal communities, altering both their taxonomic composition and metabolic functions [26,27]. These shifts may lead to the loss of specialized species or the emergence of new functional traits, directly affecting ecosystem services and the availability of biotechnologically relevant organisms [27].

Despite increasing recognition of their potential, major gaps persist in understanding the molecular and physiological bases of mangrove fungal adaptation. Genomic, transcriptomic, and metabolomic studies remain scarce for these organisms [13,14], hindering the identification of specific pathways linked to salinity tolerance, oxidative stress response, hypoxia adaptation, and ligninolytic capacity.

From an applied perspective, translating laboratory observations into industrial processes faces considerable obstacles. Strain domestication, metabolic variability among isolates, reproducibility of fermentation processes, and economic feasibility represent substantial barriers [8,22]. Furthermore, regulatory and biosafety frameworks for the use of non-conventional marine and coastal fungi remain poorly defined, potentially limiting commercial applications [28].

In this context, a critical integration of ecological, mechanistic, and biotechnological perspectives is necessary. This review examines how the ecological adaptations of mangrove-associated fungi may or may not translate into industrially relevant traits for the development of sustainable materials. By addressing current knowledge gaps, technological limitations, and regulatory challenges, we aim to provide a more rigorous conceptual basis for the responsible exploration of these microorganisms within the framework of green biotechnology and circular bioeconomy strategies under ongoing climate change. From Ecological Adaptation to Biotechnological Possibilities: Knowledge Gaps, Mechanisms, and Translational Challenges in Mangrove Fungi.

2. Mangrove Ecosystems as Hotspots of Fungal Diversity

2.1. Environmental Characteristics of Mangroves

Mangrove ecosystems are defined by steep physicochemical gradients, including fluctuations in salinity, temperature, redox potential, and nutrient availability. These dynamic conditions create a mosaic of microhabitats within sediments, roots, leaf litter, and woody substrates. Such heterogeneity supports diverse fungal assemblages, ranging from saprotrophs and endophytes to mycorrhiza-like symbionts and pathogens [14].

Salinity represents one of the most influential environmental drivers shaping mangrove microbial communities. Tidal inundation and freshwater inputs generate strong spatial and temporal variability in porewater salinity, imposing osmotic stress on resident microorganisms. Fungi inhabiting mangrove sediments and plant tissues often exhibit halotolerance or halophilicity, supported by physiological mechanisms such as compatible solute accumulation, ion transport regulation, and cell wall remodeling. These adaptations not only enable survival under fluctuating salinity regimes but may also confer enhanced stability and functionality of enzymes and metabolites under high-ionic-strength conditions, with direct implications for industrial biotechnology [13,14].

Redox heterogeneity and oxygen limitation further structure mangrove environments. Waterlogged, fine-grained sediments are typically characterized by hypoxic to anoxic conditions, resulting in steep redox gradients over millimeter scales. These conditions promote the accumulation of reduced compounds, such as sulfides, methane, and ferrous iron, which strongly influence microbial metabolism and community composition. Fungi occupying these niches must tolerate low oxygen availability and, in some cases, toxic sulfide concentrations, selecting for taxa with specialized respiratory strategies, antioxidant defenses, and alternative metabolic pathways [1,29]. Such traits may enhance the suitability of mangrove-derived fungi for bioprocesses conducted under oxygen-limited or otherwise stressful industrial conditions.

Mangrove sediments and detrital pools are also characterized by high organic matter inputs derived from leaf litter, woody debris, and root exudates. This continuous supply of complex lignocellulosic substrates fuels intense microbial activity and supports fungal communities specialized in the degradation of recalcitrant polymers, including lignin, cellulose, hemicellulose, and tannin-rich compounds. The dominance of lignocellulose-degrading fungi plays a critical role in carbon turnover and nutrient recycling, directly influencing carbon sequestration efficiency and sediment biogeochemistry in mangrove ecosystems [16, 17]. These enzymatic capabilities are of particular relevance for the development of fungal biofactories aimed at biomass valorization and green material production.

In addition to abiotic drivers, strong plant-microbe interactions further shape fungal community structure in mangroves. Roots, pneumatophores, and aerial tissues provide unique ecological niches for endophytic and rhizosphere-associated fungi, which may contribute to host stress tolerance, nutrient acquisition, and pathogen resistance. Emerging evidence suggests that some fungal symbionts enhance mangrove resilience to salinity, flooding, and nutrient limitation by modulating plant hormonal signaling and nutrient uptake pathways [30,31]. These intimate associations not only influence ecosystem stability but also represent promising sources of functionally specialized fungi with traits advantageous for biotechnological and materials-oriented applications.

Finally, projected climate-driven changes in sea level, temperature regimes, and hydrological patterns are expected to further intensify environmental gradients in mangrove ecosystems [27]. Alterations in inundation frequency, sediment dynamics, and salinity distributions may restructure fungal communities, potentially shifting functional profiles related to decomposition, stress tolerance, and secondary metabolism. Such changes are likely to have cascading effects on both ecosystem functioning and the availability of fungal taxa with desirable biotechnological traits, underscoring the importance of understanding environmental controls on fungal diversity and function in mangroves under future climate scenarios [27,32].

Importantly, although mangrove ecosystems are frequently described as reservoirs of unique fungal diversity, it is necessary to critically evaluate the extent to which these communities are truly distinct from terrestrial or other marine-associated fungi. Molecular surveys have revealed that many taxa found in mangroves also occur in adjacent coastal, estuarine, and even terrestrial habitats, suggesting a considerable degree of ecological overlap rather than strict endemism [33]. Thus, the uniqueness of mangrove fungi may lie less in taxonomic novelty and more in their functional plasticity and adaptive responses to environmental stressors. This perspective highlights the importance of integrating phylogenetic and functional approaches to avoid overestimating ecosystem-specificity [33,34].

Mechanistically, fungal adaptation to fluctuating mangrove conditions involves tightly regulated molecular and physiological processes that remain insufficiently explored. For instance, osmoadaptation is mediated not only by the accumulation of compatible solutes such as glycerol and mannitol but also by the activation of stress-responsive signaling pathways, including MAPK cascades and transcriptional regulators associated with ion homeostasis. Similarly, oxidative stress generated under redox fluctuations induces antioxidant systems involving catalases, superoxide dismutases, and glutathione pathways. Despite these insights, most studies remain descriptive, and there is a lack of integrative omics-based investigations linking gene expression, metabolite production, and ecological performance under in situ conditions [35,36].

Another critical limitation concerns the assumption that fungi dominate lignocellulose degradation in mangrove sediments. While filamentous fungi are indeed important decomposers, growing evidence indicates that bacteria and archaea also play significant and sometimes complementary roles in carbon cycling, particularly under anoxic conditions where fungal activity may be constrained [9,11].

Therefore, attributing lignocellulose turnover primarily to fungi may oversimplify the complexity of microbial interactions and overlook synergistic or competitive dynamics within the microbiome. A more balanced view that considers cross-kingdom interactions is essential for accurately assessing ecosystem functioning and for translating these processes into biotechnological applications [9,11].

From an applied perspective, several challenges remain before mangrove-derived fungi can be effectively utilized at industrial scale. Many strains are difficult to cultivate under laboratory conditions, and their metabolic performance may not be reproducible outside their native environment [37]. In addition, scaling up production of enzymes or biomaterials often faces constraints related to yield stability, contamination risks, and process optimization under high salinity or variable oxygen conditions. Regulatory frameworks governing the use of marine genetic resources, including access and benefit-sharing agreements, further complicate commercialization pathways. Addressing these bottlenecks requires interdisciplinary approaches combining ecology, systems biology, and bioprocess engineering to bridge the gap between environmental discovery and industrial implementation [37,38].

2.2. Taxonomic Diversity of Mangrove-Associated Fungi

Mangrove-associated fungi encompass a broad range of major fungal lineages, including Ascomycota, Basidiomycota, and early-diverging groups such as Mucoromycota and Chytridiomycota. Among these, Ascomycota are consistently reported as the dominant phylum in mangrove substrates, particularly within the classes Sordariomycetes and Dothideomycetes, which are frequently isolated from decaying wood, leaf litter, and sediment-associated plant debris [5,39]. These taxa play key roles in primary decomposition processes and exhibit high ecological versatility. Basidiomycota also represent an important component of mangrove fungal communities, especially in the degradation of lignin and other recalcitrant components of plant cell walls. White-rot and brown-rot basidiomycetes contribute significantly to lignocellulose breakdown, complementing the activity of ascomycetous decomposers and enhancing overall carbon turnover in mangrove ecosystems [13, 40]. Their enzymatic capacities are closely linked to lignin-modifying oxidative systems, which are essential for complete plant biomass mineralization.

Recent advances in high-throughput sequencing and environmental DNA (eDNA) metabarcoding have revealed a substantial proportion of cryptic, rare, and uncultured fungal taxa in mangrove environments. These molecular approaches have demonstrated that traditional culture-based surveys substantially underestimate true fungal diversity, particularly for early-diverging lineages and obligately marine or sediment-associated fungi [41,42]. The discovery of extensive hidden diversity underscores the need for integrative taxonomic frameworks combining morphology, culture studies, and multi-locus molecular data.

Despite the recurrent identification of Ascomycota as the dominant phylum in mangrove ecosystems, this pattern should be interpreted with caution due to methodological biases [43]. Culture-dependent approaches tend to favor fast-growing and easily cultivable taxa, which are disproportionately represented within Ascomycota, potentially underestimating the contribution of slow-growing or obligately marine Basidiomycota and early-diverging lineages. Even molecular surveys may be influenced by primer bias and incomplete reference databases, limiting taxonomic resolution and potentially skewing diversity estimates [43]. Therefore, current knowledge of fungal community composition in mangroves likely reflects both biological patterns and methodological constraints rather than a fully resolved taxonomic structure [43].

In addition, the taxonomic classification of mangrove-associated fungi remains challenging due to the high proportion of poorly described or incertae sedis taxa. Many environmental sequences cannot be confidently assigned beyond high-level taxonomic ranks, reflecting gaps in curated databases and the limited availability of well-characterized reference strains [44]. This taxonomic uncertainty complicates ecological interpretation and hampers efforts to link phylogeny with functional traits. Addressing this issue will require coordinated efforts in fungal systematics, including the formal description of novel taxa and the expansion of sequence repositories with high quality, voucher-linked data [44–46].

Finally, translating taxonomic diversity into biotechnological applications faces additional constraints related to strain accessibility and reproducibility [47]. A large fraction of detected taxa remains uncultured, limiting experimental validation of their metabolic potential. Even when isolates are obtained, maintaining stable phenotypes and consistent metabolite production under laboratory or industrial conditions can be difficult. Furthermore, regulatory and biosafety considerations associated with novel or poorly characterized fungal species may restrict their use in applied settings [47]. These limitations highlight the need for improved cultivation strategies, standardized characterization protocols, and regulatory frameworks that can accommodate the exploration of fungal diversity while ensuring safety and sustainability [47,48].

2.3. Functional Roles in Mangrove Ecosystems

Fungi play a central role in organic matter turnover within mangrove ecosystems by mediating the decomposition of lignin-rich plant tissues, including wood, roots, and leaf litter. Through the secretion of extracellular hydrolytic and oxidative enzymes, mangrove fungi accelerate the breakdown of complex polymers and facilitate the release of carbon, nitrogen, and phosphorus into bioavailable forms [31,34]. This decomposition activity is fundamental to sustaining high productivity in nutrient-limited coastal environments.

Endophytic fungi associated with mangrove plants also contribute to host health and stress tolerance. These symbiotic fungi can enhance plant resilience to salinity, flooding, and pathogen pressure by modulating plant hormone signaling, improving nutrient acquisition, and producing bioactive compounds that deter herbivores and pathogens [49,50]. Such interactions highlight the importance of fungal symbionts in shaping mangrove plant fitness and ecosystem stability.

In addition to decomposition and symbiosis, mangrove fungi influence ecosystem functioning through the production of secondary metabolites and the regulation of microbial community dynamics. Antimicrobial compounds and competitive exclusion mechanisms can structure microbial assemblages, indirectly affecting nutrient cycling and plant–microbe interactions [34,51]. These ecological functions are closely linked to metabolic traits that also underpin the biotechnological potential of mangrove-associated fungi.

3. Fungi as Biofactories: Metabolic Potential and Adaptations

3.1. Enzymatic Systems for Biomass Conversion

Mangrove-associated fungi produce a broad repertoire of hydrolytic and oxidative enzymes, including cellulases, hemicellulases, laccases, manganese peroxidases, and lignin peroxidases, which enable the depolymerization of lignocellulosic biomass common in coastal environments [31,40]. These enzymatic capacities support their ecological participation in nutrient cycling and have motivated interest in their application for industrial biomass processing.

A frequently cited feature of these enzymes is their tolerance to elevated salinity, temperature variability, and changing redox conditions [14,52]. While such properties are attractive for industrial bioconversion processes, comparative studies demonstrating superior performance over established terrestrial fungal enzymes under real process conditions remain scarce. This gap highlights the difference between observed environmental tolerance and validated industrial robustness.

The potential use of mangrove fungal enzymes in the conversion of agricultural residues and marine biomass into fermentable sugars has been proposed as part of integrated biorefinery concepts [34,53]. However, challenges related to enzyme yield, purification, stability, and cost-effectiveness under scaled conditions still limit practical implementation, indicating that most applications remain at the proof-of-concept stage.

3.2. Biopolymers and Fungal-Derived Materials

Mangrove-associated fungi synthesize structural biopolymers such as chitin, chitosan, and extracellular polysaccharides (EPSs) with physicochemical properties of industrial interest [54, 55]. Fungal chitosan has been highlighted as an alternative to crustacean sources due to more controllable production and reduced allergenic concerns. Nonetheless, industrial scalability, extraction efficiency, and regulatory acceptance continue to pose barriers to widespread adoption.

EPSs produced by marine and mangrove fungi exhibit rheological behavior, bioactivity, and chemical modifiability that support applications in hydrogels, coatings, moisture retention systems, and biomedical materials [14,52,56]. These properties suggest versatility, yet variability among strains and cultivation conditions complicates standardization and reproducibility.

Fungal bioemulsifiers and biosurfactants, composed of polysaccharides and glycoproteins, further expand the spectrum of potential applications to bioremediation, cosmetics, and food systems [56]. Their ability to reduce interfacial tension and stabilize emulsions under saline conditions is particularly relevant for coastal and wastewater treatment contexts.

Mycelium-based materials grown on lignocellulosic residues have emerged as low-carbon alternatives to petroleum-based plastics and foams [13, 23, 57]. These composites rely on the self-assembling fibrous network of fungal hyphae to bind substrates into lightweight and biodegradable structures. Mangrove fungi, due to their tolerance to humidity and salinity, may offer advantages for materials intended for coastal or high-moisture environments. However, most current developments rely on well-established terrestrial species, and empirical data using mangrove isolates are still limited.

Beyond materials, mangrove fungi have attracted attention for bioremediation due to the production of laccases, peroxidases, and hydrolases capable of degrading dyes and persistent organic pollutants under saline conditions [58,59]. These enzymatic traits reflect both ecological function and applied potential, although field-scale validations remain rare.

Recent studies also emphasize the low immunogenicity, adhesive capacity, and chemical reactivity of fungal EPSs, enabling applications in drug delivery systems, tissue engineering, and functional biomedical materials [23,56]. Despite these promising attributes, isolation, purification, and formulation strategies must be optimized before these polymers can move beyond experimental contexts.

Overall, while mangrove fungi present a wide array of metabolic traits relevant to biopolymer synthesis, enzyme production, material science, and bioremediation, translating these properties into reliable industrial platforms requires advances in strain domestication, process standardization, and economic assessment.

3.3. Biosurfactants and Secondary Metabolites

Mangrove-associated fungi are capable of producing biosurfactants with high emulsifying activity and stability across wide ranges of salinity, pH, and temperature. These amphiphilic molecules reduce surface and interfacial tension, facilitating applications in bioremediation, enhanced oil recovery, and formulation of eco-friendly detergents and dispersants [14,60]. Their environmental compatibility makes fungal biosurfactants attractive alternatives to synthetic surfactants.

In parallel, mangrove fungi are prolific producers of secondary metabolites, including pigments, antioxidants, antimicrobial compounds, and enzyme inhibitors. These bioactive molecules reflect adaptations to competitive and stress-prone mangrove environments and have demonstrated potential for pharmaceutical, cosmetic, and functional material applications [51,52]. The chemical diversity of these metabolites supports ongoing bioprospecting efforts in coastal ecosystems.

The integration of biosurfactants and secondary metabolites into functional materials can add environmental and health-related benefits, such as antimicrobial surfaces, antioxidant packaging, and self-cleaning coatings. Such multifunctional materials exemplify the concept of fungi as biofactories capable of producing both structural and functional components [5,60]. This multifunctionality strengthens the strategic role of mangrove-associated fungi in sustainable materials science and green biotechnology.

4. Applications in Green Materials and Circular Bioeconomy

4.1. Bioremediation and Waste Valorization

Mangrove-associated fungi have been increasingly investigated for their potential role in bioremediation, particularly due to their capacity to degrade complex organic pollutants such as petroleum hydrocarbons, synthetic dyes, and persistent agrochemical residues. The production of oxidative and hydrolytic enzymes, including laccases, peroxidases, and monooxygenases, enables the transformation of recalcitrant compounds frequently detected in contaminated coastal and estuarine environments [31,61]. While these traits suggest possible applications in remediation strategies for areas affected by industrial and port-related activities, further validation under field-relevant conditions is still needed to confirm their practical effectiveness.

Beyond pollutant degradation, mangrove fungi have also been examined for their role in waste valorization through the conversion of agricultural and industrial residues into value-added products. Lignocellulosic wastes such as crop residues, sawdust, and food processing by-products can be biologically transformed into enzymes, organic acids, biosurfactants, and fungal biomass [14,53]. Although this bioconversion process aligns conceptually with circular bioeconomy principles by reducing waste streams and generating useful bioproducts, scalability and process standardization remain important challenges.

Additionally, several mangrove-derived fungi have demonstrated the ability to immobilize or bioaccumulate heavy metals, contributing to the potential detoxification of contaminated sediments and aquatic systems. Mechanisms such as biosorption and intracellular sequestration may reduce the bioavailability of toxic elements including cadmium, lead, and mercury [34,62,63]. Taken together, these remediation and valorization capacities indicate that mangrove fungi could function as multifunctional components in integrated environmental biotechnology approaches, provided that ecological variability and operational constraints are carefully addressed.

4.2. Biocomposites and Sustainable Construction Materials

Mycelium-based biocomposites have gained attention as potential sustainable alternatives to synthetic materials, offering biodegradable, lightweight, and lower-carbon options for applications in construction, insulation, and packaging. These materials are generated through the growth of fungal mycelium on lignocellulosic substrates, forming natural binding networks that produce structurally cohesive composites [64–66]. Such systems illustrate how fungal biotechnology can contribute to the development of green materials, although performance consistency and durability under real-use conditions require further assessment.

Mangrove fungi, due to their adaptation to high humidity, salinity fluctuations, and temperature variability, may offer functional characteristics relevant for biocomposites designed for tropical and coastal environments. Their stress tolerance could potentially enhance resistance to moisture, microbial degradation, and environmental stressors, which are common limitations of bio-based materials [13,23]. However, experimental comparisons with established terrestrial strains are necessary to determine whether these ecological adaptations translate into measurable material advantages.

The use of locally sourced agricultural and forestry residues as substrates for mycelium growth also supports resource efficiency and reduces reliance on energy-intensive synthetic binders. Life cycle assessment studies indicate that mycelium-based materials can reduce greenhouse gas emissions and embodied energy relative to conventional construction materials [13,24]. In this context, mangrove-derived fungal strains may contribute to strengthening the sustainability profile of biocomposites, provided that their cultivation, performance, and environmental benefits are rigorously evaluated.

4.3. Integration into Circular Bioeconomy Frameworks

The integration of mangrove fungal biotechnology into circular bioeconomy frameworks presents potential pathways to connect ecosystem conservation with more sustainable material production. By valorizing locally available biomass and exploring the use of native or environmentally adapted fungal strains, it may be possible to design decentralized production systems that reduce waste streams and transportation-related emissions [14,38]. However, the practical feasibility of such place-based systems depends on technical validation, economic assessment, and the establishment of reliable production protocols that remain largely underexplored.

Linking mangrove conservation with biotechnological innovation may also contribute to the maintenance of ecosystem services, including habitat protection, carbon sequestration, and biodiversity preservation. The conservation of healthy mangrove ecosystems supports the long-term availability of diverse fungal genetic resources that could be relevant for future discovery and strain development [5, 27]. Nevertheless, these potential synergies require careful evaluation to ensure that biotechnological interest does not inadvertently promote extractive practices that undermine ecological integrity.

At the same time, meaningful integration into circular bioeconomy strategies depends on the existence of robust governance structures capable of regulating ethical bioprospecting, equitable benefit sharing, and responsible access to genetic resources. Alignment with international agreements such as the Convention on Biological Diversity and the Nagoya Protocol is essential to ensure that the use of mangrove-associated fungi complies with regulatory frameworks and supports regional stakeholders [38, 66]. Transparent and accountable governance is therefore a prerequisite for embedding mangrove fungal biotechnology within genuinely sustainable and socially responsible bioeconomy models.

Despite the growing interest in mangrove-derived fungi for sustainable materials and biotechnology, significant translational barriers remain [5, 14]. Many strains exhibit unstable growth and metabolite production outside their native environments, complicating strain domestication and process standardization [8,22]. In addition, scale-up from laboratory conditions to industrial systems often results in reduced yields and increased variability, particularly under saline or oxygen-limited conditions [14, 53]. Regulatory uncertainty surrounding the use of non-conventional marine fungi, coupled with economic constraints and limited techno-economic assessments, further restricts commercial implementation [21, 67]. Consequently, most proposed applications remain at an early developmental stage, and their feasibility under real-world production scenarios remains to be critically validated [22,68].

5. Climate Change Impacts on Mangrove Fungi and Biotechnological Potential

5.1. Effects of Rising Temperatures and Sea Level Rise

Rising global temperatures and accelerated sea-level rise are among the most significant drivers reshaping mangrove ecosystems worldwide. Increased thermal stress can directly influence fungal physiology, growth rates, and reproductive cycles, potentially favoring thermotolerant taxa while suppressing temperature-sensitive species [27,69]. As mangrove forests migrate landward or experience habitat loss due to inundation, associated fungal communities may undergo substantial restructuring, leading to altered ecological interactions and nutrient cycling dynamics.

Sea level rise also affects sediment deposition, oxygen availability, and root architecture, which are critical determinants of fungal colonization and diversity in mangrove systems. Changes in hydroperiod and soil anoxia can selectively pressure fungal assemblages, favoring facultative anaerobes and stress-tolerant saprotrophic fungi [5,31]. These shifts may reduce overall fungal diversity while increasing dominance of opportunistic species adapted to fluctuating redox and temperature conditions.

From a biotechnological perspective, temperature-driven selection pressures may influence the availability of fungal strains with industrially relevant traits, such as thermostable enzymes and stress-resilient metabolic pathways. While thermotolerant fungi may offer advantages for high-temperature bioprocesses, reduced ecosystem diversity could limit the discovery of novel bioactive compounds [40,52]. Therefore, climate-induced restructuring of mangrove fungal communities has direct implications for future bioprospecting and sustainable resource utilization.

5.2. Salinity Shifts and Metabolic Performance

Alterations in salinity regimes driven by sea-level rise, shifts in precipitation patterns, and changes in freshwater inputs can substantially influence fungal metabolism and enzymatic activity in mangrove environments. Salinity acts as a major selective force structuring fungal communities by affecting osmotic regulation, membrane integrity, and overall metabolic fluxes [14,31]. As salinity fluctuates, taxa with greater osmotolerance may become more prevalent, which can alter community composition and potentially reduce functional redundancy within these ecosystems.

Salinity variability can also influence gene expression patterns associated with extracellular enzyme production, secondary metabolite biosynthesis, and stress-response pathways. Evidence from marine and mangrove-derived fungi indicates that salinity stress modulates lignocellulolytic enzyme activity as well as the diversity and quantity of secondary metabolites produced [13, 53]. This physiological plasticity may either favor or limit the industrial applicability of specific strains, depending on how closely industrial process conditions align with the fungi's adaptive range.

Although many mangrove fungi display notable adaptive capacity, prolonged or extreme shifts in salinity can reduce growth efficiency, metabolic stability, and overall productivity in more sensitive species. These effects may translate into inconsistent enzyme yields and variable biochemical outputs, creating challenges for downstream industrial processes that rely on predictable performance [5,14]. Therefore, understanding the mechanisms underlying salinity-driven metabolic regulation is essential for the reliable selection of fungal candidates for biotechnological purposes.

In addition, salinity-driven shifts in fungal communities may indirectly affect interspecific microbial interactions that influence nutrient cycling and substrate degradation in mangrove sediments. Changes in fungal dominance can modify competitive and cooperative relationships with bacteria and other microorganisms, potentially altering overall ecosystem functioning and the availability of metabolic traits relevant for biotechnological exploration. Recognizing these community-level dynamics is important to avoid oversimplified interpretations based solely on individual fungal isolates and to better predict how environmental salinity changes may impact the functional potential of mangrove microbiomes. Despite increasing recognition of these adaptive mechanisms, their mechanistic basis remains only partially resolved, particularly under conditions relevant to industrial application [13,14]. Most current knowledge is derived from indirect observations or extrapolated from model fungi, with limited experimental validation in mangrove-derived strains [8,22]. In particular, the regulation of stress-response pathways, including MAPK signaling, ion transport systems, and metabolic reprogramming under combined salinity and temperature stress, remains insufficiently characterized [35,36].

5.3. Implications for Scalability and Industrial Use

Climate-driven stressors, particularly rising temperatures and salinity variability, introduce considerable uncertainty into the scalability of fungal-based biotechnological processes derived from mangrove environments [52]. Such environmental pressures can alter growth kinetics, metabolite profiles, and enzyme stability parameters that are central to fermentation performance and bioprocess optimization at industrial scale [52,53]. If these sources of variability are not carefully accounted for during strain selection and process design, climate sensitivity may compromise reproducibility, process reliability, and ultimately economic feasibility [52,53].

Adaptive strategies are therefore necessary to reduce climate-related variability in fungal performance. The isolation of stress-tolerant strains, combined with the development of controlled cultivation systems that simulate environmental fluctuations, can improve the identification of isolates capable of maintaining consistent metabolic outputs under projected future climate scenarios [5,13]. Incorporating environmental simulation assays into early-stage screening protocols represents a practical step toward selecting fungal candidates with greater robustness for industrial applications and supports the concept of climate-resilient fungal biofactories.

In addition, the long-term sustainability of mangrove-derived biotechnological resources depends on explicitly linking conservation strategies with industrial innovation. The preservation of mangrove habitats safeguards fungal genetic diversity, which is essential for ongoing discovery, comparative screening, and strain improvement efforts [27,69]. Consequently, scalable industrial applications must be embedded within ecosystem-based management frameworks to ensure that economic exploitation does not undermine the ecological systems that sustain these biological resources.

An additional consideration relates to the need for standardized bioprocess parameters and benchmarking frameworks when working with non-model fungal strains. Variability in cultivation media, salinity conditions, aeration, and substrate composition across studies makes it difficult to compare results or predict performance under industrial settings. Establishing reproducible cultivation protocols and performance metrics will be essential to determine whether mangrove-derived fungi can meet industrial consistency requirements and compete with well-established terrestrial model organisms [8].

6. Knowledge Gaps and Future Research Directions

Despite increasing attention to mangrove-associated fungi, important limitations persist in the taxonomic resolution, functional characterization, and ecological interpretation of these communities [69]. A significant proportion of available studies still rely on culture-dependent methods or a restricted set of molecular markers, approaches that are known to underestimate diversity and overlook cryptic, rare, or unculturable taxa. Although high-throughput sequencing techniques such as metabarcoding, metagenomics, metatranscriptomics, and metaproteomics provide powerful means to assess community structure, functional potential, and in situ activity, their application in mangrove ecosystems remains comparatively limited. This gap is particularly evident in tropical and subtropical regions, where fungal diversity is likely to be highest but remains insufficiently documented [41,69,70].

A second major limitation concerns the translation of reported fungal biodiversity into scalable biotechnological and materials-oriented applications. While many mangrove-derived fungi have been described as producers of enzymes and secondary metabolites, systematic efforts to establish clear links between genotype, phenotype, process parameters, and material performance are still scarce [71, 72]. Difficulties related to strain domestication, controlled cultivation, reproducibility of metabolic outputs, and bioprocess scale-up continue to restrict the progression from laboratory observations to industrial implementation. Addressing these constraints will require closer integration of functional genomics, metabolic engineering, and bioprocess modeling to determine whether mangrove fungi can reliably function as consistent biofactories under controlled production conditions [71–74].

Finally, future research on mangrove-derived fungal materials requires a more explicit incorporation of material science, life cycle assessment (LCA), and socio-environmental evaluation frameworks. Mechanical performance, durability in humid conditions, biodegradability rates, and environmental footprints must be rigorously assessed to determine whether fungal-based materials offer demonstrable sustainability advantages over conventional alternatives. In addition, interdisciplinary approaches that connect fungal biotechnology with mangrove conservation, environmental governance, and local stakeholder participation are necessary to ensure that scientific advances translate into socially equitable and environmentally responsible applications. Such integrative perspectives are essential to align fungal biofactory research with broader sustainability agendas, including climate mitigation, circular economy strategies, and ecosystem-based adaptation [72,73].

7. Conclusions

Mangrove-associated fungi represent a biologically rich but still insufficiently characterized resource at the interface of ecology, biotechnology, and materials science. Their adaptations to dynamic coastal environments underpin metabolic traits of potential relevance for enzymes, biopolymers, and biomaterials. However, realizing this potential depends on addressing ecological knowledge gaps, improving functional characterization, overcoming scale-up challenges, and ensuring alignment with conservation and governance frameworks.

Bridging mangrove ecology with industrial biotechnology requires interdisciplinary approaches capable of translating ecological adaptation into reproducible, sustainable production systems without compromising ecosystem integrity.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable. This study did not involve experiments with human participants or animals.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study. All information was obtained from previously published articles available in public scientific databases and is properly cited in the manuscript.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this study.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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