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Biotechnological Advancements in Fungi: A Review of Opportunities and Challenges

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ABSTRACT

This review examines recent advancements in fungal biotechnology and explores their opportunities and challenges across medical, agricultural, and industrial sectors. Drawing on recent literature in fungal genomics, metabolic engineering, and applied biotechnology, this paper critically analyses developments in fungal-derived pharmaceuticals, sustainable agriculture, and environmentally relevant applications. Evidence highlights fungi as versatile biological platforms for the production of enzymes, antibiotics, and various other bio-based industrial products. Their role in sustainable agriculture and environmental management offers promising alternatives to chemical-intensive practices, with significant implications for resource efficiency and ecological balance. However, challenges such as antifungal resistance, biosafety concerns associated with genetically modified strains, regulatory limitations, and technological disparities, particularly in developing regions, remain significant. Fungal biotechnology holds considerable potential to address contemporary issues in public health, food security, and environmental sustainability. Its long-term success, however, will depend on responsible innovation, strong regulatory oversight, capacity-building initiatives, and equitable access to emerging technologies.

Keywords: Fungal biotechnology; Metabolic engineering; Industrial enzymes; Biofertilizers; Bioremediation; Antifungal resistance; Sustainable development

1. INTRODUCTION

Fungi represent one of the most diverse and ecologically significant kingdoms of organisms on Earth (Sudheep and Sridhar, 2012; Nevalainen, 2020; Sridhar *et a*l., 2022). They occupy a unique biological position, more closely related to animals than plants, and perform essential ecological roles as decomposers, symbionts, and pathogens. Historically, fungi have been exploited for traditional purposes such as food fermentation, brewing, and baking (**Figure 1**) (Sudheep and Sridhar, 2013; Case *et al*., 2025). However, in recent decades, they have gained renewed scientific attention due to their remarkable biochemical and metabolic capabilities (Sudheep and Shahina, 2023). Modern biotechnology has enabled researchers to move beyond conventional uses of fungi and explore their potential as biological factories for producing valuable compounds (Sudheep *et al*., 2017; Kržišnik and Gonçalves, 2023).

The increasing global demand for sustainable technologies in healthcare, agriculture, and industry has driven renewed research interest in fungal biotechnology (Sudheep *et al*., 2017; Roth *et al*., 2023). Fungi are capable of producing a wide range of secondary or beneficial metabolites, enzymes, and organic acids that have direct applications in pharmaceuticals, food processing, and environmental management (Baker, 2020; Sudheep and Shahina, 2023). The discovery of penicillin from *Penicillium* species marked a turning point in biomedical science and demonstrated the immense therapeutic potential of fungi. Since then, numerous

fungal-derived products have entered commercial use, including statins, immunosuppressants, and anticancer agents (Sánchez and Demain, 2017).

Advances in molecular biology, genomics, and bioinformatics have fundamentally transformed fungal research. Whole-genome sequencing has enabled identification of genes responsible for metabolite production, stress tolerance, and pathogenicity. This knowledge has facilitated targeted strain improvement and metabolic engineering, thereby increasing product yields and process efficiency in industrial applications. At the same time, emerging challenges such as antimicrobial resistance, environmental pollution, and climate change have created an urgent need for biological solutions that are both effective and sustainable (Case *et al*., 2022).

Despite their immense potential, the biotechnological exploitation of fungi is not without risks and limitations. The emergence of drug-resistant fungal pathogens poses serious threats to human and plant health (Lockhart *et al*., 2023). Concerns have also been raised about the ecological impact of genetically modified fungal strains and the ethical implications of manipulating living organisms (Almeida *et al*., 2019; Roth *et al*., 2023). Furthermore, technological and economic barriers limit the adoption of advanced fungal technologies in many developing countries. Against this background, the present article aims to critically examine recent biotechnological advancements in fungi, identify major opportunities across different sectors, and analyze the challenges that constrain their wider application (Hyde *et* al., 2024). By bringing together recent research findings, this review article highlights the growing importance of fungi in modern biotechnology and underscores the need for innovation that is both responsible and inclusive. The article is organized into five main sections. Section 2 discusses recent biotechnological advances in fungal research. Section 3 explores the expanding opportunities of fungi in medicine, agriculture, and industry. Section 4 examines the key challenges and ethical concerns related to fungal biotechnology. Section 5 presents future prospects and overall conclusions.

2. BIOTECHNOLOGICAL ADVANCES IN FUNGAL RESEARCH

The rapid progress of fungal biotechnology is closely linked to developments in Molecular Genetics, Genomics, and Systems Biology (Mapook *et al*., 2022). The sequencing of fungal genomes has provided unprecedented insights into their metabolic pathways and regulatory networks. Genome-wide analyses have revealed clusters of genes responsible for the biosynthesis of secondary metabolites such as antibiotics, pigments, and toxins. These discoveries have allowed researchers to manipulate metabolic pathways and increase the yield of commercially valuable products (Mohite, 2021).

Metabolic engineering has become a key strategy in fungal biotechnology. By modifying specific genes or introducing foreign genes, scientists can redirect fungal metabolic fluxes toward desired compounds. For example, filamentous fungi such as *Aspergillus* and *Trichoderma* species are widely used as hosts for the production of industrial enzymes. Advances in CRISPR-Cas9 gene editing have further improved the precision and efficiency of fungal strain development, enabling targeted gene knockouts and insertions (Gandía and Garrigues, 2024).

Another major advancement lies in fermentation and bioprocess technology. Modern bioreactors provide controlled conditions for fungal growth, including temperature, pH, oxygen supply, and nutrient availability (Chai *et al*., 2022). These systems allow large-scale production of fungal metabolites with consistent quality and yield. Submerged fermentation and solid-state fermentation techniques have been optimized for different fungal species, depending on their physiological requirements. Such technological improvements have significantly reduced production costs and increased commercial viability (Sudheep and Limya, 2016).

Fungal enzymes represent one of the most valuable outcomes of biotechnological research, bridging fundamental science with large-scale industrial application (Lange, 2017). Enzymes such as cellulases, proteases, amylases, and lipases are widely employed in food processing, textile manufacturing, detergent formulation, and the paper industry, where they enhance process efficiency and product quality. heir remarkable ability to remain active under extreme conditions of temperature and pH makes them especially suited for harsh industrial environments (Khan, 2025). Additionally, fungal enzymes are often preferred for their substrate specificity, reduced energy requirements, and eco-friendly nature compared to conventional chemical processes. Recent advances in protein engineering and strain improvement have further strengthened enzyme stability, catalytic efficiency, and adaptability, broadening their

commercial potential and reinforcing their role in sustainable industrial biotechnology (Khan, 2025).

In addition to industrial applications, fungal biotechnology has benefited from improvements in culturing, preservation, and identification techniques. High-throughput screening methods now allow rapid evaluation of fungal strains for traits such as metabolite production, enzyme activity, and stress tolerance. Molecular tools such as polymerase chain reaction (PCR) and DNA barcoding have improved the accuracy of fungal identification, which is essential for both research and regulatory purposes (Lücking *et al*., 2020). Together, these technological developments have transformed fungi from wild-type organisms into sophisticated platforms for biotechnological innovation (**Table 1**).

Table 1. Scientific and Medical advancements in fungi (2010-2025)

Year	Category	Advancement	Significance
2010	Pharmacology	Fingolimod (FTY720) approved by the US FDA - the first oral drug derived from a fungal metabolite for treating relapsing multiple sclerosis	First fungus-derived oral MS therapy; opened new neurological applications for mycology
2011	Science	Endophytic fungi found to biodegrade polyurethane plastic (*Pestalotiopsis microspora*) in anaerobic conditions - a landmark environmental discovery	First confirmed plastic-degrading fungi, sparking major research into fungal bioremediation
2012	Genomics	DOE Joint Genome Institute MycoCosm portal launched, sequencing hundreds of fungal genomes and enabling large-scale comparative genomics	Accelerated discovery of biosynthetic gene clusters and novel enzymes across fungal kingdom
2013	Conservation	Chile became the first country globally to include fungi in national environmental legislation, enabling formal species assessment of 22 fungal species	Established a legal framework for fungal conservation, later influencing IUCN Red List inclusion
2014	Science	Peptide Pattern Recognition (PPR), the first non-alignment-based sequence analysis method, developed to predict enzyme function directly from fungal genetic sequences	Accuracy of 80–97%; transformed enzyme discovery for biomass conversion
2015	Medical	Global fungal infection burden quantified: fungi cause over 1 billion skin infections, 100 million mucosal infections, and more than 1 million deaths per year - mortality comparable to tuberculosis and HIV	Galvanised global health investment and policy focus on neglected fungal diseases
2016	Medical	WHO and CDC issued urgent alerts on *Candida auris* - a multidrug-resistant nosocomial yeast first isolated in Japan in 2009, now spreading globally across hospital ICUs	First fungal pathogen classified as an "urgent antimicrobial threat" by the CDC
2017	Genomics	DNA sequence analysis used in 94% of published fungal taxonomic studies; Meta genomics and Meta transcriptomics became mainstream in mycological biodiversity research	Transformed species identification accuracy and enabled study of non-culturable fungi
2018	Genomics	CRISPR-Cas9 successfully applied to major fungal pathogens including Candida, *Cryptococcus neoformans*, *Aspergillus fumigatus*, and Mucorales - enabling precise gene editing	Revolutionised functional genomics and virulence research in medically relevant fungi
2019	Medical	*Candida auris* listed by the CDC as the first fungus among urgent antimicrobial resistance threats; cases confirmed in 39+ countries on every inhabited continent	Triggered global surveillance networks and emergency treatment protocols
2020	Pharmacology	Olorofim (F901318), the first orotomide-class antifungal, entered Phase 2b clinical trials; targets dihydroorotate dehydrogenase - a completely novel mechanism of action	First truly new antifungal drug class in decades; effective against azole-resistant moulds
2021	Science	AlphaFold protein structure prediction applied to fungal plant pathogens, uncovering shared structures of secreted virulence proteins across large evolutionary timescales	Enabled rational design of antifungal proteins and faster identification of drug targets
2022	Medical	WHO published the first-ever Fungal Priority Pathogens List, designating *C. auris*, *C. albicans*, *A. fumigatus*, and *C. neoformans* as "critical priority" threats	First WHO global framework for prioritising dangerous fungi, driving targeted research funding
2023	Science	Mycena, long considered strictly saprotrophic, discovered to invade and parasitise living plant hosts - overturning	Reshaped understanding of fungal trophic strategies and forest

Year	Category	Advancement	Significance
		decades of ecological consensus	ecosystem dynamics
2023	Medical	Natural plant compounds confirmed to inhibit drug-resistant *Candida auris* in vitro, providing a new botanical lead for antifungal drug development	Opened plant-derived antifungal pipeline against a near-untreatable pathogen
2024	Genomics	907 novel fungal-derived compounds catalogued in a single year - a 64% increase over 2023 - including 362 terpenoids, 284 polyketides, 108 alkaloids, and 75 peptides	Marked an unprecedented acceleration in fungal drug discovery, guided by metabolomics platforms
2025	Medical	Weak spot identified in *Candida auris*: specific nutrient-hunting genes activated during infection mapped using a new living-host model, pointing to targets for drug repurposing	Potential breakthrough treatment pathway for a pathogen that resists virtually all existing antifungals
2025	Science	Molecular dating revised the evolutionary origin of fungi to ~1.4 billion years ago-far earlier than previously estimated-using advanced gene transfer analysis	Rewrote the timeline of eukaryotic evolution and Earth's early terrestrial ecosystems

Source: Compiled by author from Bao *et al*. (2025); Bhargava and Klamer (2025); Kała (2025); Garg *et al*. (2023); Mapook et al. (2022); Gow and Netea (2016); Seong and Krasileva (2023)

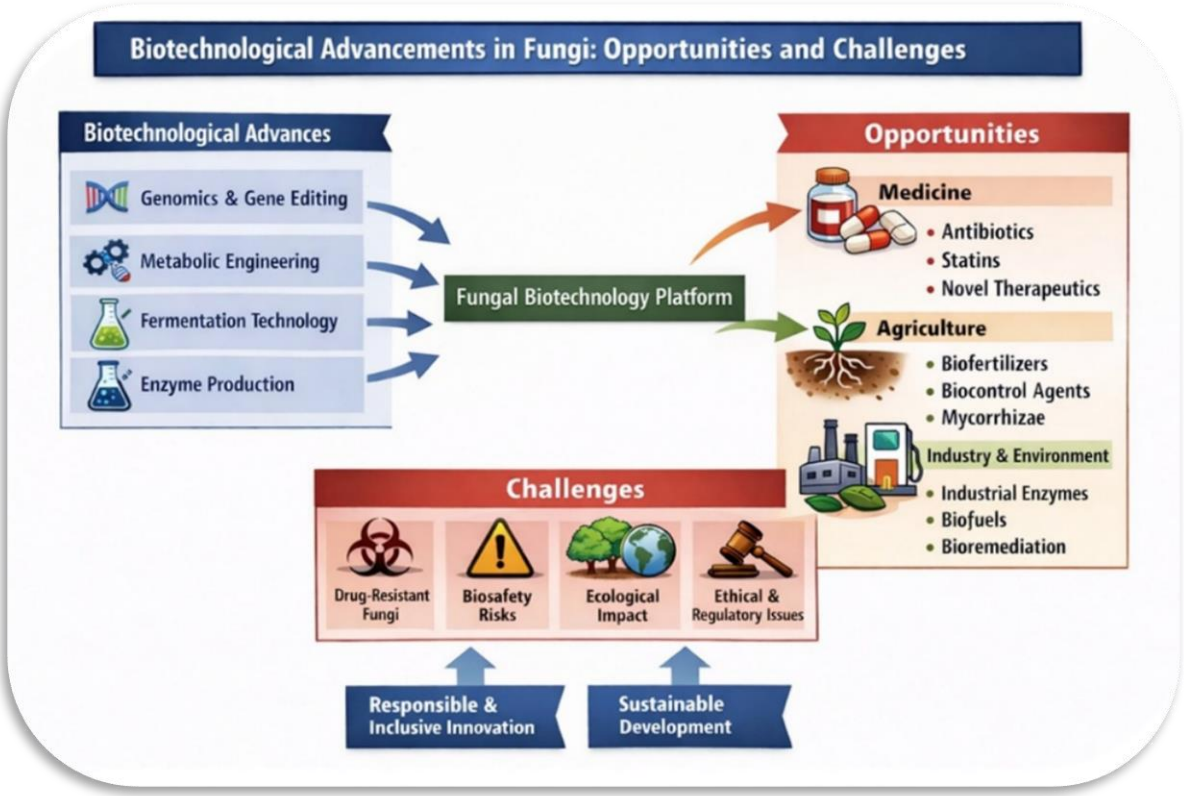


Figure 1: Graphical abstract illustrating core applications, future prospects, and existing challenges in fungal biotechnology.

2.1 Applications of Fungi in Biofuel Production and Biomass Conversion

The global demand for sustainable energy solutions has intensified research into fungal capabilities for generating biofuels and facilitating biomass deconstruction, driven by the substantial market valuation of biofuels, projected to exceed USD 200 billion by 2030 (Niego *et al*., 2023). This economic impetus underscores the critical role of fungal biotechnology in transforming lignocellulosic biomass, particularly through the action of fungal enzymes, into fermentable sugars for biofuel production, thereby mitigating reliance on fossil resources (Hyde *et al*., 2019; Lange, 2014). Beyond biofuel production, fungal biotechnology offers versatile applications in bioremediation, leveraging fungal metabolic pathways to degrade recalcitrant pollutants and transform industrial byproducts into

valuable resources (Nygard and Meyer, 2026). These fungi, characterised by their diverse metabolic and genetic functions, exhibit exceptional adaptability, making them prime candidates for use in developing cost-effective and resource-efficient industrial solutions (Garg, 2025) (**Table 2**). For instance, certain fungal species are highly effective in degrading lignocellulosic residues, converting these complex plant materials into simpler sugars that can then be fermented into biofuels such as ethanol and butanol (Dashtban *et al*., 2009).

Table 2. Biotechnology and Applied advancements in fungi (2010-2025)

Year	Domain	Advancement	Impact
2010	Biotech	Cutinase enzyme CUTAB1 from *Alternaria brassicicola* characterised and expressed heterologously - advancing fungal enzyme engineering for industrial applications	Foundation for using fungal cutinases in plastic degradation and textile processing
2011	Environment	Biodegradation of polyester polyurethane by endophytic fungi-demonstrating anaerobic plastic breakdown for the first time	Proved fungi could solve plastic waste in low-oxygen environments (e.g. landfills)
2013	Genomics	MycoCosm "1000 Fungal Genomes" project initiated, systematically sequencing representative species across the fungal tree of life	Largest coordinated fungal genomics effort; uncovered biosynthetic pathways for hundreds of bioactive compounds
2015	Biotech	Mycelium-based biomaterials (e.g., Ecovative Design) commercialised at scale as sustainable packaging and construction alternatives to polystyrene	Established fungi-based materials as a viable green manufacturing industry
2017	Biotech	Filamentous fungi engineered as cell factories for recombinant protein and secondary metabolite production, using improved promoter systems and secretion pathways	Reduced production costs for pharmaceutical enzymes and industrial proteins
2018	Genomics	CRISPR-Cas9 applied in filamentous fungi including *Aspergillus*, *Trichoderma*, and *Fusarium* to unlock silent biosynthetic gene clusters (BGCs) for secondary metabolite discovery	Enabled systematic awakening of dormant natural product pathways previously invisible to researchers
2019	Pharmacology	Ibrexafungerp (first triterpenoid antifungal, derived from enfumafungin, a fungal endophyte metabolite) advanced into Phase 3 trials - first pharmaceutical drug developed from a fungal endophyte for human use	Introduced a new structural class of antifungal active against echinocandin-resistant Candida
2020	Biotech	Machine learning algorithms (SVMs, decision trees, neural networks) applied broadly to mycological research for species identification, metabolite prediction, and gene function inference	Dramatically accelerated pattern recognition across large fungal genomic and metabolomic datasets
2021	Environment	Multiple *Aspergillus*, *Fusarium*, and *Penicillium* species confirmed capable of degrading various plastic polymer types (HDPE, LDPE, PVC, PET) via secreted laccase and peroxidase enzymes	Established a diverse fungal toolkit for multi-polymer plastic bioremediation
2022	Environment	Hydrophobic properties of fungal mycelia studied for concrete reinforcement-mycelium shown to help structures shed water and resist weathering	Proof-of-concept for fungi-integrated sustainable construction and infrastructure
2023	Biotech	Metabolic engineering of *Pichia pastoris* achieved production of triacetic acid lactone and other platform chemicals, demonstrating fungi's role in green chemistry	Validated fungal cell factories as alternatives to petroleum-based chemical synthesis
2024	Biotech	Plant-associated fungi (38%) and marine-derived strains (30%) dominated novel bioactive compound isolation in 2024, collectively accounting for two-thirds of all fungal natural product discoveries	Expanded ecological frontiers of pharmaceutical prospecting beyond terrestrial soil fungi
2024	Genomics	AI-driven integration of CRISPR-Cas9, CRISPR-Cas12a, TALEN, ZFN, and RNAi demonstrated across filamentous and mycorrhizal fungi, enabling simultaneous multi-gene edits	Made complex fungal metabolic engineering feasible for agricultural and pharmaceutical applications
2025	Environment	Fungal microbiome identified as a major source for next-generation antibiotics; advances in cultivation methods and genetic engineering opened new discovery pipelines from unculturable species	Addresses the critical global antibiotic resistance crisis with a largely untapped biological resource
2025	Pharmacology	Olorofim Phase 2b trial (204 patients, 22 centres) results published in Lancet Infectious Diseases: 28.7% global response at Day 42 with no resistance emerging during therapy	Strongest clinical evidence yet for a novel antifungal class targeting resistant invasive mould infections

Source: Compiled by author from Russell *et al.* (2011); Grigoriev *et al*. (2012); Bao *et al*. (2025); Garg *et al*. (2025); Wiederhold (2020).

2.2 Use of Fungi in Bioremediation and Environmental Sustainability.

Fungi play a crucial role in ecological systems by recycling nutrients and supporting food webs (Roth et al., 2023). Their inherent metabolic versatility enables them to degrade complex organic compounds and even recalcitrant pollutants, positioning them as essential agents in bioremediation and environmental sustainability efforts (Horta *et al*., 2025; Selvakumar, 2025). This metabolic adaptability facilitates the detoxification of various contaminants, including heavy metals, pesticides, and hydrocarbons, thereby contributing to the restoration of contaminated environments (Hyde *et al*., 2024). Moreover, their extensive enzymatic machinery, encompassing laccases, peroxidases, and hydrolases, allows for the breakdown of recalcitrant organic pollutants, underscoring their potential for environmental clean-up across various matrices such as soil, water, and air (Dinakarkumar *et al*., 2024). This biological approach is considered more sustainable than physicochemical methods like adsorption or chemical oxidation for addressing xenobiotic pollution (Khan *et al*., 2023). Furthermore, fungi contribute significantly to global sustainability initiatives by offering bio-based resources and reducing environmental impacts, directly supporting several United Nations Sustainable Development Goals (Boukid *et al*., 2022; Tiwari & Park, 2024). For example, fungal biotechnology can enable production of biodegradable goods through processes that consume less energy and generate less waste, contributing to a circular economy (Sreekumar *et al*., 2024).

2.3 Advances in genetic engineering and synthetic biology of fungi for improved metabolite production

The advent of CRISPR-based genome editing, coupled with systems biology approaches, has significantly expanded the capacity to manipulate fungal genomes, thereby unlocking the potential for enhanced biosynthesis of novel metabolites and bioactive compounds (Chaudhari *et al*., 2025). This includes programmable regulators and combinatorial pathway optimization for tailoring fungal strains to overproduce targeted molecules or even synthesize non-native materials with industrial relevance (Hinneburg *et al*., 2025). These advancements facilitate the development of fungal cell factories for pharmaceutical production, including antibiotics, anticancer agents, and immunosuppressants, through the overexpression of genes involved in secondary metabolite biosynthesis (Mapook *et al*., 2022; Zou *et al*., 2023). Furthermore, synthetic biology tools enable the development of custom genetic circuits and regulatory elements, facilitating precise control over metabolic fluxes for optimizing yield and purity of desired bioproducts (Billerbeck *et al.*, 2022; Hannes *et al*., 2025). This precision engineering allows for tailoring fungal strains not only for enhanced substrate conversion rates but also for improved environmental adaptability, further contributing to circular agricultural economic practices (Zou *et al*., 2024). The application of computational designs alongside synthetic biology has further enhanced the production of natural compounds in fungi by facilitating genome-based engineering of ligninolytic enzymes and other valuable metabolites (Asemoloye *et al*., 2021).

2.4 Development of fungal enzymes for industrial applications

The unparalleled catalytic power of fungal enzymes is increasingly harnessed for various industrial applications, including the production of textiles, detergents, and food additives, replacing chemical processes with more sustainable biocatalytic alternatives (Meyer *et al.*, 2020). Fungi produce a wide array of enzymes, such as ligninolytic enzymes (e.g., lignin peroxidase, manganese peroxidase, and laccase) that are particularly effective in breaking down recalcitrant compounds like those found in industrial waste and contaminated environments (Selvakumar, 2025). This enzymatic diversity, particularly involving oxidoreductases and hydrolases, facilitates diverse biotransformations, offering a sustainable alternative to conventional chemical processes in various industrial sectors (Gupta *et al.*, 2024). The ability to engineer fungi at a genetic level to produce novel or enhanced enzymes with targeted functionalities further expands their utility, offering greener and more efficient manufacturing pathways across biotechnology and industrial applications (Giménez *et al*., 2023; Meyer *et al*., 2016).

2.5 Emerging concepts such as living materials, 3D-printed mycelium structures, and fungal electronics.

These emerging fields leverage the intrinsic biological properties of fungal mycelia, such as self-assembly and hierarchical growth, to create functional materials with tunable mechanical, electrical, and structural characteristics (Baker, 2020). For instance, mycelial composites are being

explored for their potential in construction and packaging due to their lightweight, biodegradable nature and inherent flame retardancy (Rekdal et al., 2024). Mycelium-based materials, which can grow on diverse waste substrates, offer a sustainable alternative to synthetic materials, aligning with circular economy principles (Dhiman *et al*., 2024; Madusanka *et al.*, 2024).

These innovative applications capitalize on the intrinsic properties of fungal mycelia, such as self-assembly and biological versatility, to create bio-based materials with tailored structural and functional attributes (Elsacker *et al*., 2023; Madusanka *et al*., 2024). This includes the development of mycelium-based composites for construction and packaging, offering biodegradable and renewable alternatives to conventional plastics and building materials (Hüttner et al., 2020; Nguyen *et al*., 2018). Moreover, the inherent electrical conductivity of certain fungal species, combined with their capacity for self-repair and environmental responsiveness, positions them as promising candidates for bioelectronic devices and sustainable computing (Hüttner *et al*., 2020). The rapid growth rate of mycelium, coupled with its capacity for material property modulation through species alteration, offers significant promise for widespread implementation in engineered living materials (Nguyen *et al*., 2018).

3. OPPORTUNITIES IN MEDICINE, AGRICULTURE, AND INDUSTRY

Fungal biotechnology offers extensive opportunities across multiple sectors, particularly in medicine, agriculture, and industry. In the medical and nutraceutical field, fungi remain one of the most important sources of bioactive compounds (Sudheep and Sridhar, 2014). Antibiotics such as penicillin and cephalosporins, cholesterol-lowering drugs such as statins, and immunosuppressants such as cyclosporine are all derived from fungal metabolites (Sánchez and Demain, 2017). These compounds have revolutionized modern medicine and continue to save millions of lives worldwide.

Recent research has focused on discovering novel fungal metabolites with anticancer, antiviral, and anti-inflammatory properties. Advances in genomics and metabolomics have enabled the identification of previously silent gene clusters that encode potential therapeutic compounds (Robey *et al*., 2021). This has expanded the scope of drug discovery beyond traditional chemical synthesis to include natural product-based approaches (Valayil, 2016). As antimicrobial resistance becomes an increasing global threat, fungi provide a valuable reservoir of new molecules that may serve as next-generation drugs.

In agriculture, fungi play a crucial role in promoting sustainable farming practices. Mycorrhizal fungi form symbiotic associations with plant roots, enhancing nutrient uptake and improving crop resilience to stress (Sridhar *et al*., 2011). These natural partnerships reduce the need for chemical fertilizers and contribute to soil health. Similarly, certain fungal species act as biological control agents by suppressing plant pathogens and insect pests (Sadia *et al*., 2026). The use of fungal biopesticides represents an environmentally friendly alternative to synthetic chemicals (Singh *et al*., 2020).

Fungal biotechnology also contributes to food security through fermentation processes. Yeasts and moulds are used in the production of bread, cheese, soy sauce, and alcoholic beverages. Modern biotechnological methods have improved fermentation efficiency and product quality, making fungal-based food production more reliable and scalable (Sudheep and Limya, 2016).

Industrial and environmental applications collectively highlight the broad significance of fungal biotechnology (Corbu *et al*., 2023). Fungi possess powerful enzymatic systems capable of degrading complex organic pollutants such as dyes, pesticides, and hydrocarbons, making them effective agents in bioremediation and wastewater treatment. At the same time, they are extensively used in industry for the large-scale production of organic acids, particularly citric acid, which functions as a preservative and flavouring agent in the food sector (Hyde *et al*., 2019). Fungi also play a key role in biofuel production by degrading lignocellulosic biomass into fermentable sugars through specialized enzymes, thereby supporting renewable energy development and reducing dependence on fossil fuels (Rosas-Vega *et al*., 2025). Furthermore, by converting waste materials into value-added products, fungal systems promote circular economy principles and sustainable resource management (Sreekumar *et al*., 2024).

4. CHALLENGES AND ETHICAL CONSIDERATIONS

Despite the wide range of opportunities, fungal biotechnology faces several important challenges (Hyde *et al*., 2024). One of the most serious concerns is the emergence of drug-resistant fungal

pathogens. Fungal infections have become increasingly difficult to treat due to the limited availability of antifungal drugs and the rapid emergence of resistance. Pathogens such as *Candida auris* have demonstrated resistance to multiple drug classes, posing significant risks to public health (Choudhary *et al*., 2022).

Biosafety and ecological risks also present major challenges (Lea-Smith *et al*., 2025). The use of genetically modified fungal strains raises concerns about unintended environmental consequences. If released into natural ecosystems, such strains may disrupt microbial communities or transfer genes to native species. Strict containment measures and thorough risk assessment protocols are therefore essential to prevent unintended gene transfer and disruption of native microbial communities.

Technical and economic barriers further limit the adoption of fungal biotechnology, especially in low- and middle-income countries. Advanced molecular tools and bioreactor systems require substantial financial investment and skilled personnel (Roth *et al*., 2023). The lack of infrastructure and training restricts the capacity of many regions to benefit from fungal-based technologies. This creates inequalities in access to biotechnological innovations and represents a significant challenge to global scientific equity.

Ethical considerations also play a role in shaping fungal biotechnology. Genetic manipulation of organisms raises concerns about long-term ecological effects and the moral limits of scientific intervention (Roth *et al*., 2023). Intellectual property rights associated with genetically engineered strains and fungal metabolites may restrict access to essential medicines and agricultural inputs (Hüttner *et al*., 2020). These issues highlight the need for balanced regulatory frameworks that protect both innovation and public interest.

Regulatory challenges further complicate the development of fungal biotechnology. Approval processes for genetically modified organisms and fungal-based products vary widely across countries (Arnau *et al*., 2020). This lack of harmonization creates uncertainty for researchers and industries seeking to commercialize fungal technologies. Clear and consistent national and international regulations are required to ensure biosafety while encouraging continued innovation in fungal biotechnology (Garg *et al*., 2023).

5. FUTURE PROSPECTS AND CONCLUSION

The future of fungal biotechnology is closely linked to interdisciplinary research and responsible innovation. Continued exploration of fungal biodiversity is expected to reveal new species and metabolites with significant biotechnological value (Meyer *et al*., 2020; Sudheep and Shahina, 2023). Advances in gene editing, synthetic biology, and systems biology will further enhance the precision and efficiency of fungal strain development (Baker, 2020). These tools will enable scientists to design fungi with tailored functions for specific industrial and medical applications.

The integration of fungal biotechnology with digital technologies such as artificial intelligence and machine learning is likely to accelerate discovery and optimization processes. Predictive modelling of metabolic pathways may reduce trial-and-error experimentation and improve production yields (Han *et al*., 2023). Such approaches can significantly shorten the time required to bring fungal-based products to market.

However, scientific progress must be accompanied by strong regulatory oversight and ethical reflection. Policies should promote open access to research findings, encourage international collaboration, and ensure that biotechnological benefits are shared equitably. Capacity-building initiatives in developing countries can help bridge technological gaps and promote inclusive growth. Fungi represent a powerful yet underutilized resource in modern biotechnology. Their ability to produce valuable compounds, improve agricultural sustainability, and support environmental remediation highlights their growing importance in scientific and industrial contexts. At the same time, challenges related to resistance, biosafety, and accessibility cannot be ignored. By combining technological innovation with responsible governance, fungal biotechnology can contribute significantly to sustainable development and global health. The continued study and application of fungi hold promise not only for scientific advancement but also for addressing some of the most pressing challenges of the twenty-first century.

Conflict of Interest

The authors declare no conflicts of interest.

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