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Fungal by-products: New Potentials in Pharmaceutical and Biotechnological Industries

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Abstract
Fungi are increasingly recognized as prolific producers of bioactive secondary metabolites with considerable pharmaceutical and biotechnological potential. This review offers an overview of the recent advances in fungal by-products from 2021 to 2026, including their diversity, biosynthetic regulation, and new applications. Different ecological sources like marine fungi, endophytic fungi, coral-associated fungi, mangrove fungi and symbiotic fungi, have been sources of metabolites with antimicrobial, antioxidant, anti-inflammatory, anticancer, antiviral, neuroprotective and enzyme-inhibitory activities. Besides their therapeutic potential, fungal metabolites have shown promising applications in agriculture, nanomedicine, industrial biotechnology, metabolomics and environmental management. The research work presents an overview of current obstacles which affect metabolite production and purification and commercial distribution. The research identifies developing potential from genomic studies together with synthetic biology and artificial intelligence and metabolomics systems. The research shows that fungal by-products serve as an essential resource for discovering sustainable scientific and industrial solutions.

Keywords: Fungal by-products; Secondary metabolites; Endophytic fungi; Bioactive compounds; Pharmaceutical biotechnology; Industrial biotechnology.

1. Introduction

The fungi are one of the most metabolically versatile and diverse organisms that occupy various terrestrial, marine and symbiotic habitats. This flexibility has allowed them to develop elaborate metabolic routes that result in the biosynthesis of a large number of secondary metabolites that have unique chemical skeletons and biological activities. Secondary metabolites are involved in processes of ecological interactions, including defence, competition, communication and adaptation to the environment, while primary metabolites are involved in growth and reproduction processes. These compounds serve multiple biological functions which have made them an emerging focus for pharmaceutical and biotechnological research according to Bao et al. (2025). Secondary metabolites produced by fungi are a good source of bioactive compounds that have antimicrobial, antiviral, anti-inflammatory, anti-oxidant, anti-cancer and enzyme inhibitory properties. Now, thanks to natural product chemistry, genomics and molecular biology, the extent of fungal derived compounds that have been discovered is mind-boggling, including polyketides, terpenoids, alkaloids, peptides, steroids, and glycosides. Fungi can provide access to an amazing diversity of chemicals that could serve as the basis for finding new therapeutic agents and industrially useful biomolecules. More than 900 new fungal metabolites have been identified in the last several years alone, highlighting the vast biosynthetic capabilities of fungal species and its continued growth in fungal metabolite research (Bao et al. 2025). Drug discovery has only been the beginning of fungal based biotechnology products being utilised in more and more ways, such as in the fields of nanotechnology, agriculture, enzyme production, bio-catalysis, environmental remediation and sustainable bio-based manufacture. Combine metabolomics, genomics, synthetic biology and metabolic engineering to identify and use fungal metabolites, expanding fungal biotechnology into a multi-disciplinary, ever more important industrial area (Bao et al., 2025).
Although significant advances have been made, existing knowledge is still scattered as most studies are based on individual fungal species or on particular classes of metabolites. Therefore, a detailed overview of fungal metabolites of both pharmaceutical and biotechnological interest is required. The demand for new therapeutic

agents, improvement of analytical technologies and looking for sustainable industrial solutions has made this area of hot interest over the last five years (2021–2026) (Bao et al., 2025). Thus, the present review attempts to explore diversity and biosynthesis of fungal metabolites, their pharmaceutical applications, biotechnological potential and challenges and future prospects for their industrial utilization.

2. Sources of Fungal Metabolites

Ecological diversity of fungal species plays a significant role in fungal secondary metabolites diversity. Marine fungi, fungi growing on plants and fungi in symbiotic systems are grown under different environmental conditions, which have different effects on the production of structurally diverse bioactive compounds. Consequently, fungi have emerged as an important source for metabolites that are relevant to pharmaceutical and biotechnological applications, with the ecological source having become an important clue for the discovery of these metabolites.

Marine Fungi

Marine fungi are known to be prolific producers of novel natural products as they grow in extreme environment such as salinity, pressure and limited nutrients. Under such conditions, special metabolites that are not normally produced on land are synthesized. For instance, the deep-sea fungus Phomopsis lithocarpus FS508 yields a number of structurally unique metabolites such as isoindolinone lactams and triterpenes that exhibit potential for cytotoxic and anti-inflammatory properties. The research findings demonstrate that marine fungi offer players who are ready to discover fresh bioactive natural products and upcoming drug development candidates (Hu et al., 2023).

Coral-Associated Fungi

Another valuable by-product source of coral associated fungi. Close association with marine invertebrates results in production of metabolites that play a role in ecological adaptation and defense of the organism. The soft-coral derived Penicillium sp. was investigated. Cyclopiazonic acid alkaloids were identified from SCSIO 41038 with an antitumor activity, and phloroglucinol derivatives were identified with an acetylcholinesterase inhibitory activity. These findings show that the fungi associated with corals produce metabolites that have pharmaceutical potential in cancer and neurodegenerative diseases research (Li et al., 2024).

Mangrove Fungi

The mangrove ecosystem has a number of fungi, which are salt-tolerant and stress-tolerant. These conditions have resulted in the development of a biosynthetic pathway that is unique for the production of structurally novel metabolites. The mangrove endophytic fungus Diaporthe pseudooculi HHUF 30617 was recently reported to produce several metabolites, one of which is a new polyketone with good anti-inflammatory activity. The results reveal that mangrove fungi can be a rich source of natural products that have therapeutic potential (Yang et al., 2025).

Ant-Associated Symbiotic Fungi

The fungus-farming ants are a new source of metabolites. These microorganisms are a symbiotic set, which engage in complicated ecological interaction; chemical communication and defense mechanisms play a significant role in this interaction. Genomic analyses of Escovopsis species and related fungal symbionts uncovered a large number of metabolically divergent clusters in their genomes, suggesting a long-term evolutionary adaptation. As the number of unexplored biosynthetic pathways indicates, ant-associated fungi can be a valuable source of undiscovered bioactive compounds of potential pharmaceutical and biotechnological use in the future (Berasategui et al., 2024).

2.2 Endophytic Fungi as Metabolite Factories

Endophytic fungi are microorganisms colonizing the internal tissues of plants without obviously causing disease symptoms. They have received much attention because of their complex mutualistic association with the host plants and their remarkable biosynthetic ability. Endophytic fungi have evolved over time to produce a variety of secondary metabolites that help the plants survive, adapt, and thrive. The metabolites produced by these fungi have a wide range of biological significance and endophytic fungi serve as a rich source of pharmaceutical and biotechnological products. Agarwood-Associated Fungi

The plants growing in the vicinity of agarwood can also be found to have exceptionally unique communities of fungi that contribute to the development of the agarwood, and the generation of valuable aromatic compounds. Recent studies have shown that endophytic fungi in agarwood play a significant role in the production of fungal metabolites and in the production of metabolites resulting from the action of the host. They are metabolites such as terpenoids, chromones, phenolic compounds, and others which play a role in plant defense and resin production. The intricate relationship between the agarwood host plant and the fungus associated with it is ideal for studying the metabolic interactions between the fungi and the plants, thereby discovering new natural products with potential applications (Ma & Yang, 2026).

Rosaceae-Associated Fungi

The Rosaceae family's plants are host to a wide variety of endophytic fungi that secrete a variety of bioactive secondary metabolites. Fungi isolated from Rosaceae species have been subjected to comprehensive analyses and compounds with antimicrobial, antioxidant, anticancer, anti-inflammatory and enzyme inhibitory activity have been found. The results indicate the potential of Rosaceae-associated fungi as sources of metabolites with wide-range chemical diversity and the possible pharmaceutical applications. Through scientists' efforts to identify fungal colonies, they have made new discoveries of biologically active compounds that they currently use in biotechnology and drug development applications (Younis et al., 2025).

Houttuynia-Associated Fungi

Another example of beneficial fungal–plant interactions is the endophytic fungi found in Houttuynia cordata. Experimental investigations have shown that the fungal infection can greatly induce the production of the secondary metabolites of medicinal value in the host plant. This enhancement has increased the pharmacological use of the plant and is an example of the potential of endophytic fungi to affect the plant's metabolism outside their own biosynthetic pathways. The results indicated that fungal endophytes could be considered as promising biological resources to enhance the biosynthesis of bioactive metabolites in economically valuable plants and can also be utilized for the production of medicinal metabolites for pharmaceutical applications (Ye et al., 2021).

2.3 Regulation of Secondary Metabolite Biosynthesis

The synthesis of fungal secondary metabolites is regulated by highly complex regulatory networks, which are composed of signals from the surrounding environment, genetic factors and the internal communication system of the cell. A knowledge of the mechanisms of regulation is critical for improving metabolite production and unlocking the potential of hidden biosynthetic gene clusters that are not expressed in conventional laboratory settings. In recent years, fungal biotechnology has yielded some fascinating ideas for altering metabolite biosynthesis and for the discovery of new compounds.

Co-cultivation Strategies

Cryptic biosynthetic pathways and metabolites are activated and diversified by microbial co-cultivation. Fungal–fungal interactions can trigger for each other competitive or cooperative response that leads to the activation of otherwise latent gene clusters. The fungal–fungal co-cultivation studies have shown that significant changes in secondary metabolite profiles have occurred, which led to the production of new metabolites and the increased yield of metabolites. These responses are mediated by the VeA1 regulatory protein, which has been found to be crucial in interspecies communication in fungal secondary metabolism.

RNA-Mediated Regulation

Post-transcriptional regulation is an important mechanism for regulating fungal metabolite biosynthesis. Recently, an RNA-binding protein complex, CsdA/RsdA, was discovered to be a hub of control for secondary metabolic pathways. This complex controls the expression of multiple biosynthetic gene clusters and controls the biosynthesis of multiple secondary metabolites. Detailed knowledge of RNA-mediated regulation will give new light on how fungi metabolize, and provide a target for genetic engineering in metabolite production (Song et al., 2023).

Epigenetic Regulation

Another very effective approach to the activation of silent biosynthetic pathways is by means of epigenetic modification. Chemical epigenetic modifiers are able to modify chromatin structure and gene expression without changing the sequence of DNA. It has been found that metabolites, which were not detected in fungal cultures when grown in the absence of the drug, can be produced when the cultures are treated with 5-azacitidine, as well as the known metabolites.5-azacitidine has been found to induce the production of previously unknown metabolites and to improve the formation of known metabolites in fungal cultures. Scientists have established that epigenetic methods allow researchers to create new fungal chemical substances which lead to discovering bioactive compounds which were previously unknown (Li et al., 2024).

Extraction and Expression Technologies

Efficient extraction, purification and expression methodologies are required for successful exploitation of fungal metabolites in addition to their biosynthesis. The use of new extraction techniques, heterologous expression systems, genome mining, and metabolic engineering, has greatly facilitated the identification and characterization of secondary metabolites of fungi. Modern protocols allow researchers to tie up knots in cryptic biosynthetic pathways, alter metabolite production to make more optimal products, and speed the pathway from lab discovery to industrial use. These technological advances are indispensable for the modern fungal biotechnology and natural products research (Nickles et al., 2021).

The diversity of fungal by-products mentioned in this section is summarized in Table 1, which gives a representative sample of fungal sources, major classes of by-products, and some biological activities described. The table summarizes the general taxonomic and ecological diversity of fungi that produce metabolites, including marine, coral-associated fungi, endophytic and symbiotic fungi. It also provides an example of the versatility of fungal metabolites in their function and their possible applications in pharmaceutical and biotechnological fields.

Table 1: Diversity of fungal by-products according to fungal source, metabolite type, and biological activity

Fungal Source	Species/Association	Major Metabolite Type	Reported Biological Activity	Reference
Marine fungus	*Phomopsis lithocarpus* FS508	Isoindolinone derivatives, triterpenes	Cytotoxic and anti-inflammatory effects	Hu et al. (2023)
Coral-associated fungus	*Penicillium* sp. SCSIO 41038	Alkaloids, phloroglucinol derivatives	Antitumor and acetylcholinesterase inhibition effects	Li et al. (2024)
Mangrove endophytic fungus	*Diaporthe pseudooculi* HHUF 30617	Polyketone metabolites	Anti-inflammatory effect	Yang et al. (2025)
Ant-associated symbiotic fungus	*Escovopsis* spp. and allies	Biosynthesis of diverse secondary metabolites using gene clusters	Ecological protection and symbiosis adaptation	Berasategui et al. (2024)
Agarwood-associated endophytes	Multiple fungal taxa	Terpenoids, chromones, phenolics	Production of aromatic resin and its biological functions	Ma & Yang (2026)
Rosaceae-associated endophytes	Multiple fungal taxa	Diverse bioactive metabolites	Antimicrobial, antioxidant, anticancer, and anti-inflammatory effects	Younis et al. (2025)
***Houttuynia cordata* endophytes**	Multiple fungal taxa	Medicinal metabolites induced by host	Stimulation of medicinal compound production	Ye et al. (2021)

Table 1 reveals that the fungal metabolites come from various ecological habitats and have different biological activities. The diversity is a testament to the extraordinary biosynthetic potential of fungi and its potential as a sustainable source of novel bioactives. The knowledge of the ecological origin and the biosynthetic regulation of these metabolites lay the basis to the study of their possible therapeutic and industrial applications which are described in the subsequent parts of this report.

3. Pharmaceutical Potential of Fungal By-products

The increasing need for new drugs has led to increased interest in fungal by-products as valuable sources of compounds with biological activity. Secondary metabolites of fungi are structurally diverse and have a broad spectrum of pharmacological properties such as antimicrobial, antioxidant, anti-inflammatory, anticancer, antiviral, neuroprotective and enzyme-inhibitory effects. The biological activities have made fungi one of the most promising natural resources for drug discovery and pharmaceutical development. The identification of fungal metabolites with therapeutic potential has been further accelerated by recent advances in metabolomics, biotechnology and natural product chemistry.

3.1 Antimicrobial Activities

Antibacterial Metabolites

The era of "super germs" or "super bugs" has made it vital to find new antimicrobial agents. Fungal secondary metabolites are a large source of structurally diverse compounds with the ability to inhibit bacterial growth in a variety of ways. Medicinal plants are especially useful in this aspect with endophytic fungi.

As demonstrated in the research above, endophyte secondary metabolites exhibit great antimicrobial and antioxidant properties that make it easy to develop natural antibiotic alternatives from the endophytes of Ziziphus spina-christi (Farouk et al., 2025). The endophytic fungus Phyllosticta fallopiae isolated from Aloe Vera exhibits antimicrobial properties against bacteria that lead to wounds of diabetic origin, hence making it useful for treating such wounds (Taher et al., 2023). Endophytic fungi have been identified as growing in the interior of Vochysia divergens plants and different antimicrobial compounds have also been found attacking bacteria causing different diseases (Souza et al., 2024). Research by Siebatcheu and team (2023) discovered that T. erinaceum produces secondary metabolites which fight against Pythium ultimum thus proving fungal metabolites function as antimicrobial agents for medical and agricultural applications.

Antimicrobial Resistance-Related Applications

Fungal metabolites are also known to have antimicrobial resistance. Secondary metabolites of Penicillium christenseniae SD exhibited properties to overcome the intrinsic microbial mechanism of resistance and enhance the antimicrobial activity. The research findings will assist pharmaceutical companies to create new medications which fight against worldwide fungal infections that do not respond to current drug treatments (Wang et al., 2024).

3.2 Antioxidant Activities

Oxidative stress is known to play an important part in the emergence of various chronic diseases like cancer, cardiovascular diseases, diabetes, and neurodegenerative diseases. This is why natural antioxidants are particularly important in pharmaceutical use. Below you can see the metabolites obtained from Curvularia sp. Antioxidant and anticholinesterase activity of G6-32 have been found to be statistically significant as well, which means that there are potential uses of G6-32 in oxidative stress-induced diseases and neurodegenerative diseases (Polli et al., 2021). The research proves that secondary metabolites obtained from Botryosphaeria fabicerciana are powerful antioxidants with high antimicrobial properties, thus making them useful for medicine (Silva et al., 2022). It has been discovered that the metabolites produced by endophytes of C. blinii increase the life span of Caenorhabditis elegans while enhancing their antioxidant defense system. Based on the results, fungal antioxidants have the possibility to be applied in future anti-aging and health-promoting interventions (Qi et al., 2026).

3.3 Anti-inflammatory Activities

Anti-inflammatory compounds are promising drugs as they are a common feature of plenty of chronic diseases. Metabolites from fungi have proven to be a valuable source of molecules that can regulate inflammatory pathways. The anti-inflammatory activity was exhibited by secondary metabolites extracted from Aspergillus niger IMBC-NMTP01 which also showed cytotoxic and antimicrobial effects. These multifunctional metabolites can have added applications such as in the pharmaceutical industry (Quang et al., 2022). The fungal species Diaporthe pseudooculi HHUF 30617 which scientists obtained from mangrove Glandirhamma sp. displayed strong anti-inflammatory properties through its metabolic products which show promise for developing anti-inflammatory medications from mangrove fungi (Yang et al., 2025).

3.4 Anticancer Activities

Cancer is among the primary causes of mortality around the globe, thus, continuous development of new antitumor agents. Metabolites isolated from fungi have a variety of different structural configurations, which makes them able to act upon several signaling pathways of cell proliferation. The metabolites are synthesized by the endo-fungal fungus Penicillium sp. The CPCC 401423 revealed cytotoxic activity towards MIA PaCa-2 pancreatic cancer cells, which suggests its use in the creation of cancer treatments (Pang et al., 2023). Another source of antitumor substances is a mangrove-derived endophytic fungus Aspergillus sp. According to the scientific team, GXNU QG1a was a strong anti-cancer substance, and this finding proves that fungi from natural habitats have many useful biological features (Bo et al., 2025). Additional metabolites have been discovered as a result of scientists' research of Coniochaeta sp. It was found that F-8 possessed both antioxidant and cancer cell-killing activities. The multipurpose substances may potentially be useful for developing therapies for oxidative stress and cancer progression (Fu et al., 2021).

3.5 Neuroprotective and Cognitive Applications

Neurodegenerative disorders are a huge problem in the world and there is a need to identify new neuroprotective agents. As recently as the last few years, fungal metabolites have come under the spotlight for their modulatory effects on neurological function and anti-cognitive decline properties. Secondary metabolites extracted from the Galactomyces geotrichum that was isolated from Laminaria japonica were shown to be having the potential of alleviating cognitive deficits and brain oxidative stress in an Alzheimer's disease mouse model induced by D-galactose. These findings indicate the potential of fungal metabolites as candidates for the development of therapies targeting neurodegenerative diseases and age-related cognitive impairment (Wang et al., 2021).

3.6 Antiviral Potential

SARS-CoV-2 as a Case Study

Owing to the outbreak of coronavirus (COVID-19), the search for antiviral compounds from nature gained importance that exceeded its earlier importance. In the context of the COVID-19 pandemic, the search for antiviral compounds gained even greater importance compared to before. The secondary metabolites of fungi have been explored as possible inhibitors of viral proteins which are involved in the process of replication and pathogenesis of viruses. The metabolites isolated from fungi were identified as potent inhibitors of the main protease of the SARS-CoV-2 using molecular docking and molecular dynamics simulations. Some of the compounds showed excellent binding stability, making them potential candidates for developing antiviral drugs (Ebrahimi et al., 2025).

3.7 Enzyme Inhibition and Novel Therapeutics

Current drug discovery relies on the inhibition of enzymes as one of the primary principles of the procedure. There exist several metabolites produced by fungi that have the ability to inhibit enzymes responsible for the advancement of diseases. Secondary metabolites derived from the fungus Virgaria nigra CF-231658 had a high level of inhibition for elastase enzyme. It is clear from the study that the metabolites produced by fungi serve as templates to develop drugs against elastase due to their role in inflammation and tissue destruction (Samy et al., 2022). In the next section, a variety of examples of different pharmaceutical products that are derived from fungal by-products and have therapeutic applications in a range of disease areas are presented to illustrate the wide-ranging therapeutic potential of fungal byproducts across disease targets. The major pharmacological activities, experimental models and therapeutic applications emerging from recent investigations have been summarized, and are reported in Table 2 for comparison among reported metabolites. The table shows that fungal secondary metabolites are versatile and have increased importance in recent drug discovery research.

Table 2: Pharmaceutical applications of fungal by-products and their mechanisms of action

Metabolite Source	Pharmacological Activity	Experimental Model	Potential Application
***Ziziphus spina-christi* endophytic fungi**	Antibacterial, antioxidant	In vitro microbial assays	Anti-infective agents

Phyllosticta fallopiae	Antimicrobial	Diabetic wound pathogens	Wound infection management
Endophytic fungi from *Vochysia divergens*	Broad-spectrum antimicrobial	In vitro microbial assays	Novel antibiotics
Trichoderma erinaceum	Antimicrobial	Pathogen inhibition assays	Agricultural and medical antimicrobials
***Penicillium christenseniae* SD.84**	Antimicrobial resistance modulation	Resistance-related assays	Antimicrobial adjuvants
***Curvularia* sp. G6-32**	Antioxidant, anticholinesterase	Biochemical assays	Neuroprotection and anti-aging
Botryosphaeria fabicerciana	Antioxidant, antimicrobial	In vitro assays	Oxidative stress-related disorders
***Conyza blinii* endophytic fungi**	Antioxidant	*Caenorhabditis elegans* model	Healthspan enhancement
***Aspergillus niger* IMBC-NMTP01**	Anti-inflammatory	Cellular bioactivity assays	Inflammatory disorders
***Diaporthe pseudooculi* HHUF 30617**	Anti-inflammatory	Bioactivity-guided evaluation	Anti-inflammatory therapeutics
***Penicillium* sp. CPCC 401423**	Anticancer	MIA PaCa-2 cell line	Cancer therapy
***Aspergillus* sp. GXNU QG1a**	Cytotoxic	Cancer cell assays	Anticancer drug discovery
***Coniochaeta* sp. F-8**	Cytotoxic, antioxidant	Cellular assays	Multifunctional anticancer agents
Galactomyces geotrichum	Neuroprotective	Alzheimer's disease mouse model	Neurodegenerative disease treatment
Fungal endophyte metabolites	Antiviral	Molecular docking and dynamics simulations	SARS-CoV-2 drug development
***Virgaria nigra* CF-231658**	Elastase inhibition	Enzyme inhibition assays	Enzyme-targeted therapeutics

Fungal by-products contain various pharmacological benefits which extend beyond their ability to fight microbial infections (Table 2). Their target of oxidative stress, inflammation, cancer progression, neurodegeneration, viral replication, and enzymatic dysfunction, shows their great value as a source for future therapeutics. In addition to their pharmaceutical applications, fungal metabolites have been found to have important industrial and technological potential, as detailed in the next section.

4. Biotechnological Applications of Fungal By-products

In addition to their pharmaceutical applications, fungal by-products are also valuable for many biotechnological applications. New fungal biotechnology, metabolomics and microbial engineering has led to the wider application of fungal metabolites in sustainable bioeconomy, environment, nanotechnology, industrial production and agriculture. The amazing array of fungal secondary metabolites, along with their ecological versatility, has made fungi promising biological factories that can produce compounds of potentially commercial and technological value.

4.1 Agricultural Biotechnology

Plant Growth and Host Modulation

The fungal endophytes are important for plant development, growth, stress resistance, and productivity. These microorganisms produce biochemical compounds which help control growth processes, defense systems, nutrients absorption, and ecology of the plants. From the research done, it has been found that foliar fungal symbionts exert significant influence on plant development and resource distribution. The research findings indicate that fungal secondary metabolites help plants adapt while they serve agricultural purposes to increase crop yields and improve plant defense against pathogens (Sandy et al., 2023). Endophytic fungi are known to induce the production of beneficial medicinal compounds within the host plant besides host modulation. Research on Houttuynia cordata showed that the concentration of bioactive compound is increased through fungal colonization, and thereby the medicinal value of the host plant. These interactions offer exciting potential for creating sustainable methods for producing these high-value phytochemicals using microbial biotechnology (Ye et al., 2021).

4.2 Metabolomics and Community Engineering

With recent developments in metabolomics, fungal community-host interactions are now being better understood. Combining metabolomic and metagenomic studies will help researchers uncover the metabolites linked to community assembly, adaptation and microbial communication. Fungal metagenomic diversity was significantly correlated with the composition of metabolites in the root of horseradish, a plant that is associated with fungi. The results of the study showed that several metabolite groups influenced the structure of microbial communities and their interactions. The results of this study help pave the way to the development of community engineering strategies by means of fungal metabolites in agriculture, environment, and industry (Plaszkó et al., 2022).

4.3 Industrial Biotechnology

Nanomedicine Applications

One of the fastest growing areas where fungal metabolites are proving to be useful is nanotechnology. Secondary metabolites have unique physicochemical properties which can be utilized for the development of advanced therapeutic systems, improve the bioavailability, and enhance the drug delivery. In recent years, the use of fungal secondary metabolites (SM) in nanomedicine has been emphasized, especially for the treatment of infectious diseases. Their inclusion in the delivery systems based on nanoparticles has shown to have positive therapeutic effects, targeted drug release, and better antimicrobial activity. The properties make the fungal metabolites emerge as candidates for biomedical nanotechnologies of the future (Sahoo et al., 2024).

Discovery of Novel Metabolites

As a result of investigating Cladosporium xylophilum, previously unreported secondary metabolites have been discovered, further contributing to the growing chemical diversity of fungal natural products (Yang et al., 2024). The endophytic fungus Fusarium guttiforme which lives inside P. insulana plants has generated new phenolic compounds that show both biological activity and industrial value according to Yue et al. (2024). The presence of endophytic fungi that thrive inside medicinal plants was discovered by scientists during their studies. Chemicals were isolated from Aspergillus strains that scientists found in T. wilfordii plants. The chemicals have the potential to produce chemical structures that industries can utilize (Deng et al., 2022).

The chemical substances which scientists extracted from Talaromyces assiutensis JTY fungus demonstrated strong biological effects which will increase the variety of chemicals available for future biotechnological applications (Li et al., 2022). Scientists discovered valuable bioactive compounds and metabolites in fungal biodiversity which also includes Colletotrichum gloeosporioides metabolites that researchers extracted from Artocarpus heterophyllus fungus to discover antibacterial properties and cytotoxic effects which prove fungal biodiversity manages industrial value (Riga et al., 2024).In addition, research on T. citrinoviride identified several bioactive metabolites which could have potential applications in industrial biotechnology, agricultural and pharmaceutical industries for future research (Kong et al., 2022).

4.4 Ecological and Environmental Applications

Wood Decomposition and Ecosystem Interactions

Fungi are an integral part of the ecosystem and have crucial roles in nutrient cycling, decomposition and ecological interactions. Secondary metabolites play a major role in these activities, as they are involved in competition, communication and adaptation in complex environmental communities. Fungal community composition was strongly related to the interaction of invertebrates and tree derived secondary metabolites in studies of the dead-wood ecosystem. They have consequences for ecological processes associated with decomposition and nutrient cycling, and point to the importance of fungal metabolic activity in the environment. This knowledge might contribute to the development of sustainable environmental management, bioremediation technologies and programme of ecosystem conservation (Lunde et al., 2022). Together these results demonstrate the high potential of fungal by-products, which can be used for purposes beyond pharmaceuticals. They play a key role in various fields, including agriculture, industrial innovation, microbial engineering, and environmental sustainability, and their contributions in these areas underscore their significance in the modern bioeconomy. The various biotechnological uses mentioned in this section, indicate the importance of fungal by-products in different industrial sectors. For easy comparison with the other technologies, Table 3 outlines some of the metabolites, producing fungi and their applications in agriculture, industrial biotechnology, nanotechnology and environmental management. The table emphasises the versatility of fungal metabolites and their growing importance in sustainable biotechnological innovations.

Table 3: Biotechnological applications of fungal by-products in agriculture, industry, nanotechnology, and environmental management

Application Area	Representative Metabolite/Metabolite Class	Producing Fungus	Industrial Significance
Agricultural biotechnology	Host-modulating secondary metabolites	Foliar fungal symbionts	Enhancement of plant growth and stress tolerance
Agricultural biotechnology	Plant metabolite-enhancing compounds	Endophytic fungi associated with *Houttuynia cordata*	Increased production of medicinal phytochemicals
Metabolomics and community engineering	Community-structuring metabolites	Endophytic fungal communities of horseradish roots	Microbiome engineering and ecological management
Nanomedicine	Bioactive secondary metabolites incorporated into nanocarriers	Diverse fungal sources	Drug delivery and therapeutic enhancement
Industrial biotechnology	Novel fungal metabolites	*Cladosporium xylophilum*	Natural-product discovery
Industrial biotechnology	Phenolic metabolites	*Fusarium guttiforme*	Bioactive compound development
Industrial biotechnology	Novel secondary metabolites	*Aspergillus* sp.	Pharmaceutical and industrial applications
Industrial biotechnology	Bioactive metabolites	*Talaromyces assiutensis*	Drug discovery and biotechnology
Industrial biotechnology	Cytotoxic and antibacterial metabolites	*Colletotrichum gloeosporioides*	Therapeutic and industrial applications
Industrial biotechnology	Bioactive metabolites	*Trichoderma citrinoviride*	Agricultural and industrial biotechnology
Environmental biotechnology	Ecologically active secondary metabolites	Dead-wood fungal communities	Ecosystem management and nutrient cycling

As revealed in Table 3, fungal by-products have a wide range of potential applications in biotechnology, including in sustainable agriculture, the management of microbiome, the nanomedicine, and environmental management sectors. They are very adaptable, showcasing how well fungi can metabolize, and the fact that they could become renewable biological feedstock for future technological innovations. Though significant progress has been made, there are still some issues to consider with metabolite production, scale-up, characterisation and commercialisation. The questions are addressed in the subsequent section.

5. Current Challenges and Future Perspectives

Although tremendous strides have been made in the study of fungal metabolites in the past ten years, many scientific, technological and industrial issues remain that hold back the complete utilization of fungal by-products. Overcoming these challenges will be key to bringing discoveries from the lab to commercial products. Concurrently, novel technologies in the fields of genomics, metabolomics, artificial intelligence, and bioprocess engineering are opening up unprecedented opportunities to discover and utilize fungal metabolites in industry.

5.1 Low Yield and Production Bottlenecks

The main challenge in fungal biotechnology is the low productivity of several important secondary products in laboratory and industrial cultivation. There are many biosynthetic gene clusters which are silent or under-expressed, and so only produce low levels of potentially valuable substances. In addition, environmental conditions, nutrient availability, growth conditions and interactions with microorganisms often affect metabolite biosynthesis, thus making it difficult to optimize large-scale production. Variability among strains of fungi and complexity of metabolic regulation further complicates industrial fermentation processes. Therefore, the development of metabolically more productive strains, metabolic engineering, optimization of culture conditions and synthetic biology are still very important research areas for the future.

5.2 Challenges in Metabolite Purification

There are still challenges to the purification and characterization of fungal metabolites, involving both their technical difficulty and economic cost. Most of the fungal extracts consist of very complex mixtures of structurally similar compounds which needs several chromatographic and spectroscopic methods for separation and identification. Moreover, bioactive metabolites are often present in minute amounts, making their biological testing and industrial development challenging. But the difficulty of standardisation of extraction and purification procedures also reduces the reproducibility of the studies and also obstructs commercialisation efforts. It is believed that the efficiency of the fungal metabolite isolation and characterization will be further enhanced by future developments in analytical chemistry, high-resolution mass spectrometry, automated purification systems, and metabolite profiling techniques.

5.3 Genomic and Metabolomic Integration

In recent years, progress in fungal genomics has led to the discovery that numerous fungal species may have a much greater biosynthetic capacity than previously thought. Genome sequencing studies have revealed many biosynthetic gene clusters whose metabolites are produced under non-conventional cultivation conditions, which are not currently being explored. Combining genomic, transcriptomic, proteomic and metabolomic information can be a very effective approach to correlating biosynthetic genes with their metabolites. These multi-omics approaches have potential to help identify new compounds, to gain insight into biosynthetic pathways, and can aid in the rational engineering of fungal strains to better produce metabolites. The integrated omics platforms will be increasingly used in the future to unlock hidden metabolic potential of fungi.

5.4 AI-Assisted Discovery of Fungal Metabolites

Predictive tools for natural products research and development are becoming increasingly important, such as AI and machine learning. The AI-driven algorithms can quickly process vast amounts of genomic and metabolomic data, forecast biosynthetic gene clusters, spot potentially interesting metabolites, and rank them for testing.

Machine learning models can also forecast biological activities, toxicity, molecular targets and pharmacological properties prior to experimental testing. These properties may alleviate time and expenses on conventional drug discovery processes. With ongoing advancements in computing power, AI techniques are likely to play increasingly vital roles in the research and development of fungal metabolites.

5.5 Future Industrial Commercialization

There are some regulatory, economic and technical challenges to transfer fungal metabolites from the research laboratory to commercial products. In large production systems, there is a need to guarantee yield of the metabolites, quality, safety and cost of the product. Furthermore, the regulatory approval process for pharmaceutical, agricultural or industrial products can involve extensive safety and efficacy testing. Despite this, the world's growing demand for sustainable bio-based products, natural therapeutics, agricultural products with a low environmental footprint, and new biotechnology products is also offering significant opportunities for the commercialization of fungal metabolites.

New products derived from fungi are anticipated to be developed in various sectors because of recent advancement in fermentation technology, synthetic biology, precision biotechnology and optimization of industrial bioprocess. Other future commercialization activities will likely be on high value pharmaceuticals, functional ingredient, agricultural biostimulant, industrial enzymes, and environmentally friendly bioproducts.

6. Conclusion

Fungi are a rich source of bioactive compounds for modern pharmaceutical and biotechnological uses, as their by-products. Fungi produce structurally diverse secondary metabolites which have antimicrobial, antioxidant, anti-inflammatory, anticancer, antiviral, neuroprotective and enzyme-inhibitory properties due to their extraordinary metabolic versatility.

These activities illustrate the enormous therapeutic potential of the metabolites produced by fungi and emphasize the significance of fungi in contemporary drug discovery. The metabolites produced by fungi have also been found to have significant applications in various fields such as pharmaceutical applications, agricultural applications, industrial biotechnology applications, nanomedicine applications, metabolomics, microbial community engineering and environmental management.

They have numerous technological applications such as improving plant performance, helping to sustain industrial processes, and participating in ecosystem functioning. Despite significant hurdles in metabolite yield, purification, characterization and commercialization, recent progress in genomics, metabolomics, synthetic biology and AI is making it a rapidly changing field. The combination of multi-omics technologies and computational tools promises to significantly speed up the discovery of new fungal metabolites and optimization of their industrial production.

Overall, fungi are an important and sustainable biological resource with much of their metabolic potential still unexploited. Next step research and innovation in alternative fields will be essential to discovering more fungal-based products for pharmaceutical, industrial, agricultural, and environmental applications.

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