

FRESHWATER FUNGI AS RESERVOIRS OF ANTIMICROBIAL NATURAL PRODUCTS: A BIBLIOMETRIC ANALYSIS

**FUNGOS DE ÁGUA DOCE COMO RESERVATÓRIOS DE PRODUTOS
NATURAIS ANTIMICROBIANOS: UMA ANÁLISE BIBLIOMÉTRICA**

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ABSTRACT

Freshwater fungi represent an underexplored ecological and biotechnological group, despite their relevance in organic matter decomposition and production of secondary metabolites. This study performed a bibliometric analysis of freshwater fungi as sources of natural products with antimicrobial potential. Data were retrieved from Scopus and PubMed on July 7, 2026, using descriptors related to freshwater or continental aquatic fungi, natural products, secondary metabolites, bioactivity and antimicrobial activity. After duplicate removal and screening by title, abstract and keywords, 53 documents were included in the main corpus, of which 38 formed the antimicrobial subcorpus. Scientific production showed recent growth, with the highest concentration between 2020 and 2026. *The Journal of Natural Products* was the most frequent source, whereas the United States and China were the most represented countries. The most recurrent genera were *Fusarium*, *Aspergillus*, *Massarina*, *Tubeufia*, *Campylospora*, *Delitschia*, *Talaromyces* and *Penicillium*. The analysis showed the centrality of the terms freshwater fungi, antimicrobial activity, secondary metabolites, aquatic fungi and natural products. These findings indicate that freshwater fungi are promising reservoirs of bioactive chemical diversity, although the field remains geographically concentrated and poorly explored in tropical ecosystems, especially in the Amazon.

Keywords: freshwater fungi; natural products; secondary metabolites; antimicrobial activity; bibliometrics.

RESUMO

Fungos de água doce representam um grupo ecológico e biotecnológico ainda subexplorado, apesar de sua relevância na decomposição de matéria orgânica e na produção de metabólitos secundários. Este estudo realizou uma análise bibliométrica sobre

fungos de água doce como fontes de produtos naturais com potencial antimicrobiano. Os dados foram recuperados nas bases Scopus e PubMed em 07 de julho de 2026, utilizando descritores relacionados a fungos de água doce ou aquáticos continentais, produtos naturais, metabólitos secundários, bioatividade e atividade antimicrobiana. Após remoção de duplicatas e triagem por título, resumo e palavras-chave, foram incluídos 53 documentos no corpus principal, dos quais 38 compuseram o subcorpus antimicrobiano. A produção científica mostrou crescimento recente, com maior concentração entre 2020 e 2026. O Journal of Natural Products foi o periódico mais frequente, enquanto Estados Unidos e China foram os países mais representados. Os gêneros mais recorrentes foram *Fusarium*, *Aspergillus*, *Massarina*, *Tubeufia*, *Campylospora*, *Delitschia*, *Talaromyces* e *Penicillium*. A análise evidenciou centralidade dos termos freshwater fungi, antimicrobial activity, secondary metabolites, aquatic fungi e natural products. Os resultados indicam que fungos de água doce constituem reservatórios promissores de diversidade química bioativa, mas o campo permanece geograficamente concentrado e pouco explorado em ecossistemas tropicais, especialmente na Amazônia.

Palavras-chave: fungos de água doce; produtos naturais; metabólitos secundários; atividade antimicrobiana; bibliometria.

1. INTRODUCTION

Antimicrobial resistance is one of the main contemporary challenges to public health because it reduces the effectiveness of antibacterial and antifungal agents, prolongs hospitalization, increases healthcare costs and limits essential clinical interventions. Global estimates indicate a substantial burden of mortality associated with bacterial antimicrobial resistance, reinforcing the need for new strategies for

the discovery and prioritization of anti-infective compounds (Murray *et al.*, 2022). In this context, the bioprospecting of microbial natural products remains relevant because many approved drugs derive directly or indirectly from natural metabolites (Newman; Cragg, 2020).

Among microbial groups with biotechnological potential, fungi stand out because they produce structurally complex secondary metabolites, including polyketides, terpenoids, alkaloids, peptides, xanthenes, naphthalenones, pyrones, quinones and meroterpenoids. Traditionally, much of the prospection of fungal metabolites has focused on terrestrial, endophytic, marine or plant-associated fungi. However, freshwater fungi constitute a distinct ecological group associated with substrates such as submerged wood, decomposing leaves, sediments, water, biofilms, macrophytes and riparian environments.

Freshwater fungi play relevant ecological roles, especially in the decomposition of lignocellulosic organic matter and in carbon and nutrient cycling. Continuous exposure to physicochemical variation, microbial competition, recalcitrant substrates and specific environmental pressures may favor distinct metabolic repertoires. This makes these fungi plausible sources of compounds with antibacterial, antifungal, cytotoxic, nematocidal, antioxidant, antibiofilm and quorum-sensing-modulating activities (El-Elimat *et al.*, 2021; Chen *et al.*, 2026).

Despite this potential, it remains unclear how scientific production on freshwater fungi and bioactive natural products is temporally distributed, which countries and groups lead the field, which fungal genera are most recurrent, which journals concentrate the literature

and to what extent antimicrobial studies occupy a central position in this production. In addition, important gaps remain regarding the representation of tropical environments, South American rivers and Amazonian ecosystems, although regional studies already indicate the potential of submerged-wood-associated fungi in the Amazon to produce antibacterial metabolites (Canto *et al.*, 2023).

Therefore, this study aimed to map global scientific production on freshwater fungi as sources of bioactive natural products, with emphasis on compounds and extracts with antimicrobial potential. Specifically, the study sought to characterize the temporal evolution of publications, identify the most relevant journals, countries, authors and documents, map recurrent keywords and fungal genera, delimit an antimicrobial subcorpus and discuss strategic gaps associated with tropical and Amazonian ecosystems.

2. THEORETICAL BACKGROUND

The literature on fungal natural products shows that fungi are important sources of chemical diversity and bioactivity. This potential results from secondary metabolism pathways capable of generating compounds with ecological functions related to competition, defense, signaling and environmental adaptation. In the context of antimicrobial discovery, this diversity can be explored through extract screening, compound isolation, bioactivity-guided fractionation and integration with analytical methods such as liquid chromatography, mass spectrometry and nuclear magnetic resonance (Balouiri; Sadiki; Ibnsouda, 2016).

Freshwater fungi can be broadly defined as fungi that occur in freshwater habitats and/or colonize substrates submerged or

periodically associated with fluvial, lacustrine and riparian environments. They include aquatic hyphomycetes, lignicolous ascomycetes, fungi associated with submerged wood, decomposing leaves, sediments, aquatic plants and biofilms. El-Elimat *et al.* (2021) reviewed metabolites published between 1992 and 2020 and highlighted that this group presents diverse chemical classes and relevant bioactivities. More recently, Chen *et al.* (2026) expanded this panorama by summarizing 307 natural products from freshwater fungi reported between 1988 and October 2025. In addition, Cicero, Mirabile and Venturella (2025) reinforced the medicinal relevance of freshwater macro- and micromycetes, emphasizing antimicrobial, anticancer, anti-inflammatory, antioxidant and immunomodulatory activities.

Antimicrobial activity is one of the main bioactivities reported for extracts and compounds from freshwater fungi. Examples include antifungal cyclic depsipeptides produced by *Clavariopsis aquatica* (Kaida *et al.*, 2001), antibacterial metabolites and quorum-sensing inhibitors from *aquatic fungi* (Paguigan *et al.*, 2019), antimicrobial compounds isolated from *Trichoderma flavipes* (Kim *et al.*, 2025) and antibacterial/antibiofilm metabolomic profiles of novel lignicolous *freshwater fungi* (Khruengsai *et al.*, 2026). El-Elimat *et al.* (2017) also reported α -pyrone derivatives, tetrahydroxanthones, hexahydroxanthones and cyclodepsipeptides from freshwater fungi, reinforcing the chemical diversity associated with this ecological group. In the Brazilian Amazon, Canto *et al.* (2023) demonstrated antibacterial activity of ethyl acetate extracts obtained from fungi isolated from decaying wood in freshwater environments.

Bibliometric analysis is useful for organizing fragmented fields because it enables the identification of production trends,

collaboration networks, citation patterns, leading sources, dominant keywords and emerging thematic axes (Aria; Cuccurullo, 2017; van Eck; Waltman, 2010). For freshwater fungi, this approach is particularly relevant because the field intersects mycology, natural product chemistry, microbiology, pharmacology, ecology and biotechnology. Thus, a bibliometric approach can reveal both consolidated hotspots and underexplored niches, such as tropical freshwater environments.

3. METHODOLOGY

A bibliometric study was performed using records retrieved from Scopus and PubMed. Scopus was adopted as the main bibliometric database because it provides broad metadata on authors, affiliations, journals, citations, countries and keywords. PubMed was used as a complementary biomedical database to expand the retrieval of studies related to freshwater fungi, natural products, secondary metabolites and antimicrobial activity.

The searches were conducted on July 7, 2026. The strategy combined terms related to freshwater or continental aquatic fungi with terms associated with natural products, secondary metabolites, fungal extracts, bioactivity and antimicrobial activity. In Scopus, the search was conducted in title, abstract and keyword fields using the following expression: TITLE-ABS-KEY (("freshwater fungi" OR "freshwater fungus" OR "aquatic fungi" OR "aquatic fungus" OR "aquatic hyphomycetes" OR "freshwater ascomycetes" OR "submerged wood fungi" OR "submerged wood") AND ("natural product*" OR "secondary metabolite*" OR metabolite* OR "bioactive compound*" OR "fungal extract*" OR bioactivity OR bioactive)).

In PubMed, the search was adapted to title and abstract fields using the following expression: ("*freshwater fungi*"[Title/Abstract] OR "*aquatic fungi*"[Title/Abstract] OR "aquatic hyphomycetes"[Title/Abstract] OR "submerged wood fungi"[Title/Abstract]) AND ("*natural products*"[Title/Abstract] OR "*secondary metabolites*"[Title/Abstract] OR antimicrobial[Title/Abstract] OR antibacterial[Title/Abstract] OR antifungal[Title/Abstract] OR bioactive[Title/Abstract]). No initial restriction by publication year was applied. Original articles, reviews and book chapters were considered eligible when related to the study scope. The screening flow was organized according to the transparency principles of the PRISMA 2020 statement, although this study was designed as a bibliometric analysis rather than a systematic clinical review (Page *et al.*, 2021).

Documents were included when they addressed freshwater fungi, continental aquatic fungi, submerged wood fungi or fungi from riparian environments associated with natural products, secondary metabolites, fungal extracts, bioactivity or antimicrobial activity. Studies exclusively focused on marine fungi, purely ecological or taxonomic studies without connection to bioactivity or natural products, ecotoxicological studies without bioactive prospection, studies on water contamination without focus on bioactive metabolites, records on bacteria or actinobacteria and documents without minimum metadata were excluded.

Records were exported as CSV files from Scopus and TXT files from PubMed. The files were combined, standardized and deduplicated using DOI, title and year of publication. After deduplication, records were screened by title, abstract and keywords. Included documents were classified into two sets: a main corpus and an antimicrobial

subcorpus. The antimicrobial subcorpus was defined by the presence of terms related to antimicrobial, antibacterial, antifungal, antibiofilm, antibiotic or anti-infective activity in titles, abstracts, author keywords or indexed keywords.

The following indicators were analyzed: number of documents per year, document type, most frequent journals, most productive countries, most recurrent authors, most cited documents, most frequent author keywords, most mentioned fungal genera and collaboration/co-occurrence networks. Country, genus and keyword counts were treated as non-exclusive because the same document may contain multiple countries, genera or terms. Therefore, these values express frequency of occurrence in the corpus metadata rather than the absolute number of independent studies per category.

Data cleaning, deduplication and descriptive bibliometric indicators were performed using spreadsheet-based tabulation and computational processing of the exported metadata. Keyword, country and author co-occurrence matrices were generated from the standardized corpus. Co-occurrence and collaboration patterns were interpreted from standardized metadata, while descriptive figures and tables were generated from the cleaned dataset.

This study used Scopus and PubMed as bibliographic sources. The absence of Web of Science may have reduced the coverage of some records and limited analyses that depend on complete cited references, such as co-citation and bibliographic coupling. Nevertheless, the combination of Scopus and PubMed allowed the recovery of a coherent corpus aligned with the study objective,

integrating broad bibliometric coverage and complementary biomedical literature.

4. RESULTS AND DISCUSSION

4.1. Composition Of The Bibliometric Corpus

The search retrieved 116 raw records, of which 93 were obtained from Scopus and 23 from PubMed. After removal of 14 duplicates, 102 deduplicated records remained. Screening by title, abstract and keywords resulted in 53 documents included in the main corpus. Among these, 38 composed the antimicrobial subcorpus. Forty-nine records were excluded because they did not meet the thematic scope, mainly because they addressed ecotoxicology, environmental fungicides, exclusively marine studies, taxonomy without bioactivity or non-fungal organisms.

Regarding document type, the main corpus was composed predominantly of original articles (46/53; 86.8%), followed by reviews (5/53; 9.4%) and book chapters (2/53; 3.8%). In the antimicrobial subcorpus, original articles also predominated (33/38; 86.8%), followed by reviews (4/38; 10.5%) and one book chapter (1/38; 2.6%). This profile indicates that the field remains primarily experimental, with emphasis on isolation, chemical characterization and biological evaluation of fungal extracts and metabolites.

Table 1. Flow of document selection used in the bibliometric analysis.

Stage	Number of records
Records retrieved from <i>Scopus</i>	93

Records retrieved from <i>PubMed</i>	23
Raw total	116
Duplicates removed	14
Deduplicated corpus	102
Records excluded after screening	49
Main corpus included	53
Antimicrobial subcorpus	38

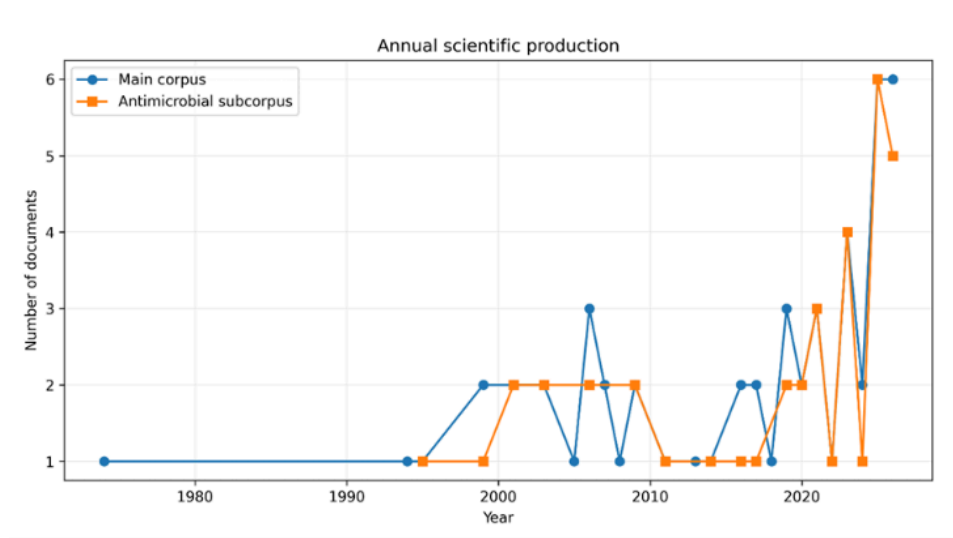
Source: research data (2026).

4.2. Temporal Evolution Of Scientific Production

The main corpus included publications from 1974 to 2026. Production was sparse in the initial decades, with only one document in 1974 and slow growth between the 1990s and 2010s. The highest concentration occurred in the 2020s, with 24 documents published between 2020 and 2026. The years 2025 and 2026 showed the highest absolute values, with six documents each.

In the antimicrobial subcorpus, the first retrieved publication occurred in 1995. Growth became more evident after 2020, with 22 documents between 2020 and 2026. The years 2025 and 2026 concentrated six and five antimicrobial documents, respectively. This recent increase suggests that freshwater fungi have gained visibility as sources of bioactive metabolites, probably influenced by methodological advances in metabolomics, LC-MS/MS, dereplication and renewed interest in neglected microbial niches.

Figure 1. Annual scientific production in the main corpus and antimicrobial subcorpus.



Source: research data (2026).

4.3. Journals, Countries And Collaboration Patterns

The Journal of Natural Products was the most frequent journal in the main corpus, with 10 documents, corresponding to 18.9% of the included records. Tetrahedron Letters and Journal of Fungi appeared next, with three documents each. Natural Product Research and Vegetos presented two documents each. The remaining journals appeared with one record each, indicating editorial dispersion of the field. In the antimicrobial subcorpus, the Journal of Natural Products was also the most frequent source, with eight documents, confirming the centrality of natural product chemistry in this research area.

Scientific production was concentrated in a few countries. In the main corpus, the United States appeared in 17 documents, followed by China (13), Mexico (6), India (6), Jordan (6), Thailand (3) and Brazil (3). In the antimicrobial subcorpus, the United States also led with 13 documents, followed by China (7), Mexico (5), India (5), Jordan (4), Thailand (3) and Brazil (3). Country collaboration data indicated

stronger connections among Jordan, the United States and Mexico, reflecting consolidated international networks in fungal natural products research.

The low representation of Brazil is notable given the extension of its continental aquatic systems and the biological diversity of the Amazon. This finding suggests that tropical freshwater ecosystems remain underrepresented in the international literature on bioactive natural products from freshwater fungi, despite their potential for bioprospecting.

Table 2. Most frequent journals in the main corpus.

Journal	Documents
Journal of Natural Products	10
Tetrahedron Letters	3
Journal of Fungi	3
Natural Product Research	2
Vegetos	2
Microbiology Research	1
Chiang Mai Journal of Science	1
Plant Biosystems	1

Source: research data (2026).

Table 3. Most frequent countries in the main corpus.

Country	Documents
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United States	17
China	13
Mexico	6
India	6
Jordan	6
Thailand	3
Brazil	3
Egypt	2

Source: research data (2026).

4.4. Keywords And Recurrent Fungal Genera

The most frequent author keywords were freshwater fungi (13 occurrences), antimicrobial activity (12), secondary metabolites (7), aquatic fungi (7) and natural products (5). Terms such as bioactive compounds, fungal extract, nematocidal, zone of inhibition, cytotoxicity, LC-HRMS and quorum sensing appeared with lower frequency. This structure indicates that the field is organized around three main axes: ecological origin of fungi, chemical diversity and biological evaluation, particularly antimicrobial screening.

The most frequently mentioned genera in the main corpus were *Fusarium* (seven occurrences), *Aspergillus* (six), *Massarina* (three), *Tubeufia* (two), *Campylospora* (two), *Delitschia* (two), *Talaromyces* (two), *Penicillium* (two), *Tetracladium* (two), *Alternaria* (two) and *Trichoderma* (two). In the antimicrobial subcorpus, *Fusarium* and *Aspergillus* were also the most frequent genera. This pattern

suggests coexistence between cosmopolitan, easily cultivable genera and more characteristic aquatic or lignicolous taxa.

The recurrence of *Fusarium*, *Aspergillus* and *Penicillium* is not unexpected because these genera are widely distributed and known for producing diverse *secondary metabolites*. However, the presence of *Massarina*, *Tubeufia*, *Delitschia*, *Clohesyomyces*, *Anguillospora*, *Longipedicellata*, *Wicklowia*, *Fluviatispora*, *Helicascus* and *Jahnula* indicates that the freshwater fungal literature also contains taxa that are less represented in conventional terrestrial fungal collections. These groups may therefore offer less redundant chemical repertoires.

Table 4. Most frequent fungal genera in the main corpus.

Fungal genus	Occurrences
<i>Fusarium</i>	7
<i>Aspergillus</i>	6
<i>Massarina</i>	3
<i>Tubeufia</i>	2
<i>Campylospora</i>	2
<i>Delitschia</i>	2
<i>Talaromyces</i>	2
<i>Penicillium</i>	2
<i>Tetracladium</i>	2
<i>Alternaria</i>	2

Source: research data (2026).

Table 5. Most frequent author keywords in the main corpus.

Author keyword	Occurrences
freshwater fungi	13
antimicrobial activity	12
secondary metabolites	7
aquatic fungi	7
natural products	5
endophyte	2
fungal extract	2
nematicidal	2
bioactive compounds	2
zone of inhibition	2

Source: research data (2026).

4.5. Most Cited Documents And Antimicrobial Subcorpus

The most cited documents included studies by Oh, Gloer and Shearer (1999), El-Elimat *et al.* (2003) and El-Elimat *et al.* (2021), indicating that the field has historically been driven by isolation and structural elucidation of bioactive metabolites.

The antimicrobial subcorpus comprised 38 documents, corresponding to 71.7% of the main corpus. These studies involved extracts, fractions or isolated compounds with antibacterial, antifungal, antibiofilm, antibiotic or anti-quorum sensing activity. The main genera associated with this subcorpus were *Fusarium*,

Aspergillus, *Tubeufia*, *Talaromyces*, *Penicillium*, *Tetracladium*, *Alternaria*, *Massarina*, *Clohesyomyces*, *Delitschia* and *Anguillospora*.

Recent literature shows methodological expansion. Khruengsai *et al.* (2026) integrated antibacterial assays, antibiofilm activity and metabolomic profiling of *Longipedicellata megafusiformis* and *Wicklowia fusiformispora*. Kim *et al.* (2025) characterized antimicrobial compounds from *Trichoderma flavipes* isolated from a freshwater environment, including cordyol C, diorcinol, violaceol I, tryptophol and violaceol II. These studies indicate progress toward approaches that connect bioactive phenotypes with chemical profiles, although attribution of activity to individual compounds still requires fractionation and experimental validation.

In the Brazilian context, the study by Canto *et al.* (2023) evaluated fungi isolated from decaying/submerged wood in Amazonian lakes and reported extracts active against *Staphylococcus aureus*, MRSA, *Escherichia coli* and ESBL-producing *Escherichia coli*. This record reinforces the relevance of Amazonian environments as sources of bioactive fungi and highlights the underrepresentation of tropical ecosystems in the global corpus.

Table 6. Most cited documents in the main corpus.

Title	Year	Journal	Citations
Massarinolins A-C: New bioactive sesquiterpenoids from the aquatic fungus <i>Massarina tunicata</i>	1999	Journal of Natural Products	77
New bioactive rosigenin analogues and aromatic polyketide metabolites from	2003	Journal of Natural Products	68

the freshwater aquatic fungus <i>Massarina tunicata</i>			
Freshwater Fungi as a Source of Chemical Diversity: A Review	2021	Journal of Natural Products	63
Ymf 1029A-E, preussomerin analogues from the freshwater-derived fungus YMF 1.01029	2008	Journal of Natural Products	59
Massarilactones A and B: Novel secondary metabolites from the freshwater aquatic fungus <i>Massarina tunicata</i>	2001	Tetrahedron Letters	59
Nematicidal resorcylics from the aquatic fungus <i>Caryospora callicarpa</i> YMF1.01026	2007	Journal of Chemical Ecology	55

Source: research data (2026).

4.6. Scientific Gaps And Opportunity For Tropical Ecosystems

The results demonstrate that the field of freshwater fungi as sources of antimicrobial natural products is emerging, chemically promising and geographically concentrated. Scientific production has been led by a small number of countries and collaboration networks, while South American tropical ecosystems remain poorly represented. This gap is not only geographical but also ecological and chemical because tropical freshwater environments may harbor fungi adapted to substrates, competitive pressures and environmental conditions distinct from those observed in temperate regions.

The Amazon represents a strategic gap in this context. Large rivers, streams, floodplain lakes, blackwater lakes, sediments and submerged wood compose microhabitats with intense lignocellulosic decomposition and high microbial diversity. Fungi associated with these substrates may present enzymatic and biosynthetic repertoires compatible with the production of antimicrobial metabolites, in addition to potential for biotransformation and metabolic elicitation of bioactive scaffolds.

From a methodological perspective, future studies should integrate molecular identification of isolates, cultivation oriented toward metabolic diversity, standardized extraction, quantitative antimicrobial screening, minimum inhibitory concentration determination, cytotoxicity assessment, untargeted metabolomics, dereplication, bioactivity-guided fractionation and structural elucidation. Such integration is essential to transform the ecological diversity of freshwater fungi into chemical candidates with greater translational potential.

5. CONCLUSION

The bibliometric analysis shows that freshwater fungi constitute a promising reservoir of bioactive natural products, especially compounds and extracts with antimicrobial activity. The analyzed corpus is small but has shown recent growth, mainly between 2020 and 2026. The field is led by specific groups and countries, especially the United States and China, and is strongly associated with natural product chemistry, particularly the Journal of Natural Products.

The genera *Fusarium*, *Aspergillus*, *Massarina*, *Tubeufia*, *Talaromyces*, *Penicillium*, *Delitschia* and *Trichoderma* appear as recurrent taxa,

whereas the central keywords are freshwater fungi, antimicrobial activity, secondary metabolites, aquatic fungi and natural products. The antimicrobial subcorpus represents most of the main corpus, indicating that anti-infective prospection is a structuring axis of the field.

Nevertheless, scientific production remains concentrated in a few countries and poorly representative of tropical ecosystems. The Amazon emerges as a strategic gap and scientific opportunity, especially for studies with fungi associated with submerged wood, sediment, water and other continental microhabitats. Future studies should integrate antimicrobial screening, molecular identification, metabolomics, bioactivity-guided fractionation and cytotoxicity assessment to qualify the translational potential of metabolites obtained from freshwater fungi.

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