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REVIEW PAPER

A bibliometric study on Sordariales fungi covering genetic diversity, ecological interactions and biotechnological applications

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ABSTRACT

The kingdom fungi, with its vast diversity and applications, is crucial in maintaining ecosystem balance and supporting industries like food production and environmental protection. Despite their ecological value, research on Sordariales is limited compared to other fungal orders. The aims include outlining the Sordariales research landscape, recognizing important themes and areas lacking attention, and showcasing potential uses in biotechnology. The data retrieval from Scopus from 1978 to 2024 for various aspects of Sordariales, including agricultural, nutritional, and industrial dimensions. Carefully selected search terms were implemented throughout all sections, such as titles, abstracts, and keywords. These terms were subsequently filtered to incorporate the latest relevant literature and subjected to a comprehensive bibliometric analysis, employing visualization of similarities (version 1.6.20) and the bibliometric R package. Publication trends with minimal research output were recorded until the 1990s, and an increase starting in 1995, which was widely published in high-impact journals with the top journals. Sordariales studies emphasize its ecological, genetic, and industrial importance across multiple scientific fields. The worldwide distribution of Sordariales research indicates that China is in the lead, with the United States ranking second. Research pattern shows the first cluster was fungal ecology and microbial diversity, the second cluster delves into the genetic and molecular biology of Sordariales, and the third cluster centers on the biochemical and enzymatic properties of Sordariales, despite emerging research assisting researchers in recognizing key trends and future directions. The role of Sordariales in carbon and nitrogen processes, as demonstrated by biotechnological applications, is crucial for converting livestock waste into compost, bio-based products, or biofuels. This conversion can help mitigate the environmental impact of animal agriculture and improve soil health and nutrient availability, which are vital for supporting plant growth and the functioning of microbial communities. Soil-related function highlights Sordariales fungi's significant role in soil ecosystems, underscoring their interactions with other microorganisms and their impact on nutrient cycling. Sordariales contribute to soil health by decomposing organic matter, recycling nutrients, and supporting biogeochemical cycles, thus aiding ecosystem stability. he metabolic diversity and biotechnological possibilities of fermentation and enzymes are prominently displayed. Plant-root related function reveals significant linkages between Sordariales and plant-root functions. Concurrently, enzymes decompose cellulose into simpler sugars, promoting nutrient cycling and boosting soil fertility. Co-occurrence analysis of Sordariales identified major clusters-fungal ecology, molecular genetics, biochemistry, and phylogenetics-reflecting interconnected research themes and highlighted genetic studies, soil functions, and enzyme applications. Sordariales' roles in carbon and nitrogen cycling, enzyme production, and plant interactions. Upcoming studies should enhance data collection methods and delve into the molecular mechanisms, since Sordariales fungi are essential for ecological functions and offer promising opportunities for biotechnological advancements.

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INTRODUCTION

With its vast diversity and applications, the kingdom of Fungi is crucial in maintaining ecosystem balance and supporting industries like food production and environmental protection (Corbu *et al.*, 2023; Hussin *et al.*, 2023). Fungi linked to marine plastic waste, such as those from the Sordariales order, demonstrate intricate relationships with different ecosystems, highlighting the significance of researching fungi to gain deeper insights into ecological dynamics (Vaksmaa *et al.*, 2024; Nakbi *et al.*, 2024). The Sordariales, an order within the Sordariomycetes class in the phylum Ascomycota, occupy diverse ecological niches, playing essential roles in nutrient cycles, decomposition, and symbiotic relationships in both terrestrial and aquatic ecosystems (Bao *et al.*, 2023; Debeljak and Baltar, 2023). Although Sordariales hold significant ecological importance, studies focusing on this fungal order are relatively scarce in comparison to others (Wang *et al.*, 2023b). Sordariales serve as reservoirs of secondary metabolites, offering valuable applications and warranting further study, especially given the potential of omics tools for discovering new secondary metabolites in this group (Charria-Girón *et al.*, 2022; Shao *et al.*, 2022). The complexity of Sordariales is further demonstrated through interactions with animals, as they serve dual roles as both pathogens and symbionts. For example, species like *Sordaria fimicola* typically release spores from mammalian dung, playing a role in nutrient cycles. Their spores found in ancient sediments can even indicate past herbivore activity (Wang, 2020). In addition to their role in decomposition, Sordariales species establish advantageous partnerships with plants, promoting their growth and resilience, which is essential for sustainable agricultural practices (Voigt *et al.*, 2021). This study uses a bibliometric approach to explore Sordariales genetic diversity, ecological interactions, and biotechnological applications, reviewing research trends and identifying areas for further analysis (Bao *et al.*, 2023). The progress in genomics and molecular biology, particularly through high-throughput sequencing and bioinformatics, has paved the way for new research into the genetic diversity of Sordariales. These technologies help uncover new genes and metabolic pathways, potentially leading to discoveries in enzymes, antibiotics, and bioactive compounds. Given the extensive data available, a systematic literature review is necessary to synthesize insights effectively and drive biotechnological advancements (Hensen *et al.*, 2023). Conducting a bibliometric analysis is vital for recognizing major research areas, impactful studies, and leading scholars in the Sordariales discipline (Maltseva and Batagelj, 2024). Citation patterns and publication trends reveal the evolution and expansion of Sordariale's research, benefiting researchers navigating vast literature and funding agencies allocating resources efficiently (Hensen *et al.*, 2023). Combining bibliometric and content analyses yields an in-depth understanding of themes and trends, highlighting dominant research methods, focal topics, and emerging patterns (Wang *et al.*, 2023a). This approach, widely used across various fields from 2000 to 2024, gives a holistic view of current knowledge, helping identify areas needing further exploration (Corbu *et al.*, 2023; Marin-Felix *et al.*, 2020). Combining bibliometric and content analysis offers a comprehensive insight into Sordariale's research. While bibliometric analysis offers quantitative insights into publication and citation patterns (Charria-Girón *et al.*, 2022; Hensen *et al.*, 2023; Marin-Felix and Miller, 2022; Bao *et al.*, 2023), content analysis delivers qualitative assessments. These techniques facilitate an in-depth evaluation, steer research initiatives, and encourage cooperation among scholars. Currently, a dedicated bibliometric study on Sordariales is lacking, highlighting the need for systematic analysis to map this study landscape (Wang *et al.*, 2023b). This study improves the understanding of the ecological roles and genetic diversity of Sordariales by analyzing publication and citation trends, pinpointing key themes, identifying knowledge gaps, and exploring potential biotechnological applications (Voigt *et al.*, 2021; Wang *et al.*, 2023b). This analysis will spotlight prevalent topics in current literature, reflecting the group's ecological significance and opening doors for future research and innovation. Interdisciplinary collaboration, integrating biosystematics, and biotechnology promises to accelerate discoveries in Sordariales research, enhancing both ecological insights and industrial applications. The aims include outlining the Sordariales research landscape, recognizing important themes and areas lacking attention, and showcasing potential uses in biotechnology. By mapping the research landscape, we aim to highlight opportunities for future innovation. Specifically, the study addresses several questions: 1) What are the key publication and citation trends in Sordariales

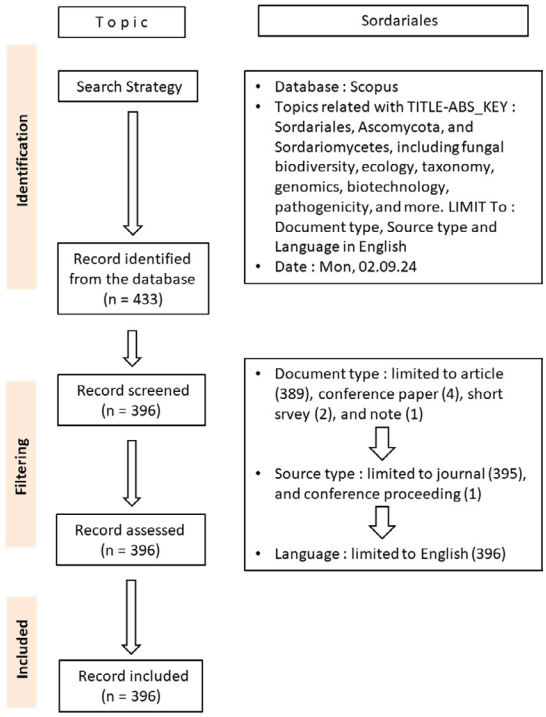

Fig. 1: A review procedure adapted from the preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram

research? 2) What predominant themes and topics emerge What significant patterns can be observed in the publication and citation of the current literature? 3) How do these themes reflect the ecological roles and genetic diversity of Sordariales? 4) What potential biotechnological applications have been explored? 5) What new opportunities exist for future research and innovation? Achieving these goals contributes to the expanding knowledge base on Sordariales, stimulating further research in mycology. This study underscores the importance of Sordariales in both ecological and biotechnological contexts, urging a comprehensive analysis of their diverse contributions, such as nutrient cycling, plant symbiosis, and industrial applications. This study has been carried out in National Research and Innovation Agency of Indonesia, in 2024.

METHODOLOGY

The data extraction from Scopus database was executed with a systematic and rigorous methodology. Scopus, an Elsevier-managed database, provides access to over 70 million records, offering researchers a vast repository of high-quality publications and analytical tools for efficient research. In order to address the comprehensive aspects of Sordariales, which include agricultural, nutritional, and industrial factors, strategically selected search terms were employed throughout all sections, including titles, abstracts, and keywords. This comprehensive strategy yielded 433 data points (Fig. 1), essential for a multidimensional analysis of Sordariales research.

A temporal filter limited results to the last five years (2020–2024), including the latest relevant literature. This period was selected to capture the latest research trends and developments in the field. Notably, between 2020 and 2024, there has been a significant increase in publications related to Sordariales, reflecting growing global interest in the topic. Concentrating on this specific time period allows for a more pertinent and current analysis, which can aid in shaping future research endeavors. After the initial search, records underwent thorough screening with stringent criteria, primarily focusing on English-language articles and proceedings. Through a meticulous selection process, the dataset was condensed to 396 entries, providing a strong foundation for an extensive bibliometric analysis of current research on Sordariales.

Table 1. Terminology mapping for network visualization: VOSviewer Term Replacement Data

Label	Replace by	Label	Replace by
Animals		Deoxyribonucleic acid (DNA), fungal	Fungal DNA
Article		DNA, ribosomal	Ribosomal DNA
Comparative Study		Fungal proteins	Fungal protein
Controlled Study		Fungus	Fungi
Human		Gene expression regulation, fungal	Gene expression regulation
Humans		Gene, fungal	Gene
Nonhuman		Genes, fungal	Gene
Priority Journal		Ribosome DNA	Ribosomal DNA
Unclassified Drug		Soils	Soil
Bacteria (Microorganisms)	Bacteria	Sp.	Species
Bacterium	Bacteria	Spores, fungal	Spore

Bibliometric and content analysis

The bibliometric analysis of Scopus metadata utilized visualization of similarities (VOSviewer) (version 1.6.20) and the Bibliometrix R package (version 4.1.1 on R software 4.4.1) to explore the key trends and future directions in Sordariales research (van Eck and Waltman, 2023; Aria and Cuccurullo, 2017; Team, 2018). Through a meticulous selection process, the dataset was condensed to 396 entries, providing a strong foundation for an extensive bibliometric analysis of current research on Sordariales. Bibliometric tools are useful for tracking research trends in Sordariales, but they have limitations. High impact factor (IF) journals are often used as quality indicators, yet studies show that significant fungal discoveries frequently occur in journals with low or no impact factors (Ifs). Furthermore, the presence of incomplete author information in databases, along with biases associated with gender or institutions, can distort the findings. These issues highlight the need for cautious interpretation of bibliometric data, especially in niche fields like fungal taxonomy. The research used both descriptive and co-occurrence analyses, combining Bibliometrix descriptive capabilities with VOSviewer structured keyword mapping. By analyzing co-occurrence patterns, VOSviewer grouped frequently occurring keywords into clusters, highlighting the thematic connections present the literature (Baker *et al.,* 2020). Sordiariales order is gaining more attention for their roles in nature and their uses in science. Nevertheless, the fungal order *Sordariales* remains largely unexplored in terms of bibliometric analysis. There is no comprehensive overview of how research on this group has grown or changed over time. The current study aims to bridge that gap by implementing a minimum occurrence threshold of five, thereby ensuring the inclusion of pertinent results and excluding less important keywords. The 100 keywords with the highest total link strength were selected to capture core themes and emerging trends within Sordariale's research. The next step in the refinement process included the standardization of keywords by consolidating both singular and plural forms (for instance, "bacterium" with "bacteria") and uniting synonyms (such as "fungus" with "fungi"), while eliminating irrelevant terms like "animals," "article," and "controlled study." This ensured the analysis focused solely on Sordariales-relevant literature (Table 1).

The visualization of keyword clusters was achieved through network maps, illustrating that keywords with a high degree of co-occurrence are situated near each other and connected by network pathways. An overlay visualization was generated with nodes meeting a minimum strength of 30 and displaying the 500 strongest links among them. It established a network of nodes in yellow or bright green, signifying the most recent research topics (Fig. 2).

Finally, these clusters were further explored within Bibliometrics to retrieve full-text papers. Prominent and well-cited articles from each cluster were identified, serving as a foundation for grasping upcoming research paths in the field of Sordariales studies. No bibliometric studies specifically addressing the order Sordariales were identified in the search. Nonetheless, there is relevant research, particularly in the form of phylogenetic studies concerning Sordariales. This work has culminated in the formation of several new families that more effectively illustrate the natural relationships among various taxa. While not

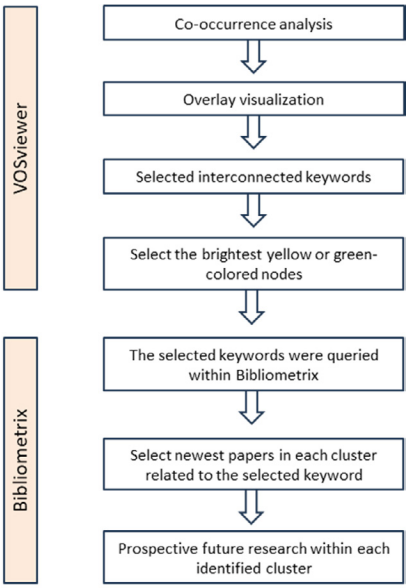

Fig. 2: Procedure of content analysis created by the authors

bibliometric in nature, such studies can still contribute valuable context and understanding of research trends related to Sordariales. This rigorous approach enables a comprehensive insight into evolving topics and identifies critical research areas for continued exploration in the field.

Descriptive analysis

Through descriptive analysis, one can investigate publication trends, research platforms, and the contributions of different countries, yielding a detailed understanding of patterns within a discipline. This encompasses the frequency of topics, leading journals, and the regions that are most prolific in research output (Nielsen, 2022).

Publication trend

The examination of Sordariales research articles over time, including their average yearly citation rates from 1978 to 2024, reveals a rising interest and significance in this field (Fig. 3). Research trends concerning Sordariales, a fungal order within the class Sordariomycetes, have markedly progressed from 1978 to 2024, highlighting improvements in molecular phylogenetics, genomics, and insights into ecological roles and secondary metabolites. The study originally focused on morphological classification, but recent research has shifted towards molecular systematics and genomic analysis, leading to a deeper comprehension of the evolutionary relationships and functional diversity within Sordariales. This shift in study emphasis underscores both the advancements achieved and the persisting deficiencies in the literature relative to other fungal taxa. Minimal research output was recorded until the 1990s, with a noticeable increase starting in 1995 and a surge in 1998, when publications reached 11 with a mean citation rate of 2.84 per year. Key years include 2006, 2009, 2014, 2016, 2019, and 2021, with 2020 peaking at 32 articles and the highest mean citations per year (7.01), signaling rapid growth.

This upward trend underscores the increasing interest in Sordariales, particularly in genetic diversity, ecology, and biotechnology. The findings suggest a bright outlook for future research, propelled by advancements in technology and efforts that span multiple disciplines. Similar trends in other fields reflect this heightened interest in biology and biotechnology globally (Castillo *et al.*, 2023; Gupta and Ahmed, 2019; Pautasso, 2012). In addition, a bibliometric analysis of *Nattrassia mangiferae* research revealed a sharp increase in studies, particularly from 2018 to 2021, reflecting increased attention to its pathogenicity and broader climate change implications on plant and human health (Samad, 2022). The effects of climate change are notably altering the distribution and ecological functions of Sordariales, which are fungi

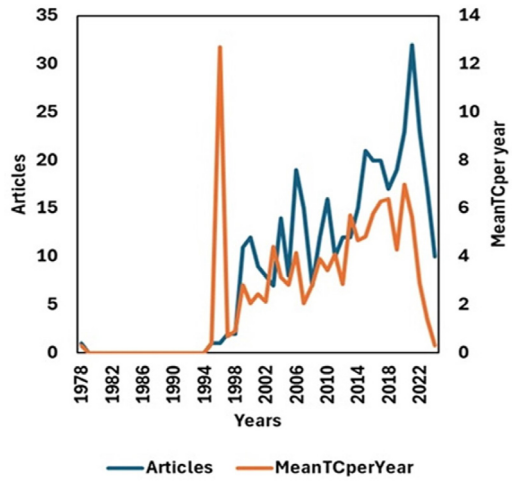

Fig. 3: Temporal trends in article count and mean citations per year (1978-2024)

that inhabit soil, wood, and aquatic environments. Factors such as temperature, humidity, and rainfall patterns greatly influence the life cycle and distribution of these groups. Studies conducted recently reveal that Sordariales species with particular substrate preferences, like Sordaria fimicola found in mammalian feces, are likely to shift towards higher latitudes and altitudes as global temperatures continue to increase. Changing environmental conditions can also affect the process of sporulation, mycelium growth, and secondary metabolite production, thereby interfering with their ecological function as a decomposer and an indicator of paleoecology. However, the case of Zootaxa, a mega-journal in zoological taxonomy, highlights the complexity and potential pitfalls of relying heavily on bibliometric indices such as the Journal Impact Factor, which can sometimes misrepresent the true impact and importance of research in a particular field (Pinto *et al.,* 2021). Numerous significant studies have greatly influenced research on Sordariales by offering essential insights into their classification and evolutionary connections. One key study created a detailed framework for Sordariomycetes using a four-gene phylogeny, which has greatly improved our understanding of their evolution. In a different study, researchers merged molecular and morphological data to refine the classification within the Sordariaceae family. Additionally, a third paper redefined the taxonomy of both Sordariales through molecular systematics. These studies are frequently cited because of their rigorous methods and clear taxonomic contributions, making them foundational to the understanding of fungi and evolutionary biology. Their widespread citation reflects their crucial role within the discipline.

Publication outlet

Research on Sordariales is widely published in high-impact journals, each offering essential advancements. According to Table 2, this distribution plays a vital role for researchers looking to emphasize the importance of their work to stakeholders, including funding bodies and government officials (Nielsen, 2022). The top journals publishing Sordariales studies emphasize its ecological, genetic, and industrial importance across multiple scientific fields.

Leading the list, Mycologia holds significant influence with 36 articles and a strong h-index of 20, reflecting its focus on fungal biology and ecology (Mondal *et al.,* 2023; Rousseau and Zhang, 2019). PLoS One and Fungal Diversity contribute substantially, underscoring Sordariales' broad relevance. Emerging journals like Frontiers in Microbiology highlight its interdisciplinary appeal and potential (Mylonakis, 2023). The movement towards open-access (OA) publishing has greatly enhanced the accessibility of research, particularly in areas such as mycology and Sordariales. From 2015 to 2020, the percentage of openly accessible full-text articles rose from 56.5% to 61.8%, with Gold OA publications increasing from 24.1% to 37.4%. This trend emphasizes a global effort to advance the openness and sharing of scientific information. While specific

Table 2. Top 10 journals publishing articles on Sordariales from 1978-2024

Journals	Publication on year start	Number of articles	Total citation	Production and citation impact (h-index)	Cumulative citation (g-index)	Productivity speed (m-index)
Mycologia	1996	36	1921	20	36	0.690
PLOS One	2008	16	816	12	16	0.706
Applied Microbiology and Biotechnology	1999	11	470	10	11	0.385
Fungal Diversity	2006	10	1458	10	10	0.526
Molecular Microbiology	2001	10	398	10	10	0.417
Applied and Environmental Microbiology	2004	11	492	9	11	0.429
Mycological Research	2002	10	434	9	10	0.391
Bioresource Technology	2012	8	317	8	8	0.615
Frontiers in Microbiology	2016	9	400	7	9	0.778
Fungal Genetics and Biology	2002	7	209	7	7	0.304

data on OA in Sordariales is scarce, it is likely to benefit from this broader momentum in fungal taxonomy and ecology. Open access fosters collaboration, particularly in resource-limited regions, while enhancing the visibility and citation opportunities for authors.

Country scientific production

The global distribution of research on Sordariales, depicted in Fig. 4, highlights notable regional disparities, with China leading by a significant margin, contributing 686 publications (Fig. 5). This preeminence showcases China's considerable investment in mycological studies, concentrating on fungal biodiversity and biotechnology, underpinned by a solid research framework and ample funding (Dong *et al.,* 2017; Wang *et al.,* 2023b; Zhang and Xie, 2023; Abdukerim *et al.,* 2025).

Following China, the United States ranks second with 283 publications, driven by its renowned research institutions and interdisciplinary collaborations that have expanded knowledge on Sordariales' genetic diversity and ecological roles, which are key to biotechnological advancements (Newcombe *et al.,* 2016; U'Ren *et al.,* 2016). The quick increase in omics data has significantly contributed to the progress of Sordariomycetes research, with various institutions concentrating on evolutionary genomics and transcriptomics. These studies have been instrumental in understanding the genetic and biological characteristics of Sordariales, with significant contributions from researchers (Wang *et al.*, 2023). Institutions focused on the diversity of secondary metabolites within Sordariales have pointed out the potential medicinal and industrial applications of these substances (Charria-Girón *et al.*, 2022). With 271 publications, Germany excels in genetic and molecular studies, employing advanced technologies to investigate fungal genomes (Blumenstein *et al.*, 2021). A total of 112 publications from Spain examine the ecological relationships and biotechnological applications associated with Sordariales (Agustí-Brisach *et al.,* 2021; Charria-Girón *et al.,* 2022). But multidisciplinary approaches combine ideas from several fields to respond coherently to challenging problems (Li *et al.,* 2024). Thailand and Brazil, with 87 and 81 publications, respectively, utilize their rich biodiversity to explore Sordariales' ecological and economic potential, indicating an increasing interest in fungal research in these biodiversity-rich regions (U'Ren *et al.,* 2016). Concurrently, the Netherlands, boasting 74 publications, and France, with 73 publications, highlight the significant presence of mycological research in Western Europe, particularly in the areas of advanced diagnostics and collaborative efforts (Hannula *et al.,* 2020; Salmanton-García *et al.,* 2023). With long traditions of excellence in biological sciences, these countries focus on both fundamental and applied aspects of Sordariales, advancing the understanding of fungal biology and its applications (Bretagne *et al.,* 2022; Buil *et al.,* 2020). India, boasting 66 publications, and Canada, with 40, are emerging research hubs that highlight the environmental and biotechnological significance of Sordariales (Gnanesh *et al.,* 2021; Haldeman, 2021). Collaboration between

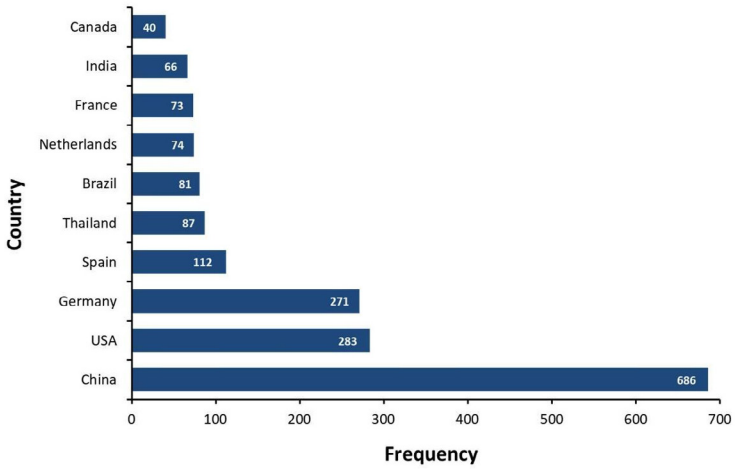

Fig. 4: The top 10 country ranks of the scientific paper production

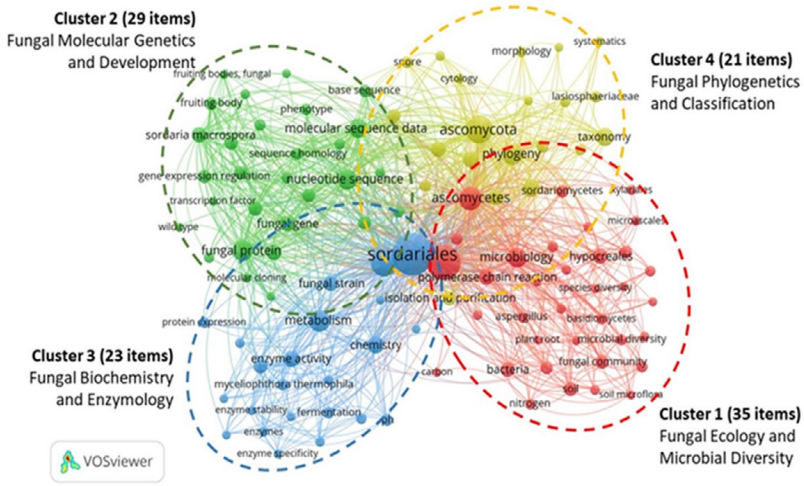

Fig. 5: Network visualization from co-occurrence analysis

developing countries in Sordariales research is still relatively limited, but is starting to show improvement, especially through regional cooperation in the exploration of local biodiversity. Nations like Indonesia, Thailand, Brazil, and India, which possess tropical ecosystems, significantly contribute to the discovery of new Sordariales species owing to their diverse biological resources. International partnerships have contributed significantly to the progress of Sordariales research, in several ways viz: 1) Access to advanced molecular technologies and methods, such as DNA sequencing and phylogenetic analysis, which are often not readily available in developing countries. 2) Capacity building of human resources through joint training, researcher exchange and publication collaboration. 3) Strengthening global scientific networks that accelerate data dissemination, new taxonomic discoveries, and potential applications of Sordariales in industry and ecology. 4) International collaborative funding that enables exploration of biodiversity and development of cross-border studies. The collaboration of developing countries in Sordariales research plays a crucial role in advancing the field, facilitated by mechanisms like the sharing of knowledge and resources. Together, these nations contribute substantially to the field, advancing fundamental and applied research on Sordariales and

reinforcing the importance of fungal studies globally. Research funding on Sordariales fungi remains limited, especially in developing countries, where attention tends to focus on more commercially valuable fungi. Nevertheless, there is a glimmer of optimism as global initiatives are starting to create new opportunities for researching Sordariales, particularly in tropical regions. The lack of funding has hindered the ability to investigate local species, employ advanced molecular methods, and produce significant publications or engage in international collaboration. The advancement is particularly apparent in the discovery of new species and the examination of their potential applications in biotechnology and environmental sustainability.

Research pattern

The co-occurrence analysis of research on Sordariales reveals distinct thematic clusters, each underscoring unique areas of study within the field. These clusters reveal significant insights into the diversity of research subjects and the connections among various scientific areas linked to Sordariales (Fig. 5). The first cluster was fungal ecology and microbial diversity, especially around the taxonomy and classification of fungi such as Ascomycetes and their interactions with soil microorganisms, with Sordariales standing out for their ecological significance. The importance of fungi, particularly those in microbial communities, is critical for sustaining environmental equilibrium. Their substantial representation, indicated by a count of 238 in community analyses, underscores their essential function in these ecosystems (Niego *et al.*, 2023). Ascomycetes are crucial in nutrient cycling, decomposition, and forming symbiotic relationships with plants, especially through mycorrhizal associations that enhance nutrient absorption and support plant growth (TlÁskal *et al.*, 2021). Other notable fungal orders, such as Hypocreales and Eurotiales, illustrate fungal communities' diversity and ecosystem contributions (Khaliq *et al.*, 2022; Devi *et al.*, 2020). The first cluster investigates the influence of fungi on plant ecosystems, underscoring their critical role in improving water and nutrient absorption, which is essential for sustainable agriculture. It also points out that recognizing this diversity is key to effective ecosystem management and conservation.

Fungi significantly influence plant ecosystems by affecting plant health, growth, and productivity. Mycorrhizal fungi, which belong to the Ascomycetes and Basidiomycetes groups, establish mutualistic associations with plant roots, enhancing water absorption and essential nutrients such as phosphates and nitrates (Ayana, 2020). Saprophytic fungi from the Ascomycetes and Basidiomycetes classes are integral to forest ecosystems, as they decompose organic material and facilitate the recycling of vital nutrients like nitrogen and phosphorus into the soil (Khaliq *et al.*, 2022; Leifheit *et al.*, 2024). Key genera, including Aspergillus and Penicillium, play pivotal roles in these processes. Innovations in molecular methods, including polymerase chain reaction and high-throughput sequencing, have substantially advanced the knowledge of microbial diversity and species identification, which in turn supports ecosystem management and conservation efforts (Gnanesh *et al.*, 2021; Voigt *et al.*, 2021). A second cluster delves into the genetic and molecular biology of Sordariales, where studies focus on terms like "fungal protein," "nucleotide sequence," and "gene expression." Model organisms such as *Sordaria macrospora* and *Neurospora crassa* are central to this research, contributing significantly to the understanding of fungal development, gene regulation, and protein synthesis. The findings from these studies might facilitate the discovery of new genes and pathways that could be utilized in biotechnological applications, including the production of enzymes and the creation of pharmaceuticals. Further, research has identified key genes involved in fruiting body development through transcriptional studies, thus expanding the prospects for biotechnological innovation (Kim *et al.*, 2022; Wang *et al.*, 2023b). Studies have demonstrated the significance of model organisms like *Neurospora crassa* and *Sordaria macrospora,* which play a crucial role in elucidating gene regulation and developmental processes. As an example, research has demonstrated the critical roles chromatin-associated proteins such as ASF1 (Anti-Silencing Function 1, a histone chaperone) and RTT109, a histone acetyltransferase (HAT) play in the development of sexual behavior and the DNA damage response in *Sordaria macrospora* (Breuer *et al.*, 2024). This second cluster enhances the understanding of fungi and opens up new possibilities for biotechnological applications, such as the production of enzymes and pharmaceuticals. The third cluster emphasizes fungi's promise in environmental biotechnology and bioenergy. It shows that fungi

can do much more than play ecological roles. The cluster centers on the biochemical and enzymatic properties of Sordariales, highlighting terms such as "enzyme activity" and "metabolism." Research on fungi like *Myceliophthora thermophila* has shown great promise in industrial applications, especially in biofuel production, waste degradation, and synthesis of valuable chemical compounds. Known for its production of potent enzymes in harsh conditions, this fungal species is well-suited for applications in environmental biotechnology and bioenergy (Dahiya *et al.*, 2021; Zhang *et al.*, 2023). Finally, the phylogenetic and taxonomic cluster underscores the importance of understanding evolutionary relationships through terms like "phylogeny," "taxonomy," and "classification." Genetic data, such as fungal DNA sequences, are instrumental in refining taxonomic classifications and providing a more comprehensive picture of Sordariales' evolutionary history (Voigt *et al.*, 2021). *Sordariales* taxonomy uses several genetic markers for better accuracy. The high variability of ITS is instrumental in identifying different species. Furthermore, the large subunit (LSU) and small subunit (SSU) ribosomal ribonucleic acid (rRNA) genes facilitate a more comprehensive classification. β-tubulin and ribosomal-ribonucleic-acid polymerase II subunit B (RPB2) improve resolution at species and genus levels. Combining markers gives clearer, more reliable evolutionary insights. This avoids the limits of single-gene analysis. The importance of this phylogenetic framework cannot be overstated in the fields of ecology, agriculture, and medicine, where accurate classifications are essential for elucidating ecological roles and interactions (Marin-Felix *et al.*, 2020). The final cluster is crucial for many areas, such as ecology, agriculture, and medicine. Accurate classifications help us understand ecological roles and interactions. New biosystematic approach using phylogenetic data can refine Sordariales classification, aiding ecological and functional studies. This facilitates a more efficient evaluation of fungal diversity and the creation of robust ecosystem management strategies. Within plant ecosystems, Sordariales fungi are essential for symbiotic associations, particularly mycorrhizal relationships that improve nutrient absorption, supporting plant growth and soil health (Frac *et al.*, 2018; Khaliq *et al.*, 2022). Achieving taxonomic clarity enhances biodiversity conservation efforts, allowing for improved assessments of fungal diversity and more effective strategies for managing ecosystems (Zeng *et al.*, 2019). Understanding these relationships helps ecologists maintain ecosystems where Sordariales fungi contribute significantly.

Emerging topics

A thematic map offers a structured overview of central themes and emerging research areas within Sordariales studies, assisting researchers in recognizing key trends and future directions (Pillay *et al.*, 2019). This visualization plays a crucial role in pinpointing major topics and comprehending the progression of research in this area throughout the years. The effectiveness of thematic mapping in observing spatiotemporal changes has been demonstrated across multiple domains, particularly in the context of shifts in forest cover (Dias *et al.*, 2020). When linked open data (LOD) is integrated with spatial data infrastructures, it enhances the interoperability of geospatial data, which is vital for creating effective thematic maps (Wiafe, 2018). Moreover, universities highlight the principles of thematic mapping, stressing its importance in education and training for effective communication through maps (Köbben, 2018). Thus, thematic maps are powerful tools for illustrating complex data, aiding decision-making processes in fields like Sordariales research (Köbben, 2018; Lange and Raposo, 2022; Pillay *et al.*, 2019). In Sordariale's research, "motor themes" are essential topics characterized by high centrality and density, marking them as well-developed, vital areas pushing the field forward. These subjects typically highlight important breakthroughs in genetic and developmental studies, with essential keywords including "gene," "sordaria," "macrospora," and "development" (Fig. 6). These terms highlight *Sordaria macrospora* as a crucial model organism, contributing profoundly to understanding fungal biology and molecular mechanisms. Research on this organism's developmental genes and regulatory proteins of this organism have revealed critical mechanisms such as autophagy and transcriptional regulation, which are vital for the growth of fungi (Teichert *et al.*, 2020; Werner *et al.*, 2021). Such themes reflect innovation in genetic research, advancing insights into fungal growth and development with broad applications in biotechnology and other scientific domains.

"Niche themes" within Sordariales research represent well-developed topics but are less central to the field, characterized by high density yet low centrality.

Examples include “fungal DNA,” “soil,” “diversity,” and “microbial.” These topics focus primarily on ecological factors and genetic variation of Sordariales fungi within soil habitats. By focusing on the contributions of microbial and fungal communities to soil health and ecosystem processes, these specific topics provide significant understanding of the ecological dynamics associated with Sordariales fungi (Corbu *et al.*, 2023). Even though these themes possess significant depth, they often occupy a marginal position within the wider research agenda, typically failing to take on a central role in guiding the field’s trajectory. They delve into specialized areas, such as Sordariales’ role in nutrient cycling, yet have limited influence on the larger scientific discourse. Themes in Sordariales research that are either emerging or in decline, characterized by low centrality and density, represent research areas gaining attention or losing relevance. The terms “species,” “molecular,” and “phylogeny” highlight the active research focused on species classification and the evolutionary relationships present within Sordariales. These areas are still developing and may grow in importance with new methodologies and discoveries. While peripheral to the core research focus, they provide essential insights that support the foundation without serving as the main drivers of the research. The dynamic nature of these themes shows how some areas may gain prominence, while others may fade as scientific priorities shift. “Primary themes,” marked by high centrality but low density, spotlight fundamental yet developing concepts central to Sordariale’s research. Keywords like “fungi,” “production,” “myceliophthora,” “characterization,” and “thermophile” indicate essential study areas related to Sordariales fungi biology and industrial applications. These themes are indeed crucial, yet their development is still underway, emphasizing the importance of ongoing research to fully grasp their effects in both industrial and scientific applications. This thematic map is a valuable bibliometric tool, allowing researchers to categorize and analyze Sordariale’s research themes based on density and centrality, thus helping shape the research landscape.

Potential biotechnological applications

Carbon (C)-related function of Sordariales

The network map’s visualization highlights the intricate interactions and relationships among key terms associated with Sordariales research, revealing their vital role in carbon-related functions. A key theme that has emerged from the network is the important ecological and biotechnological relevance of Sordariales fungi in carbon cycling (Fig. 7A). These fungi are pivotal in breaking down and transforming organic matter, thus playing a crucial role in the global carbon cycle (Leifheit *et al.*, 2024). Their metabolic processes enable the decomposition of complex organic compounds, contributing to the development of soil organic matter and the emission of carbon dioxide, essential for nutrient cycling and the overall fertility of the soil (Ye *et al.*, 2020). Sordariales fungi produce a variety of extracellular enzymes, such as cellulases, hemicellulases, and ligninases, which are instrumental in breaking down plant cell walls. This enzymatic

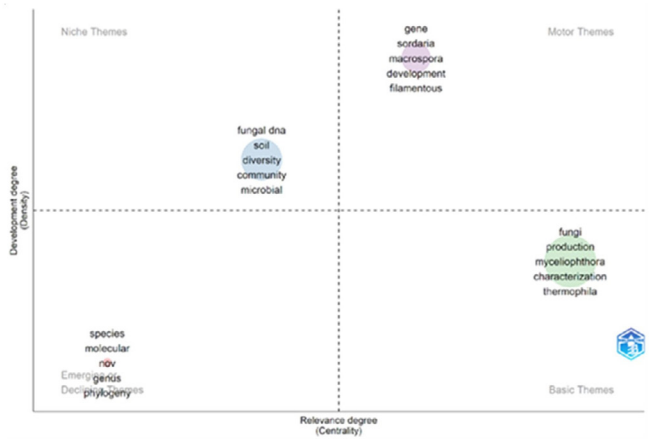

Fig. 6: Thematic map of Sordariales research using bibliometric analysis to identify and describe research themes, divided into four quadrants based on density and centrality

activity, influenced by the transcriptional control of genes involved in carbon metabolism, plays a crucial role in ecological nutrient cycling and is also applicable in industries such as biofuel production (Manuela del Rosario and Rita, 2022). The network map also shows a strong connection between Sordariales and "soil," underscoring their role in soil carbon sequestration. By decomposing organic matter and enhancing soil structure, these fungi contribute to carbon storage within the soil ecosystem (Rodrigues *et al.*, 2023). The study focus on Sordariales' carbon-related functions has intensified recently, with particular emphasis on their metabolic applications for industrial processes. Studies since 2010 have explored these fungi's potential in developing efficient biofuel production techniques and sustainable agricultural practices. The scalability of Sordariales-based bioprocessing is evidenced by their high enzyme yields and adaptability to industrial conditions, making them viable for large-scale applications such as biofuel production and bioremediation. Studies at the pilot scale has illustrated the capability of converting lignocellulosic biomass into bioethanol, resulting in a reduced reliance on chemical pretreatment processes (Manikandan *et al.*, 2022). Sordariales fungi play an essential role in animal husbandry systems by decomposing carbon-rich compounds like cellulose and lignin found in livestock waste. By releasing carbon back into the soil, this decomposition process enhances soil fertility and stimulates plant growth, contributing to the nutrient cycling in pasture ecosystems (Jørgensen *et al.*, 2007; Fu *et al.*, 2021). Moreover, the carbon degradation pathways of Sordariales offer biotechnological potential for converting livestock waste into compost, bio-based products, or biofuels, potentially reducing the environmental impact of animal farming (Xie *et al.*, 2014). Seeking sustainable biofuel production, researchers are exploring Sordariales microbes as a groundbreaking substitute for traditional chemical pretreatments, which typically rely on hazardous substances. Instead, these microbes produce enzymes like cellulases and xylanases that efficiently break down lignocellulose into simple sugars, which can be fermented into ethanol. By facilitating quicker biomass conversion, this enzymatic process boosts production efficiency and sustainability, playing a vital role in fostering a greener future (Mignogna *et al.*, 2024; Manikandan *et al.*, 2022). Research by Nargotra *et al.*, (2022) demonstrated the isolation of lignocellulolytic enzymes from Sordariales species with high efficiency in biomass pretreatment for biofuel production.

Nitrogen (N)-related function of Sordariales

The network image presents a detailed perspective on research concerning Sordariales fungi, underlining their contributions to the nitrogen cycle in multiple ecosystems (Fig. 7B). It shows the significant impact of Sordariales in nitrogen cycling, highlighting their contributions to soil health and nutrient availability, which are essential for plant growth and microbial community dynamics (Zeng *et al.*, 2019; Li *et al.*, 2023). Sordariales fungi transform nitrogenous substances in the soil, releasing nitrogen in forms that plants and other organisms can absorb. This process of nitrogen transformation boosts soil fertility, which in turn supports plant development. Sordariales interact with soil, nitrogen, and the broader fungal community, releasing enzymes and secondary chemicals that affect nitrogen availability and influence bacterial communities vital to the nitrogen cycle. The nitrogen cycle, shaped by fungi and bacteria, involves mineralization, nitrification, and nitrogen immobilization processes. In this context, Sordariales play a crucial role by metabolizing a range of nitrogen sources, including ammonium, nitrates, and organic nitrogen (Li *et al.*, 2023). The adaptability of Sordariales to different nitrogen types renders them particularly beneficial in high-nitrogen intensive agricultural environments. Nitrogen leaching and imbalances between nitrogen sources and crop demand are common issues in these settings. Sordariales fungi contribute to reducing these challenges by metabolizing excess nitrogen, making them essential players in nutrient cycling in diverse environments (Tei *et al.*, 2020). The interest in the nitrogen-related contributions of Sordariales has markedly intensified since 2010, indicating a heightened understanding of the significance of nitrogen cycling for sustainable agricultural practices and overall ecosystem well-being. Understanding Sordariales' nitrogen usage is crucial for advancing organic and sustainable farming practices. Their denitrification capabilities are also critical, as they help reduce nitrates to nitrogen gases, mitigating excess nitrogen's adverse effects, especially where nitrate-rich soils can foster bacterial pathogens (Huang *et al.*, 2020). Furthermore, some species within the Sordariomycetes class generate nitrous oxide (N_2O), which affects the cycling of nitrogen in soil and

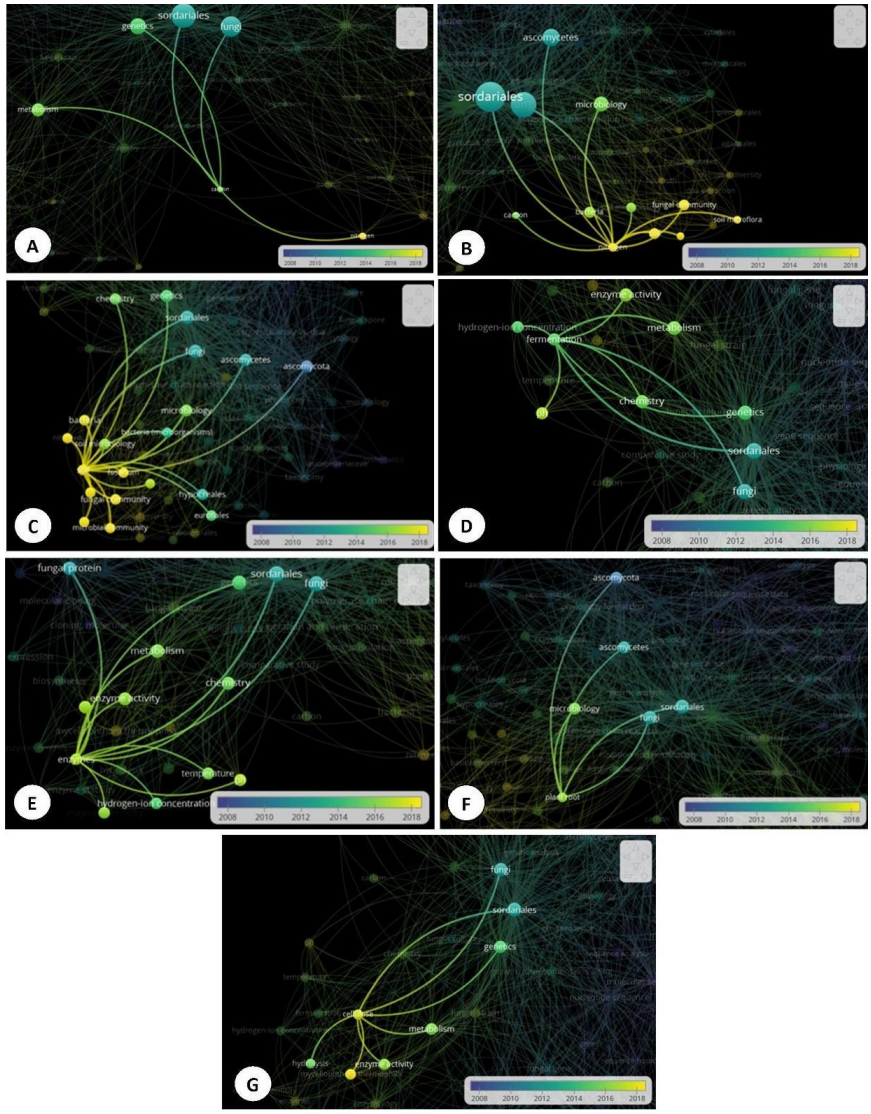

Fig. 7: Potential biotechnological relevance of Sordariales fungi A) Carbon-related function, B) Nitrogen-related function, C) Soil-related function, D) Fermentation-related function, E) Enzyme-related function, F) Plant root-related function, and G) Cellulose-related function of Sordariales

its emissions. The role of Sordariales in the nitrogen cycle extends to soil biocrusts, where nitrogen-related activities such as mineralization and nitrification occur more actively than in deeper soil layers. A range of functional groups, including bacteria and fungi, contributes to nutrient cycling, emphasizing the vital ecological role of microbial diversity in optimizing nitrogen efficiency (Mueller *et al.*, 2015). Sordariales fungi, especially within the Sordariomycetes group, are essential denitrifiers in various ecosystems, notably in arable soils where denitrification processes are crucial. Although fungal denitrifiers remain underexplored, Sordariales contain genes like nitrite reductase (nirK), which are linked to denitrification. The relationship between Sordariales and bacteria is shaped by certain genes and soil factors, including hydrogen (pH) and nitrate levels, which play a crucial role in determining nitrogen availability and enhancing soil fertility (Xu *et al.*, 2019). This process, regulated by nitrogen-responsive genes, mitigates excess nitrogen in agricultural soils,

supporting plant growth and microbial dynamics (Li *et al.*, 2023). Their metabolic flexibility permits them to utilize a range of nitrogen sources, including ammonium and organic nitrogen, making them essential for sustainable farming practices. Molecular studies reveal how these fungi influence bacterial communities through secondary metabolites, further shaping nitrogen cycles (Zeng *et al.*, 2019). The findings of Ibrahim *et al.* (2021) revealed that bioactive compounds derived from Sordariales demonstrate antibacterial and anticancer effects, pointing to their possible applications in the pharmaceutical industry. In addition to their ecological roles, Sordariales are significant in biotechnology, agriculture, and medicine. For instance, members of the Lamiaceae family generate enzymes and bioactive substances that could be valuable in industrial and pharmaceutical applications. Their antifungal properties offer promising avenues for new antibiotics and plant protection agents. Additionally, marine fungi within Sordariales demonstrate diverse functions such as saprotrophy, parasitism, and symbiosis, with potential applications in marine biotechnology (Ibrahim *et al.*, 2021; Cunliffe, 2023). Sordariales play a significant role in nutrient cycling in livestock farming, especially nitrogen. *Sordaria fimicola* and similar species serve as saprotrophs, decomposing organic substances, including animal dungs. This decomposition process liberates nitrogen into the soil, fostering plant growth that is crucial for the health of pasture ecosystems (Zhang *et al.*, 2021). This activity also helps maintain soil structure and microbial diversity, which are crucial for the health of grazing lands (Jørgensen *et al.*, 2007). Sordariales flourish in nitrogen-rich habitats thanks to their adaptability, allowing them to break down substances such as urea and undigested proteins found in dung. This transformation of nitrogen into usable forms supports soil fertility in agricultural contexts. Their spores, preserved in ancient sediments, offer insights into past herbivore activity and nitrogen dynamics, providing a historical perspective on ecosystems (Lee *et al.*, 2022). Recent studies suggest that some Sordariales may live endophytically within plant tissues, potentially influencing plant nitrogen metabolism, which expands their ecological role beyond decomposition (Sieber, 2007). Studies on Sordariales highlight their essential contributions to nitrogen dynamics and their significant ecological roles. In aquatic environments, these fungi contribute to the breakdown of organic matter, affecting nitrogen and carbon cycles (Goh *et al.*, 2020; Gutiérrez *et al.*, 2020). Sordariales' involvement in marine nitrogen cycling demonstrates the importance of fungi in nutrient regulation, supporting the view that fungi are central to nitrogen balance in diverse ecosystems. While the challenges associated with nitrogen cycling are often more localized than those related to carbon dioxide, the roles of Sordariales underscore their significance in maintaining ecosystem health and nutrient cycling (Zhang *et al.*, 2020). Sordariales' flexible metabolism makes them particularly effective in nutrient-poor environments. Although nitrogen deficiency might reduce their growth rate, it does not obstruct their contribution to nutrient cycling. For instance, *Sordaria macrospora*, a Sordariales species, serves as a model organism for studying fungal development and nitrogen's influence on growth (Charria-Girón *et al.*, 2022; Teichert *et al.*, 2020).

Soil-related function of Sordariales

The network visualization highlights Sordariales fungi's significant role in soil ecosystems, underscoring their interactions with other microorganisms and their impact on nutrient cycling (Fig. 7C). Co-occurrence analysis indicates potential connections; however, further studies are needed to substantiate these interactions (Wang *et al.*, 2023). Sordariales contribute to soil health by decomposing organic matter, recycling nutrients, and supporting biogeochemical cycles, thus aiding ecosystem stability (Charria-Girón *et al.*, 2022; Zhang *et al.*, 2024). These fungi decompose intricate organic compounds, thereby releasing vital nutrients that promote plant growth and sustain soil fertility (Du *et al.*, 2024; Leifheit *et al.*, 2024). Sordariales association with "decomposition" and "nutrient cycling" reflects their role in carbon and nitrogen cycling, which enhances soil structure and water retention. Their interactions with bacteria shape microbial communities, reinforcing soil health and agricultural productivity. Interest in soil functions has surged since 2012, propelled by developments in molecular biology and the critical need for sustainable agricultural practices (Mamatha *et al.*, 2024).

Fermentation-related functions of Sordariales

The network visualization underscores the fermentation capabilities of Sordariales fungi, demonstrating their diverse metabolic processes

and promising biotechnological prospects (Fig. 7D). Known for their robust enzyme production, these fungi break down complex organic compounds through fermentation, crucial for nutrient cycling and energy flow within ecosystems. Important concepts such as "fermentation," "enzyme activity," and "metabolism" underscore the significance of Sordariales in transforming plant biomass into valuable products, including biofuels (Li *et al.*, 2020). Fungi in the Chaetomiaceae family, such as *Myceliophthora thermophila*, produce enzymes like cellulases and xylanases, essential for industrial fermentation processes. Fungal phytases are widely used in food and animal feed additives. They facilitate better phosphorus uptake in animals and aid in decreasing phosphorus-related environmental pollution, highlighting their importance in agricultural and ecological settings. Fungi from the order Sordariales, particularly *Neurospora species*, show strong potential in biotechnology, especially fermentation. *Neurospora sitophila* showed the highest level of phytase production at 195.66 unit per gram (U/g) followed by Jatuwong *et al.* (2020). Conditions like pH and temperature are vital for optimizing these enzymes, as demonstrated by *M. thermophila*'s endoxylanase activity at pH 5.0 and 60 degrees Celsius (°C) (Dahiya *et al.*, 2021). Developments in genetic engineering have increased the fermentative efficiency of Sordariales, facilitating their application in bioenergy and organic acid production, which underscores their importance in sustainable technology (Naureen *et al.*, 2024; Aguilar-Paredes *et al.*, 2023).

Enzyme-related function of Sordariales

The network visualization highlights key terms connected to the enzyme-related functions of Sordariales, illustrating their ecological and biotechnological importance (Fig. 7E). These fungi are recognized for their powerful enzymatic functions, making them vital to nutrient cycling in ecosystems and leading to a wide range of industrial applications. Marine and freshwater environments host rich microbial communities, including fungi that decompose organic matter and regenerate nutrients. Tailored to thrive in marine settings, Sordariales synthesize hydrolytic and oxidative enzymes that are utilized in a variety of industrial applications (Bonugli-Santos *et al.*, 2015). Sordariales are prolific producers of enzymes like cellulases, hemicellulases, ligninases, and proteases, which break down complex organic materials, playing a crucial role in nutrient cycling and energy flow (Hemati *et al.*, 2022; Leifheit *et al.*, 2024). Their enzymatic processes they exhibit enable extensive industrial applications, particularly in biofuel generation and waste management. Large-scale bioprocessing becomes more viable due to the production of stable enzymes that can function under different conditions, which helps to decrease costs relative to synthetic alternatives (Alabdalall *et al.*, 2023). Fungi from the order Sordariales produce diverse enzymes like phytase, cellulases, laccases, and proteases, which are valuable in industries such as animal feed, textiles, biofuels, and bioremediation. Species like *Sporotrichum thermophile* and *Neurospora nobile* are notable for phytase production. These enzymes aid in biomass degradation and dye removal. While their industrial capabilities are promising, obstacles like the cost of production and the stability of enzymes still exist. Progress in fermentation, genetic engineering, and enzyme immobilization are vital for facilitating more extensive application. The activity of enzymes, vital for applications including biofuel production, waste management, and the paper industry, is heavily influenced by factors such as temperature, pH, and hydrogen-ion concentration (Sedek *et al.*, 2024; Abdel-Azeem *et al.*, 2021). Specifically, cellulases and ligninases from Sordariales facilitate plant biomass conversion into fermentable sugars, supporting bioethanol production and reducing fossil fuel dependency (Alabdalall *et al.*, 2023; Ilić *et al.*, 2023). The network map further links "enzyme activity", "metabolism", and "chemistry", emphasizing the study of Sordariales' enzymatic reactions and metabolic pathways (Kalntremtziou *et al.*, 2023). The degradation of cellulose by glycoside hydrolase genes is fundamentally linked to their expression, which is augmented by metabolic pathways that feature β-glucosidases and oxidative enzymes such as laccases. Genetic research advances the understanding of the genes responsible for enzyme production, aiming to enhance enzyme stability and specificity for industrial applications. Biotechnological techniques, such as Clustered regularly interspaced short palindromic repeats-based gene (CRISPR)-based gene editing can enhance enzyme production for industrial use by precisely modifying Sordariales' genomes to overexpress genes encoding enzymes like cellulases and ligninases, increasing yields and improving

stability for applications such as biofuel production. This approach, when combined with synthetic biology and directed evolution, maximizes enzyme efficiency and adaptability, thereby decreasing costs and improving scalability in industrial bioprocessing. These advancements further optimize enzyme yields, making Sordariales a promising candidate for industrial-scale biorefineries (Hensen *et al.*, 2023; Alabdalall *et al.*, 2023). In natural ecosystems, Sordariales enzymes like lignin peroxidase and laccase decompose lignin, while cellulases and hemicellulases release nutrients such as nitrogen, phosphorus, and carbon, improving soil fertility and plant growth (Kalntremtziou *et al.*, 2023; Kumar and Chandra, 2020). Moreover, Sordariales enzymes are effective in decomposing organic substances in animal excrement, facilitating nutrient cycling and providing possibilities for biofuel creation and eco-friendly agricultural practices, including the use of bio-based fertilizers and soil enhancements (Aguilar-Paredes *et al.*, 2023; Mignogna *et al.*, 2024).

Plant-root-related function of Sordariales

The network visualization reveals significant linkages between Sordariales and plant root functions, emphasizing their ecological and agricultural roles (Fig. 7F). Sordariales facilitate the uptake of essential nutrients, particularly phosphorus, in plants, in return for carbohydrates that are vital for plant development and soil vitality (Zhang *et al.*, 2020; Khaliq *et al.*, 2022; Tejakusuma *et al.*, 2025). Root metabolites play a crucial role in regulating root-fungi interactions. Agaricales and Sordariales are beneficial fungal orders with increased tread, possibly because of root compounds that aid nutrient absorption and soil carbon protection (Jingjing *et al*., 2022). The network demonstrates considerable connections among "Sordariales," "plant root," "fungi," and "microbiology," underscoring the critical nature of these connections (Pellerigno *et al.*, 2022). Additionally, Sordariales produce phytohormones that promote root growth and health, decompose organic matter, and recycle nutrients, benefiting soil fertility and plant vitality (Charria-Girón *et al.*, 2022). By controlling pathogens and strengthening soil structure, they facilitate better root access to nutrients, a vital aspect of sustainable agricultural methods (Aguilar-Paredes *et al.*, 2023). The presence of "Sordariales" in the soil is linked to soil structure and health improvements. Their hyphal networks help to stabilize soil aggregates, improving soil aeration and water retention. Modifications to the soil conditions can promote deeper root penetration and increase nutrient availability. The association with "fungi" and "microbiology" underscores the integral role of Sordariales in the soil ecosystem, contributing to the overall health and productivity of the soil (Alahmad *et al.*, 2023).

Cellulose-related function of Sordariales

The network visualization reveals key connections between Sordariales and cellulose-related functions, emphasizing their ecological and biotechnological importance (Fig. 7G). Sordariales, a group within the Sordariomycetes, decompose cellulose-a major plant biomass component-using cellulolytic enzymes like endoglucanases, exoglucanases, and β-glucosidases (Li *et al.*, 2012). These enzymes decompose cellulose into basic sugars, promoting nutrient cycling and improving soil fertility. This process can be scaled for biofuel production, transforming lignocellulosic biomass into fermentable sugars (Wu *et al.*, 2024). The network map shows strong associations between "Sordariales", "cellulose", "enzyme activity", and "hydrolysis" highlighting their roles in both natural and industrial contexts. Research focuses on optimizing enzyme production for cost-effective biomass conversion. Research focuses on refining enzyme production to facilitate affordable, large-scale biomass conversion, with successful trials indicating its feasibility for industrial applications (Bello *et al.*, 2022). Genetic advancements aim to boost enzyme yields, enhancing Sordariales' potential in large-scale industrial applications (Komorowicz *et al.*, 2023). The network connections between "Sordariales", "genetics", and "fungi" reflect this focus, indicating a substantial interest in understanding and leveraging the genetic basis of these fungi's cellulolytic functions. The progress in genetics is essential for maximizing the potential of Sordariales in various industrial and environmental applications (Sruthy *et al.*, 2023). From an ecological perspective, Sordariales contribute to soil health through the decomposition of plant litter, which helps in the creation of humus. This not only supports carbon sequestration but also releases nutrients, both of which are critical for maintaining forest sustainability (Wang *et al.*, 2024; Naureen *et al.*, 2024).

Sordariales in bioremediation

Evidence and potential applications: Despite the

limited research specifically addressing Sordariales in the context of bioremediation, recent evidence points to the promising capabilities of certain species in this order for environmental cleanup, particularly in the degradation of complex organic pollutants and the enhancement of soil health. Genera such as Chaetomium, Neurospora, and Sordaria well-known members of Sordariales produce robust extracellular enzymes like cellulases, laccases, peroxidases, and esterases. These enzymes are crucial for breaking down lignocellulosic compounds, dyes, pesticides, and polycyclic aromatic hydrocarbons (PAHs). For instance, *Chaetomium globosum* has been studied for its ability to degrade textile dyes and reduce heavy metal toxicity in soil, showcasing its role in mycoremediation. Sordariales have been noted to recolonize and restore ecological functions in agricultural soils that have been contaminated following pollution incidents. Their adaptability to stressful environments, such as areas affected by salinity, drought, or chemical exposure, is partly due to their strong antioxidant and detoxification systems, which may be harnessed for remediation purposes. Furthermore, the fact that certain species, like Sordaria fimicola, thrive in dung indicates their potential application in the biotransformation of animal waste and organic contaminants. These species thrive in nitrogen-rich, microbially active conditions, which are commonly found in contaminated compost or sludge environments. The evolution of omics technologies, particularly in the fields of transcriptomics and proteomics, has the potential to identify stress-response pathways and gene clusters that degrade pollutants in Sordariales, thus creating new opportunities for focused bioremediation strategies. Future research integrating metabolic profiling, microcosm experiments, and genetic manipulation is crucial to fully validate and optimize their application in polluted terrestrial and aquatic ecosystems. While still underexplored compared to other fungal taxa like Trametes or Aspergillus, Sordariales exhibit substantial untapped potential for bioremediation and deserve greater attention in mycoremediation research and sustainable environmental management.

Past and future recommendations

Research to date highlights the ongoing necessity for enhanced taxonomic clarity in the Sordariales order, especially concerning families such as Lasiosphaeriaceae, where the boundaries between genera and species are often ambiguous. Advances in molecular systematics, especially through the use of LSU rDNA sequences, offer promising tools to revisit and refine these classifications. Improving taxonomic resolution enables scientists to better understand the evolutionary relationships that exist within this wide-ranging group of fungi. Model organism utilization, *Sordaria macrospora* continues to serve as a valuable model for unraveling the complexities of fruiting body development in fungi. Its use has already contributed significantly to the understanding of fungal genetics and developmental biology. In order to delve deeper into the complex molecular mechanisms that control fungal growth and reproduction, it is vital to enhance genetic resources, such as well-organized mutant libraries and cutting-edge molecular tools (Teichert *et al*., 2020). For future research, exploration of marine fungi, marine fungi, especially those belonging to the Sordariales represent a largely untapped area of research with immense potential. These organisms could serve as a significant source of innovative enzymes with important applications in industry. Nevertheless, they have not been thoroughly investigated. Future research should prioritize bioprospecting marine-derived fungal enzymes, not only to expand the understanding of their unique adaptations but also to help tackle existing challenges in enzyme technology and bioprocess development (Muthusamy and Murugaiyan, 2023). In the climate change and fungal interactions, Sordariales fungi play a vital, yet often overlooked, role in the global climate system. In particular, understanding how Sordariales species interact with their surrounding ecosystems could shed light on their contributions to carbon cycling and ecosystem resilience. This information might be crucial in the development of nature-oriented solutions for mitigating climate impacts and restoring ecological balance. As climate change continues to reshape ecosystems, exploring the ecological functions of fungi becomes more urgent than ever (Case *et al.,* 2022).

CONCLUSION

This study delves deeply into Sordariales fungi, focusing on their ecological roles and significant potential for biotechnological advancements. Through bibliometric and content analysis, identified key research trends and themes that shape the scientific understanding of this fungal group. The results

highlight four major interconnected research areas: fungal ecology, molecular genetics, biochemistry, and phylogenetics. Additionally, thematic mapping demonstrated their vital contributions to nutrient cycling, enzyme generation, and their relationships with plants and animals, further reinforcing their ecological and industrial significance. Large-scale bioprocessing of Sordariales is feasible due to their metabolic flexibility and enzyme efficiency, as demonstrated in biofuel production and waste management. Sordariales fungi are essential decomposers in natural ecosystems, playing a fundamental role in breaking down organic matter and maintaining soil health. These fungi play an essential role in the carbon and nitrogen cycles, which is critical for the stability of ecosystems. Furthermore, they demonstrate considerable potential for applications in biotechnology. Their ability to produce diverse and powerful enzymes enables their use in industries such as biofuel production, bioremediation, and pharmaceuticals. Although these applications show great potential, a substantial lack of understanding persists regarding the molecular and biochemical processes that underpin their ecological roles and industrial functions. One major limitation of this study is its dependence on bibliometric analysis, which primarily reflects published research and may not capture ongoing or unpublished findings. As a result, while this study effectively maps broad scientific trends, it does not necessarily represent the latest experimental breakthroughs. Moreover, bibliometric approaches, despite their usefulness in mapping research trends, lack the capacity to deliver direct experimental validation concerning the ecological roles or industrial applications of Sordariales fungi. Future research should prioritize experimental studies alongside bibliometric analysis to gain a more comprehensive understanding of Sordariales fungi. Analyzing their genetic regulation, the processes involved in enzyme production, and their responses to diverse environmental factors will yield greater insights into their biological functions. The deployment of advanced omics technologies, which encompass genomics for the identification of functional genes linked to decomposition, transcriptomics for exploring environmental responses including stress adaptation, proteomics for optimizing enzyme production to improve industrial yields, and metabolomics for assessing metabolites such as biofuels and signaling compounds, can substantially enrich the understanding of the biochemical processes that underscore the importance of these fungi. Interdisciplinary collaboration will be essential in unlocking the full potential of Sordariales fungi. By bringing together experts in biosystematics and evolutions, mycology, biotechnology, marine and freshwater environment, animal husbandry, veterinary, ecosystem function, agriculture, researchers can develop innovative applications ranging from sustainable agriculture to industrial bioprocesses. By leveraging phylogenetic data, biosystematics enhances taxonomic structures, whereas biotechnology increases enzyme output through gene editing methods such as CRISPR. Furthermore, AI-driven strategies, particularly machine learning, enable predictions of metabolic functions and ecological roles, facilitating rapid research advancements. These efforts can address knowledge gaps, fostering sustainable solutions in agriculture and industry through enhanced collaboration across mycology, biotechnology, and computational sciences. In addition to their scientific and industrial relevance, studying Sordariales fungi can also contribute to broader sustainability goals. Their proficiency in breaking down sophisticated organic compounds and contributing to natural recycling processes positions them as vital players in confronting environmental challenges such as waste management and soil recovery. Harnessing their capabilities can support the development of greener technologies, contributing to a more sustainable future. As research on fungal biotechnology continues to expand, Sordariales fungi remain an exciting and dynamic field of study. Their vital ecological contributions, paired with a wide range of applications, emphasize the importance of sustained exploration and creative advancements. By deepening the understanding of these fungi, scientists can unlock new possibilities for sustainable solutions, environmental conservation, and biotechnological advancements that can benefit both nature and industry.

AUTHOR CONTRIBUTIONS

N.F. Wulandari performed the study conception and methodologies, conducted data analysis, collected data, drafted the manuscript, performed validation of results, and drafted and edited manuscript. A.R. Syam performed study methodologies, conducted data analysis, analyzed data using bibliometrix and VOSviewer, drafted the manuscript, and performed

validation of results. L. Alhamd conducted study methodologies, collected data, performed validation of results, drafted the manuscript, and performed validation of results. B. Gunadi collected and visualized the findings, analyzed data, drafted the manuscript, and performed validation of results. Yosmaniar drafted the manuscript, and validated the results. E. Widjaja drafted the manuscript, and validated the results. B.N. Utomo drafted the manuscript, and validated the results. S. Wahyuwardani drafted the manuscript, and validated the results. R. Widiastuti drafted the manuscript, and validated the results. T. Kadarini drafted the manuscript, and validated the results. S. Dody performed study conception, drafted the manuscript, and validated the results.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

°C	Degree Celsius
ASF1	Anti-silencing function 1, a histone chaperone, a protein support histone, fold and interact correctly
BRIN	Badan Riset dan Inovasi Nasional (National Research and Innovation Agency)
C	Carbon
CO_2	Carbon dioxide
CRISPR-based gene	Clustered regularly interspaced short palindromic repeats-based gene
DNA	Deoxyribonucleic acid
IF	Impact factor
ITS	Internal Transcribed Spacer
LOD	Linked open data
LSU	Large subunit
LSU nrDNA	Large subunit nuclear ribosomal DNA
N	Nitrogen
N_2O	Nitrogen oxide
nirK	Nitrite reductase
OA	Open access
PAHs	polycyclic aromatic hydrocarbons
pH	Potential of hydrogen
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
R	Programming language
rRNA	Ribosomal ribonucleic acid
RPB2	Ribosomal-ribonucleic-acid polymerase II subunit B
RTT109	A histone acetyltransferase, an enzyme that catalyzes the addition of an acetyl group to lysine residues on histones.
SSU	Small subunit
TC	Total citation

U/g	Unit per gram
USA	United States of America
VOS	Visualization of similarities

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