Wood decay fungi: an analysis of worldwide research

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Received: 30 January 2022 / Accepted: 23 April 2022 / Published online: 5 May 2022 © The Author(s) 2022

Abstract
Purpose Wood decay fungi are the only forms of life capable of degrading wood to its initial constituents, greatly contributing to the soil ecosystem. This study summarizes the current research status and development characteristics of global wood decay fungi research, in order to better understand their role in soils.

Methods A bibliometric analysis was applied to the literature from 1913 to 2020, based on data from the Web of Science (WOS) Core Collection. For this, various bibliometric analysis methods, R (Biblioshiny package), and VOSviewer were applied.

Results A total of 8089 documents in this field were identified in the WOS Core Collection. The annual number of publications tended to increase, with exponential growth after 2008. Researchers in this field were mainly concentrated in North Europe, the USA, and China. Biotechnology, applied microbiology, environmental sciences, and microbiology were the most popular WOS categories. *Bioresource Technology* and *Applied Environmental Microbiology* were the top two journals with the most citations. The top three authors with the most published papers were Dai YC, Martinez AT, and Cui BK. Co-occurrence analysis of author keywords identified six clusters, mainly divided into three categories: the classification and diversity, the degradation mechanisms, and the ecological functions of wood decay fungi. Clustering results further showed that the lignin degradation process and the application of wood decay fungi in industrial production and soil contamination remediation are current research hotspots.

Conclusions We present a comprehensive and systematic overview of research related to wood decay fungi and provide a deep perspective to understand the associated research progress. This is important for facilitating the development of a profound understanding of the contribution of wood decay fungi to soil systems and the degradation of soil contaminants.

Keywords Wood decay fungi · Keywords co-occurrence · Bibliometric analysis · Research hotspot

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1 Introduction

The degradation of dead wood is a critical process for nutrient cycling (Olson et al. 2012; Koffi et al. 2017), soil formation (Bugg et al. 2011a), and carbon balance in forest ecosystems (Alshammari et al. 2021). The rate of wood decay, as a combination of biological respiration, leaching, and fragmentation, is mainly the result of the organic activity (e.g., by fungi or insects), determined by both intrinsic (e.g., tree species properties) and environmental (e.g., temperature, moisture) factors (Lasota et al. 2018). Among the associated organisms, wood decay fungi are essential and extremely important, being the only forms of life capable of degrading wood to its initial constituents (Harley 1971; Bodeker et al. 2014). Without them, material cycles and energy flows cannot be realized, and the whole ecosystem will collapse (Alshammari et al. 2021). Thus, wood decay fungi are some of the most important decomposers in the forest ecosystem (Hottola et al. 2009; Riley et al. 2014; Hyde et al. 2016). “Wood decay fungi” is not a species or taxonomic term but, instead, a generic term for a group of fungi, including those fungal species which grow on various forms of wood substrates (e.g., standing wood, dead wood, fallen wood, and decaying wood) (Wendiro et al. 2019). According to the type of decay they cause, wood decay fungi can be classified into white-rot fungi, brown-rot fungi, and soft-rot fungi (Morrell 2002). They partially or completely degrade the lignin, cellulose, or hemicellulose that make up plant cell walls in wood by secreting extracellular enzymes (Procópio and Barreto 2021), such as oxidases and hydrolytic enzymes, and use the resulting products as nutrients (Alshammari et al. 2021). More specifically, white-rot fungi can degrade lignin, cellulose, and/or hemicellulose (Blanchette 1991; Tuor et al. 1995), accounting for 90% of total wood decay fungi and showing high diversity (Dai et al. 2007). Brown-rot fungi cannot degrade lignin but, instead, modify its chemical properties (Tuor et al. 1995; Dai et al. 2007; Dai 2012). Most wood-decaying species belong to Basidiomycota (Basidiomycetes), which are typically classified as either white- or brown-rot fungi (Riley et al. 2014). Sac fungi (Ascomycetes) comprise a small quantity of wood decay fungi, which can also degrade cellulose or hemicellulose (Liers et al. 2011). Therefore, they also contribute to the material cycle in forest ecosystems (Alshammari et al. 2021).

Wood decay fungi are important for a whole web of other organisms. They are a key part of the biodiversity in a forest ecosystem, and are important indicators for forest conservation, as they maintain biodiversity (Stokland et al. 2012). They play essential roles in forest regeneration by creating habitats and providing nutrients for other biological communities (e.g., small animals, plant seedlings) (Stokland et al. 2012). Most of them rely on dead wood as a growth substrate and have been shown to be sensitive to changes caused by forest management (Penttilä et al. 2004; Hottola et al. 2009). Moreover, some wood decay fungi can form huge mycelial networks with plants and apoplast at the soil surface, fostering connectivity and robustness (Bebber et al. 2007), both to exploit trophic heterogeneity over an extensive habitat and to remain robust to attacks by grazing arthropods, such as Collembola and other soil animals that feed on mycelium (Watkinson and Eastwood 2012). Wood decay fungi are not only a major element keeping forest ecosystems healthy, but they also play important roles in social, economic, and environmental pollution control. Laccases, a product of white-rot fungi when degrading a wood substrate, have been widely used in dealing with paper waste liquid, a variety of soil pollutants (e.g., antibiotics, heavy metals, polycyclic aromatic hydrocarbons), and incompletely utilized products of industrial production (Bilal et al. 2017). In addition, some fungi are important forest pathogens, while others have important medicinal and edible attributes (Hyde et al. 2019; Swislowski et al. 2020). Even in desert areas—which are often overlooked—studies have found that some fungal types can be effective in improving agricultural development (Ameen et al. 2020, 2022). Considering their importance, wood decay fungi have received increasing attention from forest ecologists, pathologists, and managers, including research focused on the factors that drive the species richness of wood-decomposing organisms, their functions within ecosystems, and their economic value (e.g., for the degradation of soil pollutants) (Eastwood et al. 2011; Floudas et al. 2012; Kahl et al. 2017; Couturier et al. 2018).

However, few studies have focused on the application of wood decay fungi using systematic bibliometric methods. Xiao et al. (2022) have conducted global research on white-rot fungi biotechnology for environmental application through a bibliometric analysis. In contrast, bibliometric research methods have been widely used in other similar research fields, including those related to mushrooms (Swislowski et al. 2020), fungal taxonomy (Michan and Llorente-Bousquets 2010), Taxus medicinal resources (Hao et al. 2012), bioherbicides (Triolet et al. 2020), ethnopharmacology (Yeung et al. 2020), and marine fungi (Noman et al. 2021). A comprehensive bibliometric analysis concerning the application of wood decay fungi has not yet been conducted, which makes it impossible to gain more insight to understand their contribution to soils through a systemic overview.

Several bibliometric methods and tools have been developed to help researchers in different fields to construct knowledge maps, to assess the collective state of thought...
on various topics, and to identify research hotspots (Liu et al. 2020). Bibliometrics provides useful quantitative tools for analyzing the progress of a certain research topic, from a macro or micro perspective (a macro perspective is based on analysis of the whole research, including various papers, categories, research countries, institutions, journals, and authors; while a micro perspective interprets the keywords, co-cited literature, and highlighted literature), based on the scientific peer-reviewed literature (Hu et al. 2017; Li et al. 2021). Such methods integrate computer engineering, big data applications, and statistics, and have been used in many fields. These applications have become more extensive, and rich evaluations can be provided at different levels (Chen 2017). Bibliometrics may provide in-depth qualitative features, in the form of a knowledge map and analyses of citations or cited references (Chen 2013). Generally, the more documents or references obtained, the deeper the understanding of the research topic (Chen 2017).

To evaluate the development status and entire landscape of wood decay fungi research, we carried out a comprehensive bibliometric study aimed at the global development of the topic. We analyzed all documents in various aspects, from publication output to critical research areas. Based on the results, we aim to (1) reveal the publishing trends of wood decay fungi research at a global scale; (2) elucidate the current research status and popular research focus; and (3) clarify the intellectual structure and research performance in the field.

### 2 Data and methods

#### 2.1 Literature search strategy

A comprehensive research methodology was adopted for the literature search in this study (Fig. 1). The ISI Web of Science (WOS) Core Collection was selected as the data source, and the topic was determined through expert consultation as well as literature investigation. The search formula for the advanced method was selected, according to the wood decay fungi research subject, after repeated tests. Retrieval was carried out in September 2021. The document type was article, and the review language was English. All records collected included (1) publication year; (2) WOS research categories; (3) countries/regions; (4) journals; (5) authors and their affiliations; (6) keywords; (7) abstract; and (8) references.

#### 2.2 Scientometric analysis methods

We used the Microsoft Excel, R 3.6.2 (Biblioshiny package), and VOSviewer (version 1.61.) software to mine, analyze, process, and visualize the literature data. Biblioshiny was developed by Dr. Massimo Aria (Federico II University of Naples, Italy), based on Bibliometrix’s shiny software package for R Biblioshiny allowing for relevant scientific measurement and visualization through the use of an interactive web interface. Research countries and
institutions, influential journals, and important authors are systematically analyzed using online analysis. The total local citation score (TLCS) represents the total frequency of the literature cited in the current literature list. “Web of Science Research Categories” have been assigned by Clarivate Analytics, which were used to classify the research papers. Each paper can be divided into at least one research field using the network science database.

VOSviewer, a free software based on java, was developed in 2009 by van Eck and Waltman from the Centre for Science and Technology Studies (CWTS) of Leiden University in the Netherlands (van Eck and Waltman 2010). It is mainly designed for document data and uses “network data,” which allows for relationship construction and visual analysis from the document knowledge unit. It can draw scientific knowledge graphs to indicate the relationships between the structure, evolution, and cooperation in the knowledge field (van Eck and Waltman 2010). The generated graphics include network visualization, overlay visualization, and item density visualization. In the item density visualization, neighboring items with higher weights will be colored closer to red. In the opposite case, the color will be closer to blue (van Eck and Waltman 2010).

Keywords can reveal the research topic in the literature, and the frequency of keywords can reflect research hotspots in the field. A research hotspot is the concentrated presentation of a certain area of research within a specific period, which can be considered the research frontier. The analysis of research hotspots helps in clarifying the development process of the research field, grasping the research context, and providing reference for exploration of directions for novel research. A co-word network composed of these word pairs can be formed by counting the frequency of subject words appearing in the same document (van Eck and Waltman 2010). High-frequency keywords can be used to assign research hotspots and important research topics within a period in a given field. Through the VOSviewer software, keywords were analyzed in terms of co-occurrence, and clusters representing the current research areas were formed (van Eck and Waltman 2010). These clusters indicate the most recent lines of interest by related researchers and may be used to determine the future directions of wood decay fungi research, based on keyword co-occurrence.

3 Results and discussion

3.1 Basic data information

After classifying the retrieved document data sets and eliminating irrelevant documents, a total of 8089 documents and 206,250 references were obtained. We found that the earliest publishing date of wood decay fungi research was 1878. The first publication (a book on wood decay fungi) was by Robert Hartig, entitled “Die Zersetzungerscheinungen des Holzes der Nadelholzbäume und der Eiche in forstlicher botanischer und chemischer Richtung” (Berlin 1878). This initiated the modern era of understanding of wood decay fungi. However, the WOS index was started in 1900. Therefore, the first paper indexed by WOS in our results was in 1913. Over the past 40 years, an average of 8.41 documents on wood decay fungi research has been published per year, with the average number of citations per document being 22.62. These results demonstrate the rapid and high-quality development of wood decay fungi research (Fig. 2).

3.2 Temporal evolution of documents

Figure 2 shows the number of annual documents related to wood decay fungi research from 1913 to 2020. This number increased from 1 in 1913 to 567 in 2020 (updated to 2020, data for 2021 are incomplete), with an average annual growth rate of 16.38%. The number of articles published each year since 2006 has exceeded 300. Since 1991, the number of wood decay fungi research studies published each year has exceeded 100; as such, 1991 can be considered as the turning point. The earliest wood decay fungi research study was by Matheny WA in 1913, entitled “A comparison of the American brown-rot fungus with Sclerotinia fructigena and S. cinerea of Europe” (Matheny 1913), published in the Botanical Gazette, which officially began the era of wood decay fungi research.

3.3 Global landscape

The distribution of the number of documents related to wood decay fungi research studies by country is shown in Fig. 3. The results show that 135 countries have engaged in this research. There were 14 countries with over 500 publications in total. The United States of America (the USA; 2832), China (2506), and Japan (1389) were the countries with the most published papers. In addition to the number of documents, the centrality of national cooperation can also be used as an indicator to measure a country’s research strength. Considering the cooperation centrality, the USA and China had the highest cooperation density (Fig. 3), demonstrating that these two countries could be at the forefront of international advancement in this field.

3.4 Research institutions

The cooperation overlay visualization considering institutions researching wood decay fungi is depicted in Fig. S1 (Online Resource). The results show that the University of Helsinki, Swedish University Agricultural Science, Forest Prod Lab USD, Kyoto University, and Beijing Forestry University have published the most papers in this field. These
five were the most influential research institutions among 5032 institutions globally engaged in this field of research, and accounted for 1111 articles together, including cooperation achievements for each institution (Table 1). Meanwhile, the results of the network visualization for research institutions demonstrated that Beijing Forestry University is a newly emerging research institution (the yellow color shown in Fig. S1 indicates that many studies were published after 2014).

### 3.5 Web of Science research categories

According to the WOS research category distribution result, the areas of wood decay fungi research increased from nine fields in 1980 to 97 in 2020, concentrated mainly in the fields of biotechnology, applied microbiology, environmental science, microbiology, paper wood materials science, forestry, biochemistry, molecular biology, plant sciences, and mycology. The main three research areas represented 6223 of the 8089 documents, accounting for approximately 76.93% of the total (Fig. 4), while 120 other categories accounted for only approximately 16.33% of the total. This revealed that the wood decay fungi literature has mainly been focused on environmental and microbiological research; however, many other research areas, such as soil science, water resources, toxicology, and biodiversity conservation, have been covered.

### 3.6 Journal analysis

The obtained wood decay fungi studies appeared in 1290 journals. The distribution of wood decay fungi research documents within major journals was examined, as shown in Fig. S2 (Online Resource). The top 20 (1.55%) journals published 2730 (26.14%) of the documents. To the contrary, 646 journals (50.07%) had published only one paper, and 401 journals (31.08%) had published two to five papers focused on wood decay fungi. As demonstrated in Table 2, *International Biodeterioration & Biodegradation* (421), *Holzforschung* (281), *Bioresource Technology* (277), *Applied and Environmental Microbiology* (277), and *Applied Microbiology and Biotechnology* (277) were the top five journals with the most papers published. According to Bradford’s law, the results revealed that the wood decay fungi research documents were highly dispersed, with a large portion being published in 20 journals, as shown in Table 2. The core sources are marked with asterisks (*); these journals can be considered playing an essential role in wood decay fungi research. Therefore, following the articles published in these journals may help to understand the latest developments in the field.

Citation statistics are generally used to evaluate the relative impact of an academic journal. The journals *Bioresource Technology, Applied and Environmental Microbiology, Applied Microbiology and Biotechnology, Enzyme and Microbial Technology*, and *International
Biodeterioration & Biodegradation were ranked in the top five, in terms of citations, in the collected data set (Table 2). These results indicated that these journals published documents than others and have highly cited times in WOS core collection as well as the local data collection. Among the core resources, Bioresource Technology is an important journal for the study of wood decay fungi, based on both quantity and quality (i.e., impact factor and TLCS).

3.7 Author analysis

Next, we identified highly productive authors, as shown in Table 3. The results suggested that the top three authors with the most published papers were Dai YC (94), Martinez AT (94), and Cui BK (87). Dai YC and Martinez AT were ranked first, with the same number of publications; however, considering the average number of citations, that of Martinez AT is about 47 higher than that of Dai YC, which is 25. According to Price’s law, authors who publish more than seven papers should be defined as the core authors in wood decay fungi field, of which there were 736. The top 10 core authors are shown in Table 3. The results of the author analysis can identify those who are more active, productive, or cited in the wood decay fungi literature, and their network contributions to the field.

These 10,444 papers involved 21,990 authors. A total of 360 independent authors published 518 studies. The remaining documents had 2.11 co-authors per document on average. The cooperation index was 2.18. Overall, each author

![Fig. 3 Density visualization of the number of documents, with respect to countries, in the wood decay fungi research field](image-url)

| Table 1 Top 10 productive institutions in wood decay fungi research |
|------------------|------------------|-----------|
| Institution                  | Total number of articles | Country   |
| University of Helsinki      | 254                | Finland   |
| Swedish University Agricultural Science | 228                | Sweden    |
| Forest Prod Lab USD         | 222                | USA       |
| Kyoto University            | 205                | Japan     |
| Beijing Forestry University | 202                | China     |
| Institute of Microbiology of the CAS | 181                | China     |
| University of Minnesota     | 169                | USA       |
| Kyushu University           | 144                | Japan     |
| University of Wisconsin     | 121                | USA       |
| Ctr Invest Biol             | 119                | USA       |
Fig. 4 Main research disciplines in Web of Science for wood decay fungi research studies

Table 2 Top 20 cited journals, ranked using the total local citation score (TLCS), in wood decay fungi research

| Journal                                 | TLCS   | ND  | H_i | AC   | PY_s | IF   |
|-----------------------------------------|--------|-----|-----|------|------|------|
| Bioresource Technology*                 | 26,411 | 277 | 68  | 95   | 1991 | 9.642|
| Applied and Environmental Microbiology* | 21,125 | 277 | 87  | 76   | 1983 | 4.016|
| Applied Microbiology and Biotechnology* | 13,496 | 277 | 61  | 49   | 1985 | 4.700|
| Enzyme and Microbial Technology*        | 12,602 | 189 | 64  | 67   | 1981 | 3.448|
| International Biodeterioration & Biodegradation* | 11,764 | 421 | 50  | 28   | 1992 | 4.340|
| Fems Microbiology Reviews               | 5852   | 21  | 20  | 279  | 1994 | 16.408|
| Journal of Biotechnology                 | 5826   | 96  | 40  | 61   | 1988 | 3.503|
| Holzforschung*                          | 5746   | 281 | 38  | 58   | 1965 | 2.120|
| Chemosphere*                            | 5351   | 144 | 47  | 37   | 1982 | 7.086|
| Process Biochemistry                    | 4856   | 84  | 38  | 58   | 1991 | 2.952|
| Journal of Hazardous Materials*         | 4563   | 91  | 41  | 50   | 1995 | 9.038|
| Mycologia*                              | 3711   | 108 | 34  | 34   | 1954 | 2.149|
| Biotechnology Advances                  | 3460   | 16  | 15  | 216  | 1992 | 10.744|
| World Journal of Microbiology & Biotechnology* | 3266 | 138 | 31  | 24   | 1992 | 2.477|
| Fems Microbiology Letters*              | 3165   | 99  | 33  | 32   | 1987 | 2.742|
| Water Research                          | 2780   | 36  | 28  | 77   | 1989 | 9.130|
| Environment International               | 2684   | 6   | 6   | 447  | 1994 | 7.577|
| Mycological Research                    | 2618   | 83  | 30  | 32   | 1990 | 2.789|
| Phytochemistry                          | 2566   | 30  | 20  | 86   | 1978 | 3.044|
| Soil Biology & Biochemistry             | 2535   | 56  | 31  | 45   | 1992 | 6.080|

*This journal is a core resource for wood decay fungi research

TLCS total local citation score, ND number of documents, H_i H index, PY_s first published (year), AC average citation, IF impact factor (in 2020)
contributed to 0.48 documents on average, and each document had an average of 2.11 authors. This also indicates that wood decay fungi research is typically a multi-author, cooperative field. It should also be noted that we did not distinguish between the order of authors in the list of names, the calculated document, and citations; rather, we recorded a name if it was on the list of authors.

### 3.8 Highly frequent terms and the current research hotspots

We detected 11,854 keywords in the 8089 wood decay fungi research documents from 1913 to 2021. These keywords were analyzed by co-occurrence, and six clusters were formed. These clusters are shown in Fig. 5, according to the relationships between the weights of the attributes of links and the total link strength between different keywords. For the top 20 high-frequency keywords detected in the 8089 articles, ranked by the number of occurrences in articles in which they appeared, specific data are given in Fig. S3.

In Fig. S3 (Online Resource), an overlap visualization map showing the keywords from the beginning 1913 to 2021 is presented. When the color of a node in the graph is redder, the keyword is newer. The keywords in deep blue represent those proposed before 2000. Obviously, most keywords appeared over 10 years. This may reflect that the study of wood decay fungi comprises a very classic research field.

Figure 5 shows the network of keywords selected from the full set of documents, based on the co-occurrence method. These keywords were divided into six clusters and their links

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**Table 3** Top 10 research authors, in terms of local impact, as ranked by total documents

| Author              | TD  | TLCS | H_i | ACS | TS     | Institution                                  | Country |
|---------------------|-----|------|-----|-----|--------|----------------------------------------------|---------|
| Dai YC              | 94  | 2249 | 25  | 24  | 1994–2020 | Beijing Forestry University                  | China   |
| Martinez AT         | 94  | 7260 | 47  | 77  | 1991–2020 | Biological Research Center, CSIC             | Spain   |
| Cui BK              | 87  | 1762 | 25  | 20  | 2005–2020 | Beijing Forestry University                  | China   |
| Hatakka A           | 72  | 4436 | 36  | 62  | 1980–2016 | University of Helsinki                       | Finland |
| Martinez MJ         | 71  | 4673 | 38  | 66  | 1991–2020 | Biological Research Center, CSIC             | Spain   |
| Kondo R             | 70  | 1641 | 27  | 23  | 1988–2020 | Kyushu University                            | Japan   |
| Zhang XY            | 70  | 1809 | 25  | 26  | 2004–2020 | Huazhong University Science & Technology     | China   |
| Blanchette RA       | 65  | 4348 | 32  | 67  | 1984–2020 | University of Minnesota                      | USA     |
| Hoferichter M       | 63  | 3878 | 33  | 62  | 1993–2020 | Technische Universität Dresden               | Germany |
| Watanbae T          | 62  | 1730 | 25  | 24  | 1998–2019 | Kyoto University                             | Japan   |

TLCS refers to citations in the data set, not Web of Science

\[TD\] total number of documents, \[TLCS\] the total local citation score, \[ACS\] average citation score, \[H_i\], \[H\] index, \[TS\] time span

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![Fig. 5 Network visualization map based on the keyword co-occurrence method in the wood decay fungi research field (colors represent different clusters)](image-url)
were grouped; each group was identified using a different color. The size of each cluster represents its relative contribution to the group (with respect to the associated keywords), and the thickness of the line between two clusters reflects the number of interactions established between the two different communities. The color of a node represents the cluster to which it belongs, and different clusters are represented by different colors, as shown in Fig. 5. To show the density of keywords, a density map of the keywords was produced based on the co-occurrence method, as depicted in Fig. S4 (Online Resource).

The top 20 keywords associated with wood decay fungi research studies were roughly associated with three areas: fungal diversity (taxonomy, Basidiomycetes, white-rot fungi, Phanerochaete chrysosporium, white-rot fungus, Trametes versicolor, Pleurotus ostreatus, brown rot, wood-rotting fungi); degradation mechanism (laccase, lignin, manganese peroxidase, ligninolytic enzymes, manganese peroxidase, lignin peroxidase); and ecological function (decolorization, bioremediation, wood decay).

Table 4 provides the six clusters that were examined, which were labeled using the keyword with the most occurrences and ranked by the percentage of keywords included, as follows: cluster 1 (red), brown rot; cluster 2 (green), wood; cluster 3 (deep blue), laccase; cluster 4 (yellow), fungi; cluster 5 (purple), white-rot fungi; cluster 6 (light blue), ligninolytic enzymes. The weight of the link and the total link strength contributed by each representative keyword is included, and the ten most important keywords are provided.

Keyword clusters are important forms of visualization for many studies and are considered highly important for understanding the current state of research (Fig. 5). Next, we introduce and further discuss each research area. The research in cluster 1 was focused on brown- and white-rot fungi (e.g., their differences in wood decomposition). This cluster had the most members, as many as 215. Based on Fig. 5 and Fig. S3 (Online Resource), cluster 2 is a relatively new research field, emerging within the past 10 years. This cluster focuses on evaluating preservatives in woods. Cluster 3 mainly focuses on discussion of the decomposition process of white-rot fungi. The studies associated to cluster 4 are also relatively recent, and mainly discuss the classification and biodiversity of wood decay fungi (e.g., taxonomy, Basidiomycetes). The fifth cluster is relative to the classic research which appeared earlier, predominantly focused on the degradation mechanism of white-rot fungi. Cluster 6 mainly relates to the application of ligninolytic enzymes. In the “Discussion” section, the key content of each cluster is expanded upon.

### 3.8.1 Cluster 1—brown rot

Most wood-rot fungi belong to Basidiomycetes (Gabriel and Švec 2017), and their degradation modes can be divided into white or brown rot. Brown-rot fungi can degrade cellulose and hemicellulose, but do not significantly degrade lignin, which can only modify. The wood shrinks, causing brown rot residues to decompose into cubic shapes with brown discoloration, due to the oxidation of lignin (Gilbertson 1980; Monroy et al. 2011). The lignin remains as a polymer in the rotting wood (Arantes and Goodell 2014). The main lignin modification performed by brown-rot fungi is demethylation. For a long time, most brown-rot Basidiomycetes were considered unable to produce cellulase, especially outer cellulase. Instead, their response is based on Fenton reactions ($\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + \text{OH}^- + \text{OH}^{-}$) (Arantes and Milagres 2007; Baldrian and Valášková 2008). It is very important to

| ID | M | C | Name | O | L | TLS | Top 10 keywords |
|----|---|---|------|---|---|-----|-----------------|
| 1  | 215 | Red | Brown rot | 185 | 186 | 463 | White rot, antifungal activity, oxalic acid, soft rot, white rot, brown-rot fungi, biological control, lignin biodegradation, gene expression, Fenton reaction |
| 2  | 161 | Green | Wood | 105 | 169 | 323 | Wood decay fungi, decay, decay resistance, Gloeophyllum trabeum, Coniophora puteana, wood degradation, brown rot, durability, mechanical properties, wood preservation |
| 3  | 153 | Deep blue | Laccase | 603 | 398 | 1713 | Biodegradation, Phanerochaete chrysosporium, Trametes versicolor, white-rot fungus, decolorization, decolorization, bioremediation, lignin peroxidase, white-rot fungus, biosorption |
| 4  | 149 | Yellow | Fungi | 283 | 340 | 724 | Wood decay, taxonomy, Basidiomycetes, wood-rotting fungi, brown rot, wood decay fungi, phylogeny, Basidiomycota, decomposition, polypore |
| 5  | 147 | Purple | White-rot fungi | 609 | 438 | 15 | Manganese peroxidase, lignin, lignin degradation, lignocellulose, Basidiomycete, cellulose, Ceriporiopsis subvermispora, delignification, cellulase, wheat straw |
| 6  | 120 | Light blue | Ligninolytic enzymes | 121 | 132 | 285 | Pleurotus ostreatus, solid-state fermentation, immobilization, laccases, peroxidase, versatile peroxidase, optimization, fungus, Bjerkandera adusta, ethanol, brown-rot fungus, Trametes hirsuta, pentachlorophenol |

*ID* cluster ID, *M* cluster members, *C* color in Fig. 5, *O* occurrences, *L* weight links, *TLS* weight total link strength
generate hydroxyl radicals in order to depolymerize polysaccharides (Crescenzi et al. 1997; Yoon et al. 2007). White-rot fungi degrade cellulose and lignin, leaving behind bleached fiber residues. In the process of wood decomposition, white-rot fungi secrete a large amount of organic acids (e.g., oxalic acid) into their microenvironment, creating ideal conditions (pH 3–5) for lignin-decomposing enzymes to function, while also promoting Fenton-based reactions, thereby leading to the decomposition of crystalline cellulose (Noll et al. 2016; Kahl et al. 2017).

3.8.2 Cluster 2—wood

As mentioned above, unlike white-rot fungi, brown-rot fungi alter lignin through non-enzymatic decomposition. This decay usually forms columns of decay in the wood. Brown rot generally occurs on conifers, and may be called heart rot. Hardwood is more resistant to brown-rot fungi than to white-rot fungi. Brown-rot fungi found on conifer trees all belong to Basidiomycota, with typical brown-rot fungi including Gloeophyllum trabeum and Serpula lacrymans (Gilbertson 1980; Seifert 1983). G. trabeum uses alcohol oxidase as an extracellular source of H₂O₂ in the brown rot of wood, contributing to the Fenton reaction which, in turn, contributes to the decomposition of lignin. Coniophora puteana is a common brown-rot fungus, which is very common in European buildings (Watkinson and Eastwood 2012). It has been widely used as an important test fungus in decay tests, in which the tolerance of a fungus to several organic wood preservatives is determined. In terms of the number of brown-rot fungi, it has been estimated that only 7% of wood-rot fungi are brown-rot fungi (Mäkelä et al. 2021); however, they are very common in nature. Wood protection and the impacts that wood decay fungi have on wood impregnated with preservatives are other key research areas (Schwarze and Schubert 2011; Schubert et al. 2012).

3.8.3 Cluster 3—laccases

Wood decay is mainly caused by wood decay fungi. They possess a series of enzymes, which are used to destroy the structural strength and physiological functions of living trees. In the process of wood degradation, white-rot fungi mainly secrete cell oxidases for delignification. Phanerochaete chrysosporium has become the standard laboratory fungus for studying the physiology and chemistry of lignin degradation, due to its good ligninolytic properties, rapid growth, and ease of handling in culture (Riley et al. 2014; Giri and Sharma 2020). Typical white-rot fungi secrete a key group of extracellular oxidases, namely, peroxidases and laccases (Lundell et al. 2010). Laccases are the most common enzymes, with relatively strong degrading ability. Among the peroxidases, only manganese peroxidase (MnP), lignin peroxidase (LiP), and multifunctional peroxidase (VP) have been shown to decompose polymerized lignin, making them real lignin-decomposing enzymes (Hofrichter and Ullrich 2014). These three enzymes can significantly reduce the lignin content in fallen wood (Schwarze 2007). The peroxidases secreted by white-rot fungi function differently, depending on whether they utilize manganese. Manganese peroxidase (MnP) strictly takes Mn³⁺ as the substrate and oxidizes it to active Mn⁴⁺ as a strong diffusion oxidant. Multifunctional peroxidase (VP) can also oxidize Mn⁴⁺, in addition to phenols and methoxylated aromatics. The action of several other peroxidases (e.g., lignin peroxidase, LiP; GP), including universal peroxidases (non-specific peroxidase, UPO; dye decoloring peroxidase, DyP), does not involve manganese (Schwarze 2007; Hatakka and Hammel 2010).

3.8.4 Cluster 4—fungi

From a taxonomic point of view, “wood-rot fungi” is not a taxonomic term, or a species term, but instead denotes a type of fungus that attacks and degrades wood (Wei et al. 2021). Most wood decay fungi are likely to be Ascomycetes or Basidiomycetes (mainly including most fungi of Basidiomycota and some fungi of Ascomycota). As important decomposers in forest ecosystems, they represent a large and poorly understood component, with about 1500 species of saprophytic fungi having been found in Finland (Siitonen 2001) and about 2000 species of wood-rot fungi reported in China. Among them, polypores are among the most efficient decomposers of lignin and cellulose, the main components of wood (Dai 2012). They are best identified according to the type of decay they cause. The most common types are white rot, brown rot, and soft rot. About 10,000 species of white-rot fungi have been estimated to exist, having different abilities to degrade lignin, cellulose, and hemicellulose (Maciel et al. 2012); however, only a few dozen have been properly studied. The most-studied species of white-rot fungi can be sub-divided into six families: Fomitopsidaceae, Ganodermataceae, Hymenochaetaceae, Marasmiaceae, Phanerochaetaceae, and Polyporaceae. Similarly to white-rot Basidiomycetes, soft-rot fungi of the Ascomycetes group secrete laccases as key enzymes for oxidation (lack of lignin peroxidase) (Liers et al. 2011), while brown-rot Basidiomycetes perform Fenton chemical reactions, instead of utilizing enzymes, and are responsible for wood oxidative attack (Liers et al. 2007; Hatakka and Hammel 2011). To understand the cluster better, combined with burst keywords, clarifying the taxonomy of wood decay fungi species is the most important and fundamental step to utilize this valuable bioresource. In particular, more wood-decaying fungal species have no fruiting body, and the associated community relationships also require more attention. Reorganizing the taxonomic status and
phylogenetic relationships of wood decay fungi is also an important future concern. Therefore, researchers should pay more attention to the related research, and seek to develop further fundamental research. Moreover, very important research considering white-rot fungus has been performed; for example, genome sequencing of the model mushroom *Schizophyllum commune* has been carried out by Ohm R et al. (2010).

### 3.8.5 Cluster 5—white-rot fungi

The lignin degradation ability of several white-rot fungi, such as *Phanerochaete chrysosporium*, has been studied (Giri and Sharma 2020). These white-rot fungi degrade lignin, making the decayed wood whitish and fibrous in texture. Some white-rot fungi, such as *C. subvermispora*, *Phellinus pini*, *Phlebia* spp., and *Pleurotus* spp., by preferentially attacking lignin, preferentially delignify wood over degrading hemicellulose and cellulose, leaving behind rich cellulose resources. However, other white-rot fungi, such as *Trametes versicolor*, *Heterobasidion annosum*, and *Irpex lacteus*, degrade cell wall components at the same time (Wong 2009). Compared to white-rot fungi, brown-rot and soft-rot fungi cannot degrade lignin to CO$_2$ completely (Janusz et al. 2017).

### 3.8.6 Cluster 6—ligninolytic enzymes

Some screening studies have found that, under certain conditions, fungi preferentially degrade lignin, rather than cellulose, in wood or straw. These lignin-selective fungi include *Pleurotus ostreatus* (Shirkavand et al. 2016). At the same time, some fungal species with a strong preference for lignin (e.g., *Bjerkandera adusta* and *Trametes hirsuta*) can survive and delignify in textile industry wastewater. The term white rot is related to the bleached (white) appearance often observed on wood attacked by these fungi. A common feature of white-rot fungi is their ability to degrade all the main components of plant cell walls: cellulose, hemicellulose, and lignin (Lundell et al. 2010; Riley et al. 2014; Shirkavand et al. 2016). The decomposition of lignocellulose is achieved through a series of enzymes (hydrolases and oxidoreductases) and non-enzymatic mechanisms (Liers et al. 2011; Kracher et al. 2016; Mäkelä et al. 2021).

Therefore, the use of this feature can effectively solve the environmental problems caused by pulp bleaching in the paper-making process. Therefore, exploiting the typical features of white-rot fungi to produce lignin-decomposing enzymes may effectively address many industrial pollution problems (Bilal et al. 2017; Peralta et al. 2017).

### 4 Discussion

In this study, we explore the research performance of the wood decay fungi literature in a global context by applying various bibliometric analysis tools. We analyze wood decay fungi research from a bibliometric perspective for the first time, extending the application of bibliometric analysis and providing a paradigm for further expansion of research in this field.

#### 4.1 Analysis and characteristics of the papers, countries, institutions, journals, and authors

Through bibliographic coupling analysis (considering documents, journals, authors, institutions, and countries), co-citation analysis (considering cited references, cited journals, cited authors), and keyword co-occurrence analysis, we identified the global publication patterns and development of wood decay fungi research. We found that the two most important historical inflection points for wood decay fungi research were 1991 and 2006, with over 100 and 300 publications per year after these years, respectively. The obtained publications mainly came from 14 countries, led by the USA (2832) and China (2506). Beijing Forestry University is an emerging research institution, while Kyoto University is an earlier classical research institution.

Through bibliographic coupling journal analysis and journal co-citation analysis, our results suggested that *Bioresource Technology*, *Applied and Environmental Microbiology*, and *Applied Microbiology and Biotechnology* are important knowledge-source journals in the wood decay fungi field, each having a large impact. This result is consistent with the main research category analysis, focusing on biotechnology, applied microbiology, environmental sciences, and microbiology. This indicates that research on wood decay fungi has focused on the study of physicochemical properties and metabolic processes, products, and applications, and is not limited to the study of taxonomy and diversity. The citations of articles are also informative, as they indirectly reflect important concepts within a topic. Therefore, in this study, co-citation analysis was used to identify the main knowledge base in the wood decay fungi literature. Among the top 10 co-cited references, Kirk TK published five frequently cited papers, and it is worth paying more attention to this researcher. The three authors with the highest number of publications were Dai YC, Martinez AT, and Cui BK. While Martinez AT had the highest average number of citations, Dai YC and Cui BK did not have very high average citation numbers. Furthermore, the academic community was determined using author co-citation analysis, which is of great
academic value for in-depth understanding and study of the cutting-edge research on wood decay fungi.

4.2 Analysis of main keywords and clusters

Keywords are used to condense and refine the core content of the research ideas in each study. Each article has unique keywords. Therefore, every keyword represents a document, serving as the core generalization of the paper. The analysis of keywords in a paper can reveal the paper’s theme. However, some correlation must exist among the keywords in a paper, which can be expressed using the co-occurrence frequency. It is generally believed that the more often a lexical pair appears in the same document, the closer the relationship between the two topics. Co-occurrence analysis uses the common occurrence of lexical pairs or noun phrases in a document set to determine the relationships between topics in the subject represented by the relevant literature. Keyword co-occurrence analysis is an important tool for finding key research directions, and is also important for understanding the current state of research (Duan et al. 2020). The results of the keyword co-occurrence analysis allowed for a systematic classification and summary of current wood decay fungi research, mainly focusing on “biodiversity,” “decay mechanisms,” and “ecological functions.”

By analyzing the above clusters, they can be divided into three main subjects: (1) the classification and diversity of wood-rot fungi (clusters 1 and 4); (2) the degradation mechanisms of wood-rot fungi (clusters 1, 3, and 5); and (3) the ecological functions of wood-rot fungi (clusters 2 and 6). In summary, during the degradation of wood, white-rot fungi mainly secrete peroxidases and laccases to degrade the lignin in dead wood, while brown-rot fungi can only effectively degrade hemicellulose and cellulose. The activity and type of degradation enzymes used directly affect the decay rate and nutrient content of wood, while the fungal mycelium has an important role in the uptake and transfer of nutrients, such as C and N, in wood. Analysis of the functional traits of wood-rot fungi can reflect the adaptation of species to various environmental conditions, as well as helping to understand the mechanisms influencing the aggregation of fungal communities in different environments.

Wood decay fungi can degrade complex compounds (Martínez et al. 2004; Routoula and Patwardhan 2020) and, so, have important application potentials in the remediation of soils and effluents contaminated with a wide range of organic pollutants (Fayeulle et al. 2019), making them important bioengineering bacteria in industrial applications. White-rot fungi can produce a variety of enzymes, such as manganese peroxidase and laccases (Wei et al. 2021). These enzyme systems are unique in their ability to degrade lignin, as well as being able to degrade many structurally complex environmental pollutants. Wood-rot fungi can be used for the treatment of industrial wastewater from processes such as paper-making, printing, and dyeing. They also have shown promise for applications in soil bioremediation, the paper industry, and environmental treatment (Grandclement et al. 2017; Nurika 2019; Sharma et al. 2019). In particular, some species have already been applied for soil bioremediation, paper-making, and environmental treatment (Arantes and Milagres 2007; Fu et al. 2013).

In total, the keyword co-occurrence analysis determined six clusters, and the most common and important keywords that appeared in the clusters were related to white-rot fungi. Numerous studies have shown that these special fungi are the only group that can degrade the lignin in wood. These white-rot fungi can help to maintain the wood debris content in forests, thus promoting nutrient recycling, soil formation, and the carbon budget of forest ecosystems. Meanwhile, during degradation, they can release a great variety of laccases (Bugg et al. 2011b; Bilal et al. 2017; Kahl et al. 2017). These laccases have been widely used for the degradation of straw, paper waste liquid, and a variety of pollutants (e.g., antibiotics, heavy metals, polycyclic aromatic hydrocarbons), and play very important and irreplaceable roles (Bilal et al. 2017). Under the background of “carbon neutral and carbon peak,” understanding the processes associated with wood degradation has become more vital. Meanwhile, the use of wood decay fungi metabolites (e.g., laccases) to degrade pollutants and incompletely utilized products from industrial production is of great significance and value, in order to improve resource utilization efficiency, reduce pollution, and lower carbon emissions. In addition, excluding the focus on species diversity and taxonomic studies of wood decay fungi, the decomposition of lignin and the metabolism of wood chemical fractions continue to be the focus of attention and hotspots in the wood decay fungi literature. The study of how to increase the preservative properties of wood and improve its quality is another important perspective. This knowledge plays an important role in guiding researchers towards fruitful lines of study, while the determination of common keywords is important in developing a better understanding of the state of wood decay fungi research. In this study, we detail the research performance and knowledge structure of wood decay fungi research, which may help researchers in the field to understand the relevant trends and hotspots.

5 Conclusions

Various bibliometric tools were used to reveal the publication pattern and development status of the wood decay fungi literature on a global scale. This analysis provided the current state of research; identified important institutions, journals, authors, and academic communities; and clarified
the key areas of current research. These findings are of great scientific value for researchers, in order to understand wood decay fungi research and, in particular, to further recognize their importance in soils, which is significant for ecosystem material cycling and soil remediation.

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1007/s11368-022-03225-9.

**Author contribution** Conceptualization: T.L., Z.X., Y.W., and X.C.; data curation: T.L.; funding acquisition: Y.W. and X.C.; investigation: X.S., Y.W., and X.C.; methodology: T.L., X.S., and X.C.; resources: L.C. and X.C.; supervision: Y.W.; visualization: T.L., L.T., Y.M., and L.C.; writing—original draft: T.L. and Y.W.; writing—review and editing: T.L., L.C., Z.X., Y.M., and X.C. All authors have read and agreed to the published version of the manuscript.

**Funding** Open Access funding enabled and organized by CAUL and its Member Institutions. This study was financially supported by the National Natural Science Foundation of China (32070018) and the CAS Strategic Priority Research Program, (XDA20050103). T.L. received Griffith University Postgraduate Research Scholarships for his PhD project.

**Data availability** Not applicable.

**Declarations**

**Conflict of interest** The authors declare no competing interests.

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