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ORIGINAL ARTICLE – Forest Products Science and Technology

Harnessing Microbes for Forest Commodities: Topics and Trends on Microbial Applications in Wood and Non-Wood Industries

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Abstract

Understanding the trajectory of microbial biotechnology research is essential for identifying novel processes, techniques, and applications to enhance the efficiency and sustainability of bioeconomic activities. This paper provides a comprehensive overview of global research on microbial applications in forestry-related industries to elucidate key research themes and trends within this domain. Through topic modeling of publications on microbial applications in wood and wood-based products, we identified 14 distinct topics from a dataset of 805 abstracts containing 152,265 terms. A continuing surge of research was found, particularly on microbial enzymes employed primarily in pulp and paper production. There was also a rising publication trend related to microbe applications in bioenergy and agarwood, reflecting an increasing interest in diversifying forest-based bioeconomy. Most scientific publications originated from major producers and traders of forest-based products. To advance bioeconomic objectives, it is critical to foster increased collaborative research on microbe-based technologies within the forestry industry.

Keywords: Fungi, bacteria, forest products, text mining, topic modeling.

1. INTRODUCTION

Forest-related industries are a strong contributor to the global economy with a total value that far exceeds its direct contribution to GDP. While 2000 to 2011 have seen over 0.9 to 1.2% decline in the gross value added (FAO, 2014), the total global contribution of the forestry sector (i.e., forestry, wood industry, and pulp and paper industry) had surpassed USD 1.523 billion in 2015 (Li et al., 2022). In 2021, the global volume of forest products reached approximately 12 billion m^3 with an estimated value of 1876 million USD (FAOSTAT, 2024). An enhanced forestry sector is further expected to boost development as it generates more employment and income opportunities, especially for the rural population (Li et al., 2019). Nonetheless, the sustained success of the forest sector hinges on efficient forest management practices that incorporate innovation in products and technologies, all while remaining adaptable to the changes in market demands (Lundmark et al., 2021).

Global environmental pressures have pushed forest industries to incorporate biotechnology to generate higher value forest products given the limited forest resources. Envisioned as a 'key growth sector in the emerging global bioeconomy' (Pinkard & O'grady, 2016), the forestry sector now has greater opportunities to invest in 'bioproducts' to fulfill environmental commitments while meeting market demands (Duchesne & Wetzel, 2003). Biotechnology has played an important role in developing processes to improve existing forest-based products and fostering product innovation while maintaining lower production and environmental costs (Henriksson & Teeri, 2009). It enhances yield in plantations, thereby relieving significant pressures on natural forests to meet industrial wood demands (Sedjo, 2004). Biotechnology has been incorporated into tree breeding and improvement (Kumar et al., 2015), wood processing, paper manufacturing, and wood residue utilization (Mansfield & Esteghlalian, 2003).

Microbial biotechnology has a long history in upscaling forest-based (i.e., solid wood, wood- and non-wood-based) products and processes. Certain microbial species, such as *Phanerochaete chrysosporium* and *Ceriporiopsis subcermispora*, have demonstrated the capacity to effectively delignify wood, thereby enhancing pulping and bleaching procedures (Kirk et al., 1983; Mansfield & Esteghlalian, 2003). Lignin degradation process and application of wood decay fungi in industrial production has remained to be a current research hotspot (Li et al., 2022). Bacterial and fungal strains have also been found to reduce extractives in wood chips, thereby optimizing pulping and papermaking processes (Kallioinen et al., 2003). Additionally, select fungal species have also been explored for their potential to modify wood properties, offering opportunities for the development of value-added wood products (Fackler et al., 2007; Schwarze & Schubert, 2011). However, while significant strides have been made in leveraging biotechnological applications within the pulp and paper industry, their integration into the broader wood and wood-based industry remains relatively limited (Mai et al., 2004).

With new technologies like nanotechnology and plasma treatments emerging to improve the properties of wood and wood-based materials, it is important to see how microbial biotechnology has progressed or evolved over time to support global bioeconomy. Here, we ask: How has the research landscape on microbial biotechnology shifted in response to evolving global wood demands? Understanding the trajectory of microbial biotechnology research becomes paramount to gain novel processes, techniques, and applications that can enhance the efficiency and sustainability of bioeconomic activities. The aim of this paper is to provide an overview of research worldwide on microbial applications to forestry-related industries and to gain insights into key research themes and trends within this field. Using text mining and topic modeling, we specifically extract latent topics from abstracts of available scientific literature to identify research trends related to microbes employed in wood and non-wood forest products technologies.

2. METHODOLOGY

Computational methods have greatly improved bibliometric analyses, enabling the effective utilization of the vast reservoir of scientific knowledge present in literature. Text mining is a computational text analysis tool that employs methods from data mining, machine learning, natural language processing, information retrieval, and knowledge management to extract patterns and valuable insights from unstructured text (Aggarwal, 2018; Feldman & Sanger, 2006). Text mining has recently been applied in the fields of ecology and evolutionary biology for tasks such as investigating research patterns and subjects, synthesizing evidence and conducting literature reviews, enlarging datasets based on literature, and extracting as well as incorporating primary biodiversity information (Farrell et al., 2022).

2.1. Data searching and screening

The Reporting Standards for Systematic Evidence Syntheses (ROSES) method (Haddaway et al., 2018) was partially followed to systematically search and screen literature (Figure 1). The ROSES workflow involves searching, screening, and critical appraisal and synthesis. However, as the present study focused solely on abstracts for practical reasons, article screening was limited to titles and abstracts only. No full-text screening and critical appraisal were also applied. The Clarivate Web of Science database was selected for its popularity among academics (Zhu & Liu, 2020) and was used to search for peer-reviewed papers from original research, reviews, book chapters and conference proceedings published in the English language. Other forms of literature were excluded from the search. To explore research trends, no limit was set for the publication year. A Boolean search was independently performed for two microbial technology topics [i.e., wood (WFP) and non-wood forest products (NWFP)] using a combination of search strings (Chart 1). The database search was conducted in January, February and April 2024. The search for microbial applications on wood products include research on spalting, bioincising, and pulp and paper. For the microbial technology topic on NWFP, we focused on forest products derived from trees particularly resin, agarwood, and bioenergy. Duplicate entries and those without abstracts were removed.

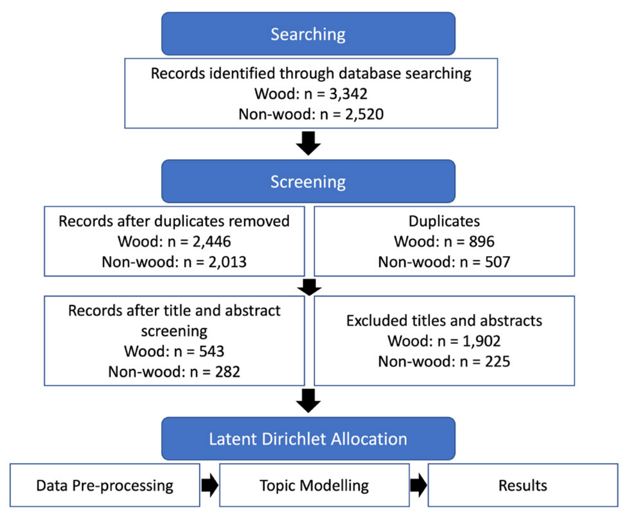

Figure 1. Workflow following partial Reporting standards for Systematic Evidence Syntheses (ROSES) protocol (i.e., database searching and article screening) and the Latent Dirichlet Allocation method.

Chart 1. Search strings used to search for scientific articles in the Clarivate Web of Science database related to microbial technology on wood and non-wood forest products.

Research Area	Search String
Wood forest products	"wood" AND "fungi" AND "biological control, "wood decay" AND "fungi" AND "biocontrol", "wood" AND "preservatives" AND "degrade" AND "fungi", "wood" AND "pathogen" AND "metabolites" AND "biocontrol", "wood" AND "fungi" AND "metabolites" AND "biocontrol", "wood" AND "fungi" AND "biopesticides", "wood" AND "bacteria" AND "biopesticides", "wood AND spalting AND fungi", "wood AND stain* AND fung*", "wood AND stain* AND bacteria*", "wood AND spalt* AND fung*", "wood AND spalt* AND bacteria*", "wood AND acoustic AND fungi", "wood AND wood permeability AND fungi", "wood AND wood permeability AND bacteria", "wood AND particle board AND fung*", "wood AND particle board AND bacteria*", "wood AND fiber board AND fung*", "wood AND pulp* AND paper* AND fung*", "wood AND pulp* AND paper* AND bacteria*", "wood AND fiber* AND paper* AND fung*", "wood AND fiber* AND paper* AND bacteria*", "wood AND pulp* AND bleach* AND bacteria*", "wood AND "wood preservatives" AND degrad* AND fung*", "wood AND "wood preservative*" AND detoxi* AND fung*", "wood AND "wood preservative*" AND detoxi* AND bacteria*", "wood AND "wood preservative*" AND degrad* AND bacteria*", "Fungi" AND "Bacteria" AND "Pulp and Paper", "Fungi" AND "Bacteria" AND "Pulp" AND "Paper", "Pathogen" AND "Pulp" AND "Paper", "Fungi" AND "Biopulping" AND "Biobleaching", "Fungi" AND "Bacteria" AND "Biopulping" AND "Biobleaching", fung* AND bioincis* AND wood, bacteri* AND bioincis* AND wood
Non-wood forest products	"wood" AND "agarwood" AND "fungi", "wood" AND "agarwood" AND "bacteria", "wood" AND "agarwood" AND "bacteria" AND "resin", "wood" AND "agarwood" AND "fungi" AND "resin", "wood" AND "agarwood" AND "fungi" AND "biodiversity", "wood" AND "agarwood" AND "microbes", "wood" AND "agarwood" AND "community", "wood" AND "agarwood" AND fung* AND "enzym*", "wood" AND "agarwood" AND "bacteri*" AND "enzym*", "agarwood" AND "fung*" AND "oleoresin*", "agarwood" AND "bacteri*" AND "oleoresin*", "agarwood" AND "aquilaria" AND "fung**, "agarwood" AND "aquilaria" AND "bacteri*", "agarwood" AND "gyrinops" AND "bacteri*", "agarwood" AND "gyrinops" AND "fung*", "agarwood" AND "bacteri*" AND "fung*" AND "sesquiterpenes", "agarwood" AND "bacteri*" AND "fung*" AND "inoculation", "agarwood" AND "bacteri*" AND "fung*" AND "stress", "agarwood" AND "bacteri*" AND "fung*" AND "formation", "Fungi" AND "Bacteria" AND "Bioenergy", "Fungi" AND "Bacteria" AND "Biomass" AND "Bioenergy", "Fungi" AND "Bacteria" AND "Lignin Biodegradation" OR "Cellulose Biodegradation", "Fungi" AND "Bacteria" AND "Lignocellulose", "Fungi" AND "Bacteria" AND "Lignocellulose" AND "Bioenergy", "Fung*" AND "Bacteri*" AND "Bioethanol", "Fung*" AND "Bacteri*" AND "Bioenergy", "Fung*" AND "Bacteri*" AND "Lignocellulos*" AND "Bioenergy", Fung* AND "Bacteri*" AND "Lignocellulos*", Fung* AND "Bacteri*" AND "Lignocellulos*" AND "Cellulos*", Fung* AND "Bacteri*" AND "Lignocellulos*" AND "Cellulos*"

2.2. Data pre-processing

Data pre-processing and all succeeding analyses were conducted in R 4.2.3 (R Core Team, 2023). A *textcleaner* function was built using several functions from R packages *tm*, *textclean,* and *stringr*. Words were transformed to lowercase, and any stop words, punctuation, spaces, numerical digits, dates, and time were omitted. Words such as 'present', 'study', and 'show' were removed to retain only meaningful words. Lemmatization was performed using the *udpipe* package to convert inflected words into one common root or base form (i.e., lemma). Words and abbreviated scientific terms not detected during lemmatization (i.e., 'fungal' and 'fungus' to 'fungi', 'bacterial' to 'bacteria', 'lignocellulosic' to 'lignocellulose', and 'spp' to 'species') were transformed to their root or original form using either the *gsub* function or manual replacement.

2.3. Topic modeling

To identify the main research topics among the collection of abstracts, topic modeling was conducted using the Latent Dirichlet Allocation (LDA) approach. LDA is a probabilistic model used to analyze collections of text, such as the collection of abstracts of research studies related to microbial technology on wood. It assumes each document is a mix of different topics, and each topic is a mix of words with certain probabilities (Blei et al., 2003). LDA analysis generates clusters of frequently co-occurring nouns, which are then interpreted as topics. Notations and algorithm involved in LDA model are thoroughly discussed by Basilio et al. (2021, 2022) and Blei et al. (2003). The analysis was performed using the *textmineR* package with the following parameters: method=Gibbs sampling, iterations=500, burn-in=180, alpha=0.1 and beta=0.05. Probabilistic coherence and prevalence were also derived to measure the association of words in each topic. The number of topics (k) was set to 8 and 6 for WFP and NWFP, respectively, following Wheeler et al. (2021). Research areas were manually interpreted through the co-occurring words in each topic. Hierarchical clustering was performed to explore the relationship of topics wherein distance between topics was calculated based on Hellinger distance and clustered using Ward's minimum variance method. Data visualization was performed using *ggplot2* package.

3. RESULTS

3.1. Data searching and screening

The search strings for WFP and NWFP research areas identified 2,424 and 2,520 scientific articles, respectively, after removing duplicates (Fig.1). About 78% (1,901) of the searched WFP articles were omitted after manual screening of the article titles and abstracts. Meanwhile, the NWFP research articles declined to 282 articles from 2,520 after duplicate removal and article screening. The remaining WFP and NWFP articles comprised 95,681 and 56,584 terms, respectively, which served as basis for the topic modeling.

Based on first author affiliation, WFP research was predominantly from Europe (34%), North America (31%), and Asia (23%). Nonetheless, other continents were also represented: South America (5%), Oceania (2%), and Africa (1%), including countries (Turkey and Russia) that fall within Europe-Asia (3%) (Fig.2). Meanwhile, the majority of the NWFP research articles were from Asia (58%) followed by North America (16.7%) and Europe (16.3%). Scholarly articles within both research domains originated in the early 1990s, with a generally increasing trend in publication frequency towards the latter part of the 2000s. While the quantity of research articles in the NWFP domain was smaller than that of WFP, there has been a dramatic surge in the number of publications since the mid-2000s, following a modest count in the early 1990s and 2000s. Many of the research studies were published in international journals that focus on areas related to bioresource technologies and various aspects of wood and wood components (Table 1). Journal articles dominate publications on microbes in both wood (98.89%) and non-wood (99.29%) forest products, with book chapters comprising only a small fraction (1.10% and 0.71%, respectively).

3.2. Topic Modeling

Topic modeling revealed eight and six distinct topics for WFP and NWFP research domains, respectively, with 10 of the most relevant words for each topic listed in Table 2. While there is a possibility of more than one topic assigned to each document, the most prevalent topic among the 134 WFP research articles fell under topic 4 (pulp and paper). The other 409 research articles represented topics 1: biological control (44), 2: wood staining (54), 3: wood permeability (51), 5: microbial enzymes (73), 6: pigmentation and spalting (56), 7: wood decay fungi (65) and 8: antagonistic fungi (66). Within the NWFP domain, about 26% of the research articles showcased topic 5 as the most prevalent. The rest of the articles were distributed in topics 1: bacterial enzymes (43), 2: agarwood compounds (37), 3: bioethanol production (38), 4: agarwood formation (42) and 6: biodegradation (49). Subsequently, topics 4 in WFP and 5 in NWFP obtained the highest prevalence scores, respectively. Probabilistic coherence, which measures the association of terms within a topic, was highest in topics 6 and 4 of the WFP and NWFP research areas, respectively.

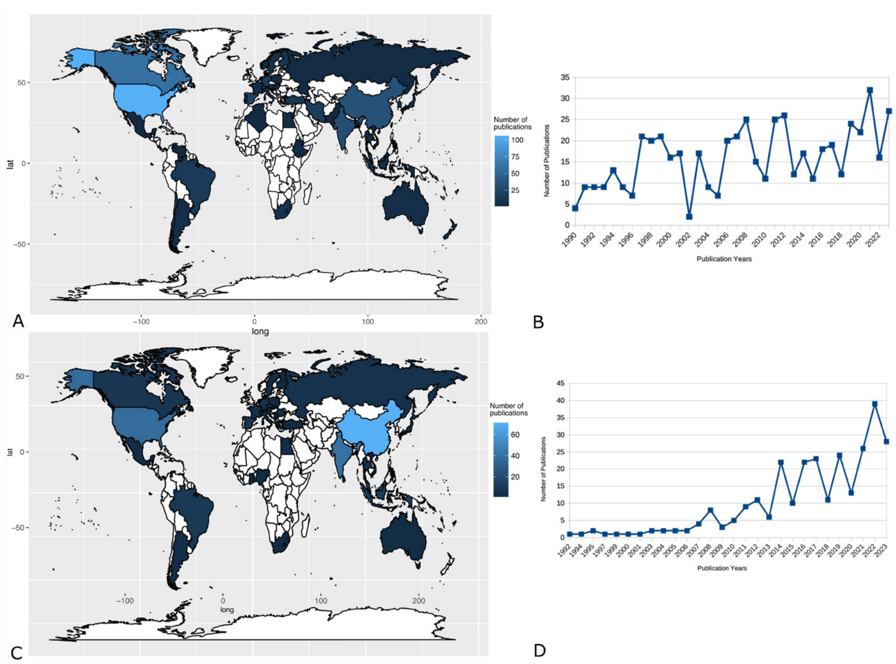

Figure 2. Geographic distribution and number of the screened research papers related to microbial technology on wood (A, B) and non-wood forest products (C, D) retrieved from the Clarivate Web of Science database.

Table 1. Profile of the 10 most active journals that published research articles on using microbes in wood (n=543) and non-wood forest products (n=282), including the count, impact factor in 2023 (IF) and total number of citations (TNC).

Journal Title	Counts	% count	IF	TNC	Average TNC
Wood forest products					
HOLZFORSCHUNG	43	7.919	2.2	1182	27.488
INTERNATIONAL BIODETERIORATION & BIODEGRADATION	38	6.998	4.1	900	23.684
MATERIAL UND ORGANISMEN	25	4.604	NA	146	5.840
BIOLOGICAL CONTROL	21	3.867	3.7	714	34.000
APPLIED MICROBIOLOGY AND BIOTECHNOLOGY	15	2.762	3.9	1393	92.867
FOREST PRODUCTS JOURNAL	15	2.762	1.1	238	15.867
BIORESOURCES	14	2.578	1.3	138	9.857
FORESTS	12	2.210	2.4	75	6.250
INTERNATIONAL WOOD PRODUCTS JOURNAL	10	1.842	1.3	77	7.700
WOOD AND FIBER SCIENCE	9	1.657	0.8	195	21.667
Non-wood forest products					
BIORESOURCE TECHNOLOGY	16	5.674	9.7	725	45.313
PLOS ONE	7	2.482	2.9	267	38.143
JOURNAL OF TROPICAL FOREST SCIENCE	6	2.128	0.6	28	4.667
BIOTECHNOLOGY FOR BIOFUELS	5	1.773	6.1	150	30.000
FRONTIERS IN MICROBIOLOGY	5	1.773	4	142	28.400
APPLIED AND ENVIRONMENTAL MICROBIOLOGY	4	1.418	3.9	256	64.000
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	4	1.418	16.3	484	121.000
BIOCATALYSIS AND AGRICULTURAL BIOTECHNOLOGY	4	1.418	3.4	21	5.250
CURRENT MICROBIOLOGY	4	1.418	2.3	53	13.250
BIOMASS & BIOENERGY	4	1.418	5.8	46	11.500

Table 2. Top 10 terms defining the topics that emerged with Latent Dirichlet Allocation among research articles related to microbial technology on wood and non-wood products.

Topic	Coherence	Prevalence	Top Terms
Wood forest products			
1: Biological control	0.012	7.541	wood, fungi, control, pine, termite, isolate, show, logs, effect, bassiana
2: Wood staining	0.062	9.682	fungi, wood, stain, ophiostoma, pine, sapstrain, control, field, piliferum, isolate
3: Wood permeability	0.044	10.600	wood, fungi, spruce, sample, vitreus, permeability, bioincising, preservative, heartwood, pit
4: Pulp and paper	0.056	21.340	pulp, fungi, wood, chip, lignin, treatment, kraft, property, brightness, increase
5: Microbial enzymes	0.051	15.783	activity, enzyme, wood, production, bacterial, fungi, culture, bacteria, paper, xylanase
6: Pigmentation and spalting	0.135	9.704	wood, fungi, pigment, produce, show, spalt, zone, line, decay
7: Wood decay fungi	0.026	13.160	fungi, wood, isolate, growth, decay, trichoderma, inhibit, test, culture, decay_fungi
8: Antagonistic fungi	0.047	12.189	fungi, species, wood, trichoderma, control, stump, isolate, biocontrol, agent, gigantea

Topic	Coherence	Prevalence	Top Terms
Non-wood forest products			
1: Bacterial enzymes	0.121	16.706	cellulose, activity, enzyme, cellulolytic, isolate, gene, cellulase, strain, bacteria, identify
2: Agarwood compounds	0.124	11.893	agarwood, compound, extract, oil, sinensis, sesquiterpene, acid, chemical, culture, production
3: Bioethanol production	0.055	14.434	production, lignocellulose, anaerobic, acid, yield, produce, bacteria, fungi, fermentation, ethanol
4: Agarwood formation	0.282	14.303	fungi, agarwood, tree, aquilaria, formation, isolate, species, malaccensis, endophytic, agarwood_formation
5: Lignin degradation	0.113	24.796	lignin, enzyme, lignocellulose, fungi, biomass, bacteria, microorganism, production, process, degradation
6: Biodegradation	0.1	17.867	community, bacteria, fungi, microbial, soil, degradation, microbial_community, activity, straw, compost

The hierarchical clustering generated two major clades within the WFP domain: clade 1 composed of topics 1-2 and 7-8, and clade 2 with topics 3-6 (Fig.3). Based on the top terms, the thematic areas of clade 1 (topics 1, 2, 7, and 8) focused on biological control. Clade 2, on the other hand, dealt with pulp and paper production. Both clades covered modifications on wood property. The themes within the NWFP domain were grouped into two main clusters, each with distinct focuses. Clade 1 centered around lignocellulosic degradation while clade 2 revolved around agarwood formation.

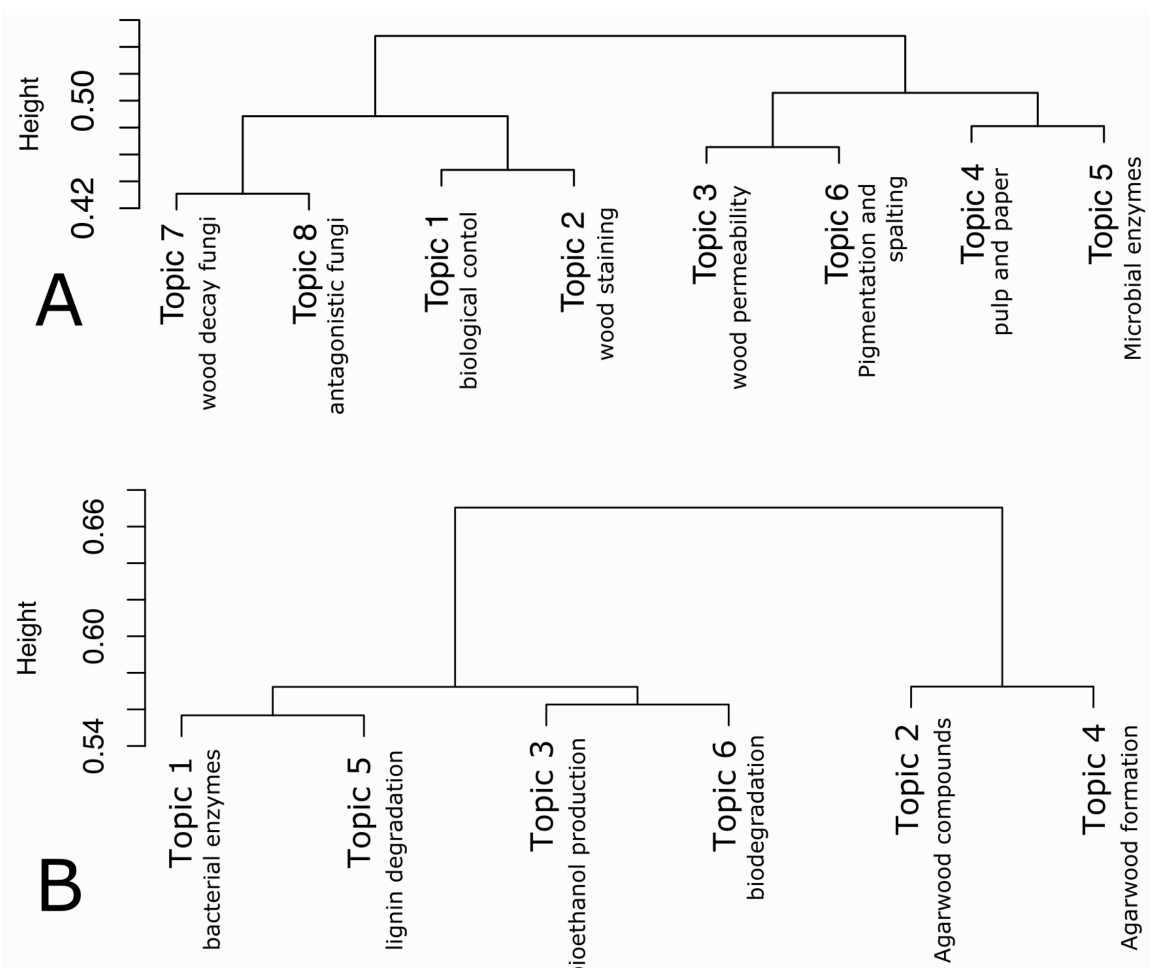

Figure 3. Hierarchical clustering of research topics generated from the Latent Dirichlet Allocation analysis based on scientific articles on microbial technology on wood (A) and non-wood forest products (C) retrieved from the Clarivate Web of Science database.

3.3. Temporal and spatial distribution

Research publications on most of the WFP topics increased towards 2023, except for topics 2, 4, and 7 (Fig.4). Published research on topics 3, 5, 6, and 8 reached their peak in the latter part of the 2000s while those related to topics 2, 4, and 7 peaked in the late 1990s to early 2000s. While research on most of the topics began in the early 1990s, research studies related to topic 6 were not published until the following decade. Topic 4 had the broadest international research efforts, with publications from 31 countries dominated by the USA, Spain, Japan, and Canada. The first authors of most WFP publications with prevalence on topics 1, 2, 4, and 6 were affiliated with institutions in the USA. Additionally, US institutions led the research efforts on topics 7 and 8, with contributions from institutions in Scotland and Switzerland. Swiss institutions notably dominated publications on topic 3 (33%), while Indian institutions made significant contributions (18%) of the research output on topic 5.

The number of research publications on all NWFP topics surged leading up to 2023 (Fig.4). NWFP topics 2 and 5 saw the highest number of publications with 10 articles each published in 2022 and 2016, respectively. Scientific papers focusing on other NWFP topics (1, 3, 4, and 6) were maintained to at most 7 in one to three years during the late 2000s. Many of the first authors of publications focused on topics 1, 2, and 6 were affiliated with institutions from China. Scientific articles under NWFP topics 3, 4, and 5 were mostly published by researchers from the USA, Malaysia and India, respectively. Publications closely linked to NWFP topic 4 had been associated with only 8 regions, primarily concentrated in South and Southeast Asia.

4. DISCUSSION

This paper explored the research topics and trends in microbial applications on wood and wood-based forest products. Using topic modeling, we have shown a generally continuing surge of research topics on microbes, particularly enzymes employed primarily in pulp and paper production. However, topics related to microbial applications on other wood and wood-based products remained scant. Nonetheless, an emerging trend was observed on topics related to microbes for non-wood forest products, which could be attributed to the gradually growing interest in diversifying forest-based bioeconomy.

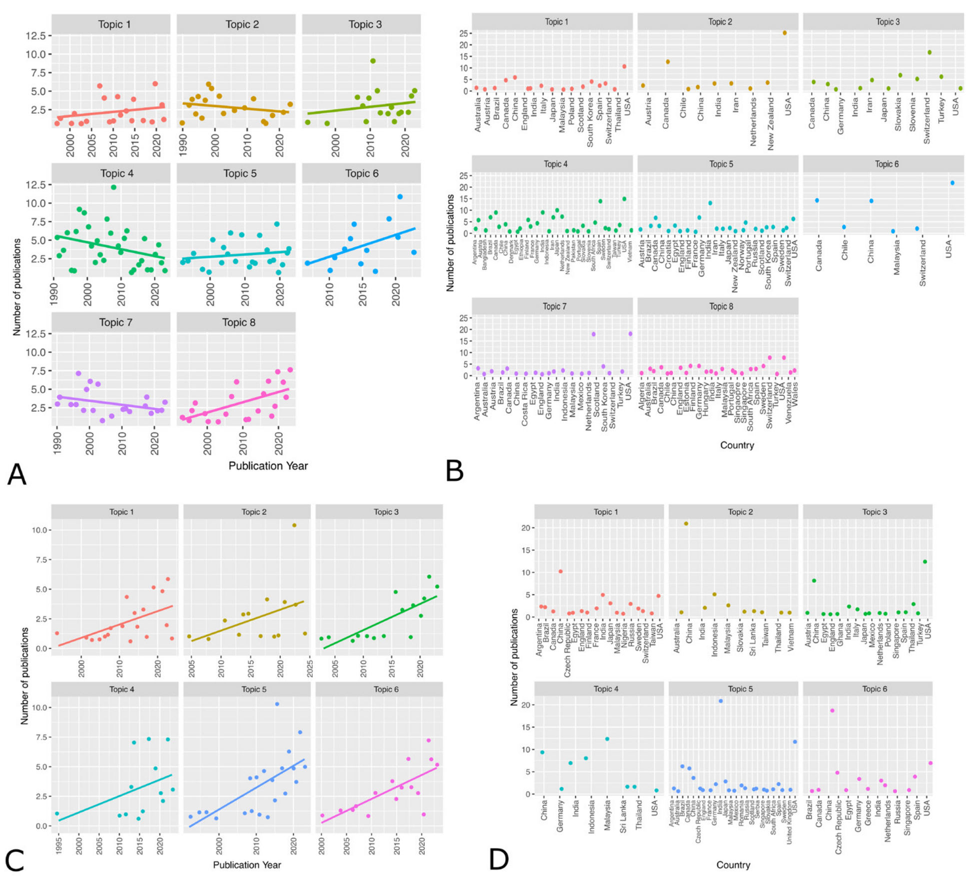

Figure 4. Number of screened research papers related to microbial technology on wood (A, B) and non-wood forest products (C, D) grouped per topic across publication years and countries.

Despite the insights derived from our analysis, this study is not without limitations. Our data was derived from publications written in the English language and available in the Web of Science database, which could lead to selection bias. Text modeling was also constrained to a relatively modest selection of document corpora derived solely from abstracts, thereby constraining the interpretive scope and the ability to draw overarching conclusions. Nonetheless, this study has shown the value of topic modeling as a method to discover unique and shared latent research topics on microbial technologies in wood and non-wood forest products. Our findings could help direct researchers and stakeholders to common literature resources and possibly foster collaborations to harness microbes for value-added forest products. Furthermore, owing to the scalability of topic modeling (Daume et al., 2014), the results from this paper can serve as preliminary insights for ongoing, dynamic topic modeling analysis of large and growing document sets on microbial applications on wood and wood-based products.

4.1. Microbial applications on wood forest products

Over the past decades, the applications of microbial enzymes in the paper and pulp industries, many of which are commercially viable, have expanded rapidly. For example, biobleaching, utilizes enzymes like laccase, xylanase and mannanase sourced from different microbes to augment the brightness of pulp (Kumar, 2021). LDA analysis also revealed that biopulping research primarily focuses on fungal delignification of wood chips, enhancing paper strength, eliminating wood extractives, and reducing energy consumption in pulping (Abdel-Hamid et al., 2013). Interest in microbial research for pulp and paper production is reflected in its extensive geographical scope. Furthermore, most publications in this research area were dominated by regions with established pulp and paper research institutions and associations. Another research theme that is gaining scholarly attention, despite limited geographic range, is the biological control mechanisms and metabolites concerning wood decay. Research on biological control has undergone significant development for the past decades due to global concerns on environmental and anthropogenic risks of using synthetic fungicides, which subsequently led to banning various classes of chemical fungicides (Collinge et al., 2022; Hyde et al., 2024). Numerous studies have identified and screened diverse microorganisms (e.g., *Pseudomonas* spp., *Burkholderia* spp., and *Trichoderma* spp.) sourced from various substrates, with varying degrees of efficacy in controlling a wide range of plant diseases including wood decay (Lahlali et al., 2022). However, biological control research is still not widely adopted for microbes affecting WFP industries, with few cases successfully documented in the USA. Potential reasons for this disparity may include: (1) complexities in the biology and ecology of the host plant, pathogen, and control agent; (2) the lengthy research process required to develop effective control strategies; and (3) challenges related to regulation processes and patent procedures (Prospero et al., 2021).

Research on enhancing wood properties remains the least studied among microbial applications on wood. While methods such as physical and chemical dyeing have been well-established and widely practiced (Liu et al., 2021), a slow shift to alternative approaches like wood dyeing, spalting, and bioincising using microbial technology can be seen in the research landscape. These microbial applications, particularly fungi, used in the wood industry can be attributed to *Myko-Holz* (i.e., wood altered by specific fungi, changing its properties, or data obtained from controlled fungal decomposition; Luthard, 2005) considered to be significant in current advancements in sound qualities in wood and in zone line production and pigmentation (Stange & Wagenführ, 2022). The relatively slow progress in research on microbial applications in wood modification may be attributed to the technical challenges to ensure consistent, high-quality results. Issues in microbe-based wood dyeing encompasses ensuring the stability and efficacy of microbial formulations over time, and addressing concerns related to microbial safety and environmental impact (Liu et al., 2021). In bioincising, strategically inducing biological responses through controlled wounds or incisions in the wood structure necessitates precise control and manipulation of biochemical pathways (Fang et al., 2023). Thus, achieving consistent and reproducible effects while minimizing damage to the wood tissue and mitigating the risk of secondary infections are paramount considerations in bioincising (Schwarze & Schubert, 2015).

Despite the potential of microbial technology to improve the value of wood, research in wood modification has been limited to developed regions, specifically North America, Europe, and East Asia. The limited geographic distribution of research on wood quality enhancement may be attributed to various factors such as the availability of raw materials, advanced technology in furniture-making, and foreign investment (Jivkov, 2019). Advancements are more concentrated on the optimization of furniture types, materials, longevity, structures, and functions, and less attention is given on decorative improvements (Xiong et al., 2023). These highlight the need for continued research and innovation in wood dyeing technology, as advancements in this area could significantly enhance not only the aesthetic appeal but also the overall performance and cost-effectiveness of wood products.

4.2. Microbial applications on non-wood forest products

Biofuel production is the most common research theme among microbial applications in wood-based forest products. Biofuels are classified as any fuel derived and produced from organic sources such as plants and their residues (Mahapatra et al., 2021), which serve as an alternative to fossil-derived fuels. While the application of microbial enzymes is not new in lignin degradation for pulp and paper production, their utilization for biofuel production is still in its infancy. Our analysis showed a steadily increasing trend in investigating the use of microbes, particularly microbial enzymes, to efficiently degrade the high lignin and cellulose content of feedstock sources from wood chips (Andlar et al., 2018; Saini & Sharma, 2021). Laccase is an example of a commonly employed lignin-degrading enzyme for biofuel production (Saini & Sharma, 2021) produced primarily by basidiomycetes (Andlar et al., 2018). Although the discovery and identification of these potent lignocellulolytic fungi have been helpful in the degradation of lignocellulosic biomass for biofuel production, Saini and Sharma (2021) recommend future studies to prioritize the utilization of modern gene editing techniques to enhance the desirable characteristics of current fungal strains.

The surge in biofuel research and production since 2016 can be attributed to policies aimed at mitigating climate change, notably the Paris Agreement of 2015, through implementing renewable fuel standards and incentives for biofuel production [e.g., European Union's targets for biofuel blending (Coelho et al., 2022); China's annual production targets for bioethanol and biodiesel (Qiu et al., 2012)]. Notably, nations considered as major emitters of greenhouse gasses (Schreurs, 2016), are leading research on lignocellulosic degradation, signaling a stronger commitment to eco-friendly alternatives. Leveraging traditional and contemporary technologies in fungal-integrated lignocellulosic biorefineries will be key to producing sustainable energy and value-added products.

Another research trend that has been slowly gaining research interest is the microbial applications in agarwood production. Agarwood is a dark resinous wood formed as a defense mechanism against microbial pathogens and is highly valuable in the market (Thompson et al., 2022). It is induced by the wounding and infection of trees from the family Thymelaeaceae, specifically from the genera *Aquilaria* and *Gyrinops*, by natural factors such as thunder strikes, animal grazing or pest and disease infestation (Shivanand et al., 2022; Tan et al., 2019). Agarwood can also be induced through artificial inoculation of fungal and bacterial strains which had been originally isolated from naturally-formed agarwood (Ngadiran et al., 2023).

While prevalence was relatively low, the slow but steady increase in research publications on agarwood may be attributed to the increasing agarwood trade from 2000 onwards (Thompson et al., 2022). This scarcity of publicly available research data may stem from researchers' decisions to safeguard the intellectual property associated with their inoculation formula, leading them to retain such information within their respective institutions (Hashim et al., 2022). Limited research may also be attributed to the policies restricting access to the endangered *Aquilaria* spp., such as the case in the Philippines. Nonetheless, there has been a noticeable surge in interest in the cultivation and trade of *Aquilaria* spp. for agarwood production (Sy & Melgar, 2023). To support the growing agarwood industry, a handful of government-funded research studies have been recently initiated (e.g., Maravilla et al., 2024; Rodriguez et al., 2024). While agarwood research is steadily growing in volume, the spatial distribution of the publications on agarwood properties and its induction methods through microbes has remained understandably restricted to regions involved in agarwood trade, particularly East and Southeast Asia where major exportation of agarwood occurs (Hashim et al., 2022; Lloren, 2023). Southeast Asia is also recognized for their extensive plantations of *Aquilaria* spp. (Thompson et al., 2022), where ongoing research focuses on inducing agarwood and enhancing commercial production. Future research on agarwood and its induction process should strive for a comprehensive understanding of the fundamental components and biosynthetic mechanisms of agarwood resin to improve agarwood yield, quality, and pricing (Tan et al., 2019).

5. CONCLUSIONS

Amid increasing global demand for wood products, microbial biotechnology research has become crucial for sustainability in the forest products industry. Using modern text analysis, we examined research on microbial applications in wood and non-wood products. The analysis highlighted extensive research on enzymatic treatments, particularly in pulp and paper production and bioenergy. However, less attention is given to microbial applications in wood property modifications and decay treatments. Meanwhile, a rising publication trend was observed related to microbe applications in bioenergy and agarwood, reflecting an increasing interest in diversifying forest-based bioeconomy. Microbial research on wood and non-wood forest products has primarily emerged from major forest product producers and traders. Opportunities in non-wood products, such as agarwood, may drive future research in underrepresented regions. This study further identifies potential future research areas in microbial biotechnology for forest products, suggesting opportunities for collaboration between the forestry industry and research institutions worldwide.

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