REVISTA CADERNOS CAJUÍNA

V. 11 N. 3 ANO 2026

Revista Interdisciplinar

e2214

Bibliometric analysis of global trends and emerging technologies in wood drying

Uma análise bibliométrica das tendências globais e tecnologias emergentes na secagem da madeira

Un análisis bibliométrico de las tendencias globales y tecnologías emergentes en el secado de madera

DOI: 10.52641/cadcajv11i3.2214
Submitted on: 3.5.2026 | Accepted on: 3.9.2026 | Published on: 3.12.2026

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ABSTRACT: Wood drying is a crucial, energy-intensive stage in the timber industry that directly impacts final product quality. This study maps the recent global scientific output on the topic, employing a bibliometric and systematic analysis to identify key trends, challenges, and the underlying knowledge structure. A search of the Web of Science and

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ISSN: 2448-0916

Scopus databases yielded 56 articles published between 2020 and 2025, selected for thematic relevance and publication in journals with a Journal Citation Report (JCR) score ≥ 1.0. The results reveal a strong geographical concentration of research, with China and Brazil as the leading countries in publication volume. Thematic analysis classified the literature into five main axes (from computational modeling to advanced monitoring) and identified a clear transition from conventional methods to a "Smart Drying" model. The current trend converges towards the integration of simulations, non-destructive sensors, and machine learning, aiming to transform drying into a predictive, adaptive, and sustainable process to optimize both quality and efficiency.

Keywords: wood drying, wood properties, wood technology, research trends.

RESUMO: A secagem da madeira é uma etapa crucial e de alto consumo energético na indústria madeireira, impactando diretamente a qualidade do produto final. Esta pesquisa teve como objetivo mapear a produção científica global recente sobre o tema, identificando as principais tendências, desafios e a estrutura do conhecimento por meio de uma análise bibliométrica e sistemática. Realizou-se uma busca nas bases de dados Web of Science e Scopus, resultando em 56 artigos publicados entre 2020 e 2025, selecionados com base em critérios de relevância temática e impacto científico (JCR ≥ 1). Os resultados revelam uma forte concentração geográfica da pesquisa, com a China e o Brasil emergindo como os líderes em número de publicações. A análise temática permitiu a classificação da literatura em cinco eixos principais, desde a modelagem computacional ao monitoramento avançado, tendo identificado uma clara transição de métodos convencionais para um modelo de secagem mais otimizado. Conclui-se que a tendência atual converge para a integração de simulações, sensores não destrutivos e aprendizado de máquina, visando transformar a secagem em um processo preditivo, adaptativo e sustentável para otimizar a qualidade da madeira e a eficiência do processo.

Palavras-chave: métodos de secagem, bibliometria, propriedades da madeira, tecnologia da madeira, tendências de pesquisa.

RESUMEN: El secado de la madera es una etapa crucial y de alto consumo energético en la industria maderera, que impacta directamente en la calidad del producto final. Esta investigación tuvo como objetivo mapear la producción científica global reciente sobre el tema, identificando las principales tendencias, desafíos y la estructura del conocimiento mediante un análisis bibliométrico y sistemático. Se realizó una búsqueda en las bases de datos Web of Science y Scopus, resultando en 56 artículos publicados entre 2020 y 2025, seleccionados con base en criterios de relevancia temática e impacto científico (JCR ≥ 1). Los resultados revelan una fuerte concentración geográfica de la investigación, con China y Brasil como líderes en número de publicaciones. El análisis temático permitió clasificar la literatura en cinco ejes principales, desde el modelado computacional hasta la monitorización avanzada, identificando una clara transición de los métodos convencionales a un modelo de secado más optimizado. Se concluye que la tendencia actual converge hacia la integración de simulaciones, sensores no destructivos y

aprendizaje automático, con el objetivo de transformar el secado en un proceso predictivo, adaptativo y sostenible para optimizar la calidad de la madera y la eficiencia del proceso.

Palabras clave: métodos de secado, bibliometría, propiedades de la madera, tecnología de la madera, tendencias de investigación.

1. INTRODUCTION

Wood drying is a critical and indispensable stage in the timber industry's production chain, essential for ensuring the stability, durability, and quality of the final product (Lima *et al.*, 2023). The process consists of the controlled removal of water from the wood (both free water, present in the cell lumens, and bound water, linked to the cell walls) until the desired equilibrium moisture content is reached (Gao et al. 2022a). The point at which all free water has been removed, leaving only bound water, is defined as the fiber saturation point (FSP), a critical threshold from which phenomena such as shrinkage begins and the wood's properties are significantly altered.

The most widespread industrial method is conventional kiln drying, which uses the forced circulation of heated air (60–100°C) with controlled humidity to extract water from the wood. However, this process is known for its high energy consumption, making it one of the most costly and energy-intensive operations in the timber industry (Simo-Tagne and Ndi-Azese 2021; Chi et al. 2024). This energy dependency, often met by non-renewable sources, leads to high costs and environmental impacts, driving the search for more efficient and sustainable technologies.

The challenges inherent in the drying process are amplified by wood's intrinsic characteristics as a biological material. Its anisotropic nature—that is, the variation of its properties in the radial, tangential, and longitudinal directions—and its heterogeneity result in differential shrinkage during moisture loss below the FSP (Fu et al. 2021). When subjected to moisture and temperature gradients, this uneven shrinkage generates internal stresses that can exceed the material's strength, culminating in a series of defects that reduce the quality and commercial value of the wood (Majka and Sydor 2023).

The main defects include: (i) cracks, which can be surface, end, or internal, often associated with high moisture gradients during the initial stages of the process (Lima et al. 2023; Rahimi et al. 2024); (ii) collapse, an abnormal and often irregular shrinkage that occurs above the FSP, caused by capillary tensions, and is a recurring problem in low-permeability species (Rittiphet et al. 2021; Zhang et al. 2024), and; (iii) warping, such as bow, crook, and twist, which results from the relief of growth stresses and anisotropic shrinkage(Moya and Tenorio 2021; Ghosh et al. 2022).

Considering this scenario, this study aims to perform a bibliometric analysis on wood drying and its influence on technological properties, identifying the main trends, challenges, and scientific advancements in the field on a global scale, in order to systematize current knowledge and suggest directions for future research.

2. THEORETICAL FRAMEWORK

To map the scientific landscape of wood drying and its technological implications, a bibliometric analysis was conducted based on a systematic search in two of the main international databases: the Web of Science (WOS) Core Collection (Clarivate Analytics) and Scopus (Elsevier). The Scopus database was selected for its broad multidisciplinary coverage, ensuring extensive data collection, while WOS was included for its selective nature and robust citation analysis tools. Access to both platforms was provided through the CAFe-CAPES portal via institutional affiliation with the Federal University of Espírito Santo (UFES).

The search was limited to a time frame from January 2020 to August 2025 to focus on the most recent research. The search strategy was systematically constructed using Boolean operators to refine the results: (i) grouping synonyms with the OR operator; (ii) combining thematic blocks with the AND operator; and (iii) excluding non-relevant terms with the NOT operator. The final search string, applied to the title, abstract, and keyword fields (TITLE-ABS-KEY), was as follows: (TITLE-ABS-KEY ("wood" OR "timber") AND

TITLE-ABS-KEY ("solar kiln*" OR "solar drying*" OR "greenhouse" OR "wood drying*" OR "kiln drying*") AND TITLE-ABS-KEY ("propert*" OR "stabilit*" OR "performance") AND NOT ALL ("fruit*" OR "seed*" OR "vegetable*" OR "food*" OR "grain*" OR "agricultur*" OR "bamboo" OR "greenhouse effect" OR "climate change" OR "global warming" OR "biomass")) AND PUBYEAR > 2019 AND (LIMIT-TO (DOCTYPE , "ar")).

To compile the final database, eligibility criteria were applied to ensure thematic relevance and scientific impact. The screening process consisted of: (a) evaluating titles, abstracts, and keywords to verify their relevance to the research scope; and (b) exclusively selecting articles published in journals with a JCR impact factor of 1 or greater (JCR ≥ 1). Articles that were not relevant to the topic were excluded, as were duplicate entries from the databases.

The metadata from the selected articles were exported from the databases in BibTeX format and consolidated into a single dataset. This dataset included citation information (authors, title, year), bibliographic details (affiliations, publisher), abstracts, and keywords.

For quantitative analysis and data visualization, RStudio software was used in conjunction with the Bibliometrix package and its graphical interface, Biblioshiny (Aria and Cuccurullo 2017). Using the consolidated database, descriptive statistics were applied to identify the leading authors, journals, keywords, and countries. Additionally, collaboration maps and networks among countries and authors were generated to visualize the social structure of research in this field. The resulting visualizations were refined using the Canva platform.

3. METHODOLOGY

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ISSN: 2448-0916

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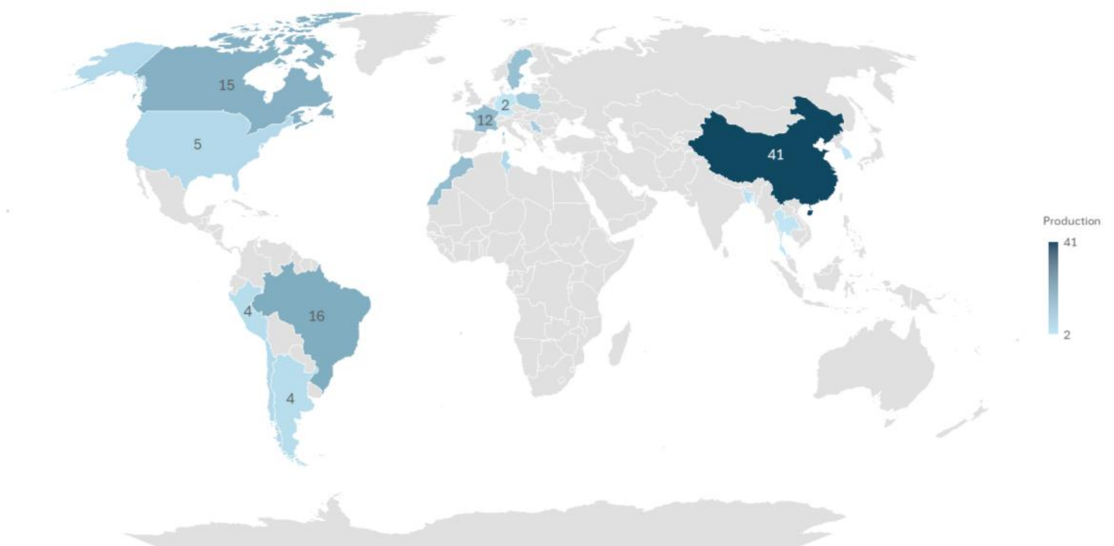
collaboration maps and networks among countries and authors were generated to visualize the social structure of research in this field. The resulting visualizations were refined using the Canva platform.

4. RESULTS AND DISCUSSIONS

The application of the search string, conducted in September 2025, retrieved 220 records from WOS and 47 from Scopus, totaling 267 papers. After the removal of 27 duplicate articles, the consolidated set consisted of 240 unique documents. The eligibility criteria were then applied, and at the end of this process, 56 articles were selected for analysis, with 43 originating from WOS and 13 from Scopus.

Figure 1. Contribution from countries with relevant publications on the research topic.



Sources: Authors.

The analysis of the geographical distribution of the 56 selected articles reveals that research on wood drying and related technologies is concentrated in a few countries (Fig. 1). The data on country-level contributions indicate that China leads with 41 publications, followed by Brazil (16), Canada (15), and France and Morocco (12 each). The total number of contributions exceeds 56 due to international collaborations, where a single article can

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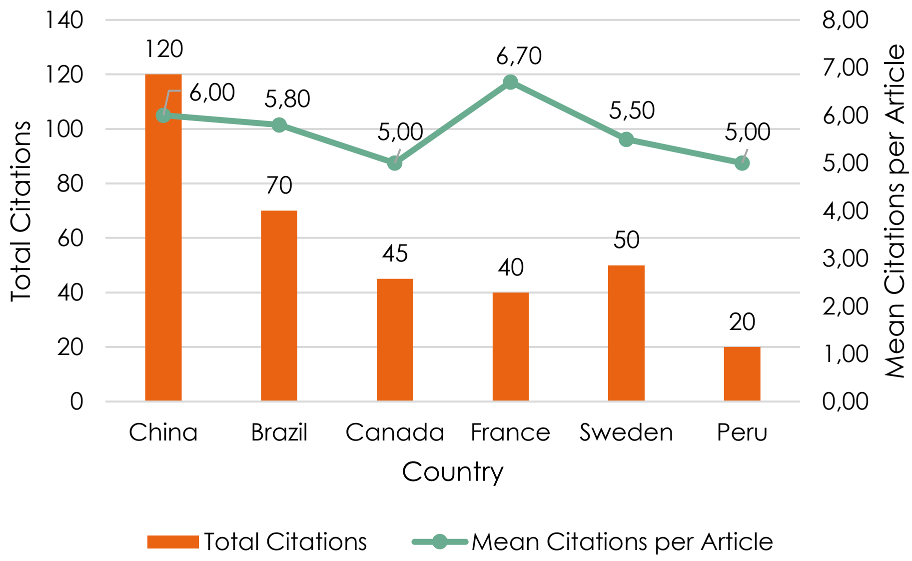
be attributed to multiple countries. Other European and American countries, such as Sweden (11), Poland (8), Serbia (8), and Chile (5), also contribute significantly to the analyzed scientific output. In contrast, countries from other regions, such as Tunisia, the United States, and Argentina, are less represented.

The analysis of geographical impact, measured by the total number of citations and the average citations per article, reveals important nuances (Fig. 2). China, in addition to leading in publication volume, also has the highest total number of citations (120), reflecting its high output, with an average of 6.0 citations per article. Brazil, with 70 total citations, shows a similar average of 5.8 citations per article.

Countries like Sweden and France, despite having a lower absolute number of citations (50 and 40, respectively), exhibit relevant averages, with France achieving the highest average of 6.7 citations per article. Canada and Peru show lower numbers in both total and average citations, maintaining an average of approximately 5.0 citations per article. Thus, although publication volume is a relevant factor, the average number of citations per article highlights the quality and relative impact of the research, with some countries with lower output demonstrating significant influence in the field.

Figure 2. Total number of citations (TC) in the last 5 years and average number of article citations on the research topic.



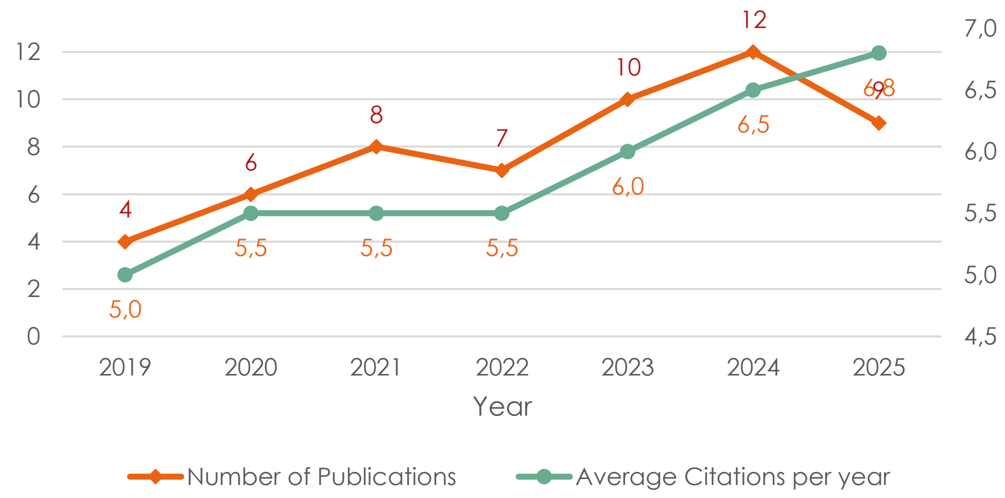
Sources: Authors.

ISSN: 2448-0916

The analysis of the annual evolution of publications reveals a clear growth trend in interest in the field of wood drying and associated technologies (Fig. 3). Between 2019 and 2022, scientific output showed a gradual progression, with the number of articles ranging from 4 to 7 per year. From 2023 onwards, an intensification in production is observed, reaching a peak of 12 publications in 2024. This represents a significant increase compared to previous years and signals the strengthening and consolidation of the topic within the scientific community. For 2025, based on data available at the time of collection, a slight decrease to 9 articles is noted; however, this figure must be considered partial, as the year has not yet concluded.

Regarding the impact of the publications, the average number of citations per article shows a pattern consistent with the length of time the studies have been available in the literature. Articles published in the initial years of the analyzed period, such as 2019 and 2020, have citation averages between 5.0 and 5.5, reflecting the natural accumulation over time. More recent works, particularly those from 2023 to 2025, show a progressive increase in average citations per article, reaching 6.8 in 2025. This indicates a rapid assimilation and relevance of current research by the scientific community. This finding suggests that in addition to the growth in volume, the quality and impact of the studies have also been increasing, reinforcing the vigor and dynamism of the field.

Figure 3. Number of publications on the research topic and average citations per year.



Sources: Authors.

It is observed that the production is concentrated in a relatively restricted group of specialized journals, which present different impact profiles (Table 1).

Table 1. Journals with highest numbers of documents, H index, number of articles and total of citations on the research topic.

Journal	H Index	G Index	M Index	Number Articles	Total Of Citations	Publication Start Year
SOLAR ENERGY	3	3	0.6	3	100	2021
DRYING TECHNOLOGY	2	4	0.5	5	22	2022
EUROPEAN JOURNAL OF WOOD AND WOOD PRODUCTS	2	2	0.4	2	16	2021
HOLZFORSCHUNG	2	3	0.4	3	19	2021
RENEWABLE ENERGY	2	2	0.4	2	27	2021
WOOD MATERIAL SCIENCE & ENGINEERING	2	3	0.667	5	13	2023
ANNALS OF FOREST SCIENCE	1	1	0.2	1	5	2021
APPLICATIONS IN ENGINEERING SCIENCE	1	1	0.25	1	2	2022
APPLIED THERMAL ENGINEERING	1	1	0.5	1	4	2024
BIORESOURCES	1	1	0.25	2	2	2022

Sources: Authors.

The journal *Drying Technology* stands out for having the highest number of articles (5), indicating its prominent role in disseminating advancements and methodologies related to wood drying; however, the journal's H-index (a measure of quality and productivity) is 2. In contrast, the journal *Solar Energy* shows a high H-index (3) with fewer published articles (3) but a total of 100 citations, revealing that its published research has substantially higher scientific recognition and impact. This may be associated with the interdisciplinary nature and growing relevance of solar energy applied to the energy efficiency of wood drying, highlighting emerging research areas with significant implications.

In addition to these, journals such as the *European Journal of Wood and Wood Products* and *Holzforschung* have H-indices of 2 and moderate citation numbers, demonstrating their consistency in disseminating knowledge and their influence within the scientific community. Furthermore, they are recurring sources for in-depth studies on the physical, chemical, and technological properties of wood.

The other journals with a lower number of articles and an H-index of 1, such as *Annals of Forest Science*, *Applications in Engineering Science*, and *Applied Thermal Engineering*, indicate an emerging thematic diversity and interdisciplinarity in the field, which appears to be early stages of consolidation. These journals represent related fields but with distinct thematic focuses, reflected in the diversity of the scientific output. Journals like *Wood Material Science & Engineering* and the *European Journal of Wood and Wood Products* focus directly on wood properties, structure, and treatment, while journals such as *Renewable Energy* and *Solar Energy* cover energy technologies applied to the drying process and research across various areas of knowledge.

Meanwhile, journals like *Holzforschung* and *Bioresources* have approaches that combine aspects of biomaterials and natural resources, enriching the thematic landscape with environmental and chemical perspectives. This variety points to a growing interdisciplinarity and methodological diversification in the field.

In addition to the H-index, the G-index (which weighs impact by cumulative citations) and the M-index (which adjusts productivity for the journal's age) provide additional insights. For example, *Solar Energy*, with a G-index of 3 and an M-index of 0.6, demonstrates not only high relative productivity but also good quality and impact, especially considering its more recent establishment. Other journals like *Drying Technology* (G=4, M=0.5) show persistent productivity. The total citation (TC) and number of publications (NP) metrics also indicate a journal's reach, as those with a higher NP tend to be more recognized in the community, even if their citation impact varies.

The analysis of the main author groups (clusters) in the field of wood drying highlights collaborative groups that stand out for both their productivity and their accumulated scientific impact (Fig. 4 and 5). The most prominent cluster is formed by researchers Avramidis S., Rahimi S., and Nasir V., who together have produced 13 articles, with Avramidis leading (5 articles), followed by Nasir and Rahimi (4 articles each). This group has accumulated approximately 85 total citations, representing a significant impact on the monitoring of internal wood moisture and the application of machine learning techniques in drying processes. The continued relevance of this group is underscored by

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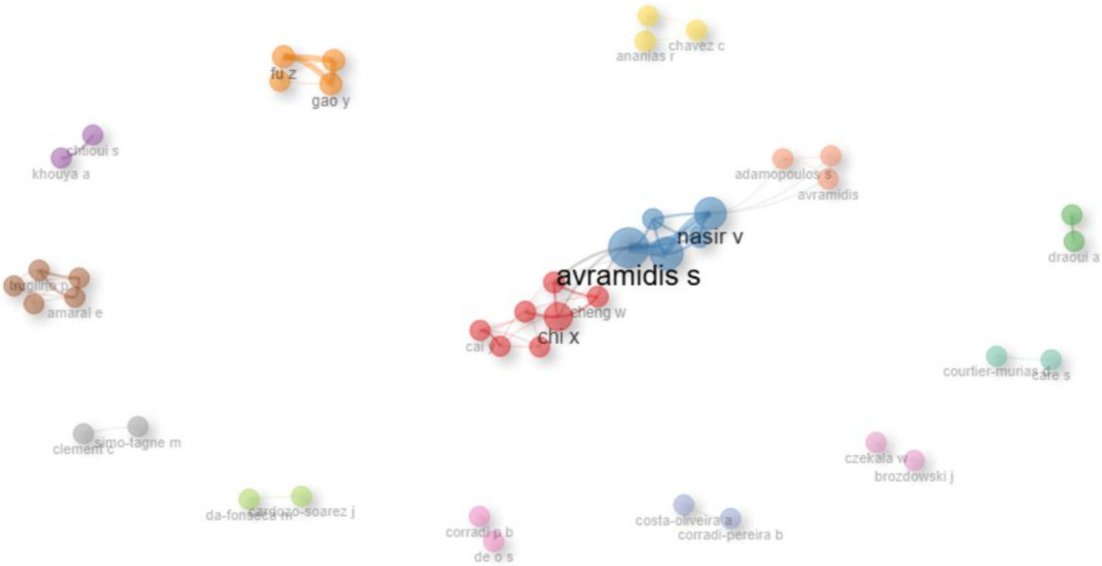
recent data, for example, that in 2022 and 2023, Avramidis S. and Rahimi S. each received 14 citations, reinforcing their current influence.

Figure 4. Collaboration Network on the research topic.



Sources: Authors.

Another notable cluster includes the authors Fu Z., Gao Y., and Zhou Y., each with 3 published articles and a total of approximately 120 accumulated citations. This group focuses its research on experimental studies addressing the hydraulic and morphological behavior of wood during drying. Their impactful publications include key articles from 2021 and 2022, which Fu Z. and Gao Y. have collectively received 27 citations, demonstrating the high visibility of their work. Similarly, the number of citations per year for these authors, such as the 6.75 citations per year for Fu Z. in 2022, reflects rapid and robust recognition from the scientific community.

A third cluster involves Khouya A., Yang L., and Chi X., researchers who focus on sustainable drying technologies, particularly solar energy and pre-treatments for process optimization. This cluster accounts for 9 articles among the three authors, with Khouya A. contributing 3 articles and standing out with 22 citations during the evaluated period. Meanwhile, Yang L. and Chi X. have more recent publications with fewer accumulated citations. The recent output from Yang L in 2024 and 2025, with articles that are already

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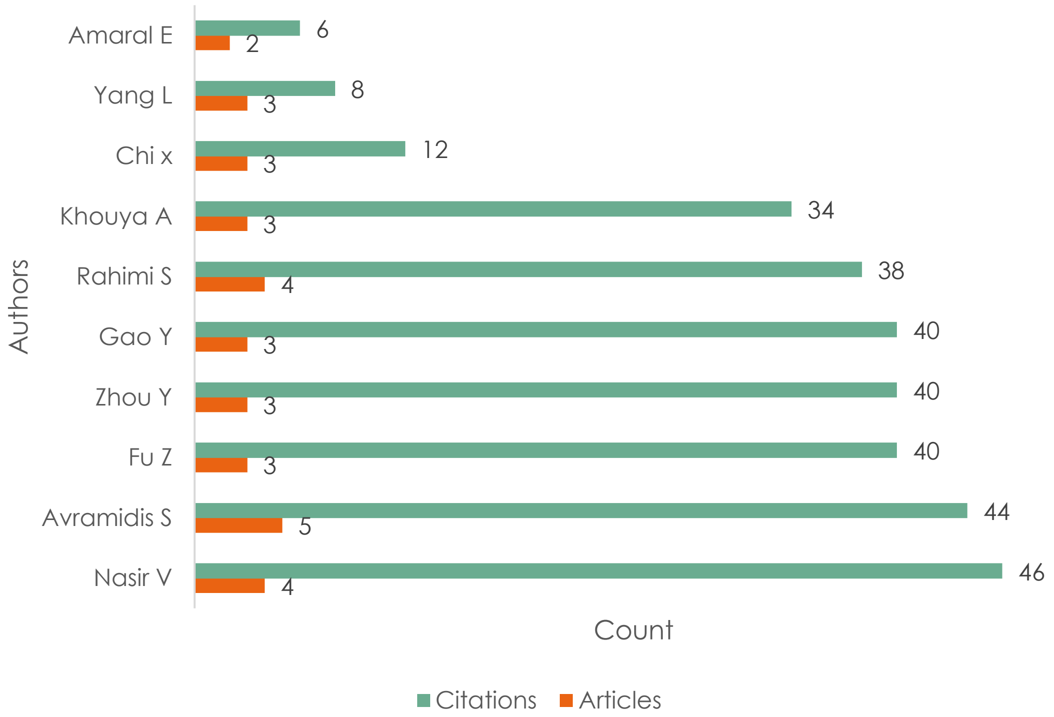
beginning to accumulate citations, indicates expansion and significant potential for future research.

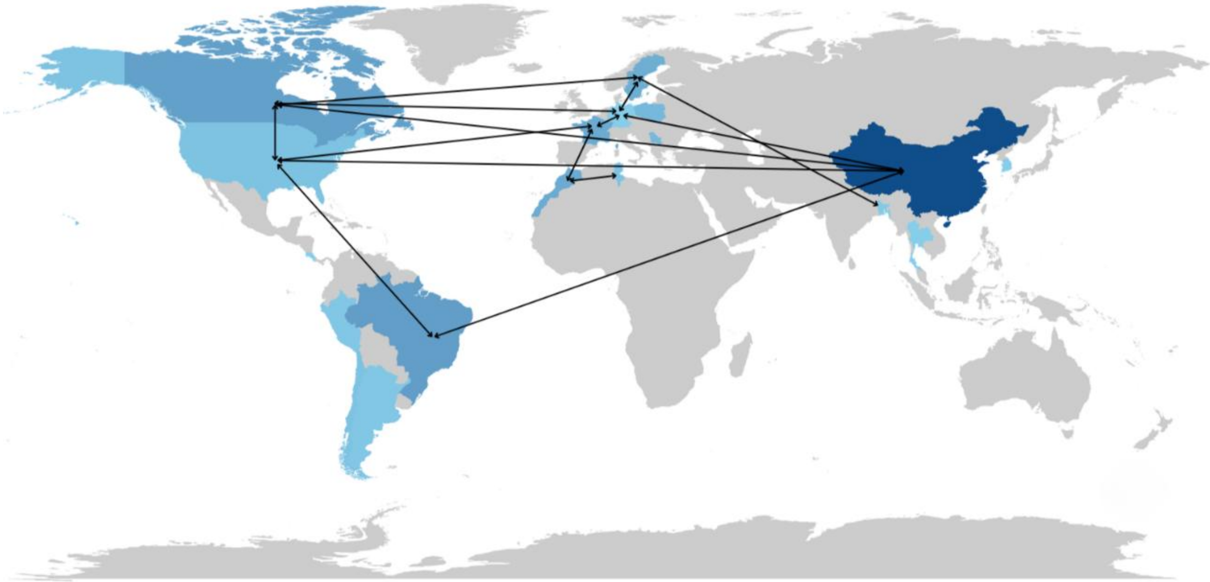
Figure 5. Most relevant authors based on number of citations on the research topic.



Sources: Authors.

The internationalization of research in wood drying is strongly evidenced by the high density of collaboration among authors and clusters from different countries, such as Canada, China, Brazil, Sweden, France, Morocco, and Bangladesh (Fig. 6).

Figure 6. Scientific collaboration network between countries based on the selected articles.



Sources: Authors.

Bibliometric data from the collaboration network show that the cluster led by Avramidis S., Nasir V., and Rahimi S. (who are highly active in Canada) has significant international collaboration, both in joint projects and scientific publications. This centrality indicates that these researchers function as bridges between research groups, especially along the Canada-Sweden axis. In the Asian context, authors from the cluster of Chi X., Cai Y., Liu Y., among others, are key representatives from China and neighboring countries, maintaining frequent collaborations with Brazil, the USA, and Canada. The global impact of this Chinese nucleus is reinforced by the scientific exchange between China-Brazil and China-Canada, with a focus on research into the physical properties of wood and innovation in energy-related and computational techniques.

The clusters formed by authors such as Draoui A. and Lamrani B. (Morocco and France) and by Khouya A. and Chtioui S. (Morocco) illustrate the intercontinental collaboration between Europe and North Africa. This highlights the influence of the French school of engineering in the formation of robust groups in the Maghreb (Northwest Africa) and their interaction with European universities. This interaction is particularly useful for sharing adapted technical solutions and for the formulation of public policies for the sustainable and efficient management of the forestry sector.

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Furthermore, connections such as Sweden-Bangladesh demonstrate the relevance of training and technology transfer initiatives between Scandinavian and Asian countries. These initiatives enhance the development of sustainable, low-cost methods in regions with significant climate challenges, leading Swedish researchers to collaborate with those in Bangladesh to adapt innovative wood drying and monitoring systems to local conditions, thereby expanding the global impact of research in emerging countries. In the Latin American landscape, the China-Brazil interaction broadens the reach of Asian research and enables the adoption and adaptation of modern technologies in the Brazilian forestry sector, which faces unique challenges such as a tropical climate and species with high anatomical variability.

The pattern of isolated clusters, likely associated with different institutions or countries, suggests that knowledge is being built in parallel by different research fronts, without an integrated international collaboration network. Thus, a small number of authors is responsible for both the largest volume of publications and the scientific impact generated on the topic.

Among the main universities and research centers with the highest bibliographic output in the field of study, the Chinese institution Nanjing Forestry University is a clear leader, leading with 16 articles and showing accelerated growth in recent years, especially from 2024 onwards. This university, the institution with the highest production of articles published in 2024-2025, not only leads in volume but is also strongly integrated into international networks, especially with researchers from China, Brazil, and Canada.

Another prominent institution is Northeast Forestry University (China) with 12 publications, which has demonstrated continuous growth. Its network includes strong collaboration with Canadian centers like the University of British Columbia and European institutes. The University of British Columbia (Canada) appears as another important institution with 11 published articles. In addition to these, centers like Poznan University of Life Sciences (7 articles), Poland, and the Research Institute of Wood Industry (6 articles) in China are also notable for their consistent scientific output, operating at the interface of biotechnology, forest sciences, and innovative technologies for wood drying and processing.

Among the Brazilian institutions, the Federal University of Lavras (UFLA) stands out with 6 published articles, and the Federal University of Rondônia (UNIR) with 2 publications, showing active involvement in emerging research from a tropical perspective. UFLA, in particular, has shown solid growth in its output since 2023. Furthermore, the participation of other universities from the Amazon Region, such as the National Agrarian University La Molina (UNALM) and the National University Toribio Rodríguez de Mendoza (UNTRM), contributes studies specifically focused on tropical species and local challenges of wood drying in Amazonian environments.

The presence of Brazilian universities highlights their relevant and growing participation in the scientific production on wood drying. They contribute relevant research within the tropical context and address specific challenges of the forest bioeconomy, with regional influence. Their work focuses on biodiversity and applied technological advances, with a strong focus on sustainability and local adaptation.

At a global level, the geographical diversity of the institutions (spanning Asia, North America, Europe, and South America) (Fig. 7) reinforces the global nature of the field of study and the importance of international cooperation for technological and scientific development. Therefore, the integration of universities into international cooperation networks, as observed through the links between countries like China, Canada, Brazil, Sweden, and France, plays a fundamental role in the global articulation of knowledge. This promotes not only scientific publication but also the training of highly qualified human resources and applied technological innovation.

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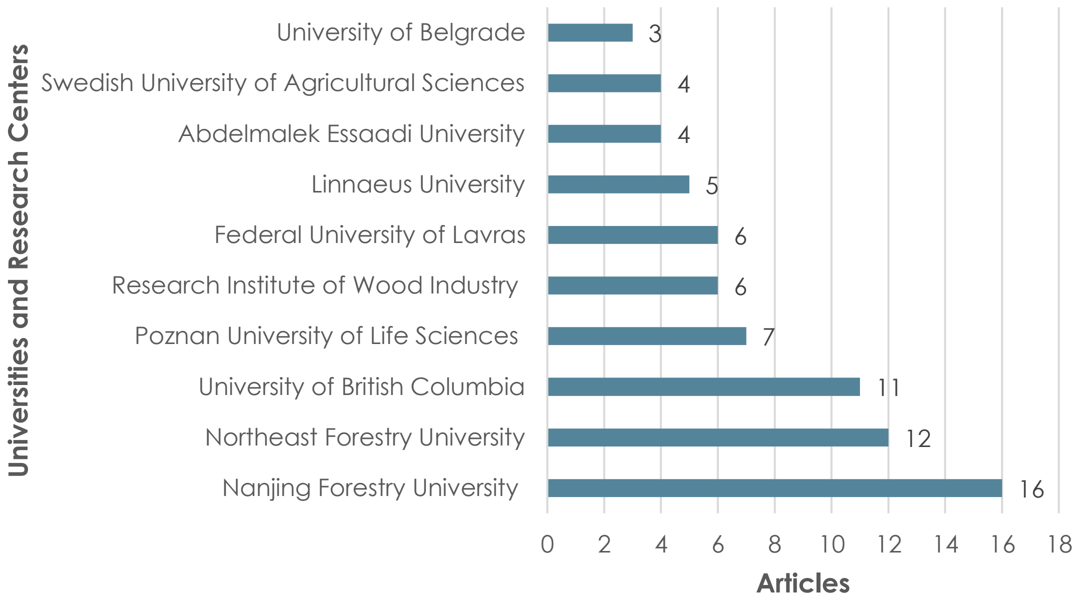
Figure 7. Most relevant universities and research centers on the research topic.



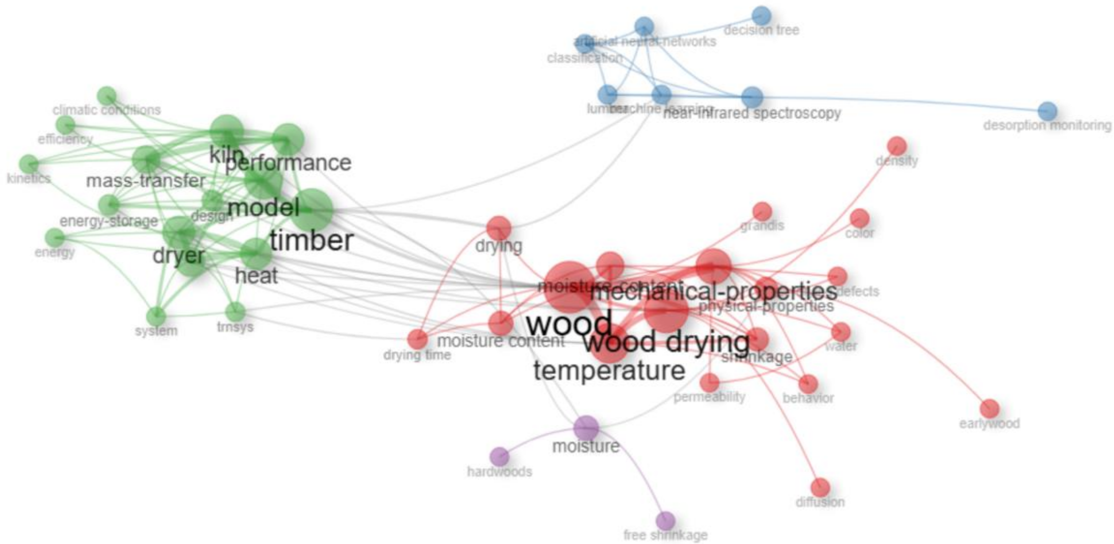
Sources: Authors.

Based on this data, it is evident that the most prominent and central cluster in the collaboration network is that of the University of British Columbia in Canada, led by researchers such as Avramidis, S., Nasir, V., and Rahimi, S. This group functions as a central hub, as evidenced by studies like Chi et al. (2023), which connects them to researchers from Northeast Forestry University in China (like Cheng, W., and Chi, X.) and the University of North Texas in the USA. The same Canadian team also establishes a bridge to Europe, demonstrated by their collaboration with Swedish researchers in the work of Van Blokland et al. (2021). Another significant intercontinental collaboration axis is the partnership between China and Brazil, materialized in the study by Baliza et al. (2023), which unites the cluster from the Federal University of Lavras (led by Hein, P. R. G., and Trugilho, P. F.) with the Chinese Academy of Forestry. In addition to these major axes, strong regional clusters are observed, such as the collaboration between Morocco and France, exemplified by the work of Lamrani et al. (2021).

The keyword co-occurrence diagram (Fig. 8) indicates three large clusters, each associated with specific sub-areas. The central terms are *wood drying*, *wood*, *mechanical-*

properties, *temperature*, *moisture-content*, and *drying*. These terms are positioned as key concepts that connect sub-themes such as *shrinkage*, *physical-properties*, *color*, *density*, and *drying defects*. Therefore, this keyword cluster focuses on investigations into how physical variables affect the behavior and final properties of dried wood, being fundamental to understanding the mechanisms of moisture loss and their structural and mechanical consequences.

Figure 8. Co-occurrence Network in the on the research topic.



Sources: Authors.

Another cluster is formed by terms such as *timber*, *model*, *simulation*, *heat*, *performance*, *dryer*, and *mass-transfer*, which represent the interface between processes and engineering. This cluster focuses on energy optimization, computational simulation, and the efficiency of drying systems. The connections suggest a systemic approach, integrating *energy*, *energy-storage*, *efficiency*, *climatic conditions*, *kinetics*, and *system*, reflecting the search for innovative solutions for energy savings and large-scale quality control.

In the third main cluster, topics such as *near-infrared spectroscopy*, *machine learning*, *classification*, *artificial neural-networks*, *decision tree*, and *lumber* are dominant. The prominence of *machine learning* shows that the use of advanced computational methods and spectroscopic analysis has been consolidated as a cutting-edge trend. These techniques make it possible to monitor and predict critical characteristics of the drying process with greater precision and to assist in the automatic classification of wood defects and properties.

The evolution of keywords demonstrates that research has been shifting from traditional approaches of analyzing physical properties to complex strategies of process simulation and modeling. Newer concepts like *machine learning*, *near-infrared spectroscopy*, and *artificial neural-networks* appear increasingly close to the classic core concepts, pointing to a radical integration between materials science, engineering, and data science.

Therefore, the co-occurrence map not only reveals the major topics of interest, such as the mechanical and stress analysis during drying (Chávez et al. 2021; Majka and Sydor 2023), the search for energy efficiency through solar and hybrid technologies (Lamrani et al. 2021; Chtioui and Khouya 2024), and characterization and prediction using artificial intelligence (AI) (Van Blokland et al. 2021; Rahimi et al. 2022a), but it also highlights the degree of interdisciplinary maturity in the field. Traditional experimental methods coexist with and are enriched by computational tools, as seen in studies that develop predictive models validated by kiln data (Simo-Tagne et al. 2024) or that apply machine learning algorithms to classify wood quality based on its initial properties (Rahimi et al. 2024). Consequently, the dynamics of the keywords show a field in full transformation, capable of responding to industrial, environmental, and technological challenges through continuous and multidisciplinary innovation.

The most cited articles in the field of wood drying reflect both the thematic diversity and the quality and scientific impact achieved in recent years (Table 2). These studies offer significant contributions related to energy efficiency, process modeling, the use of advanced techniques for wood characterization, and sustainability.

Table 2. The most cited articles identified in the literature search since 2020.

AUTOR	TITLE	JOURNAL	TC	TC PER YEAR
Lamrani B. e Draoui A. (2020)	Modelling and simulation of a hybrid solar-electrical dryer of wood integrated with latent heat thermal energy storage system	Thermal Science and Engineering Progress	60	10
Lamrani B. et al. (2021)	Thermal performance and environmental assessment of a hybrid solar-electrical wood dryer integrated with Photovoltaic/Thermal air collector and heat recovery system	Solar Energy	59	11.8
Rostom L. et al. (2021)	Analysis of water content in wood material through 1D and 2D ^{1}H NMR relaxometry: Application to the determination of the dry mass of wood	Magnetic Resonance in Chemistry	22	4.4
Khouya A. (2022)	Energy analysis of a combined solar wood drying system	Solar Energy	22	5.5
Van Blokland et al. (2021)	Machine learning-based prediction of internal checks in weathered thermally modified timber	Construction and Building Materials	19	3.8
Bekkioui N. (2021)	Performance comparison and economic analysis of three solar dryer designs for wood using a numerical simulation	Renewable Energy	19	3.8
Simo-Tagne M e Ndi-Azese M. (2021)	Thermal, economic, and environmental analysis of a novel solar dryer for firewood in various temperate and tropical climates	Solar Energy	19	3.8
Gao Y. et al. (2022a)	Moisture-Related Shrinkage Behavior of Wood at Macroscale and Cellular Level	Polymers	14	3.5
Gao Y. et al. (2022b)	Interdependence of shrinkage behavior between wood macroscopic and cellular level during moisture content loss	Drying Technology	13	3.25
Fu Z. et al. (2021)	Full-field tracking and analysis of shrinkage strain during moisture content loss in wood	Holzforschung	13	2.6

Sources: Authors.

Two studies by Lamrani B. are at the top of the list; together, they accumulate 119 citations, demonstrating a strong influence in the field (Lamrani and Draoui 2020; Lamrani et al. 2021). The 2020 article, published in the journal *Thermal Science and Engineering Progress*, has 60 citations and addresses advances in thermal processes applied to wood drying, highlighting improvements in energy efficiency. The 2021 work, published in *Solar Energy*, has 59 citations and explores solar systems applied to drying, emphasizing the use of renewable energy for process optimization.

The 2021 study by Rostom L., published in *Magnetic Resonance in Chemistry* (Rostom et al. 2021), with 22 citations, stands out for using magnetic resonance techniques for the characterization of moisture in wood, bringing innovations to the use of sensors and the control of the drying process.

The 2022 study by Khouya A. in *Solar Energy* (Khouya 2022), with 22 citations, reinforces research on solar energy applied to drying, showing the advantages of hybrid systems and the economic feasibility for the timber sector. Likewise, the studies by Bekkioui N., 2021, in *Renewable Energy* (Bekkioui 2021), with 19 citations, and Simo-Tagne M., 2021, in *Solar Energy* (Simo-Tagne and Ndi-Azese 2021), bring advances in renewable energies and sustainable techniques for drying optimization, aligning the timber industry with contemporary environmental standards.

Topics related to construction materials and techniques appear in the work by Van Blokland et al., published in 2021 in *Construction and Building Materials* (Van Blokland et al. 2021), with 19 citations, highlighting the connection between drying and the structural quality of wood treated for civil construction. Studies by Gao Y et al., published in *Polymers* (Gao et al. 2022a) and *Drying Technology* (Gao et al. 2022b), accumulate 27 citations, focusing on structural analyses of wood at different scales and consolidating the understanding of its physical and chemical behavior during drying. Meanwhile, the study by Fu Z. et al. in *Holzforschung* (Fu et al. 2021), with 13 citations, complements the picture by applying advanced analyses to study shrinkage and post-drying mechanical properties.

This research demonstrates the vitality and interdisciplinarity of the topic, where thermal and civil engineering, materials science, and renewable energies converge to improve the processes and quality of dried wood, ensuring economic and environmental relevance for the sector.

For a more in-depth analysis of the scientific landscape, the articles were categorized into thematic groups (Table 3). This approach allows for the visualization of the main research fronts, the predominant methodologies, and the areas of greatest interest to the scientific community.

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Table 3. Thematic grouping of articles analyzed in the review portfolio.

Group	Objective	Authors	Conclusion Summary
1. Modeling and Simulation of the Drying Process	To develop, validate, and apply mathematical and computational models to simulate drying phenomena (heat and mass transport, stress, deformation) and to optimize the scheduling and planning of drying operations.	(Lamrani and Draoui 2020; Bekkioui 2021; Marier et al. 2021; Chávez et al. 2021; Simo-Tagne and Ndi-Azese 2021; Vanzetti et al. 2021; Mmari and Johannesson 2022; Zriba et al. 2022; Stolic et al. 2023; Chtioui and Khouya 2024)	Based on continuum mechanics and finite element theories, these models are effective for predicting the evolution of moisture, temperature, and stress. Software such as TRNSYS and MATLAB are used to simulate and optimize solar dryers, evaluating their energy and economic performance. Linear programming models (MILP/MIP) can optimize the planning and scheduling of kilns, surpassing predefined loading patterns. Simulation is also crucial for designing and optimizing drying components, such as high-frequency generators.
2. Advanced Technologies and Drying Optimization	To investigate, compare, and optimize unconventional or enhanced drying methods (supercritical, vacuum, solar, microwave, pre-treatments) to accelerate the process, reduce energy consumption, and improve wood quality.	(Majka and Olek 2020; Lamrani et al. 2021; Khouya 2022; Cao et al. 2022; Chi et al. 2023, 2024; Lee and Oh 2023; Zheng et al. 2024; Kujawiak et al. 2024; Chtioui and Khouya 2024; Saltik 2024; Yang et al. 2025a, b; Shmulsky et al. 2025; Koelli 2025)	Supercritical CO_2 drying (SCD) is up to 5.6 times faster than conventional kiln drying (CKD), resulting in a more uniform moisture distribution and swelling instead of shrinkage. Vacuum drying improves stability, maintains color, and its drying rates are strongly influenced by temperature. Hybrid solar dryers (with a heat pump or PVT) significantly reduce energy consumption and CO_2 emissions. Pre-treatments such as freezing and mechanical compression can accelerate drying and reduce defects. Oscillating drying can decrease drying time by up to 35.8%.
3. Wood Quality, Defects, and Stress Analysis	To study the origin, prediction, and mitigation of drying-induced defects (cracks, collapse, warping) through stress analysis, wood characterization, and the evaluation of different species and treatments.	(Van Blokland et al. 2021; Fu et al. 2021; Rittiphet et al. 2021; Moya and Tenorio 2021; Ghosh et al. 2022; Lima et al. 2023; Albuês et al. 2023; Majka and Sydor 2023)	Drying temperature is a significant factor that influences tensile stress and the risk of cracking. Pre-treatment with mechanical compression can reduce internal voids caused by collapse. Full-field strain analysis (using Digital Image Correlation - DIC) shows that shrinkage strain is greater on the outer surface of the wood, increasing its susceptibility to cracks. Pre-treatments of logs with steam or heat can reduce growth stresses, decreasing warping and improving the quality of sawn timber. Kiln drying is recommended for materials of seminal origin, which show a higher incidence of cracking compared to clonal materials.
4. Monitoring and Control of	To develop and apply new sensor technologies (NIR,	(Rahimi et al. 2022a; Rostom et al. 2021; Rahimi et al. 2022b;	Machine learning models (e.g., Random Forest, Decision Tree) can predict the final moisture content and classify wood with

the Drying Process	thermography, acoustics) and machine learning methods to accurately monitor wood conditions (moisture, temperature, defects) and optimize the control of the drying process.	Amaral et al. 2023; Baliza et al. 2023; Lerman et al. 2023; Rahimi et al. 2024; Simo-Tagne et al. 2024)	high accuracy (up to 91%), using initial properties such as moisture and weight. Near-infrared spectroscopy (NIR) is a promising tool for monitoring the spatial variation of moisture content and shrinkage during drying. Infrared thermography allows for a detailed and quantitative analysis of the drying progression by correlating surface temperature with mass loss. NMR relaxometry can determine the dry mass and moisture content more accurately than conventional oven-drying methods.
5. Physical and Hygromechanical Properties of Wood	To investigate the fundamental properties of wood (permeability, thermal conductivity, shrinkage, rheological behavior) and how they are affected by moisture and temperature, at both the macroscopic and cellular scales.	(Zhu et al. 2021; Gao et al. 2022a, a; Zhang et al. 2024; Zhao et al. 2025; Portal-Cahuana et al. 2025)	The complex pore structure of wood significantly affects its thermal performance; X-ray computed tomography (XCT) technology allows for the visualization of this structure and the simulation of its thermal conductivity. Anisotropic shrinkage is a fundamental characteristic of wood; macroscopic shrinkage is the result of the interaction between the tracheids of earlywood and latewood, and it is dominated mainly by the latewood. Macroscopic shrinkage is slightly less than shrinkage at the cellular level, but the anisotropy is greater at the macroscopic level. Collapse in eucalyptus wood during the initial stages of drying makes the reversal of tensile strain difficult

Sources: Authors.

A prominent and fundamental research area focuses on the development of mathematical and computational models that seek to translate the complex physical phenomena of drying into predictive equations. A trend is observed towards the creation of coupled multiphysics models, which simultaneously consider heat and mass transport along with the mechanical response of the material. Works such as those by Chávez et al. (2021) and Mmari and Johannesson (2022) exemplify this approach, using the finite element method to predict the evolution of moisture, temperature, and, crucially, the mechanical stresses that cause defects.

In parallel, modeling is applied at the scale of industrial process optimization. Studies by Vanzetti et al. (2021) and Marier et al. (2021) employ mixed-integer linear programming (MILP/MIP) to optimize the planning and scheduling of drying operations in sawmills, demonstrating a trend of applying operational research for gains in logistical efficiency. A notable sub-trend is the simulation of sustainable drying systems, especially solar dryers, where software like TRNSYS is used to evaluate the energy, economic, and environmental performance of different designs, as seen in the works of Chtioui and Khouya (2024), Lamrani and Draoui (2020) and Simo-Tagné and Ndi-Azese (2021).

The second thematic axis reveals a continuous search for alternatives to conventional kiln drying, with research bifurcating into two main directions: high-tech methods to accelerate the process and methods focused on sustainability and energy efficiency. In the first group, supercritical carbon dioxide (CO_2) drying stands out for its high efficacy and speed. Studies by Zheng, Xu, and Yang (2024) and Cao, Wang, and Ma (2022) demonstrate that this technique can be significantly faster than conventional drying, resulting in a more homogeneous moisture distribution. Vacuum drying is also explored to improve stability and maintain wood color, with temperature being a crucial control factor, as investigated by Yang et al. (2025b) and Lee and Oh (2023). Methods using electromagnetic energy, such as microwaves and infrared, are also analyzed to shorten drying times (Saltik 2024).

In the second group of innovations, solar energy takes center stage, with a clear trend towards the development of hybrid systems. Research is advancing beyond simple solar dryers, focusing on systems that integrate heat pumps, photovoltaic/thermal (PVT) collectors, and heat recovery systems to ensure continuous operation and greater efficiency (Lamrani et al. 2021; Khouya 2022; Chi et al. 2023). The optimization of existing methods, such as oscillating drying, also shows significant gains, potentially reducing the total process time (Majka; Olek, 2020). Additionally, pre-treatments emerge as a complementary strategy. Among them, pre-freezing to improve quality (Yang et al. 2025a) and mechanical compression as a dewatering method before thermal drying (Koelli, 2025; Rittiphet, Dumyang & Matan, 2021) are notable.

The monitoring of the drying process is evolving from point measurements to rich, real-time, and non-destructive data analysis. A clear trend is the use of near-infrared

(NIR) spectroscopy to map the spatial variation of moisture content, as demonstrated by Amaral et al. (2023) and Baliza *et al.* (2023). Other techniques, such as thermography (Lerman et al. 2023) and NMR relaxometry (Rostom et al. 2021), also contribute to a more precise characterization of the process. In parallel, the application of machine learning is strongly emerging. The works of Rahimi et al. (2022b, 2024) demonstrate the feasibility of predicting the final moisture distribution and internal gradients based on the characteristics of green wood. These efforts converge towards the development of adaptive and feed-forward control systems, where real-time sensor data feed mechanistic models to dynamically optimize the drying schedule (Simo-Tagne et al. 2024).

Studies on wood quality and physical/hygromechanical properties are intrinsically linked. The predominant trend is multi-scale investigation, which seeks to connect macroscopic defects to their origins in cellular behavior. Works like those by Gao et al. (2022b) and Fu *et al.* (2021) use advanced imaging techniques to map shrinkage strain, revealing how anisotropy at the cellular level manifests at the board scale. This fundamental understanding of hygromechanical and rheological properties, as investigated by Zhang et al. (2024), directly informs applied research. This includes the analysis of growth stresses and their mitigation through log treatments (Moya and Tenorio 2021), the development of more suitable drying schedules for specific species (Ghosh et al. 2022; Lima et al. 2023) and the creation of predictive quality control models, as seen in Van Blokland et al. (2021), which use machine learning to predict the occurrence of internal cracks.

Finally, the analysis of this collection of articles reveals a dynamic research field, driven by the need for efficiency, quality, and sustainability. Future trends point towards greater integration among the thematic areas. The outlook is the consolidation of "smart drying" systems, where data from advanced sensors will feed multiphysics models in real-time to dynamically control efficient drying technologies, ensuring the final product quality based on a deep understanding of its fundamental properties. The growing application of artificial intelligence and the continuous search for low-environmental-impact solutions will certainly continue to drive innovation in this area.

5. CONCLUSION

This bibliometric analysis mapped the recent scientific production on wood drying, revealing a globally concentrated research field, led by China and Brazil, and structured into five main thematic areas. The main contribution of this study was the identification of a clear transition from conventional methods to an optimized drying model, characterized by the integration of computational simulations, advanced technologies, non-destructive sensor monitoring, and machine learning. This technological integration aims to transform drying into a predictive, adaptive, and efficient process, with the ultimate goal of optimizing wood quality, reducing energy costs, and increasing the sustainability of the timber industry.

ACKNOWLEDGEMENTS

The authors thank the Graduate Program in Forest Sciences at the Federal University of Espírito Santo (UFES) for the academic and scientific support that made the development of this work possible.

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