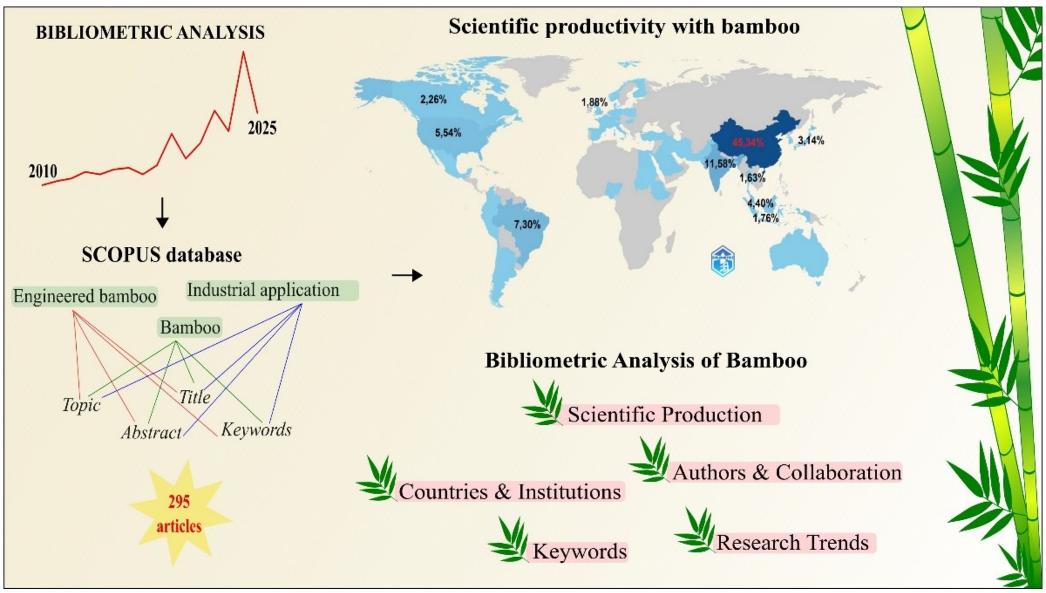
Evolution of Scientific Knowledge on the Industrial Uses of Bamboo: Bibliometric Analysis

Oxandra R. Rivera,[a] Fabricio G. Gonçalves,[a] Juarez B. Paes,[a,*] Caroline P. Araujo,[a] Tamara S. F. A. França,[b] Daniel A. Á. Lazo,[a] and Frederico J. N. França[b]

*Corresponding authors: tsf97@msstate.edu; jbp2@uol.com.br

DOI: 10.15376/biores.21.4.10166-10186

GRAPHICAL ABSTRACT



Evolution of Scientific Knowledge on the Industrial Uses of Bamboo: Bibliometric Analysis

Oxandra R. Rivera,[a] Fabricio G. Gonçalves,[a] Juarez B. Paes,[a,*] Caroline P. Araujo,[a] Tamara S. F. A. França,[b] Daniel A. Á. Lazo,[a] and Frederico J. N. França[b]

Bamboo stands out as a promising resource for sustainable industrial applications due to its rapid growth, superior mechanical properties, and environmental benefits. Its use in sectors such as civil construction, the pulp and paper industry, and energy generation reinforces its role as a strategic alternative to traditional and non-renewable materials. Thus, the effective advancement of its industrial applications can benefit from a systematic mapping of current scientific trends. This helps in identifying emerging trends, knowledge gaps, and priority opportunities for sustainable innovation. In this context, this study aimed to conduct a bibliometric analysis of scientific literature related to the industrial uses of bamboo, for the period 2010 to 2025, based on data extracted from the Scopus database and analyzed using the Bibliometrix software. The investigation maps academic output, including the temporal evolution of publications, key authors, collaborative networks, top journals, and emerging thematic trends. The results contribute to systematizing existing knowledge, identifying research gaps, and supporting the development of strategies aimed at consolidating bamboo as a sustainable industrial resource.

DOI: 10.15376/biores.21.4.10166-10186

Keywords: Engineered bamboo; Physicochemical characteristics; Indexing platforms

*Contact information: a: Federal University of Espírito Santo, Department of Forest and Wood Science, Av. Governador Lindenberg, 316, 29550-000, Jerônimo Monteiro, Espírito Santo, Brazil; b: Mississippi State University, Department of Sustainable Bioproducts, 201 Locksley Way, Starkville, Mississippi State, 39759, USA; *Corresponding authors: tsf97@msstate.edu; jbp2@uol.com.br*

INTRODUCTION

Bamboo has gained increasing prominence in recent decades as a strategic resource for sustainable development due to its rapid growth, high renewability, superior mechanical properties, and recognized environmental benefits (Akwada and Akinlabi 2020). Its versatility allows for applications in various industrial sectors, such as civil construction, pulp and paper industry, and energy generation, establishing it as a viable and ecological alternative to conventional materials such as wood and fossil fuels (Borowski *et al*. 2022; Chaudhary *et al*. 2024).

In the construction sector, bamboo has been used as a sustainable substitute for wood, standing out for its high tensile strength and excellent load-bearing capacity, attributes that are particularly valuable in contexts of scarce forest resources (Akwada and Akinlabi 2020; Borowski *et al*. 2022). In the pulp and paper industry, it is positioned as a high-yield non-timber fibrous raw material, contributing both to environmental conservation and to more responsible industrial practices (Chaudhary *et al*. 2024).

Furthermore, its use as a biofuel in renewable energy production not only promotes the diversification of the energy matrix but also contributes to mitigating climate change through carbon sequestration (Pavate *et al*. 2024).

Despite its promising attributes, bamboo possesses morphological and anatomical characteristics that present challenges for its industrial processing. The culm is essentially a hollow cylinder with relatively thin walls, varying between 10% and 50% of the external diameter, which limits the material yield in sawmilling and lamination processes to approximately 40%, compared to 60% for conventional wood (Sharma *et al*. 2015). The outer epidermis is a dense, waxy layer rich in silica (up to 10% in some species), which acts as a mechanical and chemical barrier, hindering the penetration of adhesives and accelerating the wear of cutting tools (Liese 1998).

Furthermore, bamboo exhibits pronounced radial gradients in its anatomical structure: the vascular bundles, the main load-bearing elements, are densely distributed in the outer periphery (up to 41.9% by volume) and become progressively scarce towards the inner wall (15.1%), generating a non-uniform distribution of mechanical properties across the culm's cross-section (Chen *et al*. 2015). Vertical variation also occurs, with culm diameter, wall thickness, and internode length decreasing towards the apex, introducing additional heterogeneity to this raw material.

On the other hand, bamboo possesses remarkable mechanical properties that position it as a strategic material for high value-added applications. The tensile strength of bamboo fibers reaches values of up to 600 MPa, with a Young's modulus of approximately 46 GPa, surpassing many hardwoods and approaching mild steel in terms of specific strength (strength-to-weight ratio) (Sharma *et al*. 2015). This remarkable strength-to-weight ratio, combined with high energy absorption capacity and flexibility, makes bamboo suitable for earthquake- and wind-resistant structures (Bahrin *et al*. 2023). Furthermore, its high cellulose content (40 to 50% by mass) and porous structure make it attractive for biorefinery applications, nanocellulose production, and adsorption materials (Zhang *et al*. 2024). These distinctive properties are, therefore, the main drivers of the scientific and technological developments observed in recent decades, justifying the growing bibliometric interest documented in this study.

Based on these distinctive properties, bamboo research has expanded in recent decades beyond its traditional uses, attracting increasing interest focused on the development of new sustainable technologies. Several studies have explored its potential in high-value-added industrial applications, considerably expanding the scope of use of this natural resource. Advances have been observed in the use of bamboo for the manufacture of structural panels, the production of biofuels and bio-oil through thermochemical processes, the formulation of low-impact cementitious materials, and the development of composites for the automotive industry. These studies have demonstrated that bamboo can offer competitive physical and mechanical performance, high energy efficiency, and an effective contribution to reducing emissions associated with conventional industrial processes (Subyakto *et al*. 2011; Amatosa and Loretero 2020; Carvalho and Velasco 2021; Li *et al*. 2023; Ugo *et al*. 2024).

This body of evidence reinforces the versatility of bamboo as a strategic raw material in the transition to more sustainable production models, particularly in sectors such as civil construction, energy generation, and the composite materials industry. However, the large-scale consolidation of its industrial use still depends on strengthening value chains, overcoming technological barriers, and expanding the scientific and technological knowledge base surrounding it. In this context, understanding how scientific production has addressed the topic can help identify emerging trends, knowledge gaps, and opportunities for sustainable innovation.

Thus, the systematic mapping of scientific literature on the subject can offer valuable support for the formulation of public policies and the definition of research and development strategies. Among the methods available for this purpose, bibliometric analysis has emerged as a relevant and widely adopted approach to map the state of the art and evolutionary trends within a research field (Tan *et al*. 2021). This methodology allows for a quantitative and visual examination of the dynamics of scientific production through objective indicators such as the number of publications, citations, keywords, authors, institutions, and collaboration networks (Verma and Gustafsson 2020). Furthermore, well-structured bibliometric studies provide a useful reference for advancing specific areas of knowledge, transforming large volumes of unstructured data into accessible and relevant information (Donthu *et al*. 2021).

This way, the main objective of this study is to conduct a bibliometric analysis of the scientific literature on the industrial uses of bamboo, in order to map the temporal evolution of publications, identify the most researched topics, the most productive authors, the main collaboration networks, and the most influential journals, using data extracted from the Scopus database with the support of the Bibliometrix software.

EXPERIMENTAL

This study adopted a combination of inductive and deductive approaches, applying the methodological triangulation technique for data collection. Triangulation, as a strategy inherent to qualitative research, enhances the credibility and validity of the study by integrating multiple perspectives, methods, and sources of information (Meydan and Akkaş 2024).

This methodological approach enables a broader and more in-depth understanding of the object of study through cross-verification of data from different perspectives (Ganapathy 2023). For the collection and interpretation of information, searches were conducted in the Scopus database, considering the fields *topic*, *title*, *abstract*, and *keywords*.

The search terms used in the strategy were: Bamboo, Industrial application, and Engineered bamboo, strategically combined to identify relevant research on the industrial uses of bamboo. The exact search string applied to the Scopus database was: TITLE-ABS-KEY (“bamboo” AND (“industrial application” OR “engineered bamboo”)). This string was executed in July 2025 in the title, abstract, and keywords fields. The search period covered the years 2010 to 2025. After screening the records, including removing duplicate, incomplete, and out-of-scope documents, 295 articles were obtained, which formed the basis of the analysis in this study.

The retrieved records were exported in compatible formats and analyzed using the Bibliometrix statistical package in the R programming environment, allowing for a comprehensive bibliometric analysis of the selected corpus.

In a second phase, the collected data underwent cleaning and standardization to ensure the consistency and quality of the bibliographic database. This process included correcting inconsistencies resulting from automatic export, such as standardizing references to the same author and harmonizing keywords considering singular and plural variations. Variants of author names were unified using Scopus author identifiers, when available. Generic terms automatically extracted by Keywords Plus, such as "article," were retained in the dataset for transparency purposes but excluded from thematic interpretation.

Following the procedures described by León-Gómez and Mora (2022), the bibliometric analysis process was structured around two main groups of indicators. First, activity indicators were applied, providing information on the volume and impact of scientific production, and enabling the observation of the quantitative evolution of the literature on the topic. Likewise, an analysis of the productivity of authors, journals, and geographical regions was carried out.

Secondly, a keyword co-occurrence analysis was carried out, which enabled the representation of the state of the art in this domain through the identification of thematic clusters. These clusters were subsequently classified within a strategic diagram according to their level of development and relevance, allowing for the identification of both emerging and consolidated themes within research on the industrial applications of bamboo. Within this analytical framework, it is crucial to emphasize that the bibliometric indicators and activity metrics evaluated in this study were used as quantitative tools for measuring visibility, productivity, and academic dissemination, and not as absolute parameters of scientific quality, merit, or conceptual validation. The interpretation of these data was contextualized within the structural dynamics of the research area, recognizing that publication flows and their impact on the literature reflect the dynamism of scientific debate and not necessarily a qualitative value judgment.

RESULTS AND DISCUSSION

The annual frequency of publications related to the industrial uses of bamboo provides insight into the growth of the field, the advancement of generated knowledge, and the degree of consolidation achieved by this line of research. Figure 1 illustrates the temporal evolution of scientific articles published at the global level.

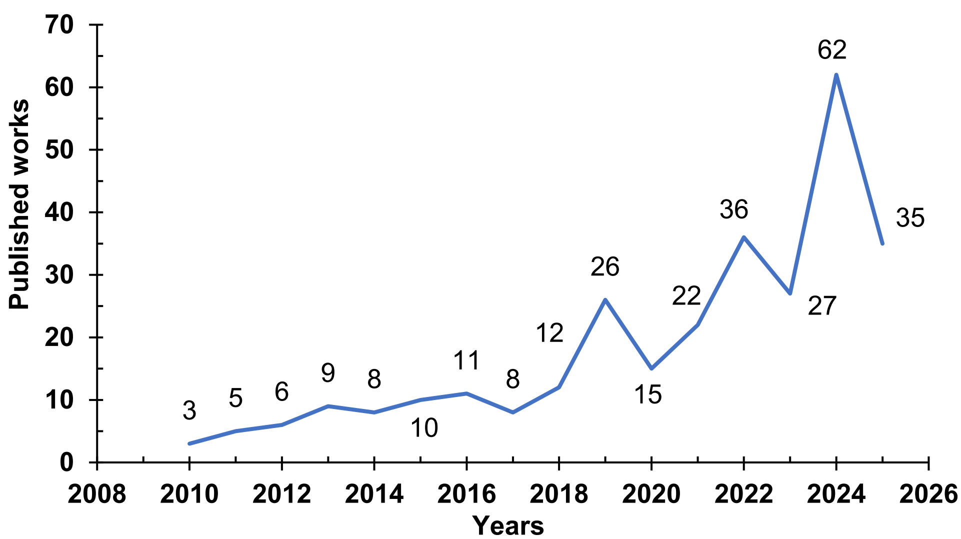


Fig. 1. Temporal dynamics of the scientific output analysed in the thematic area under study for the period between 2010 and 2025. Source: Scopus database

Figure 1 shows a significant increase in scientific output over the past decade compared to the early years covered by the study. Although this trend was not strictly linear, the number of publications peaked in 2024, with 62 articles published. This growth may be attributed to the intensified efforts of various researchers to explore the industrial potential of bamboo as a sustainable alternative to wood. Such interest has been driven by bamboo's excellent mechanical properties as well as its environmental compatibility, particularly in the context of the progressive depletion of native forests (Hernández-Mena 2024).

The geographical distribution of scientific output related to the topic under study highlights the contribution of different regions to the dissemination of knowledge on the industrial use of bamboo (Fig. 2). China stands out, accounting for 45.3% of the publications, reflecting its strong engagement in research, technological development, and the application of bamboo across various industrial sectors. It is followed by India (11.6%), Brazil (7.3%), the United States (5.5%), and Malaysia (4.4%). Among the 40 countries analyzed, only 10 were responsible for 84.8% of the total number of articles published. In this context, a comparative analysis of global scientific output, from the perspective of thematic specialization, highlights the relative performance of nations regarding their international contribution (Zacca-González *et al*. 2014).

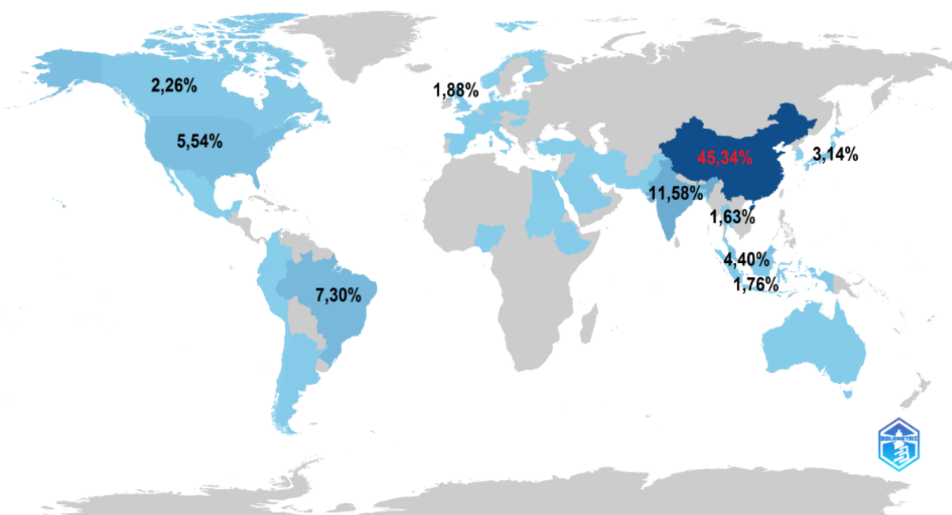


Fig. 2. Mapping of the areas with the highest scientific productivity. Source: Scopus database

Complementing this analysis, Fig. 3 highlights the countries with the highest number of citations in the context of publications on the industrial use of bamboo. Interestingly, some nations with significant influence in the dissemination of scientific knowledge, as France, Italy, Spain, Finland, and Switzerland, appear among the 10 most cited countries, despite not ranking among the top producers in terms of publication volume.

This phenomenon suggests that, although these countries publish fewer studies, their research has high academic impact and relevance, being widely referenced by other authors. This scenario underscores the importance of considering not only the quantity of publications but also the quality, originality, and reach of scientific contributions when evaluating the global dynamics of bamboo research.

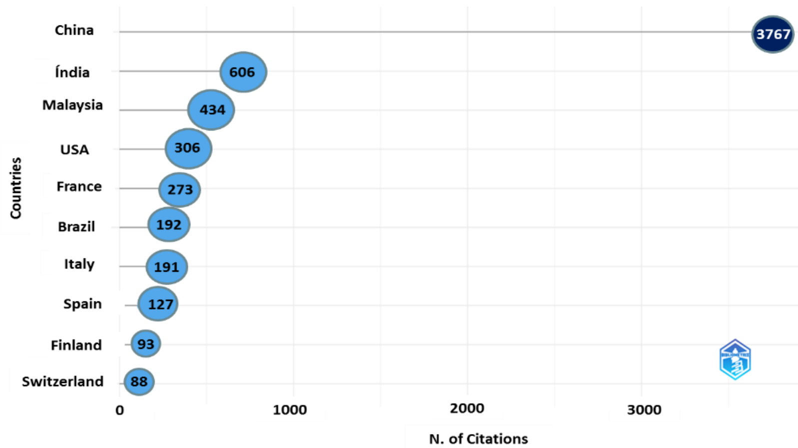


Fig. 3. The most cited countries with publications related to studies on the industrial uses of bamboo between 2010 and 2025. Source: Scopus database

To complement the absolute analysis of scientific production presented in Figs. 2 and 3, a per capita comparative analysis was carried out, normalizing the bibliometric indicators by the national population of each country (Table 1 and Fig. 4). This approach, widely used in international comparative bibliometric studies (King 2004), allows the identification of patterns of relative specialization that are not evident on absolute scales, revealing the intensity of scientific production proportional to the population size of each nation. The population data used refer to the year 2024 (in thousands of inhabitants), compiled from indicators from national statistical offices and the World Bank World Development Indicators (SP.POP.TOTL) (World Bank 2024).

Table 1. Scientific Output by Country Based on Absolute Publications and Citations, Normalized for the Population

Country	Population (2024)	Number of articles/ Absolute public (%)	Public per capita*	Absolute quotes	Citations per capita (CP)*	Ranking of Public per capita	Ranking CP
China	1,408,975,000	134/45.34	0.095	3,767	2.67	3	6
India	1,450,935,790	34/11.58	0.024	606	0.42	5	10
Brazil	211,998,570	22/7.30	0.102	192	0.91	2	8
USA	340,110,990	16/5.54	0.048	306	0.90	4	9
Malaysia	35,557,670	13/4.40	0.365	434	12.21	1	2
France	68,551,650	-	-	273	3.98	-	4
Italy	58,952,700	-	-	191	3.24	-	5
Spain	48,848,840	-	-	127	2.60	-	7
Finland	5,619,910	-	-	93	16.55	-	1
Switzerland	9,005,580	-	-	88	9.77	-	3

Public: Publications; * Per million inhabitants. Source: (World Bank 2024); Scopus database

Table 1 shows the estimated population for the year 2024, the percentage share of publications in the total set of documents analyzed (absolute publications), the number of publications normalized by population (per capita publications, calculated per million inhabitants), the total number of citations received (absolute citations), the relative impact of citations for the population size (per capita citations, calculated per million inhabitants), as well as the respective absolute and per capita rankings.

Absolute publications reflect the percentage of publications in relation to the total number of articles analyzed. Publications per capita is the number of publications normalized by the country's population. Absolute citations are the total number of citations received by published articles, while citations per capita indicate the number of citations normalized by the country's population. The absolute ranking is the classification of countries according to the absolute values of publications or citations, and the ranking of publications per capita expresses the classification of countries according to the values normalized by the population (per capita indicators).

The analysis of scientific impact, based on the number of citations normalized by population, reinforces this trend. China, which had the highest absolute number of citations (3,767), occupies an intermediate position when considering population, with 2.67 citations per million inhabitants. On the other hand, Finland, although in ninth position in absolute citations (93 citations), achieved first place in the per capita ranking, with 16.55 citations per million inhabitants, indicating a high relative concentration of scientific impact. Malaysia also showed impressive performance, occupying second place in this indicator, with 12.21 citations per million inhabitants, while Switzerland occupied third place, with 9.77 citations per million inhabitants. These results demonstrate that countries with lower absolute output can present high scientific relevance when analyzed from a proportional perspective.

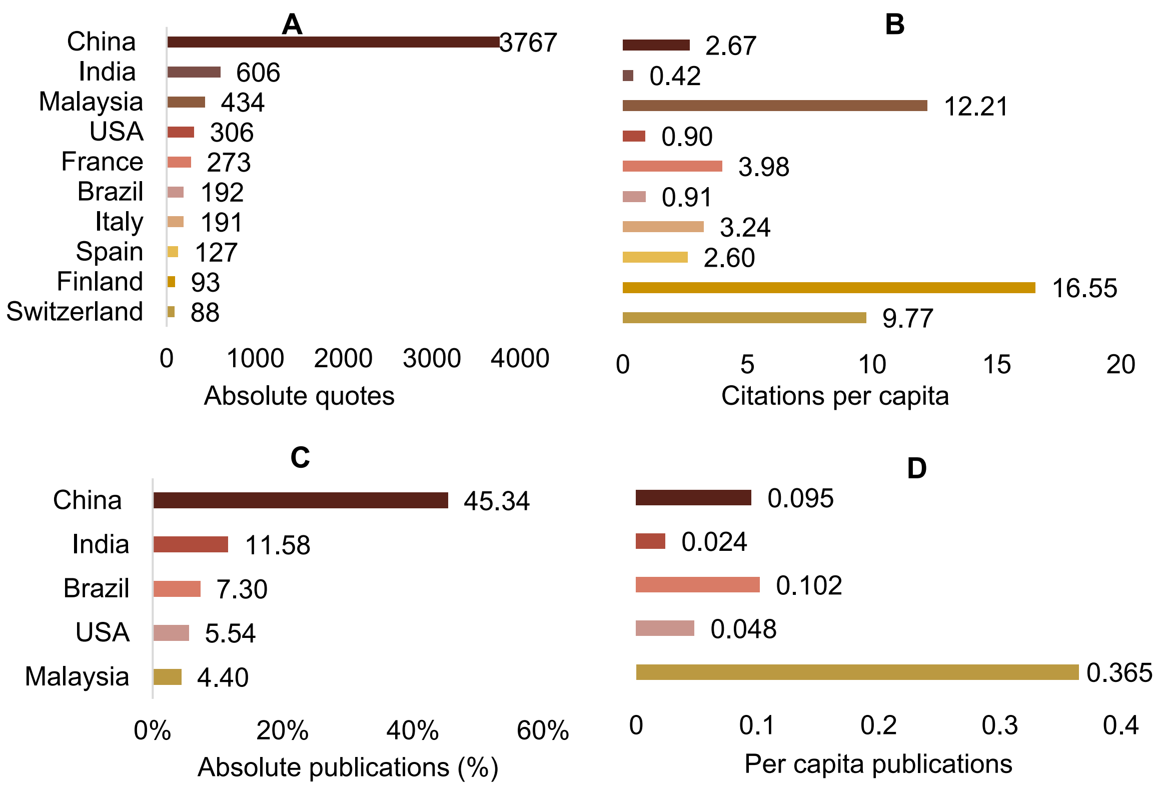


Fig. 4. Comparison between absolute and per capita bibliometric indicators for research-producing countries on industrial uses of bamboo (2010-2025). A - Absolute citations; B - Per capita citations (normalized by national population); C - Absolute publications as a percentage of the total; D - Per capita publications (normalized by national population). Population data: 2024 (in thousands of inhabitants). Source: (World Bank 2024); Scopus database

Per capita analysis shows that countries with smaller populations but high specialization in industrial bamboo research stand out prominently when considering the relative intensity of scientific output. Finland, for example, which ranks 9th in absolute citations, rises to 1st place in per capita citations (16.55 per million inhabitants), highlighting a disproportionate concentration of expertise in this field. Similarly, Malaysia becomes the leader in per capita publications (365.04 per million), while China, dominant in absolute terms, falls to 3rd place in this relative metric (Fig. 4).

The per capita calculations (Fig. 4) follow the standard bibliometric normalization approach (King 2004): Per capita indicator = (Absolute value / Total population in millions). Thus, these results show that the geographical distribution of scientific production on industrial uses of bamboo takes on distinct configurations when analyzed in absolute versus per capita terms. While China and India lead in total volume, nations with smaller populations, such as Finland, Switzerland, and Malaysia, present proportionally higher publication and citation rates. This difference is due to multiple factors, including but not limited to investment policies in Research and Development, research traditions in alternative materials, or simply the effect of population size on statistical normalization. The per capita analysis therefore offers an additional perspective, and not a definitive interpretation of international research dynamics.

The bibliometric analysis identified the five leading academic institutions contributing the most to the specialized literature on the industrial use of bamboo (Fig. 5), within a total of 510 institutions. Among them, Nanjing Forestry University stands out, topping the ranking with 18 indexed publications between 2019 and 2025, highlighting its prominence and ongoing commitment to advancing knowledge in the field.

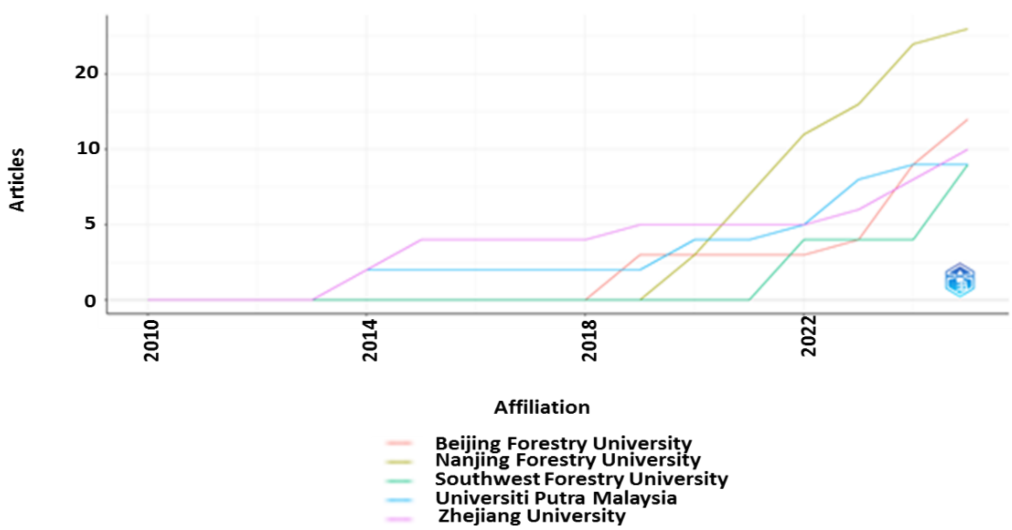


Fig. 5. Leading institutions in publishing studies on the industrial uses of bamboo between 2010 and 2025. Source: Scopus database

To provide a comprehensive overview of the most productive and influential authors in the field of study, the data were organized to present a profile of the top 10 researchers (Fig. 6), ranked based on the total number of publications (NP) and the total number of citations received (TC) during the analyzed period. In this context, Fig. 5 offers an integrated view of the relationship between productivity and impact, highlighting the authors whose work has been most significant in consolidating the field related to the industrial use of bamboo.

Among the highlighted authors, Wang Y stands out as the most productive researcher, with 12 published articles, and also leads in academic impact, with a total of 483 citations. This performance indicates not only a consistent scientific output but also one of high recognition and relevance within the international scientific community.

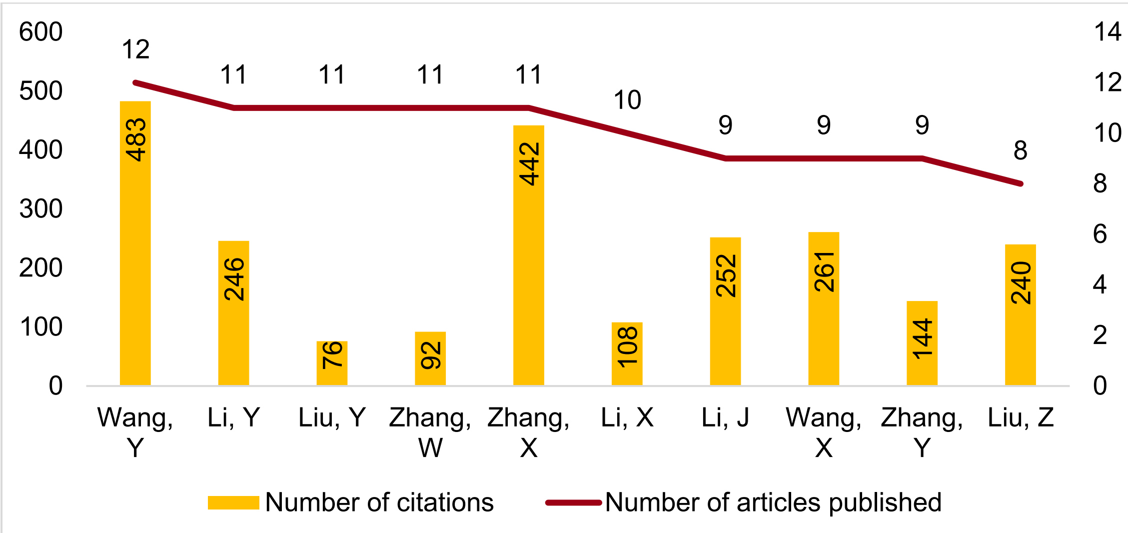


Fig. 6. Most productive authors and their scientific impact in the field of industrial uses of bamboo (2010-2025). Left Y-axis (green bars): Number of articles published. Right Y-axis (blue bars): Number of citations. Source: Scopus database

The data reveal a structural asymmetry in the analyzed literature, demonstrating that researchers with a higher volume of publications do not necessarily correspond to those with higher citation rates. This empirical divergence highlights that quantitative productivity does not translate linearly into scientific influence or impact, reiterating the need to integrate complementary bibliometric indicators for a rigorous evaluation of intellectual contributions in the field studied. From this perspective, high volumes of citations or bibliographic production are not absolute determinants of academic acceptance, intrinsic quality, or theoretical originality.

Thus, a manuscript can accumulate citations due to methodological weaknesses, conceptual debates, or structural refutations by the scientific community, just as high productivity can derive from the fragmentation of results (salami science) within consolidated co-authorship networks. For this reason, the present investigation concomitantly adopts the number of publications (NP) and the total number of citations received (TC) as complementary analytical metrics, conceiving them as proxies for academic impact and insertion into the scientific discourse, and not as qualitative value judgments about specific authors or publications.

Author Productivity According to Lotka's Law

The distribution of author productivity, illustrated in Table 2 and Fig. 7, was analyzed based on Lotka's Law, which states that the number of authors publishing n articles is approximately $1/n^2$ of those publishing only one article (Lotka 1926). In the analyzed dataset, it was observed that 82.9% of the authors contributed with only one article, while just 10.3% published two articles, with even smaller proportions applying to authors with three or more publications.

When comparing the observed data with the theoretical distribution proposed by Lotka, a slight divergence can be noted: the share of authors with only one publication was higher than theoretically expected (82.9% observed *vs*. 63.9% expected). This difference suggests an even more pronounced concentration of scientific output among occasional authors, which is characteristic of emerging or interdisciplinary fields where many researchers contribute sporadically to studies related to the topic.

Table 2. Author's Productivity

Documents written	Number of authors	Proportion of authors	Theoretical
1	1035	0.829	0.639
2	129	0.103	0.160
3	36	0.029	0.071
4	19	0.015	0.040
5	7	0.006	0.026
6	7	0.006	0.018
7	5	0.004	0.013
8	2	0.002	0.010
9	3	0.002	0.008
10	1	0.001	0.006
11	4	0.003	0.005
12	1	0.001	0.004

Source: Scopus database.

Lotka's graph confirms this trend, revealing an exponential decline in the number of authors as the number of publications increases. Thus, the results highlight a scenario in which scientific output is highly dispersed, with only a few authors playing a more consistent and central role in the development of specialised literature on the industrial use of bamboo.

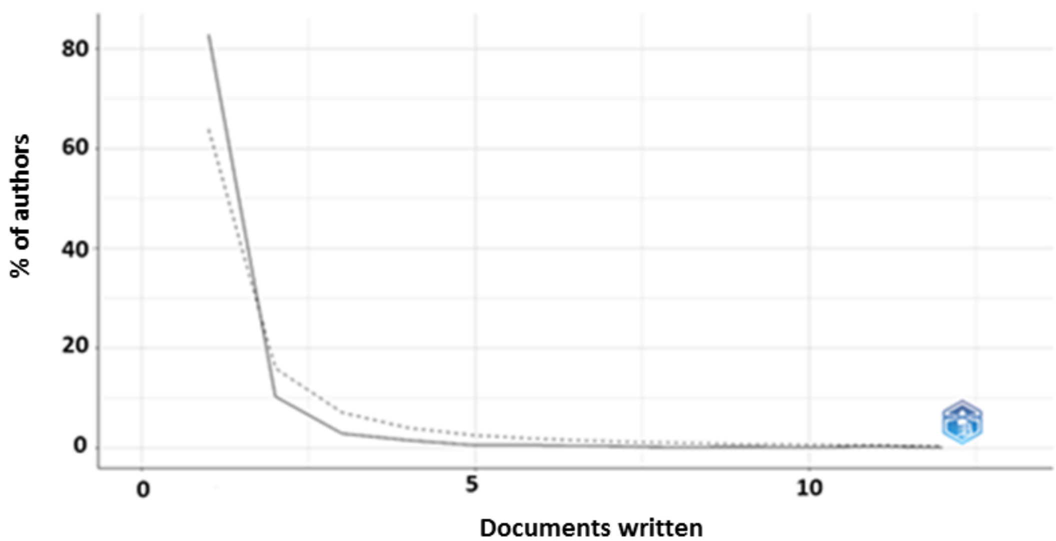


Fig. 7. Author productivity according to Lotka's Law. Source: Scopus database. The dotted line represents the expected behavior and the solid line represents the observed behavior according to Lotka's Law.

Figure 8 illustrates the collaboration network among authors within the analysed field of study, based on scientific publications indexed during the period from 2010 to 2025. In this representation, each node corresponds to an individual author, while the lines or edges connecting the nodes represent co-authorship collaborations. The size of each author's name has been adjusted according to their degree of centrality within the network—larger names indicate authors with a higher number of collaborations or a more significant role in connecting different parts of the network (Isfandyari-Moghaddam *et al*. 2023).

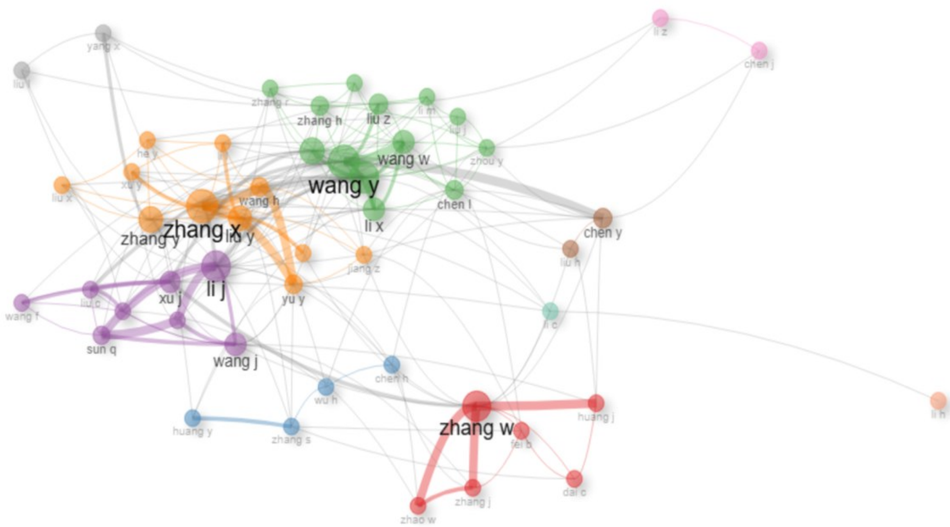


Fig. 8. Collaboration network among authors in the analysed field of study. Source: Scopus database

Authors such as Wang Y., Zhang L. X., Li J., and Zhang W. stand out visually due to the larger size of their names, indicating high centrality and a significant number of scientific collaborations. These authors function as hubs or key nodes within the network, playing a central role in the articulation of knowledge and the dissemination of information across various research groups.

In this respect, the structural prominence and size of these key nodes reflect purely mathematical criteria of indexed authorship co-occurrence, without discriminating between the hierarchical roles or institutional trajectory of the researchers. As demonstrated in the literature on scientific demography, co-authorship records inevitably aggregate different contribution profiles: permanent researchers, whose stability provides continuity to research lines, and transient researchers, who generate significant volumes of production in a short period of time (Milojević *et al*. 2018). Thus, the relational data are presented as a structural mapping of established formal connections and not as an indicator of administrative positions or institutionalized leadership.

The network is also organised into clusters of different colours, which represent communities of researchers with more intense collaboration patterns among themselves. These communities reflect thematic affinities, institutional ties, or shared geographical locations among the authors. The detection of these communities was carried out using specific social network analysis algorithms, such as the Louvain algorithm developed by Blondel *et al*. (2008), which is widely used to identify modular structures in complex networks.

Despite the presence of relatively well-defined communities, the visualisation reveals a considerable degree of interconnectivity between different clusters. This indicates the existence of knowledge flows among various research groups, suggesting a field characterised by active and cross-cutting scientific interaction. In this context, authors like Wang Y. play a strategic role as intermediaries, acting as bridges that facilitate scientific synergy and conceptual integration between different lines of research.

The analysis of the geographical distribution of corresponding authors in scientific publications reveals distinct patterns of collaboration and productivity among countries (Fig. 9). China stands out as the leader in terms of total publication volume, with a predominance of articles authored solely by national researchers (Single Country Publications - SCP), indicating a robust endogenous capacity for scientific production. However, its participation in international networks (Multiple Country Publications - MCP) remains relatively limited, suggesting opportunities to expand global partnerships.

India and Brazil also stand out for their volume of publications, which are mostly composed of SCPs. However, India shows greater engagement in international collaborations compared to Brazil, which maintains a more introspective profile. Countries such as Malaysia, the United States, and Canada exhibit a balance between SCP and MCP, demonstrating simultaneous integration into both national and international research networks.

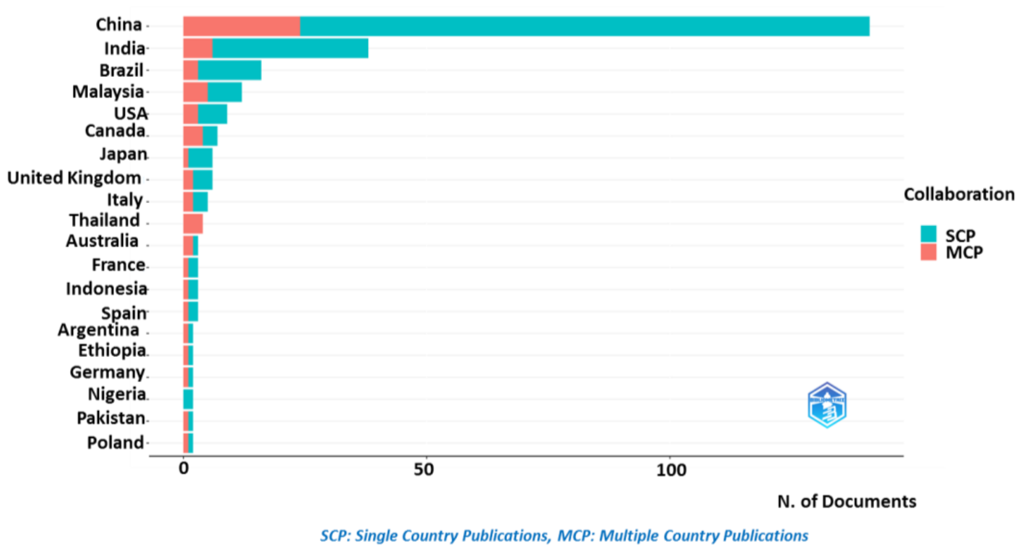


Fig. 9. Analysis of scientific collaboration by country of affiliation of corresponding authors. Source: Scopus database

In contrast, Australia, although presenting a lower absolute volume of publications, demonstrates a relatively higher participation of MCP (Multinational Research Programs), reflecting greater involvement in international scientific collaborations. The United Kingdom, Italy, France, Spain, and Germany show mixed patterns between national publications and international collaborations. Thailand stood out for exclusively publishing publications associated with international scientific collaborations, evidencing strong integration into transnational research networks. Finally, countries such as Argentina, Ethiopia, Nigeria, Pakistan, and Poland contribute more modestly to the scientific production analyzed, while Japan shows a predominance of national publications compared to international collaborations.

Distribution of Academic Output in Specialised Journals

The bibliometric analysis identified a total of 159 journals responsible for disseminating scientific documents related to the industrial applications of bamboo. In order to provide a comprehensive overview of the most productive and influential journals in the field, Table 3 presents a summary of the top 10 scientific journals during the period under analysis, ranked by the total number of publications (NP). Additionally, relevant bibliometric metrics are provided, such as the h-index, g-index, and total citations (TC), which help assess both productivity and impact.

Table 3. Influential Scientific Journals in the Dissemination of Studies on the Industrial Applications of Bamboo

Journal	h-index	g-index	Total Citations	Number of Publications
Industrial Crops and Products	8	21	441	23
Polymers	6	6	124	6
Polymer Composites	5	5	121	5
Bioresources	4	5	32	5
Chemical Engineering Journal	4	5	95	5
International Journal of Biological Macromolecules	4	6	44	7
Journal of Forestry Engineering	4	6	62	6
Molecules	4	5	84	5
ACS Sustainable Chemistry and Engineering	3	3	98	3
Carbohydrate Polymers	3	3	152	3

Source: Scopus database.

The h-index, proposed by Jorge E. Hirsch in 2005, measures a journal's productivity and impact by indicating that a publication has an h-index when h of its articles have received at least h citations each (Engel 2013). The g-index, introduced by Leo Egghe in 2006, refines this assessment by accounting for the citation distribution, giving more weight to highly cited articles (Singh and Kumar 2014).

These metrics are thus presented for the main scientific journals that have published studies on the industrial use of bamboo. Industrial Crops and Products stands out as the most influential journal, with the highest number of publications (23), total citations (441), and the highest h and g indices (8 and 21, respectively), indicating consistent and highly visible output. In contrast, journals such as Polymers and Polymer Composites display moderate h/g indices (6/6 and 5/5, respectively) but a smaller number of publications (6 and 5), suggesting thematic specialisation and impact concentrated in a few key studies.

Other journals, such as *BioResources* and *Chemical Engineering Journal*, present lower h/g indices (4/5 in both cases), associated with a limited number of citations (32 and 95) and publications (5 each), which may indicate emerging influence or activity within specific niches. Also noteworthy are journals such as *Carbohydrate Polymers* and *ACS Sustainable Chemistry & Engineering*, which, despite having relatively low h-indices (3), show a high citation density per article (≈50 and ≈33, respectively), reflecting highly referenced individual contributions.

Overall, the data reveal heterogeneity in both the productivity and reach of the publications, evidencing the coexistence of journals with a well-established interdisciplinary profile (*Industrial Crops and Products*) and others with a more specialised focus, as well as the presence of journals undergoing scientific consolidation.

Co-occurrence Analysis of Keywords and Thematic Structuring in the Literature on the Industrial Uses of Bamboo

Keyword co-occurrence analysis is a widely used technique to identify research trends and interrelationships between concepts by examining how frequently certain terms appear together in the scientific literature (Chigarev 2024). This approach involves the construction of semantic networks, in which terms function as nodes interconnected through their co-occurrences, allowing the visualisation of thematic connections and emerging knowledge structures (Ozek *et al.* 2023). The two figures presented below offer complementary insights into this approach.

Figure 10 shows a co-occurrence map of keywords (Keywords Plus), which visualises the relationships between frequently used terms in scientific publications. The keywords are grouped into three well-defined thematic communities, each represented by a different colour:

- Blue: Themes focused on the mechanical and structural properties of bamboo, such as *tensile strength, mechanical properties,* and *natural fibers*.
- Red: Research related to thermochemical processes and environmental applications, including *adsorption, carbonization, pyrolysis,* and *activated carbon.*
- Green: Studies addressing biological, chemical, and ecological aspects, such as *biomass, bioremediation, bambusa,* and *porosity.*

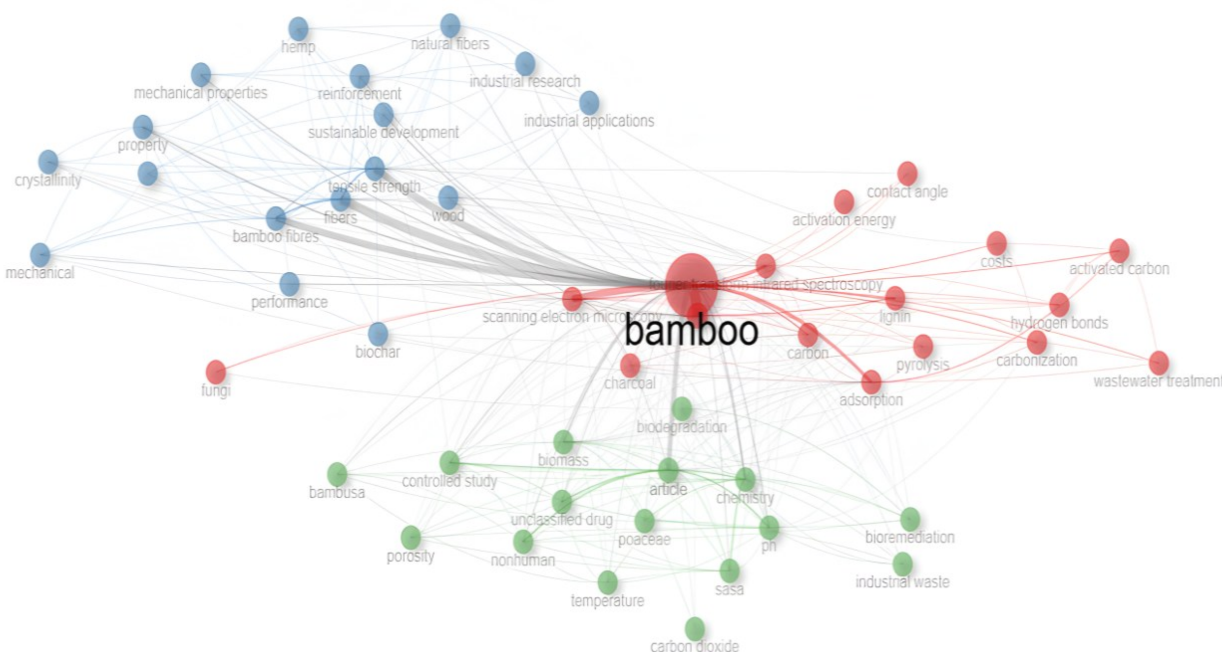


Fig. 10. Keyword co-occurrence network. Source: Scopus database

The central node *bamboo* stands out as the most frequent and highly connected term, reflecting its central role as a thematic axis across multiple research lines. Figure 11, in turn, presents a bar chart of the most relevant keywords, ranked by number of occurrences. The most prominent terms include bamboo (227 occurrences), cellulose (75), tensile strength (39), biomass (35), and adsorption (30), these being the most relevant.

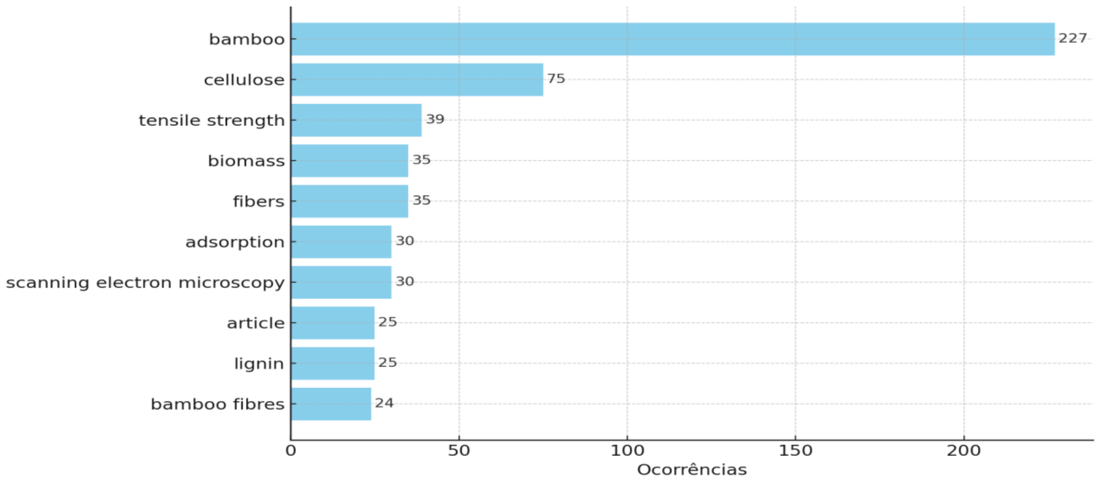


Fig. 11. Most relevant keyword. Source: Scopus database

The two visualisations are interrelated: the most frequent terms in the bar chart correspond to the most prominent nodes in the co-occurrence map. This overlap confirms that the most cited keywords are not only frequent but also serve as points of convergence between different thematic approaches, such as the mechanical use of bamboo, its application in environmental remediation processes, and its study as a biomass resource.

Together, these tools provide a solid foundation for understanding the thematic structure of the scientific literature on bamboo, facilitating the identification of well-established research lines and emerging areas.

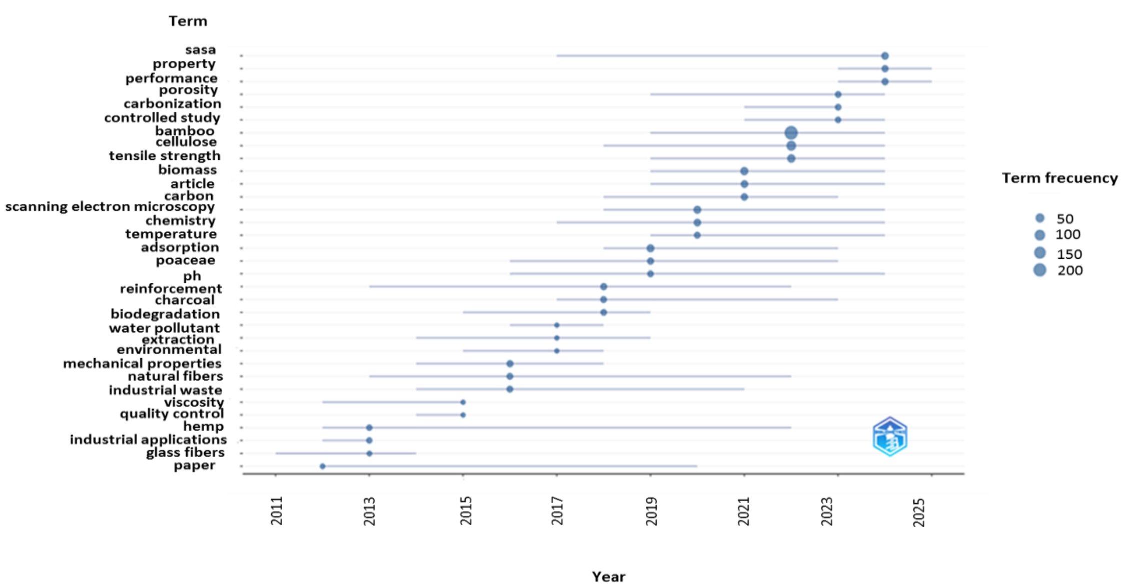


Fig. 12. Trend topics in the scientific literature on bamboo based on keyword frequency and temporal distribution (Keywords Plus). Source: Scopus database

Complementing this analysis, Fig. 12 presents a trend topics chart, which shows the temporal evolution of the most relevant terms in the scientific literature on bamboo. This visualisation combines each term's frequency of occurrence with the period during which it was most studied, offering a dynamic perspective on shifting research priorities over time. Each point on the chart represents the median period in which a term appeared in the analysed publications, while the horizontal lines indicate the interquartile range (Q1–Q3), that is, the range of years during which the term was most active in the literature. The size of each point reflects the term's total frequency of occurrence, allowing for visual identification of the most prominent and consistent themes over time.

Terms such as *bamboo*, *cellulose*, and *tensile strength* reached their highest frequency peaks in 2022, with 227, 75, and 39 occurrences, respectively. These terms maintained a consistent presence between 2018/2019 and 2024, solidifying their status as central axes of research in the field. Additionally, terms such as *sasa* - dwarf species of bamboo - (active from 2017 to 2024, peaking in 2024 with 22 mentions), *reinforcement* (from 2013 to 2022, peaking in 2018), and *natural fibers* (from 2013 to 2022, peaking in 2016) demonstrate a prolonged presence over time, indicating their sustained relevance in the literature. In contrast, concepts such as *controlled study*, which gained prominence from 2021 onwards, represent expanding areas or more recent scientific interests. This type of analysis is valuable not only for identifying well-established themes but also for highlighting emerging trends that may guide future research on bamboo and its derivatives.

To go beyond descriptive mapping, the co-occurrence network was analyzed according to a strategic diagram (Callon *et al*. 1991), which classifies themes by density (internal cohesion) and centrality (external connectivity). This identifies four quadrants that characterize the stage of development of each thematic area (Fig. 13).

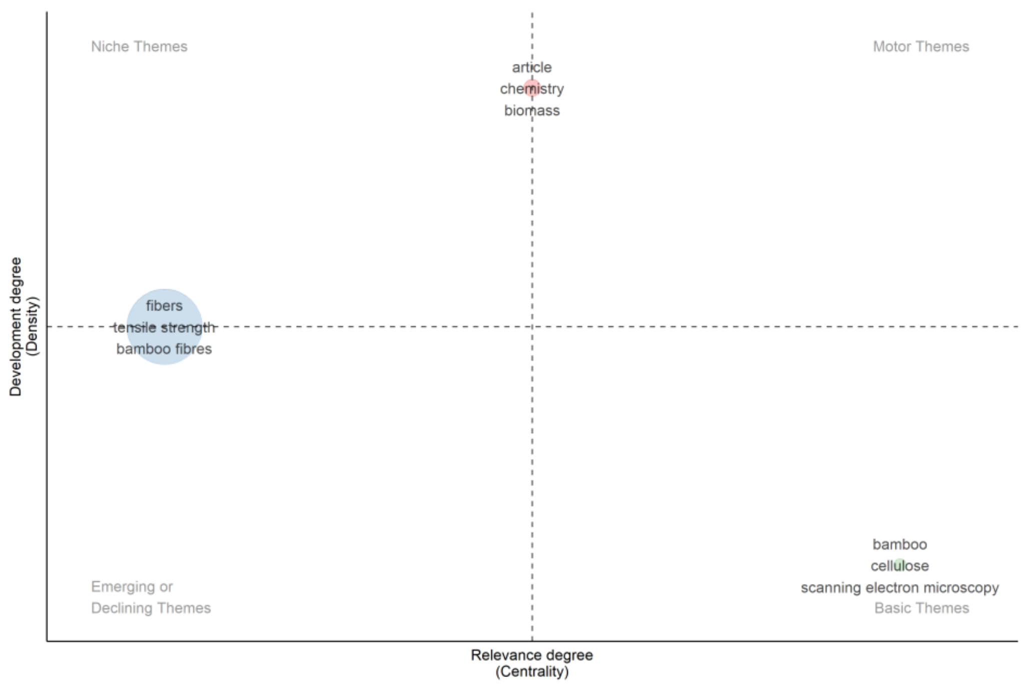


Fig. 13. Strategic diagram of keyword clusters based on density (development degree) and centrality (relevance degree). Quadrants: Motor Themes (high density, high centrality), Niche Themes (high density, low centrality), Emerging/Declining Themes (low density, low centrality), and Basic Themes (low density, high centrality). Source: Scopus database analysed through Bibliometrix

The Motor Themes quadrant (upper right) is sparsely populated, indicating that very few high-level concepts combine high internal development and broad external connectivity in isolation in the field of industrial bamboo. Instead, the field is structurally characterized by critical transition clusters. The blue cluster, containing "chemistry" and "biomass," sits directly on the border between the Niche Themes (upper left) and Driving Themes quadrants. This hybrid position indicates a highly cohesive and specialized body of research that is actively transitioning toward the mainstream, increasing its external relevance within the discipline. The presence of the term "article" is noted as an extraction artifact and excluded from thematic interpretation.

Similarly, the green cluster, comprising "fibers," "tensile strength," and "bamboo fibers," occupies a transitional boundary on the left side of the diagram, moving between the Emerging/Declining Themes (lower left) and Niche Themes (upper left) quadrants. This reflects a thematic line that gains relevant internal structure and technical specialization, transitioning from a peripheral status to a highly focused niche area, although it has not yet developed broad transversal centrality across the discipline.

The most prominent and established domain is the pink cluster in the Basic Themes quadrant (lower right), defined by fundamental terms such as "bamboo," "cellulose," and "scanning electron microscopy." These keywords have high centrality but lower density, functioning as the fundamental cross-cutting infrastructure that anchors and supports the more specialized chemical and mechanical lines of research.

Unlike previous bibliometric reviews focused on isolated dimensions (Zhang *et al*. (2024), which describes alternatives to plastic, and Bahrin *et al*. (2023) on mechanical properties), the present analysis integrates mechanical, thermochemical, and environmental lines within a unified evaluative framework, identifying not only what is researched, but how mature and strategically positioned each line of investigation is.

In general, this study presented a comprehensive overview of the current state of scientific production related to the industrial use of bamboo, identifying key emerging research lines through the application of bibliometric analysis tools. It evaluated the performance of scientific output in the field, as well as the conceptual and intellectual structures that underpin it, allowing for an understanding of the field's evolution and its main developmental directions.

The performance analysis, based on various bibliometric indicators, revealed a steady increase in interest in the subject within the scientific community, particularly since 2017. This trend aligns with the findings of Zhang *et al*. (2024), who highlighted a continuous rise in publications on bamboo as a sustainable alternative to plastic between 2017 and 2022. These results suggest that this is a relatively recent field of study with a clear and sustained trend of expansion, with scientific output expected to continue growing in the coming years.

Regarding journal productivity, 159 different journals were identified in the analysed sample. However, it is important to note that 74.8% of them published only a single article on the topic, indicating a certain degree of editorial dispersion. Nonetheless, five journals stood out for their significant impact in disseminating research on industrial bamboo applications, based on metrics such as the h-index, g-index, total citations, and number of publications: *Industrial Crops and Products*, *Polymers*, *Polymer Composites*, *Bioresources*, and *Chemical Engineering Journal*.

At the institutional level, 510 academic entities were identified as contributing to the field. Among them, Nanjing Forestry University emerged as the leading institution, with 18 indexed publications between 2019 and 2025, underscoring its prominent and ongoing role in advancing knowledge on the industrial use of bamboo.

Connections among researchers were analysed through first-order indicators and network visualisation based on scientific mapping to illustrate global co-authorship networks. This analysis enabled the presentation of the field's social and intellectual structures, revealing relatively well-defined communities with a high degree of interconnectivity, and highlighting active and cross-disciplinary scientific interaction across different research groups, with knowledge flows crossing thematic and institutional boundaries.

Among the most productive authors were Wang Y., Li Y., Liu Y., Zhong W., Zhong X., Li X., Li J., Wang X., Zhong Y., and Liu Z.—many of whom had already been identified by Zhang H. *et al*. (2024), consolidating their status as key contributors in this research area.

From a geographical perspective, China stands out as the main hub of scientific production and collaboration, followed by countries such as India, Malaysia, and Brazil. The latter shows a lower density of collaborative links compared to the others, a finding consistent with the results reported by Judijanto *et al*. (2024). These data reinforce China's dominant position in international research on bamboo applications.

In terms of thematic content, the keyword co-occurrence analysis revealed the predominance of terms such as bamboo, cellulose, tensile strength, biomass, and fibres, as also noted by Bahrin *et al*. (2023). Similarly, the trend analysis showed that terms such as *bamboo*, *cellulose*, and *tensile strength* maintained a high frequency of occurrence between 2018 and 2024, establishing themselves as conceptual pillars of the field. Meanwhile, expressions such as *sasa*, *reinforcement*, and *natural fibers* demonstrated consistent presence over time, reinforcing their value in the current scientific discourse.

Study Limitations

This bibliometric analysis presents several limitations that should be considered when interpreting the results. One of them concerns the scope of the Scopus database. Although Scopus indexes publications from multiple languages and countries, its coverage may not fully capture regional journals, technical reports, and publications in languages other than English. This could introduce bias into the geographical and institutional distribution of the results. Furthermore, the automatic keyword extraction system (Keywords Plus) sometimes includes generic terms such as "article" that have no specific thematic meaning, which can affect the accuracy of the co-occurrence networks.

Another limitation relates to the nature of bibliometric indicators. These methods track changes in the popularity of terms, but do not necessarily reflect real conceptual or technological advances. For example, the term 'engineered bamboo' has become established in the scientific literature as a unifying category for processed bamboo products (Liu *et al.* 2016), replacing or subsuming older and more fragmented designations such as 'bamboo scrimber', 'reconstituted bamboo', 'laminated bamboo lumber', and 'bamboo composite'. A study on 'bamboo scrimber' and a study on 'engineered bamboo' may examine the same material processed in a similar way, but bibliometric software classifies them separately based on semantic evolution. Citation counts also have limitations. A highly cited article may be referenced because researchers disagree with the results or identify methodological flaws, not necessarily because they support it. Thus, citations measure visibility, but not necessarily quality or positive influence.

Finally, the study period (2010 to 2025) covers a rapidly growing field in which new subtopics emerge faster than the terminology stabilizes. Keyword networks should therefore be read as provisional, not as fixed classifications. These limitations do not diminish the value of bibliometric mapping, but they indicate that quantitative results should be combined with expert knowledge and qualitative evaluation.

CONCLUSIONS

1. The findings of this study lead to the conclusion that the industrial use of bamboo represents a dynamic and rapidly expanding field of research, underpinned by a consolidated conceptual foundation and a growing international collaborative structure, particularly led by Chinese institutions.
2. Identifying thematic trends and key actors in the field can contribute to future research, as well as to the development of innovation and sustainability policies focused on this renewable, sustainable raw material with multiple applications in the areas of engineering and industry.

ACKNOWLEDGMENTS

The authors thank the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Finance Code 001, National Council for Scientific and Technological Development (CNPq), and Espírito Santo Research and Innovation Foundation (FAPES), Brazil for the scholarships and support to the research, respectively.

This publication is a contribution of the Forest and Wildlife Research Center, Mississippi State University. This paper was approved as journal article SB1182 of the Forest & Wildlife Research Center, Mississippi State University.

Conflict of Interest

The authors declare no conflicts of interest.

Use of Generative AI

No artificial intelligence tools were used in the preparation of this manuscript.

REFERENCES CITED

Akwada, D. R., and Akinlabi, E. T. (2020). "Industrial applications of bamboo in Ghana," in: *Advances in Material Sciences and Engineering*, M. Awang, S. Emamian, and F. Yusof (eds.), Springer, Singapore, pp. 409-421. https://doi.org/10.1007/978-981-13-8297-0_43

Amatosa, T. A., and Loretero, M. E. (2020). "Bamboo waste-based bio-composite substance: an application for low-cost construction materials," *Specta J. Technol.* 4(1), 41-48. http://dx.doi.org/10.35718/specta.v4i1.162

Bahrin, N. A, Kamarudin, M. K., Mansor, H., Sahol-Hamid, Y., Ahmad, Z., and Lopez, L.F. (2023). "Mechanical characterization of bamboo pole for building engineering: A review," *BioResources* 18(3), 6583-6613. http://doi.org/10.15376/biores.18.3.Bahrin

Blondel, V. D., Guillaume, J. L., Lambiotte, R., and Lefebvre, E. (2008). "Fast unfolding of communities in large networks," *J Stat Mech: Theory* 2008(10), P10008. https://doi.org/10.1088/1742-5468/2008/10/P10008

Borowski, P. F., Patuk, I., and Bandala E. R. (2022). "Innovative industrial use of bamboo as key "Green" material," *Sustainability* 14(4), article 1955. https://doi.org/10.3390/su14041955

Callon, M., Courtial, J. P., and Laville, F. (1991). "Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry," *Scientometrics* 22(1), 155-205. https://doi.org/10.1007/BF02019280

Carvalho, Y. M., and Velasco, L. F. (2021). "Bamboo ashes as an eco-friendly alternative to cement a systematic review," *ForScience* 9(2), article e00889. https://doi.org/10.29069/forscience.2021v9n2.e889

Chaudhary, U., Malik, S., Rana, V., and Joshi G. (2024). "Bamboo in the pulp, paper and allied industries," *Adv. Bamboo Sci.* 7, article 100069. https://doi.org/10.1016/j.bamboo.2024.100069

Chen, H., Cheng, H., Wang, G., Yu, Z., and Shi, S. Q. (2015). "Tensile properties of bamboo in different sizes," *J. Wood Sci.* 61(6), 552-561. https://doi.org/10.1007/s10086-015-1511-x

Chigarev, B. (2024). "Keyword co-occurrence analysis using the FPGrowth algorithm: An example of energies journal bibliometric data for 2023-2024," *Preprints.orgs* 1, 1-11. http://dx.doi.org/10.20944/preprints202406.1380.v1

Donthu, N., Kumar, S., Pandey, N., and Lim, W. M. (2021). "Research constituents, intellectual structure, and collaboration patterns," *J. Int. Mark.* 29(2), 1-25. https://doi.org/10.1177/1069031X211004234

Engel, A. (2013). "The Hirsch index: Non notationes sed notiones Carl-Friedrich Gauss," *Colorectal Dis.* 15(1), 128-136. https://doi.org/10.1111/CODI.12084

Ganapathy, N. (2023). "Methods of study," in: *Gangs and Minorities in Singapore: Masculinity, Marginalization and Resistance*, N. Ganapathy (Ed.), Bristol University Press, Bristol, pp. 60-80. https://doi.org/10.46692/9781529210668.005

Isfandyari-Moghaddam, A., Saberi, M. K., Tahmasebi-Limoni, S., Mohammadian, S., and Naderbeegi, F. (2023). "Global scientific collaboration: A social network analysis and data mining of the co-authorship networks," *J. Inf. Sci.* 49(4), 1126-1141. https://doi.org/10.1177/01655515211040655

Judijanto, L., Suhara A., and Mayasari, N. (2024). "Bibliometric analysis of green technology research trends and their impact on the global economy," *West. Sci. Nat. Technol.* 2(3), 128-141. http://dx.doi.org/10.58812/wsnt.v2i03.1260

King, D. A. (2004). "The scientific impact of nations," *Nature* 430(6997), 311-316. https://doi.org/10.1038/430311a

León-Gómez, A. M., and Mora Forero, J. A. (2022). "Análisis bibliométricos en publicaciones científicas sobre turismo sostenible en las universidades," *Hum. Rev.* 12(6), 1-12. https://doi.org/10.37467/revhuman.v11.3991

Li, C., Wang, Q., and Yu, X. (2023). "The preparation and performance of bamboo waste bio-oil phenolic resin adhesives for bamboo scrimber," *Forests* 15(1), article 79. https://doi.org/10.3390/f15010079

Liese, W. (1998). "The anatomy of bamboo culms," INBAR Technical Report No. 18, International Network for Bamboo and Rattan, Beijing, China.

Liu, X., Smith, G. D., Jiang, Z., Guan, M., and Ramage, M. H. (2016). "Nomenclature for engineered bamboo," *BioResources* 11(1), 1141-1161. https://doi.org/10.15376/biores.11.1.1141-1161

Lotka, A. J. (1926). "The frequency distribution of scientific productivity," *J. Wash. Acad. Sci.* 16(12), 317-323. https://ww w.jstor.org/stable/24529203

Meydan, C. H., and Akkaş, H. (2024). "The role of triangulation in qualitative research: Converging perspectives," in: *Principles of Conducting Qualitative Research in Multicultural Settings*, A. Elhami, A. Roshan, and H. Chandan (eds), IGI Global Scientific Publishing, Hershey, PA, USA, pp.101-132. http://dx.doi.org/10.4018/979-8-3693-3306-8.ch006

Milojević, S., Radicchi, F., and Walsh, J. P. (2018). "Changing demographics of scientific careers: The rise of the transient scientist," *Proc. Natl. Acad. Sci.* (50), 12616-12623.

Ozek, B., Lu, Z., Pouromran, F., Radhakrishnan, S., and Kamarthi, S. (2023). "Analysis of pain research literature through keyword co-occurrence networks," *PLOS Digit Health* 2(9), article e0000331. https://doi.org/10.1371/journal.pdig.0000331

Pavate, V., Jagdale, A., Shinde, R., Manechikkannara, N., and Patil, D. (2024). "Study on bamboo industry," *Int. J. Res. Appl. Sci. Eng. Technol.* 12(4), 1533-1548. http://dx.doi.org/10.22214/ijraset.2024.60085

Sharma, B., Gatóo, A., Bock, M., and Ramage, M. H. (2015). "Engineered bamboo for structural applications," *Constr. Build. Mater.* 90, 66-73. https://doi.org/10.1016/j.conbuildmat.2015.04.042

Singh, M., and Kumar, S. (2014). "Application of *h* and *g* indices to quantify scientific productivity of physicists at JNU, India," *Libr. Philos. Pract.* 1028, 1-21.

Tan, H., Li, J., He, M., Li, J., Zhi, D., Qin, F., and Zhang, C. (2021). "Global evolution of research on green energy and environmental technologies: A bibliometric study," *J. Environ. Manag.* 297, article 113382. https://doi.org/10.1016/j.jenvman.2021.113382

Ugo, U., Ajekwene, K. K., Ichetaonye, S. I., and Ogbodo, J. A. (2024). "Recycling of waste bamboo (*Bambusa vulgaris*) into value-added platform chemicals: Bioethanol and bioethylene," *Qeios* preprint 1, 1-15, 2024. http://dx.doi.org/10.32388/FBQWMV

Verma, S., and Gustafsson, A. (2020). "Investigating the emerging COVID-19 research trends in the field of business and management: A bibliometric analysis approach," *J. Bus. Res.* 118, 253-261. https://doi.org/10.1016/j.jbusres.2020.06.057

World Bank. (2024). "World Development Indicators: Population, total (SP.POP.TOTL),". https://data.worldbank.org/indicator/SP.POP.TOTL

Zacca-González, G., Chinchilla-Rodríguez, Z., Vargas-Quesada, B., and Moya-Anegón, F. (2014). "Bibliometric analysis of regional Latin America's scientific output in public health through SCImago Journal & Country Rank," *BMC Public Health* 14(632), article 632. https://doi.org/10.1186/1471-2458-14-632

Zhang, H., Zhang, X., Ding, Y., Huang, F., Cai, Z., and Lin, S. (2024). "Charting the research status for bamboo resources and bamboo as a sustainable plastic alternative: A bibliometric review," *Forests* 15(10), article 1812. https://doi.org/10.3390/f15101812

Article submitted: February 24, 2026; Peer review completed: May 11, 2026; Revised version received and accepted: August 13, 2026; Published: August 28, 2026.
DOI: 10.15376/biores.21.4.10166-10186