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Review Article

Bamboo in construction: Mapping global trends, strategic clusters, and future research pathways

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Abstract

As the construction industry intensifies its pursuit of sustainable and low-carbon alternatives to traditional materials, bamboo has emerged as a strategic resource owing to its rapid renewability, high strength-to-weight ratio, and superior environmental profile. This study presents a comprehensive bibliometric and thematic analysis of global research trends on bamboo construction, based on 1,456 peer-reviewed publications indexed in the Scopus database between 2019 and 2024. Using VOSviewer and the bibliometrix package in R, the analysis identifies three major thematic clusters: structural performance and mechanical behavior, sustainability and environmental applications, and microstructural characterization and advanced material development. The results highlight a sharp increase in scholarly output, with China, India, and Indonesia leading both in publications and citations, driven by strong policy initiatives and abundant bamboo resources. Despite significant advancements, critical gaps persist in standardization frameworks, long-term durability assessment, and integration with smart materials. This paper proposes future research pathways, including the development of hybrid composites, microstructural optimization, and regionally adaptive building codes. By systematically mapping the evolution, challenges, and opportunities in bamboo construction, the study offers a structured framework to accelerate bamboo's mainstream adoption as a high-performance, sustainable material in global infrastructure development.

1. Introduction

The construction sector, responsible for 37-40% of global energy-related CO_2 emissions, is undergoing a profound transformation as it searches for alternatives to traditional high-impact materials like concrete, steel, and conventional timber[1]. Among the emerging contenders, bamboo has gained international attention for its unique blend of mechanical robustness, rapid renewability, and environmental compatibility [2]. As a natural, fast-growing grass with high strength-to-weight ratios and carbon sequestration potential, bamboo is increasingly viewed as a strategic bio-based material that aligns with global sustainability goals, particularly those related to climate resilience, circular economy, and low-carbon development [3].

Historically, bamboo has been used in vernacular construction across Asia, Africa, and Latin America, especially in low-income rural communities. However, in recent decades, its role has shifted from a traditional material to a focus of modern engineering and material science research. Innovations in laminated bamboo (thin layers of bamboo glued together for improved strength), bamboo scrimber (compressed bamboo strips bound with adhesive), and fiber-reinforced composites have unlocked new applications in structural frame, geotechnical foundations, seismic-

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resistant design, and green architecture [4]. Studies confirm that Engineered bamboo—bamboo processed into standardized structural elements—can achieve tensile strengths exceeding 200 MPa and compressive strengths of over 130 MPa, rivalling industrial-grade timber and approaching steel in performance under specific conditions [5]. Moreover, bamboo is known for its rapid maturation cycle—3 to 5 years versus decades for hardwoods—and its capacity to regenerate without replanting, making it a prime candidate for renewable construction materials [6].

Yet, despite the growing academic and commercial interest, bamboo's adoption in mainstream construction remains uneven and underutilized. Challenges persist regarding standardization, durability under climatic exposure, jointing systems, treatment protocols, and limited inclusion in national or international building codes [6]. Although ISO standards such as ISO 22156 and ISO 22157 define test methods for mechanical behavior and safety, bamboo is rarely included in performance-based structural design frameworks [7]. These limitations are exacerbated by bamboo's natural variability across species, geography, and processing techniques, leading to inconsistent mechanical behavior and variable structural reliability [8]. Moreover, Complexities in connection techniques-stemming from bamboo's hollow culm (stem) structure remain a major barrier to the development of prefabricated and modular bamboo systems, especially in multi-story construction [9].

In parallel, Bamboo, with its low embodied energy and potential for carbon sequestration, offers a unique convergence of ecological and mechanical benefits [10]. Lifecycle assessments (LCA), a method to evaluate environmental impacts across a product's lifespan, demonstrate that bamboo-based materials can reduce greenhouse gas emissions by up to 50% compared to concrete and steel, and bamboo cultivation itself supports biodiversity, soil restoration, and water retention [11,12]. Furthermore, innovations in composite engineering, nano-modification, and microstructural design have made bamboo increasingly competitive with synthetic and mineral-based construction alternatives, both in terms of performance and cost-efficiency.

This research aims to explore the evolving role of bamboo in construction by mapping current trends, identifying strategic clusters, and proposing future pathways. Emphasis will be placed on its mechanical performance, treatment advancements, code development, and practical integration into modern infrastructure. Through this approach, the study seeks to contribute to a more sustainable construction paradigm where bamboo becomes a mainstream, structurally reliable, and ecologically responsible material.

2. Standardization and Structural Applications of Bamboo in Construction

2.1 Bamboo Standards and Regulatory Codes

The formalization of bamboo standards was first initiated by the International Organization for Standardization (ISO) in 2004. During this year, ISO introduced three key documents concerning bamboo construction: ISO 22156, ISO 22157-1, and ISO 22157-2. These standards were primarily adapted from pre-existing timber guidelines to suit the unique characteristics of bamboo materials. ISO 22156 outlines the principles for the structural design of bamboo constructions, encompassing full culm, half culm, and laminated bamboo applications [13]. Meanwhile, ISO 22157-1 [14] and ISO 22157-2 [15] detail the procedures for testing the physical and mechanical properties of bamboo, including evaluations of moisture content, density, tensile strength, compressive strength, shear strength, and flexural strength.

As the use of bamboo in modern construction continues to expand, particularly in regions abundant with bamboo resources, many countries have undertaken the development of their own national standards [16–19]. These localized efforts aim to address specific species variations, environmental conditions, and construction practices unique to each country. Table 1 provides a summary of the current national and international standards governing bamboo specifications. These national and international standards represent important milestones in the effort to integrate bamboo as a legitimate construction material within formal building codes. However, continued collaboration is needed to harmonize testing procedures and design principles globally, ensuring bamboo's wider acceptance and safe application across diverse structural contexts.

Table 1. Summary of Existing Bamboo Construction Standards by Country

Country	Standard(s)	Reference
Philippines	PNS ISO 19624:2020 – Grading of bamboo culms; PNS ISO 22157:2020 – Determination of physical and mechanical properties of bamboo culms; PNS ISO 22156:2021 – Structural design of bamboo structures.	[20]
China	JG/T 199-2007 – Testing methods for physical and mechanical properties of bamboo used in building construction.	[21]
Colombia	NSR-10 G.12 – Guidelines for seismic-resistant structures using Guadua; NTC 5407 – Structural joints with Guadua angustifolia; NTC 5525 – Testing methods for Guadua properties.	[22]
Ecuador	NEC-SE-GUADUA – Structural design of Guadua structures; INEN 42 – Specifications for bamboo cane (Caña Guadua).	[23]
India	IS 6874:2008 – Method of tests for bamboo; IS 15912:2018 – Structural design using bamboo – Code of practice.	[24,25]
Peru	Reglamento Nacional de Edificaciones, Section III, Code E.100 – Design and construction with bamboo.	[26]
United States	ASTM D5456-21– Standard specification for evaluation of structural composite lumber products, including laminated veneer bamboo.	[16]
Bangladesh	Bangladesh National Building Code (BNBC) 2020, Part 6, Chapter 4 – Bamboo structures.	[27]
International	ISO 22156:2021 – Bamboo structures – Structural design; ISO 22157:2019 – Determination of physical and mechanical properties of bamboo culms – Test methods.	[25,28]

To address practical challenges associated with bamboo construction, several innovative approaches have been successfully demonstrated. For example, the Green School Bali showcased the use of boron salt preservation techniques and laminated bamboo composites to enhance structural durability under humid tropical conditions [6] . Similarly, the ZCB Bamboo Pavilion in Hong Kong utilized prefabricated laminated bamboo members and digital fabrication to overcome standardization and connection challenges [7]. These case studies indicate that through chemical treatment, engineered bamboo processing, and precision-based manufacturing, bamboo can achieve durability and mechanical stability comparable to conventional building materials. Future initiatives should integrate advanced preservation treatments and prefabricated modular systems to further improve the long-term performance and scalability of bamboo structures in modern construction.

2.2 Structural Applications of Bamboo in Construction

Bamboo is a versatile and sustainable material with significant potential for construction purposes. It can be used either in its natural form or as a processed material, depending on structural needs. The bamboo culm, whether used whole or modified, offers architectural flexibility while contributing socio-economic benefits due to its durability, availability, and relatively low cost [29]. Bamboo's unique properties make it a promising alternative to traditional construction materials, especially for organic-shaped and lightweight structures [30]. The various structural applications of bamboo are discussed in the following subsections.

2.2.1 Use of Full and Half Culm Bamboo

Whole bamboo culms are commonly used in architectural structures, scaffolding, and resort buildings, particularly in regions where bamboo is abundantly available. Full or split culms are connected to form columns, walls, roof purlins, and poles. The mechanical property of bamboo exhibits compressive strengths ranging between 56 MPa and 132.9 MPa, and tensile strengths between 71 MPa and 216 MPa, making it highly suitable for load-bearing applications [31].

However, the hollow structure of the culm presents challenges for creating effective joints, which often rely on simple binding methods like rope lashings[32].

Recent studies emphasize the critical role of nodes in enhancing the mechanical strength of bamboo elements, although these nodes complicate joint design [31]. To improve connection efficiency, techniques such as hose clamps, concrete infill, and bolted connections have been adopted. Hose clamps offer a quick and practical solution, whereas concrete infill methods strengthen the hollow structure, significantly increasing rigidity and load capacity [33]. These innovations have enhanced the structural reliability of bamboo elements in modern architectural and engineering applications.

2.2.2 Engineered Bamboo Products

Engineered bamboo refers to bamboo that has undergone industrial processing to enhance its structural performance. Common engineered bamboo products include laminated bamboo and bamboo scrimber, widely used in flooring, wall panels, and load-bearing applications. Laminated bamboo is produced by flattening bamboo culms into uniform strips, which are then bonded together using adhesives to create laminated boards [34,35]. Research indicates that Laminated bamboo demonstrates high compressive strength, especially when the load is applied parallel to the grain. For instance, matured glue-laminated bamboo has a compressive strength of 62.78 MPa, which is significantly higher than that of juvenile bamboo at 37.58 MPa [36]. Another study reports compressive strengths of 45.07 MPa parallel to the grain at 20°C, with variations depending on temperature [37]. Its orthotropic behavior, characterized by greater compressive strength along the grain, further enhances its structural applicability [38].

Moreover, bamboo's carbon footprint is substantially lower than that of steel and even better than traditional timber when lifecycle emissions are considered. Table 2 presents a comparative overview of bamboo composites, timber, and steel properties in construction applications, highlighting bamboo's strategic advantage in sustainable infrastructure development. As shown, bamboo composites exhibit tensile strengths comparable to timber (40–80 MPa) but possess a significantly lower elastic modulus (9 GPa) relative to steel (200 GPa) and timber (10–20 GPa) [39]. Despite this lower stiffness, bamboo's mechanical performance remains sufficient for many structural applications, especially when combined with its high strength-to-weight ratio. In terms of environmental impact, bamboo stands out with low CO_2 emissions and high renewability, offering a clear advantage over steel, which has a markedly higher carbon footprint [40]. From a cost perspective, bamboo composites are more expensive than local timber but remain cheaper than steel, positioning them as an economically viable material for sustainable construction [41]. Consequently, bamboo composites offer an optimal balance between mechanical performance, environmental sustainability, and affordability, making them an attractive alternative for structural elements such as floors, roofs, and lightweight frameworks.

Table 2. Comparative properties of bamboo composites, timber, and steel

Material	Tensile Strength (MPa)	Elastic Modulus (GPa)	Environmental Impact	Cost	Typical Applications
Bamboo Composites	40–80	9	Low CO_2 emissions, highly renewable	Higher than local timber, lower than steel	Structural elements, floors, roofs
Steel	370–700	200	High carbon footprint	Expensive	High-load, critical structures
Timber	40–80	10–20	Renewable but slower growth cycle	Affordable	Residential structures, bridges

2.2.3 Bamboo-Reinforced Concrete (BRC)

Bamboo's high tensile and compressive strengths along the longitudinal axis make it an effective substitute for traditional steel reinforcement in concrete structures. Bamboo strips or full culms, often treated to prevent termite attack, are embedded within concrete to form Bamboo-Reinforced Concrete (BRC). The performance of BRC beams closely resembles that of conventional reinforced concrete (RC) beams, particularly when treated with adhesives and hose clamps to improve bond strength and water resistance [42].

Experimental studies, such as those by Sutharsan et al. [43] demonstrate that bamboo reinforcement can enhance flexural strength by up to 77.7% compared to plain concrete. Bamboo is commonly used in beams (main bars and stirrups) and columns (main bars and hoops) , offering structural behavior comparable to RC beams with lower reinforcement ratios [44]. Further improvements can be achieved through mechanical anchoring systems like rebar clamps [45]or hose clamps [46].

Bonding agents such as Sikadur 32-gel have been shown to enhance the bamboo-concrete interface, improving flexural strength performance [47]. Although BRC beams demonstrate significant strength improvements, steel-reinforced beams remain superior in terms of stiffness and ductility [48]. Bamboo has also proven effective in reinforcing slabs and shear walls, significantly improving flexural and shear capacities [49,50]. However, long-term performance is dependent on proper treatment and moisture protection

2.2.4 Bamboo Piles in Geotechnical Engineering

Bamboo piles have emerged as an eco-friendly alternative for lightweight foundation systems, particularly in soft soils [51]. Research shows that treated bamboo piles can achieve load capacities of approximately 75 kN in soft clay soils, maintaining strength even after extended environmental exposure [51]. Full-scale tests in the Philippines revealed service load capacities of up to 250 kN for bamboo piles in low-rise construction [52]. Moreover, bamboo piles enhance soil stability due to their rough surface texture, which improves frictional resistance. When bamboo piles were combined with lime stabilization, a 25% increase in soil bearing capacity [53].

Comparative studies confirm that bamboo piles can perform comparably to timber piles at a fraction of the cost, providing substantial environmental benefits [54] . Field trials in Indonesia reported a 35% reduction in settlement when using bamboo piles in untreated soft soils [55].

Despite their advantages, bamboo piles are vulnerable to biodegradation. Preservation methods, including chemical treatments (sodium borate, copper-chrome-arsenate)[56], thermal modification [57], and encapsulation with cementitious materials [58], have been shown to extend their lifespan significantly. Innovations like lime-soil caps combined with geotextile reinforcement further enhance their performance in challenging soil environments [59].

2.2.5 Bamboo Fiber Reinforced Concrete (BFRC)

The incorporation of fibers in concrete enhances its tensile strength and crack resistance. Traditionally, synthetic fibers such as glass, steel, and carbon have been used [60]. However, due to environmental concerns and the high cost of synthetic fibers, natural alternatives like wood, coconut, hemp, sisal, and bamboo are increasingly favored [61].

Bamboo fibers generally do not enhance the compressive strength of concrete and may even slightly reduce it. For instance, the compressive strength of bamboo fiber-reinforced lightweight aggregate concrete (LWAC) decreased by 3.6% to 11.1% with the addition of bamboo fibers [62]. Another study found that the compressive strength of bamboo scrimber decreased with increasing specimen size [63].

3. Primary Focus of Previous Reviews, Identified Gaps, and Research Questions

Table 3 presents a summary of key review articles on bamboo construction research published between 2019 and 2024. It highlights each study's thematic focus, methodological approach, and contributions to areas such as material innovation, structural performance, and environmental sustainability. A review of the existing literature reveals a clear gap: few studies provide a comprehensive overview that traces the evolution of bamboo research while offering a structured and strategic classification of key developments. While many papers have investigated specific aspects—such as bamboo's mechanical properties, reinforcement potential, or its role in low-carbon construction, there remains a lack of integrative frameworks that connect these diverse strands into a cohesive understanding of the field.

Although previous reviews have provided valuable insights into bamboo’s mechanical properties, reinforcement techniques, and sustainability applications, they often focus on isolated aspects without offering a holistic integration of the field. Specifically, prior studies tend to concentrate either on material performance, environmental potential, or structural applications in isolation, leaving a fragmented understanding of how bamboo research is evolving as a comprehensive construction solution. Furthermore, no existing review has systematically mapped the scientific landscape using bibliometric methods to identify thematic clusters, leading authors, institutional contributions, and future research pathways in bamboo construction. This study addresses these gaps by employing a data-driven bibliometric approach to not only analyze research output and collaboration networks but also to strategically classify emerging research fronts and propose targeted directions for advancing bamboo as a mainstream, sustainable construction material.

Table 3. Overview of Review Papers on Bamboo Construction

Ref	Year	Scope	The primary areas of discussion
[64]	2023	Structural performance and durability of bamboo	Summary of mechanical properties across bamboo species Discussion of structural adequacy and treatment methods Highlight of challenges in durability and standardization
[32]	2024	Connection techniques for raw bamboo	Review of 62 papers on raw bamboo connections Emphasis on failure modes and design limitations Recommendation for code development and research gaps
[65]	2023	Nanotechnology for bamboo improvement	Review of bamboo enhancement via nanomaterials Discussion of decay resistance and stability improvement Application of nano-cellulose and nano-lignin
[66]	2022	Amazon natural fibers in cementitious composites	Exploration of bamboo with Amazon natural fibers Use in cement-based composites for sustainability Emphasis on physical, chemical, and mechanical integration
[67]	2024	Mycelium composites with bamboo fibers	Discussion of bamboo-enhanced mycelium composites Mechanical and thermal benefits in sustainable design Focus on insulation, strength, and biodegradability
[68]	2024	Fiber-reinforced plywood including bamboo fibers	Analysis of fiber-reinforced plywood using bamboo Highlighted gains in strength and reduced material use Proposal for sustainable plywood applications

To address the identified research gap, this study is guided by a central research question: What are the emerging trends, strategic clusters, and future research directions in the field of bamboo construction? To support a structured and comprehensive analysis, this overarching question is divided into the following specific sub-questions:

- RQ1: How has research on bamboo in construction evolved over time, and what is the current state of the field?
- RQ2: Which countries, institutions, journals, and authors are most active and influential in advancing bamboo construction research?
- RQ3: What are the most cited and impactful publications that have shaped the development of this field?

- RQ4: What are the major research themes, innovation trends, and forward-looking topics that define the future landscape of bamboo construction?

To ensure clarity and logical flow, the remainder of this paper is structured as follows:

- Section 4 describes the research methodology employed, including data collection, processing, and analysis techniques.
- Section 5 presents the bibliometric analysis addressing the four research questions.
- Section 6 discusses strategic directions and emerging opportunities for future research in bamboo-based construction.
- Section 7 concludes the paper by summarizing the key insights and contributions.

4. Methodology

A bibliometric analysis was employed in this study to systematically explore and visualize the evolving landscape of research on bamboo in construction, with a focus on identifying thematic trends, mapping strategic clusters, and proposing future research pathways. Bibliometric analysis, a computer-assisted literature review technique, has been widely adopted for quantitatively assessing scientific progress and revealing knowledge structures across diverse fields [69,70]. This approach enables the identification of influential authors, institutions, countries, and emerging research fronts, while also highlighting gaps and underexplored areas within the domain of bamboo-based structural applications.

In constructing bibliometric networks, two principal counting methods are typically used: full counting and fractional counting. Full counting assigns equal weight to each occurrence and is favored for its interpretative simplicity. Fractional counting, on the other hand, distributes weights proportionally among co-authors or sources, making it suitable for nuanced attribution scenarios.

To implement this bibliometric analysis, the study utilized two established tools: VOSviewer, a well-known software for creating bibliometric maps, and the bibliometrix package in R, which supports in-depth statistical and network analysis [71]. These tools were applied to generate co-authorship networks, keyword co-occurrence maps, and citation analyses. In these visualizations, each node represents a research entity—such as an author, article, keyword, or institution—while edges denote relationships such as co-publications or shared thematic focus. The methodological framework of this research included: (1) data collection from a comprehensive scientific database, (2) performance analysis of core bibliometric indicators, (3) network mapping to reveal knowledge clusters, and (4) strategic interpretation to inform future directions in bamboo construction research.

4.1 Scope of the Study

This study aims to explore how bamboo is being used in the construction sector and how research in this area has evolved over time. By examining a wide range of publications, the analysis seeks to uncover key themes, trends, and research gaps related to bamboo in structural, geotechnical, and sustainable applications. The central question driving this investigation is: What are the major developments, research directions, and strategic focus areas in bamboo construction, and how can these insights help guide future studies?

4.2 Literature Search Strategy and Data Preparation

A critical component of this study involved selecting an appropriate and multidisciplinary data source to capture the breadth of research on bamboo in construction. Scopus was chosen as the primary database due to its extensive indexing of peer-reviewed journals across engineering, architecture, and environmental sciences, providing a comprehensive platform for conducting high-quality bibliometric analysis [72].

To retrieve relevant publications effectively, a structured search strategy employing Boolean operators was developed. Keywords were categorized into two main thematic groups. The first group targeted fundamental construction-related terms such as “bamboo construction,” “bamboo structure,” “bamboo building material,” and “bamboo pile,” ensuring the inclusion of studies focusing directly on bamboo’s application as a structural material. The second group encompassed broader emerging themes, including “sustainability,” “carbon reduction,” “green materials,” “reinforced concrete,” “geotechnical engineering,” and “engineered bamboo,” aiming to capture literature situating bamboo within the context of sustainable development and material innovation. Using this dual-group keyword approach, a comprehensive search was conducted in Scopus. The initial search retrieved 1,545 publications, encompassing journal articles, reviews, and conference proceedings from diverse fields such as civil engineering, material science, environmental technology, and architecture. This broad initial dataset reflected the multidisciplinary interest in bamboo as a sustainable construction material.

To refine the search results and ensure data quality, a systematic filtering process was applied. The first filtering phase included only peer-reviewed journal articles and review papers, excluding conference papers, book chapters, and editorial materials. Publications were restricted to the English language to maintain consistency and accessibility across the dataset. No temporal restrictions were applied, allowing both foundational studies and recent developments to be captured. Following this, a second-level screening was conducted to ensure topical relevance. Publications that did not focus specifically on the structural, mechanical, or environmental aspects of bamboo in construction were excluded. Only studies directly contributing to bamboo’s application as a construction material were retained, ensuring thematic consistency and scholarly relevance.

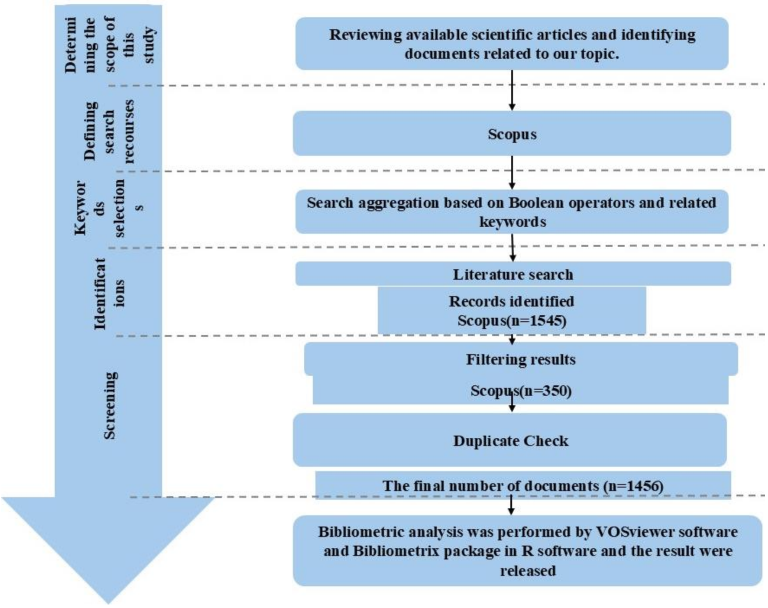

Fig. 1. Research framework outlining the sequential stages of the bibliometric analysis conducted in this study.

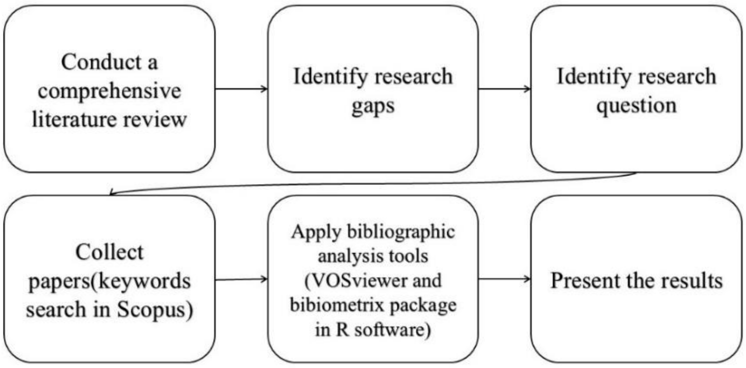

Fig. 2. Conceptual framework illustrating the linkages between past research trends, identification of strategic research clusters, and the formulation of future pathways for bamboo construction research

To finalize the dataset, a merging and deduplication process was undertaken using R software, following the bibliometric cleaning methodology outlined by Echchakoui [72]. This procedure removed duplicate entries and ensured the uniqueness of each document. After the cleaning process, the final dataset comprised 1,456 distinct publications, forming the analytical foundation for the bibliometric and thematic exploration presented in this study. To ensure a comprehensive review of the field, it was essential to select a reliable and multidisciplinary database. Scopus was chosen as the primary data source for this study because of its wide coverage of peer-reviewed literature across engineering, architecture, and environmental sciences. Its indexing quality and breadth of disciplines make it an ideal platform for bibliometric research on construction materials, especially bamboo [72].

The overall process employed in this research is summarized in a structured research framework (Fig. 1), which illustrates each step from database selection through data extraction, cleaning, and visual analysis. Additionally, a conceptual framework is presented (Fig. 2), demonstrating the logical progression of the study from mapping historical research trends to the identification of strategic clusters and the formulation of future research directions in the domain of bamboo-based construction.

4.3 Analysis and Review

The refined dataset was then analyzed using two powerful tools: VOSviewer and the bibliometrix package in R. These tools allowed for the creation of visual maps that revealed patterns in co-authorship, keyword usage, and citation behavior. Through these visualizations, it became possible to identify major research clusters, influential authors and institutions, and thematic areas that have gained attention over time. This analytical approach provided a data-driven, objective perspective on the current state of bamboo construction research.

5. Document Analysis

5.1 Trend Analysis

Analyzing publication trends offers valuable insights into the growth and evolution of a research field, revealing how academic interest has developed over time [70]. Fig. 3 illustrates the annual and cumulative publication trends in bamboo construction research from 2019 to 2024. The data demonstrate a clear and substantial increase in scholarly activity within this domain. From 2019 to 2021, the number of annual publications rose steadily, reflecting growing attention to sustainable and bio-based construction solutions. Although annual output from 2022 to 2024 stabilized somewhat, the cumulative publication curve shows a consistent and sharp upward trajectory—culminating in an overall growth of 156.6% over the six-year period.

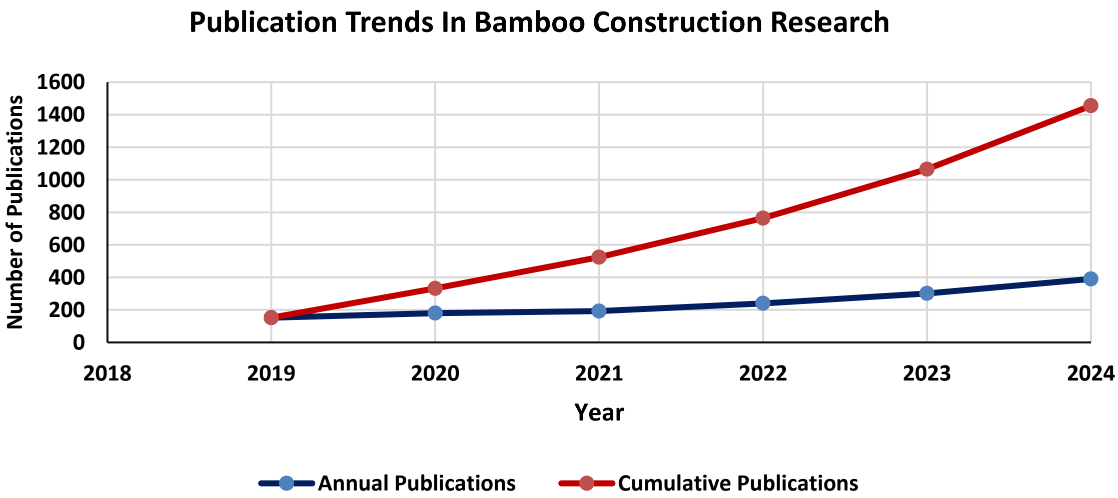

Fig. 3. Trends in research and developments in bamboo construction (2019–2024)

This upward trend underscores the increasing global recognition of bamboo as a viable, low-carbon construction material. The steady rise in research output reflects broader environmental concerns, the push for green infrastructure, and the demand for renewable alternatives to traditional building materials. The relative stabilization in annual publication counts in recent years may suggest a transition from exploratory research toward more focused investigations into structural performance, treatment technologies, and standardization frameworks.

5.2 State of Research and Developments

Understanding the geographical distribution of research contributions is key to mapping global innovation trends in bamboo construction. As illustrated in Fig. 4, China is the dominant contributor, accounting for 48.5% of all publications between 2019 and 2024. It is followed by India (17.9%) and Indonesia (10.4%), with other notable contributors including the United States (6.4%), Malaysia (4.7%), Brazil (4.1%), the United Kingdom (3.0%), and Italy (2.8%). These figures highlight a strong concentration of scholarly activity in Asia, particularly from countries that have abundant natural bamboo resources and are actively exploring sustainable construction practices.

In terms of impact, Fig. 5 presents the citation distribution by country. China again leads significantly, receiving 48.4% of all citations, reflecting not only its publication volume but also the influence and quality of its research. The United States ranks second with 13.0%, followed by India (10.4%), Malaysia (4.4%), and the United Kingdom (4.0%). Countries such as Australia, Indonesia, and Brazil also demonstrate strong visibility in citation impact, indicating the relevance of their contributions to the global discourse on sustainable and bio-based materials.

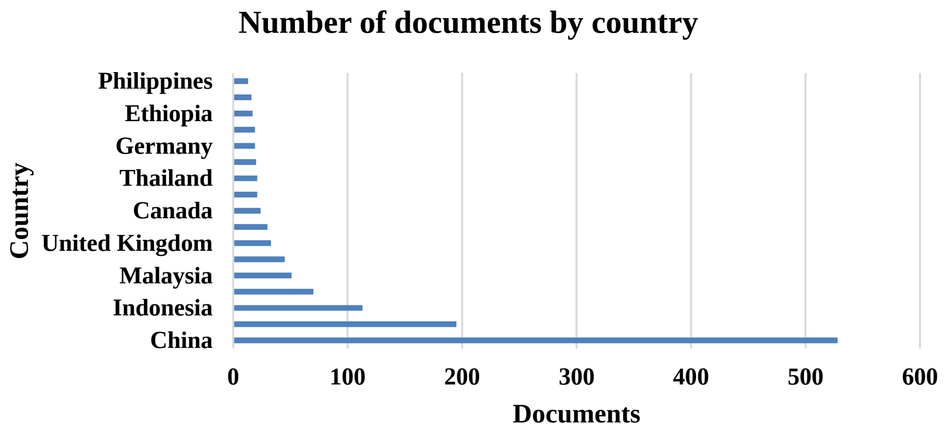

Fig. 4. Documents by country

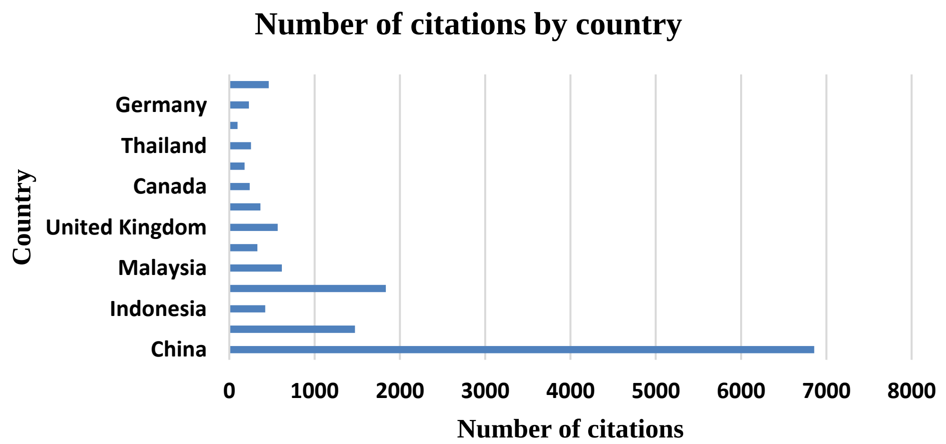

Fig. 5. Citations by country

The leadership of China, India, and Indonesia in bamboo construction research is underpinned by multiple factors. China has institutionalized bamboo development through national initiatives such as the “Bamboo Science and Technology Action Plan,” encouraging academic research and industrial applications [73]. India’s National Bamboo Mission, launched in 2018, provides policy incentives for bamboo cultivation and infrastructure development [74]. Indonesia benefits from rich native bamboo species diversity and active governmental support for green building practices using bamboo [75] These socio-economic and policy-driven factors, combined with historical usage of bamboo in vernacular architecture, explain the dominant research output from these regions.

Fig. 6 visualizes the international collaboration network in bamboo construction research. China appears as the central hub, engaging in frequent co-authorships with India, the United States, Malaysia, Indonesia, the United Kingdom, and Brazil. The dense network of linkages signifies a highly interconnected global research ecosystem, where advancements in material science, construction engineering, and sustainability policy are being collectively shaped.

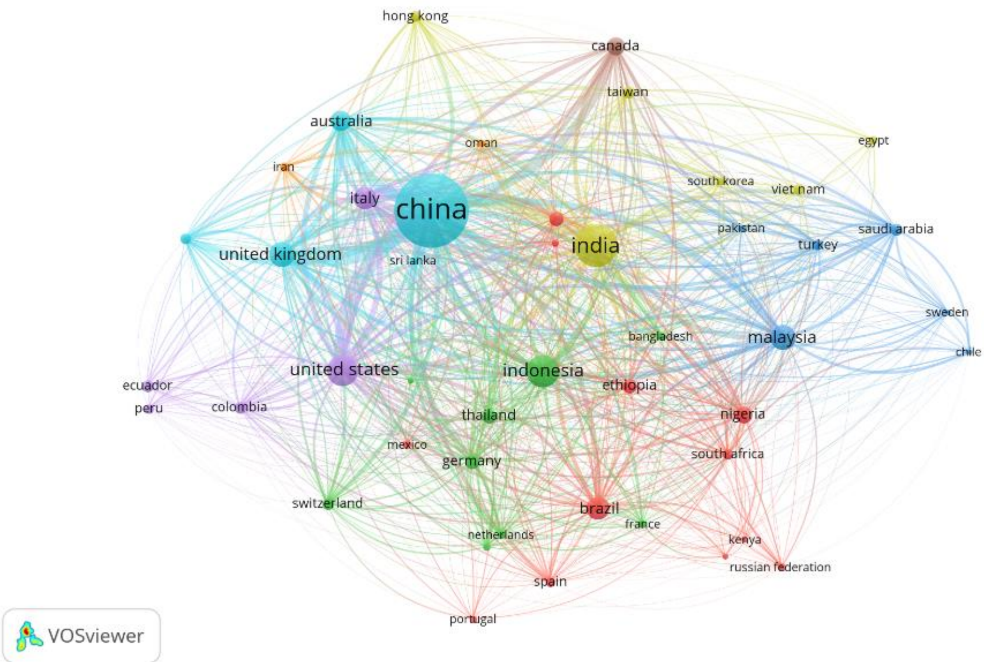

Fig. 6. Global collaboration network in railway safety research

This global collaboration map further reinforces the interdisciplinary and transnational nature of bamboo-related research. Contributions span from material performance and structural applications to emerging themes such as nanotechnology integration, engineered bamboo composites, and green infrastructure. The robust collaboration across continents suggests that bamboo construction is not merely a regional innovation, but a shared scientific pursuit aligned with broader global sustainability goals.

Table 4. Leading organizations in bamboo construction research

Organization	Articles
Research Institute of Wood Industry	13
Institute of Biomaterials for Bamboo and Rattan Resources	8
Institute of New Bamboo and Rattan Based Biomaterials	5
Civil Engineering Program	4
DICAM	4
Key Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education	4
Key Laboratory of High Efficient Processing of Bamboo of Zhejiang Province	4
State Key Laboratory of Hydraulic Engineering Simulation and Safety	4
Laboratory of Biocomposite Technology	4
International Bamboo and Rattan Organization	3

The analysis of the most active organizations, as presented in Table 4, highlights the central role of leading institutions in advancing bamboo construction research. Key contributors include research entities such as the Research Institute of Wood Industry, the Institute of Biomaterials for Bamboo and Rattan, and the Institute of New Bamboo and Rattan Based Biomaterials. These organizations consistently contribute to the field by producing high-impact studies on bamboo's structural performance, durability, and integration into sustainable building systems. Their repeated engagement illustrates a strong institutional commitment to promoting low-carbon construction and innovation in bio-based materials.

Equally significant are the contributions of individual researchers, as summarized in Table 5. Scholars such as Li H. (65 articles), Wang X. (37 articles), Wang Y. (36 articles), and Li Z. (32 articles) emerge as the most prolific authors in the field. Their research spans a wide range of areas, including engineered bamboo composites, treatment techniques, connection technologies, and performance testing under various environmental conditions. These researchers play a critical role in shaping both the theoretical foundations and practical applications of bamboo in modern construction, often leading collaborative efforts across institutions and countries.

Table 5. Top authors in bamboo construction research

Author	Articles
Li H.	65
Wang X.	37
Wang Y.	36
Li Z.	32
Li X.	32
Wang Z.	30
Li Y.	29
Li J.	28
Zhang X.	28
Liu Y.	28

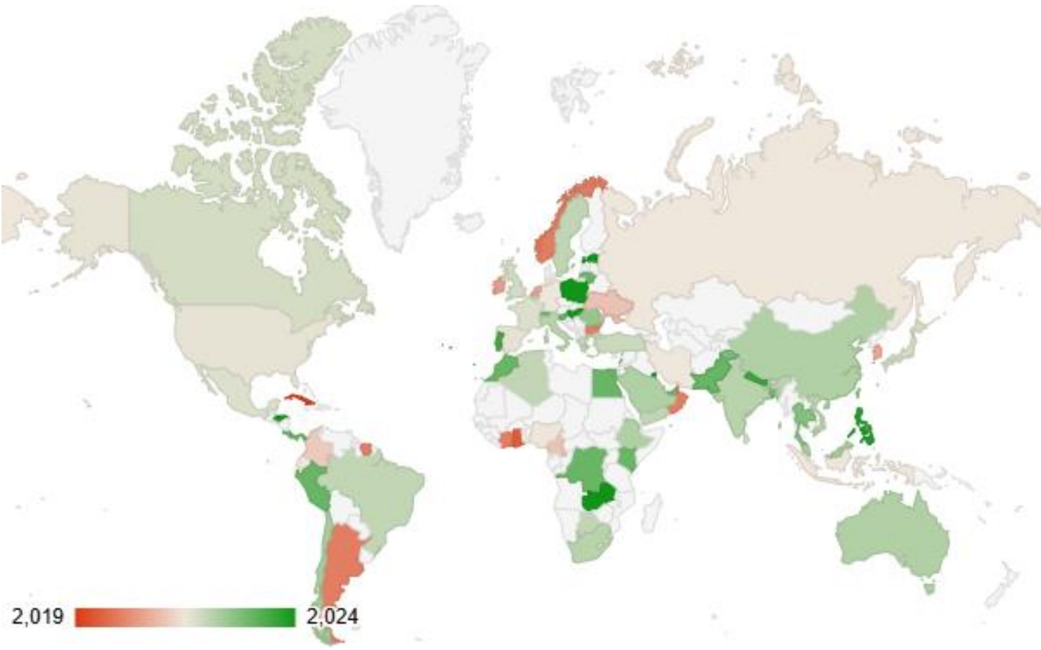

Fig. 7 Average publication year by country in railway safety research

From a global perspective, the country-level analysis presented earlier (Fig. 7) reveals a strong concentration of bamboo research in China (528 documents, avg. year 2022.2), followed by India (195 documents, avg. year 2022.1), Indonesia (113 documents, avg. year 2021.5), and the United States (70 documents, avg. year 2021.6). These countries are actively contributing to both foundational research and technological innovation, driving the development of bamboo as a mainstream construction material. The presence of nations like Malaysia, Brazil, and the United Kingdom further reflects the growing international interest in sustainable building technologies.

Collectively, these findings demonstrate the collaborative and globally integrated nature of bamboo construction research. The sustained efforts of leading institutions and researchers, along with the growing participation of countries from Asia, the Americas, and Europe, underscore a shared recognition of bamboo as a key material in the transition toward greener infrastructure. This convergence of expertise and innovation continues to propel the field forward, laying the groundwork for scalable, climate-resilient, and low-impact construction solutions.

5.3 Citation Analysis of Literature

An essential consideration for researchers in the bamboo construction domain is identifying the most impactful publications that have significantly shaped the field’s academic and technological progress. Citation analysis provides valuable insight into foundational studies, major breakthroughs, and emerging directions within bamboo-related research. Highly cited publications often serve as intellectual cornerstones, influencing both theoretical development and practical applications.

Table 6 presents the top-cited publications from the dataset, illustrating key developments in areas such as engineered bamboo composites, thermal and mechanical performance analysis, sustainable reinforcement materials, and novel material integration. Leading this list is the article titled "A Strong, Tough, and Scalable Structural Material from Bamboo" by Li et al., with 347 citations, underscoring its foundational role in demonstrating the mechanical viability of bamboo as a high-performance construction material. Another highly influential work, "Thermogravimetric Analysis Properties of Cellulose Fibers and Their Reinforcement in Polymer Composites" by Nurazzi et al., has received 271 citations, reflecting its impact in material characterization and thermal behavior analysis.

Also notable is the publication "Carbon Quantum Dots Supported AgI/ZnO/Phosphorus-Doped g-C3N4 Nanocomposite" by Hasija et al., with 220 citations, representing advancements in sustainable nanocomposite materials that include bamboo derivatives. Further, Thomas et al.'s article "Biomass Ashes from Agricultural Wastes as Supplementary Cementitious Materials" (205 citations) bridges waste valorization with cement replacement strategies, often synergistic with bamboo-based solutions. Moreover, Li et al.'s "Sustainable High-Strength Macrofibres Extracted from Natural Bamboo" (204 citations) highlights innovative approaches to enhancing fiber-based concrete performance.

Table 6. Highly Cited Publications in railway safety research

Ref	Title	Year	Total Citations	Source
[76]	A Strong, Tough, and Scalable Structural Material from Fast-Growing Bamboo	2020	347	Advanced Materials
[77]	Thermogravimetric analysis properties of cellulosic natural fiber polymer composites: A review on influence of chemical treatments	2021	271	Polymers
[78]	Carbon quantum dots supported AgI /ZnO/phosphorus doped graphitic carbon nitride as Z-scheme photocatalyst for efficient photodegradation of 2, 4-dinitrophenol	2019	220	Journal of Environmental Chemical Engineering
[79]	Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review	2021	205	Journal of Building Engineering

[80]	Sustainable high-strength macrofibres extracted from natural bamboo	2022	204	Nature Sustainability
	Chemical Composition and Mechanical Properties of Natural Fibers	2020	155	Journal of Natural Fibers
[81]	Production of sustainable construction materials using agro-wastes	2020	153	Materials
[82]	Rapid Processing of Whole Bamboo with Exposed, Aligned Nanofibrils toward a High-Performance Structural Material	2020	152	ACS Nano
[83]	Flexural strength and ductility of moso bamboo	2020	150	Construction and Building Materials
[84]	Nano-Fe3O4/bamboo bundles/phenolic resin oriented recombination ternary composite with enhanced multiple functions	2021	148	Composites Part B: Engineering

Fig. 8 shows how research on bamboo construction has been published across the five most active journals from 2019 to 2024. One journal that stands out is Construction and Building Materials, which shows steady and strong growth over the years—from just 5 articles in 2019 to 25 articles by 2024. This trend reflects the journal's central role in publishing high-quality studies focused on sustainable and innovative building materials. In contrast, IOP Conference Series: Earth and Environmental Science peaked early in 2020 but then declined, suggesting that researchers are increasingly moving towards permanent, peer-reviewed journal publications as the field matures.

Similarly, journals like Industrial Crops and Products and Journal of Building Engineering have shown significant growth, reflecting increased scholarly attention to bio-based construction materials and structural applications. Overall, this figure reflects a clear shift: researchers are increasingly choosing peer-reviewed journals over conferences to disseminate findings, and the body of work in bamboo construction is becoming more established and widely recognized.

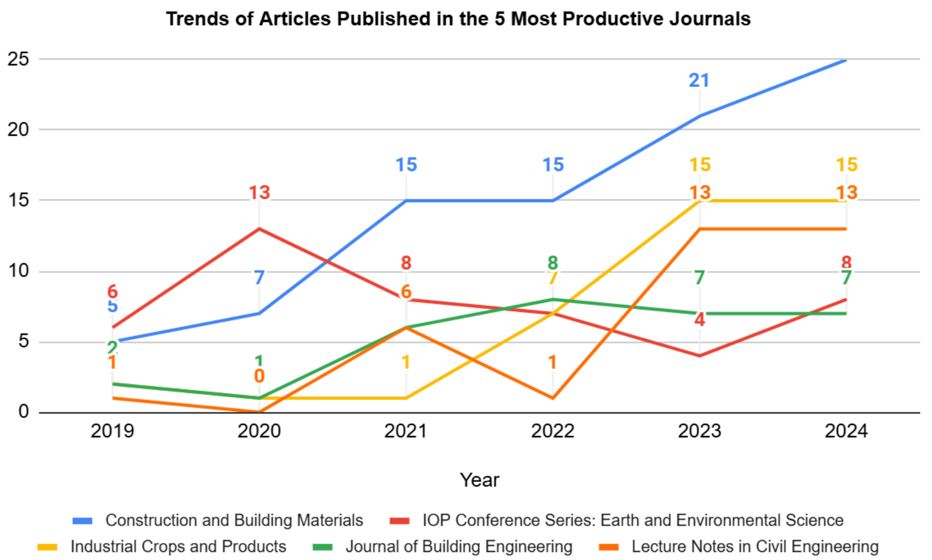

Fig. 8. Trends of Articles Published in the 5 Most Productive Journals (2019–2024)

5.4 Categorizing the Keywords

The keyword co-occurrence analysis, visualized in Fig. 9, provides a comprehensive view of the intellectual structure of bamboo construction research. This VOSviewer-generated map highlights the most frequently occurring terms and their interconnections across the literature. Based on proximity, co-usage, and network density, three primary thematic clusters emerge: (1) structural performance and mechanical behavior, (2) sustainability and environmental applications, and (3) microstructural characterization and advanced material development. Each cluster reflects a specific domain of research emphasis, offering insight into both the depth and diversity of topics explored in this rapidly expanding field.

5.4.1 Cluster 1: Structural Performance and Mechanical Behavior

This cluster is one of the most rigorously studied areas in bamboo construction research, as reflected by the frequent co-occurrence of keywords such as compressive strength, tensile strength, bending strength, laminating, and mechanical properties. These terms emphasize the centrality of structural performance in bamboo-related research, particularly in the quest to develop bio-based alternatives to conventional construction materials.

One significant line of inquiry involves the development of lightweight yet strong and tough materials suitable for demanding structural uses. Innovations in bamboo-based composites demonstrate that through scalable processing techniques, these materials can achieve performance levels comparable to synthetic structural alternatives. Such advancements align with the pursuit of both high mechanical integrity and environmental responsibility [76]. Another area of research investigates the transformation of natural bamboo into high strength macrofibres. These studies highlight the structural advantages of natural fiber systems over petroleum-based synthetic fibers, especially in terms of tensile strength and sustainability. Bamboo-derived fibers have been shown to offer not only superior mechanical performance but also lower carbon footprints, making them viable for reinforcing composite systems [80].

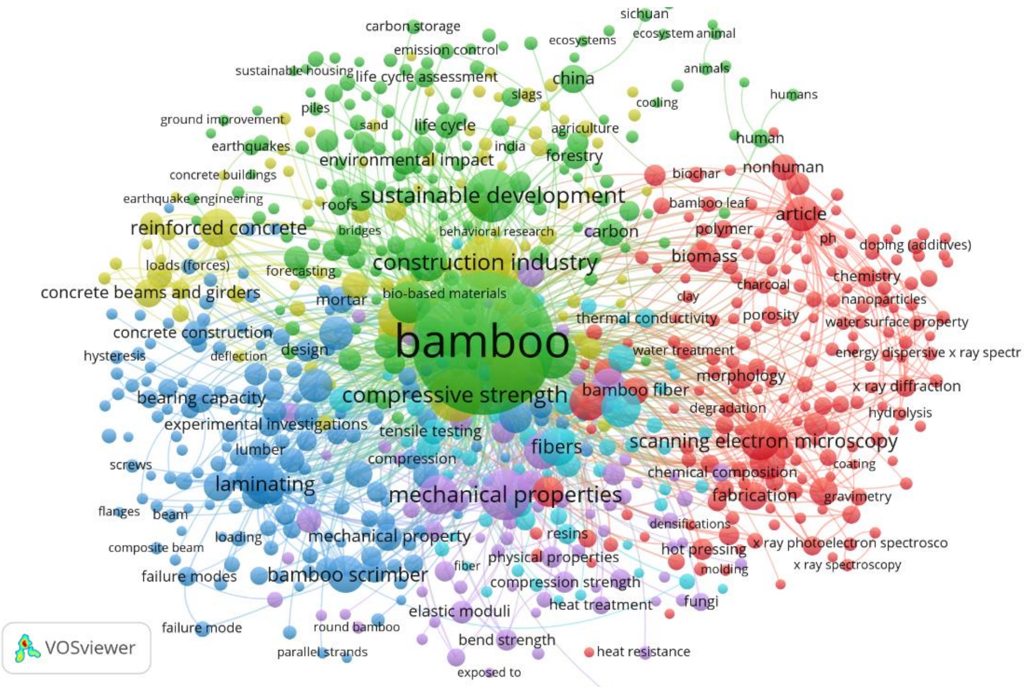

Fig. 9. Co-Occurrence Network of Keywords

The mechanical behavior of natural fibers—including bamboo—has also been extensively studied in terms of composition and durability. In these works, the structural integrity of bamboo is analyzed, and its suitability for engineering applications is confirmed through various stress tests. This includes assessments of tensile and compressive properties that are crucial for validating bamboo as a construction-grade material [85]

Recent investigations have further advanced understanding in this cluster. Bala et al. [86] explored the integration of bamboo reinforcement in geopolymer concrete, offering a novel low-carbon structural system that leverages bamboo's tensile capacity and the environmental benefits of alternative binders [86]. Similarly, Moujoud et al. [87] examined the performance of bamboo in load-bearing beams across various climatic conditions, focusing on shear capacity, bonding quality, and environmental durability. Seismic resilience is another emerging area of focus, with Wu et al.

[88] demonstrating laminated bamboo's potential to absorb energy and resist deformation in frame structures under earthquake-like loading conditions.

Material innovation has also played a pivotal role in expanding bamboo's structural applications. Meng et al. [89] introduced nanoscale reinforcement strategies to enhance the performance of bamboo fiber composites, yielding lightweight panels with improved stiffness and fatigue resistance—characteristics crucial for prefabricated modular construction. Additionally, Xu et al. [90] investigated the bond performance between bamboo strips and various polymer adhesives, revealing key parameters that influence the interfacial strength and reliability of laminated systems.

Collectively, the research within this cluster substantiates bamboo's viability as a structurally competent and environmentally sustainable material for construction. The convergence of experimental, analytical, and materials engineering approaches has not only expanded bamboo's structural capabilities but has also laid the groundwork for standardized testing methods and performance-based design guidelines. As this research domain continues to evolve, it is expected that bamboo will increasingly serve as a key component in future-ready, low-carbon structural systems.

5.3.2. Cluster 2: Sustainability and Environmental Applications

The second major thematic cluster in bamboo construction research centers around the keywords *sustainable development*, *construction industry*, *carbon*, *bio-based materials*, and *environmental impact*. This cluster captures the growing interest in bamboo as a viable solution to reduce the ecological footprint of construction activities. In alignment with global sustainability goals and climate resilience strategies, bamboo is increasingly being investigated not only for its mechanical attributes but also for its environmental credentials—positioning it as both a high-performance and low-carbon alternative to traditional building materials.

Shi et al. [91] developed eco-friendly binderless bamboo fiberboards without synthetic adhesives, utilizing mechanical refining and hot-pressing techniques. Their results demonstrated strong bonding through natural lignin activation, resulting in high flexural strength and water resistance. The panels also exhibited excellent dimensional stability and biodegradability, presenting a low-toxicity insulation and paneling alternative for sustainable building design.

Han et al. [92] fabricated bamboo-inspired bio-composites that mimic the layered structure of natural bamboo. Through optimized lamination and water-activated bonding, they achieved materials with high toughness, vibration damping, and moisture resistance. The composites maintained mechanical integrity under varying humidity conditions, proving suitable for applications requiring both flexibility and climate responsiveness

Further expanding structural design applications, Xue et al. [93] constructed a modular building prototype known as "Bamboo Cubic," emphasizing carbon-neutral design through the use of locally sourced raw bamboo in prefabricated façades. Structural tests confirmed both compressive and lateral stability of the bamboo grid system. Life-cycle impact analyses showed significant reductions in construction-phase emissions and material waste, confirming the system's compatibility with net-zero housing initiatives.

In the geotechnical domain, Gidebo et al. [94] examined the stabilization of expansive soils using bamboo ash and agricultural by-products. Laboratory tests revealed improved shear strength, reduced plasticity index, and enhanced load-bearing performance of the treated soil layers. The study concluded that bamboo ash-based additives can replace industrial lime and cement in subgrade stabilization while lowering environmental impact and construction costs.

Han et al. [95] synthesized a bamboo-inspired structural composite using renewable cellulose nanofibrils. The composite achieved an outstanding balance of high tensile strength and flexibility. This was attributed to the hierarchical fiber arrangement modeled after bamboo's internal vascular system. Their results offer a blueprint for developing next-generation load-bearing elements from fully biodegradable, plant-derived resources. Cui et al. [96] introduced an innovative use of bamboo biomass in hybrid composite membranes for indoor air filtration and insulation, showing promise for bamboo's expansion into non-structural and passive energy systems. Finally, Lou et al. proposed the development of bamboo-based insulation panels designed for low-energy buildings, combining affordability with excellent thermal resistance, thus bridging the gap between environmental performance and economic feasibility [97] .

Collectively, the studies within this cluster underscore bamboo's dual potential: it is both a technically viable material for structural applications and a key enabler of low-impact construction practices. Through applications ranging from reinforced concrete to thermal insulation and membrane technologies, bamboo's versatility continues to support the transition toward more circular, carbon-neutral, and eco-efficient construction systems. As climate change and resource scarcity drive global innovation, bamboo stands out as a strategic material capable of harmonizing environmental sustainability with practical engineering demands.

5.4.3 Cluster 3: Microstructural Characterization and Advanced Materials

The third thematic cluster centers on the microscopic and material science-based analysis of bamboo, with frequent keywords such as scanning electron microscopy (SEM), thermal conductivity, fabrication, porosity, and biomass. This area of research focuses on understanding the internal architecture of bamboo and its composites—investigating how thermal, chemical, and physical processing influence microstructural behavior, functional properties, and long-term performance. These insights are critical for optimizing bamboo's use in precision-engineered, high-performance construction systems.

Lv et al. [98] employed detailed microstructural imaging to explore bamboo-derived cellulose materials with superior piezo photocatalytic behavior. Their work identified that the alignment of nanoscale fibers and controlled porosity contributed to enhanced charge transfer and visible-light activity. This microstructural insight was crucial in optimizing bamboo-based hybrids for photocatalytic and sensor-integrated building materials. Wu et al. [99] fabricated a biomass cellulose-based adsorbent with tunable pore architecture. Using SEM and FTIR analysis, they demonstrated that precise control of internal cell wall thickness and surface functional groups significantly enhanced water absorption and thermal buffering capacities. These findings underscore how bamboo's hierarchical microstructure can be engineered for eco-friendly insulation and passive climate control in buildings.

Saravanan et al. [100] synthesized a hybrid material combining bamboo-derived nanocellulose and cassava tuber starch. Their analysis demonstrated a porous micro-network with strong interfacial compatibility and low thermal diffusivity. Mechanical tests and micro-imaging confirmed its suitability as a lightweight, biodegradable panel for thermal insulation and acoustic absorption in green construction. Niu et al. [101] integrated bamboo-derived cellulose nanocrystals into multifunctional membranes, significantly improving their mechanical integrity and filtration efficiency—demonstrating bamboo's potential in both structural and non-structural applications. Yang et al. [102] introduced a treatment method for round bamboo to enhance its dimensional stability and structural uniformity. The experimental work included cross-sectional imaging and thermal dimensional analysis, demonstrating that fiber shrinkage and deformation under moisture fluctuations could be effectively mitigated through chemical and thermal pretreatment. Additionally, Javadian et al. (2019) explored the effect of densification on bamboo, utilizing mechanical testing and SEM imaging to quantify improvements in strength and dimensional stability, confirming its suitability for load bearing uses [103].

These studies illustrate how bamboo's internal microarchitecture—characterized by fiber orientation, porosity, and cellular gradients—can be engineered to develop high-performance composites and bio-derived materials. By bridging microstructural design with environmental resilience and mechanical integrity, this research cluster supports the advancement of bamboo-based technologies for future-ready, sustainable construction systems.

6. Future Research Pathways in Bamboo Construction

Building upon the bibliometric analysis and thematic clusters identified in this study, several future research directions have emerged that merit focused investigation as in Fig. 10. These areas not only highlight gaps in current knowledge but also reflect the shifting needs of the construction industry as it moves toward more sustainable, high-performance, and resilient building solutions. As bamboo gains global recognition as a viable alternative to conventional construction materials, further research is essential to unlock its full potential through technical innovation, material synergy, and regulatory advancement.

A key area of future research lies in the advanced modeling of engineered bamboo composites. While numerous studies have successfully characterized bamboo's mechanical properties under standard testing conditions, there remains a pressing need for high-fidelity models capable of simulating their behavior under complex stress states such as multi-axial loading, long-term fatigue, and seismic activity. However, current models often fall short in capturing degradation phenomena such as moisture cycling, creep deformation, and microbial attack. Incorporating artificial intelligence and machine learning into the predictive modeling of bamboo structures—trained on robust experimental datasets—could significantly enhance design reliability and long-term performance forecasting.

A second frontier involves the development of hybrid systems using bamboo in combination with other bio-based materials. The integration of bamboo with resources such as mycelium, recycled cellulose, and agricultural residues opens the door to creating multi-functional composites that combine mechanical strength with environmental compatibility. Nevertheless, challenges remain in scaling up fabrication processes and improving the bonding mechanisms at the interface of these natural materials. Research should prioritize optimizing matrix-fiber adhesion, evaluating long-term durability, and ensuring regulatory compliance of hybrid bamboo products for structural use.

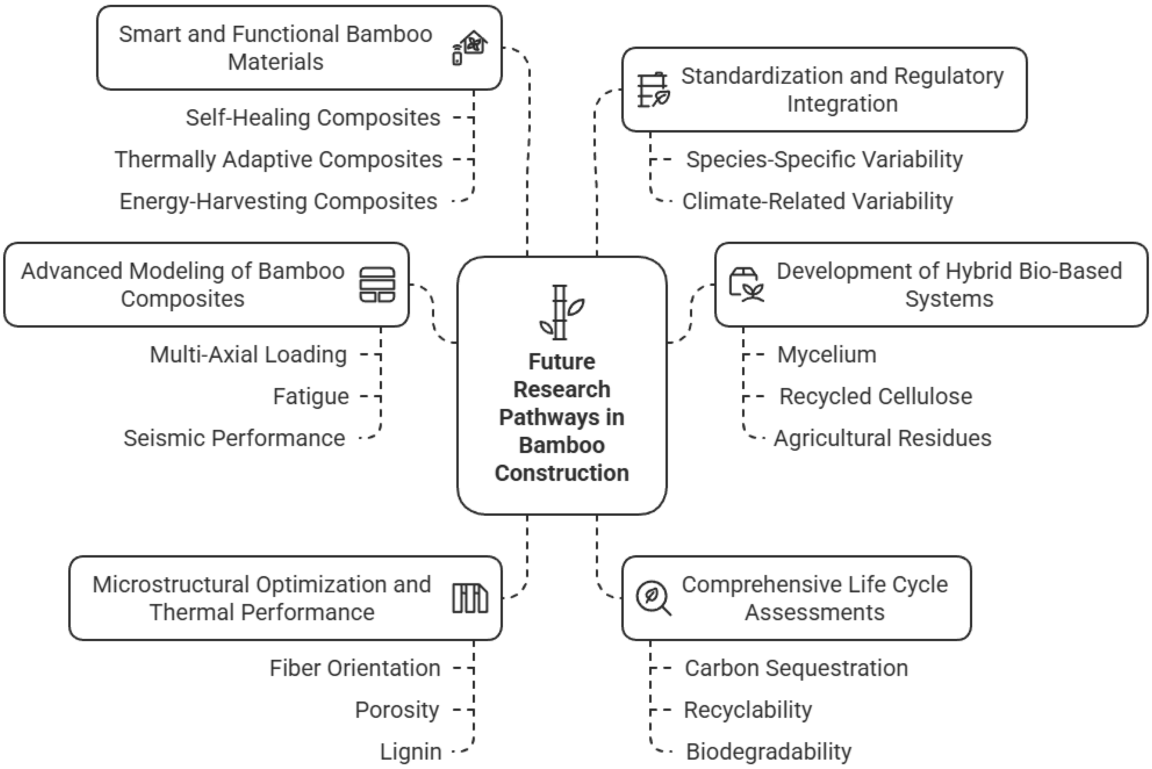

Fig. 10. Future research pathways in bamboo construction

In parallel, there is growing interest in microstructural optimization and thermal behavior enhancement of bamboo materials. Although techniques such as scanning electron microscopy (SEM) and X-ray diffraction have been widely employed to study bamboo's internal structure, few studies have successfully correlated microstructural parameters—such as fiber alignment, porosity, and lignin content—with macro-scale properties like thermal conductivity and dimensional stability. Future research should pursue integrative methods combining SEM, FTIR, and data-driven modeling to establish predictive frameworks for high-performance, thermally efficient bamboo building elements.

Despite bamboo's favorable material properties, its widespread adoption continues to be hindered by the absence of comprehensive and standardized building codes. Although ISO 22156 and 22157 provide baseline guidance, they do not account for species-specific variability or regional construction practices. Differences in treatment processes, environmental exposure, and mechanical performance further complicate the development of globally harmonized standards. Future efforts must focus on creating regionally adaptive design protocols, informed by rigorous experimental testing and lifecycle performance evaluations. Strong collaboration between material scientists, structural engineers, and policy-makers is essential to integrate bamboo into mainstream regulatory frameworks and ensure its safe, code-compliant application in construction.

Equally important is the need for more detailed and comprehensive life cycle assessments (LCAs). Although existing studies have established bamboo's role in reducing embodied carbon, most neglect broader environmental dimensions such as water usage, energy inputs across the supply chain, and end-of-life treatment. However, more work is needed to quantify the full ecological footprint of bamboo products, particularly in different climatic zones. Integrating bamboo into circular economy models—through recycling pathways, biodegradability testing, and carbon sequestration analysis—can strengthen its value proposition as a truly sustainable building material.

Finally, the frontier of smart and functional bamboo-based materials represents an exciting opportunity for interdisciplinary innovation. Emerging studies have begun to explore bamboo's potential as a base for sensors, actuators, and energy-harvesting systems. However, realizing these smart materials on a commercial scale will require overcoming challenges related to durability, cost, and integration with conventional building systems. Future research should investigate the feasibility of embedding responsive polymers, microcapsules, or energy storage elements within bamboo matrices to create self-healing, thermally adaptive, or even energy-producing construction elements.

7. Conclusions

This study provides a comprehensive bibliometric and knowledge-structure analysis of global research trends in bamboo-based construction between 2019 and 2024. Using a database of 1,456 peer-reviewed publications retrieved from Scopus and advanced mapping tools such as VOSviewer and bibliometrix in R, the research identified key thematic clusters in the domain. These clusters include structural performance and mechanical behavior, sustainability and environmental applications, and microstructural characterization and material innovation. The findings confirm that bamboo has gained increasing global attention as a sustainable construction material, supported by its mechanical strength, rapid renewability, and low environmental footprint.

Geographically, China, India, and Indonesia dominate publication and citation outputs, driven by abundant bamboo resources, government initiatives such as China's Bamboo Science and Technology Action Plan and India's National Bamboo Mission, and a growing emphasis on green construction strategies. Nevertheless, the bibliometric results also reveal critical research gaps that hinder bamboo's mainstream adoption in construction, particularly regarding international standardization, long-term durability assessment, scalability of engineered bamboo products, and lifecycle optimization methods. The limited integration of smart technologies, such as nano-enhancements and hybrid systems, further underscores the need for multidisciplinary research collaborations.

Beyond the bibliometric findings, a comparative evaluation between bamboo composites, steel, and timber highlights bamboo's competitive tensile strength, superior environmental performance, and promising cost-effectiveness, particularly in regions with limited access to traditional building materials. However, challenges related to quality consistency, market logistics, large-scale fabrication, and connection system standardization remain pressing concerns that must be addressed to ensure reliable and scalable applications.

Moving forward, future research should focus on developing regionally adaptive building codes, enhancing bamboo treatment and processing technologies, exploring bamboo's behavior under complex loading and environmental conditions, and advancing hybrid material systems to further improve performance and durability. Integrating bamboo construction into mainstream sustainable infrastructure solutions will also require strong policy support, education initiatives, and investment in industrial-scale production technologies.

In conclusion, bamboo has the potential to transition from a promising alternative to a key strategic material for achieving resilient, low-carbon, and sustainable infrastructure. Realizing this vision demands continued scientific innovation, strategic collaboration across sectors, and a commitment to advancing bamboo construction technologies globally.

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