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BIBLIOMETRIC ANALYSIS ON THE EVOLUTION OF FIRE RESISTANCE IN TIMBER STRUCTURE

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Abstract:

The increasing demand for sustainable and fire-safe construction has drawn significant attention to the fire resistance of timber structures, yet a comprehensive overview of global research trends in this field remains limited. This study addresses this gap by conducting a bibliometric analysis to evaluate the development, patterns, and collaborations in fire resistance research related to timber. Data were collected through Scopus advanced searching using defined keywords, which yielded 402 relevant documents published between 2000 and 2025. The analysis employed the Scopus analyzer to generate statistical outputs and graphical trends, while OpenRefine was applied to clean and harmonize the dataset, ensuring accuracy and consistency in author names, keywords, and institutional affiliations. VOSviewer software was then used to perform network visualizations, including co-authorship, keyword co-occurrence, citation, and country collaboration mapping. The numerical results reveal a steady increase in publications over the last two decades, with a significant surge after 2015, indicating growing global recognition of timber's role in sustainable construction and the need for enhanced fire safety performance. China, Canada, and the United States emerge as the most productive contributors, while highly cited papers are concentrated in journals focusing on fire safety, structural engineering, and material science. Co-occurrence keyword analysis highlights recurring themes such as fire resistance, charring rates, cross-laminated timber, and fire protection strategies, which together demonstrate the field's evolution from fundamental testing toward advanced modelling and engineered wood applications. The findings contribute to the body of knowledge by identifying research gaps, highlighting leading countries and institutions, and emphasising international collaboration

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as a driver of innovation. Overall, this study provides a clear bibliometric overview of research trends in fire resistance of timber structures, supporting the advancement of safe, resilient, and sustainable construction practices.

Keywords:

Fire Resistance, Timber Structure, Charring Rate, Bibliometric Analysis

Introduction

The fire resistance of timber structures is a critical aspect of building design, particularly in ensuring the safety and integrity of buildings during fire incidents. Timber, a sustainable and versatile construction material, has been used for centuries due to its natural aesthetic appeal, ease of use, and environmental benefits. However, its combustibility poses significant challenges in fire safety design. The charring of the outer layer of timber, which acts as an insulator, is a key factor in its fire resistance, but the overall performance of timber structures in fire conditions depends on various factors, including the dimensions of the timber elements, the type of connections used, and the presence of protective coverings (Ali & Kavanagh, 2005; Džidić & Aktee, 2025; Rusinová et al., 2023). This paper aims to explore the fire resistance of timber structures, focusing on the factors that influence their performance during fire exposure and the methods used to enhance their fire resistance, as shown in Figure 1.

Research on the fire resistance of timber structures has highlighted several critical factors that influence their performance during fire exposure. One of the primary considerations is the charring rate of timber, which is affected by the wood species, moisture content, and the direction of heat transfer (Cachim & Franssen, 2010). The charring of the outer layer of timber serves as an insulator, protecting the core from heat penetration and maintaining the structural integrity of the timber element. Studies have shown that larger cross-sectional dimensions of timber elements result in greater fire resistance, as the increased mass provides more material to char and insulate the core. Additionally, the moment of inertia of timber beams plays a significant role in their fire resistance, with higher moments of inertia leading to better performance under fire conditions (Džidić & Aktee, 2025).

The fire resistance of timber connections is another critical aspect of timber structures. Timber connections, particularly those involving metal fasteners, are often the weakest link in the structure during fire exposure. Heat conducted into the wood by metal fasteners causes the wood adjacent to the fasteners to char, compromising the connection's integrity (Peng et al., 2008). Research has focused on developing thermal models to predict the temperature profile of timber connections and validate these models through experimental testing (Peng et al., 2008). The use of protective coverings, such as gypsum boards, has been shown to enhance the fire resistance of timber connections by delaying or preventing ignition and charring (Rusinová et al., 2023).

Experimental and numerical studies have been conducted to evaluate the fire resistance of various timber elements and structures. Standard fire tests, such as those prescribed by ISO 834, are commonly used to assess the fire resistance of timber members by subjecting them to a standard time-temperature curve and measuring the time to failure (Harada et al., 2024). However, these tests have limitations, particularly in predicting the post-heating behavior of timber structures, as self-burning can continue during the cooling period (Harada et al., 2024).

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Numerical models, such as those implemented in the Abaqus finite element code, have been developed to predict the fire resistance of timber members by simulating the thermal and structural behavior under fire conditions (Fragiacomo et al., 2013). These models consider the reduction in mechanical properties of timber with temperature and have been validated against experimental data (Fragiacomo et al., 2013).

Recent advancements in fire protection for timber structures have focused on the use of fire retardants and protective linings. Fire retardants, such as those consisting of ammonium polyphosphate, tannic acid, and silica sol, have been shown to significantly enhance the fire resistance of timber by reducing flame spread and smoke propagation (Zhao et al., 2025). Protective linings, such as gypsum boards, have been demonstrated to delay ignition and charring, thereby enhancing the fire resistance of timber components (Rusinová et al., 2023). Additionally, the development of probabilistic performance-based approaches has allowed for more flexible and case-specific analyses of fire resistance, particularly for historic timber structures (Garcia-Castillo et al., 2025).

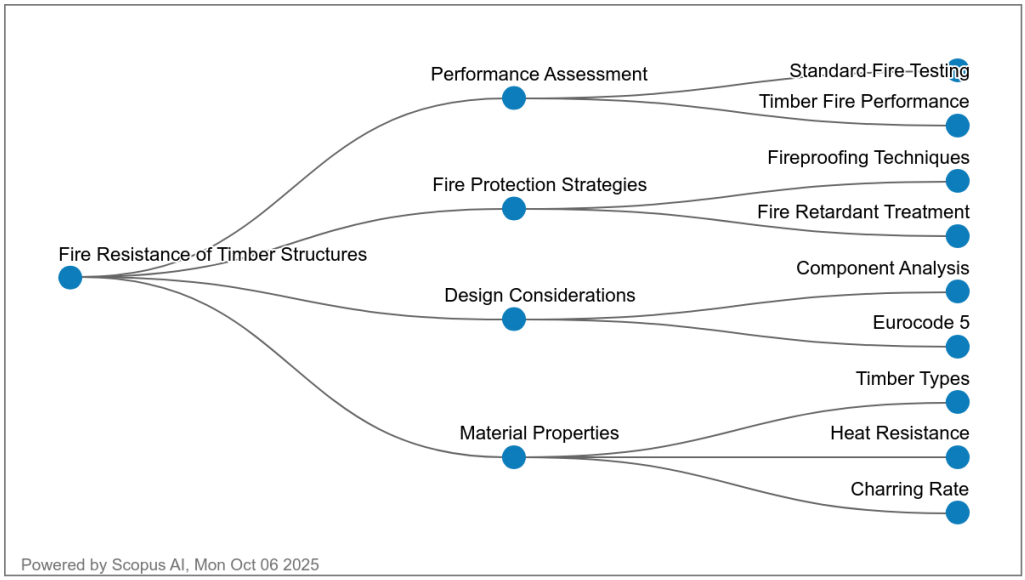

Figure 1: Thematic Mapping on Fire Resistance of Timber Structure

In conclusion, the fire resistance of timber structures is influenced by various factors, including the charring rate, cross-sectional dimensions, type of connections, and presence of protective coverings. Experimental and numerical studies have provided valuable insights into the behavior of timber structures under fire conditions, and recent advancements in fire protection methods have further enhanced their fire resistance. Continued research and development in this field are essential to ensure the safety and integrity of timber structures in fire incidents.

The importance of bibliometric research on fire resistance of timber structures is increasing, as it is essential to address several key questions that deepen our understanding of this scientific domain. First, what are the publication trends in this field over the years (RQ1)? Answering this question helps to trace the evolution and growth of knowledge related to timber fire performance. Second, which are the top 10 most highly cited articles in this area (RQ2)? Identifying these influential works reveals the most impactful studies that have shaped the direction of research and practical applications. Third, which countries rank in the top 10 based

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on the number of publications (RQ3)? This enables recognition of the leading contributors and geographic distribution of expertise in fire resistance studies. Fourth, what are the most frequently used keywords related to this study (RQ4)? Understanding keyword patterns highlights the core research themes and emerging topics within this field. Finally, how are countries collaborating in terms of co-authorship within this research domain (RQ5)? Exploring international collaboration provides insight into global research networks and partnerships that drive innovation. Therefore, this bibliometric study not only maps the intellectual structure and research productivity in fire resistance of timber structures but also offers valuable guidance for future investigations and policy development to enhance fire-safe and sustainable timber construction.

Methodology

Bibliometric analysis refers to the systematic collection, organization, and examination of bibliographic information derived from scientific publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). It extends beyond simple descriptive measures such as identifying journals, publication years, and leading authors (Wu & Wu, 2017), and incorporates advanced techniques, including document co-citation analysis, which allows deeper exploration of intellectual patterns within a research field. A rigorous literature review demands a careful and iterative process that begins with the selection of appropriate keywords, followed by a structured search and detailed evaluation of the retrieved studies. This process ensures the development of a comprehensive bibliography and strengthens the reliability of the findings (Fahimnia et al., 2015). In this study, emphasis was placed on influential publications because they provide valuable insights into the theoretical foundations guiding research in this domain. To secure accuracy and breadth of coverage, Scopus was selected as the primary database for data collection (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). Only articles published in academic journals and conference proceedings were included, while book series, books and trade journals were excluded to maintain consistency and quality (Gu et al., 2019). The final dataset consisted of publications indexed in Scopus from January 2000 to December 2025, forming the foundation for the subsequent analysis.

Data Search Strategy

The data collection process for this bibliometric study was conducted using the Scopus database, which is recognized as one of the most comprehensive sources of scientific and technical literature. The Scopus advanced search feature was applied to systematically identify publications related to the fire resistance of timber structures. The search string (as in Table 1) used was TITLE(("fire resistance" OR "fire performance" OR "fire behaviour") AND ("timber" OR "wood" OR "hardwood*" OR "softwood*" OR "lumber" OR "wooden" OR "bamboo*" OR "LVL" OR "CLT" OR "glulam")) AND PUBYEAR > 1999 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ch")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")). This search string was developed to capture research explicitly focused on the fire behaviour and performance of both natural and engineered wood materials, including laminated veneer lumber (LVL), cross-laminated timber (CLT), and glued laminated timber (glulam). The data were accessed in October 2025. To ensure relevance and quality, strict screening criteria were applied. Publications from the year 2000 to 2025 were included to reflect the most recent advances in fire testing and timber construction, while earlier studies were excluded because of outdated methodologies and limited relevance to modern building materials. Only journal articles,

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conference papers, and book chapters were retained, as these document types typically present primary research results, analytical findings, or technical developments. In contrast, review papers, notes, and books were excluded to maintain focus on original and empirical research. The selection also limited source types to journals and conference proceedings, excluding trade publications and book series that often lack scientific rigour. After applying these parameters, a total of 402 documents were identified as the final dataset for analysis.

Once retrieved, the dataset was cleaned and harmonised using OpenRefine to remove duplicates, standardise author names, correct inconsistent entries, and unify keyword terminology. This process ensured data reliability and improved the accuracy of bibliometric mapping. The refined dataset provides a representative view of global research activity in the field of fire resistance of timber structures over a twenty-five year period. The inclusion of both experimental and computational studies reflects the multidisciplinary nature of this research area, where fire safety, material science, and structural engineering intersect. The selected period also captures the global shift towards the use of sustainable construction materials, with engineered timber gaining increasing importance as a renewable and low-carbon alternative to conventional materials. This has driven research interest in fire resistance, charring behaviour, and protection strategies to ensure safe application in modern structures. The structured search and cleaning process follows standard bibliometric practices recommended by (van Eck & Waltman, 2010, 2017), ensuring accuracy and reproducibility. The details explanation can be seen in Table 2. Overall, this methodological approach provides a solid foundation for analysing research trends, collaborations, and emerging themes in the fire performance of timber, contributing to the broader understanding of safe and sustainable timber construction.

Table 1: Search string from the Scopus database

Data	String	Results
Scopus	TITLE (("fire resistance" OR "fire performance" OR "fire behaviour") AND ("timber" OR "wood" OR "hardwood*" OR "softwood*" OR "lumber" OR "wooden" OR "bamboo*" OR "LVL" OR "CLT" OR "glulam")) access date: October 2025	402 articles

Table 2: The Selection Criterion in Searching

Criterion	Inclusion	Exclusion
Published Year	2000 – 2025	< 2000
Sources Type	Journal, Conference Proceeding	Book Series, Book, Trade Journal
Document Type	Article, Conference Paper, Book Chapter	Review Paper, Note, Book

Data Analysis

VOSviewer is a bibliometric software developed by Nees Jan van Eck and Ludo Waltman at Leiden University in the Netherlands (van Eck & Waltman, 2010, 2017). It has become a widely used tool for visualizing and analysing scientific literature, with particular strengths in generating network maps, clustering related items, and producing density visualizations. The software supports the exploration of co-authorship, co-citation, and keyword co-occurrence patterns, enabling researchers to identify intellectual structures and emerging themes within

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complex research domains. Its interactive interface and continuous updates ensure both accessibility and adaptability, making it suitable for users with varying levels of expertise. By computing relevant metrics and offering flexible visualization options, VOSviewer provides a powerful platform for mapping research landscapes and uncovering meaningful scholarly connections.

For this study, datasets containing publication year, title, author name, journal, citation, and keywords in plain text format were retrieved from the Scopus database, covering the period between 2000 to October 2025. These datasets were analysed using VOSviewer version 1.6.19, which applied clustering and mapping techniques to generate the visual outputs. Unlike the traditional Multidimensional Scaling (MDS) method, which relies primarily on similarity measures such as cosine and Jaccard indices, VOSviewer places items in low-dimensional spaces so that their proximity reflects their relatedness with greater accuracy (Appio et al., 2014). This is achieved by normalizing co-occurrence frequencies through the association strength measure, expressed as

$$AS_{ij} = \frac{C_{ij}}{w_i w_j}$$

where C_{ij} is the observed number of co-occurrences of items i and j, and w_i and w_j represent their total occurrences (Van Eck & Waltman, 2007). This formulation allows VOSviewer to balance observed and expected values, thereby producing reliable and interpretable network maps that reveal the underlying structure of a research field.

Findings

The trend of publications on fire resistance of timber structures between 2000 and 2025 shows (Figure 2) a steady growth with clear acceleration in the past decade. Early research from 2000 to 2009 produced fewer than ten publications annually, reflecting a niche field with limited global focus on timber fire safety. However, from 2010 onward, the numbers began to climb, with several notable increases, such as 25 papers in 2016 and a consistent output above 20 papers per year from 2017 onward. The upward trajectory became most significant from 2022 to 2025, culminating in 50 publications in 2025 alone, the highest in the 25-year span. This sharp rise can be attributed to the global adoption of engineered wood products such as cross-laminated timber and glulam in multi-storey construction, which triggered growing interest in structural fire safety research. Increasing regulatory attention and the need to update design codes, such as Eurocode 5 also encouraged more scientific investigations in this field.

This publication's growth also aligns closely with international commitments to sustainable development. The increased focus after 2015 corresponds with the launch of the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Timber has been promoted as a renewable and low-carbon alternative to conventional construction materials, but ensuring its fire safety is essential for public acceptance and regulatory approval. The rapid expansion of research output in recent years reflects not only advances in testing and modelling but also the global demand for safer, greener construction solutions. This indicates that fire resistance of timber is no longer a marginal topic but a central part of the sustainable construction agenda, which explains why publications peaked in the most recent years.

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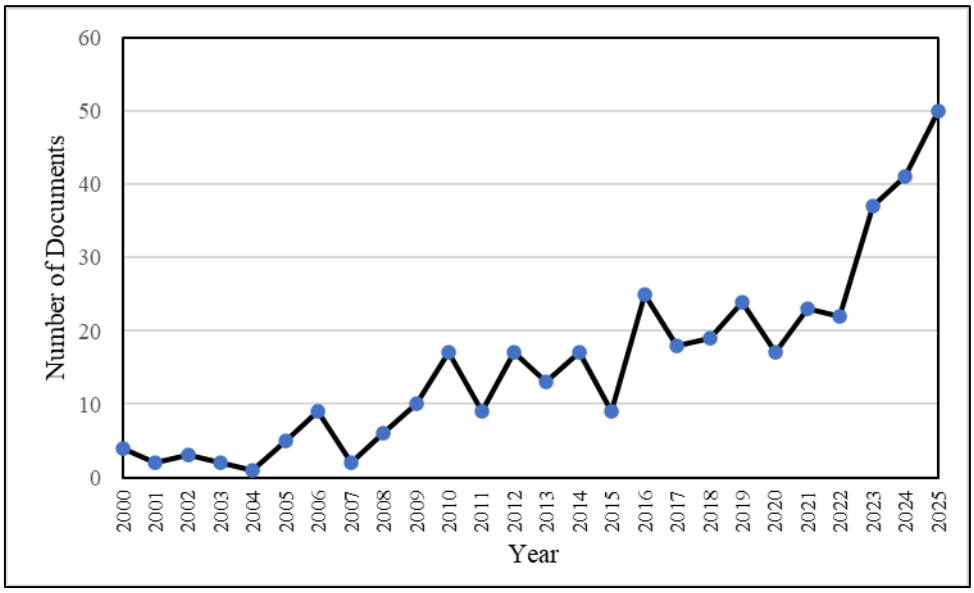

Figure 2: Explosive Growth in Publications on Fire Resistance of Timber Structure

The top ten most cited articles illustrated in Table 3 is the progressive development of knowledge in the field of fire resistance of timber structures, covering diverse aspects from material behaviour to structural design and modelling. The most cited paper by Brando et al. (2012) in Global Change Biology with 248 citations, focuses on fire-induced tree mortality and the roles of bark traits, tree size, and wood density, providing fundamental understanding of combustion and heat transfer mechanisms in natural wood. Racher et al. (2010) analysed the thermo-mechanical behaviour of dowelled timber connections, which became an essential reference for assessing connection performance under elevated temperatures. Mensah et al. (2023) explored pyrolysis and fire retardant mechanisms, reflecting the recent trend toward micro-scale chemical analysis, while Naser (2019) applied artificial intelligence to evaluate fire resistance, introducing modern predictive approaches. Yue et al. (2017) investigated chemical modification of fast-growing Chinese fir to improve its mechanical and fire resistance performance, demonstrating advancements in enhancing timber properties for sustainable construction. Schmid et al. (2015) proposed the reduced cross-section method and identified the zero-strength layer, offering a reliable analytical tool still used in design practice today.

The remaining studies also highlight the wide spectrum of timber fire research. Mena et al. (2012) analysed the fire behaviour of bamboo as an alternative renewable material, while Frangi et al. (2008) focused on cross laminated timber panels, marking a major step in the understanding of fire behaviour in engineered wood systems. Pries & Mai (2013) contributed to the study of wood treated with cationic silica sol for improved fire resistance, presenting solutions for safer construction materials. Schmid et al. (2014) reviewed and analysed timber fire resistance tests under different loading conditions, strengthening the theoretical framework for performance evaluation. Collectively, these top-cited papers are widely referenced because they provide either fundamental understanding, validated testing methods, or practical applications that have guided international fire design standards. Their influence aligns with the broader shift toward sustainable and resilient construction, where improving the fire safety of timber supports global goals related to innovation, infrastructure, and sustainable cities, particularly those outlined in the Sustainable Development Goals (SDG 9 and SDG 11).

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Table 3: Top 10 Most Cited Articles

No	Authors	Year	Source title	Cited by
1	Brando et al. (2012)	2012	Global Change Biology	248
2	Racher et al. (2010)	2010	Engineering Structures	77
3	Mensah et al. (2023)	2023	Journal of Thermal Analysis and Calorimetry	74
4	Naser (2019)	2019	Fire Safety Journal	72
5	Yue et al. (2017)	2017	Construction and Building Materials	72
6	Schmid et al. (2015)	2015	Fire Technology	70
7	Mena et al. (2012)	2012	Construction and Building Materials	63
8	Frangi et al. (2008)	2008	Fire Safety Science	61
9	Pries & Mai (2013)	2013	European Journal of Wood and Wood Products	59
10	Schmid et al. (2014)	2014	Fire Safety Journal	57

Figure 3 presents the Top 10 countries based on the number of publications, where China leads with 92, followed by Canada with 58 and the United States with 44. Japan contributes almost the same volume as the United States, with 43 publications, which reflects its long tradition of research in both timber structures and fire safety. European countries, including Italy, Switzerland, Sweden, and the Czech Republic, demonstrate steady contributions despite their smaller size, supported by strong academic networks and regulatory frameworks. New Zealand and Australia also appear in the top group, producing 18 and 17 publications respectively, which aligns with their promotion of timber as a sustainable material in building practices. The presence of these countries highlights the global spread of research activity, although concentrated leadership is clearly seen in China, Canada, and Japan, where resources, industrial needs, and national policies support higher research output.

The strong performance of China can be explained by its rapid urban growth and government commitment to green building solutions, which have led to active exploration of timber as a renewable construction material. Canada's position reflects its vast forest resources and long-standing research culture in engineered timber such as glued laminated and cross-laminated timber, supported by national standards that require continuous testing of fire performance. The United States maintains an active role through its advanced laboratories and growing interest in mass timber construction. Japan's consistent output can be linked to its earthquake and fire safety regulations that drive innovation in building design. European countries, Australia, and New Zealand contribute through collaborative projects and their emphasis on sustainable cities and resilient infrastructure. Together, these patterns suggest that publication activity is strongly influenced by the availability of timber resources, government policy on sustainable

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construction, and the need to align with international development goals such as SDG 9 on industry and innovation and SDG 11 on sustainable cities and communities.

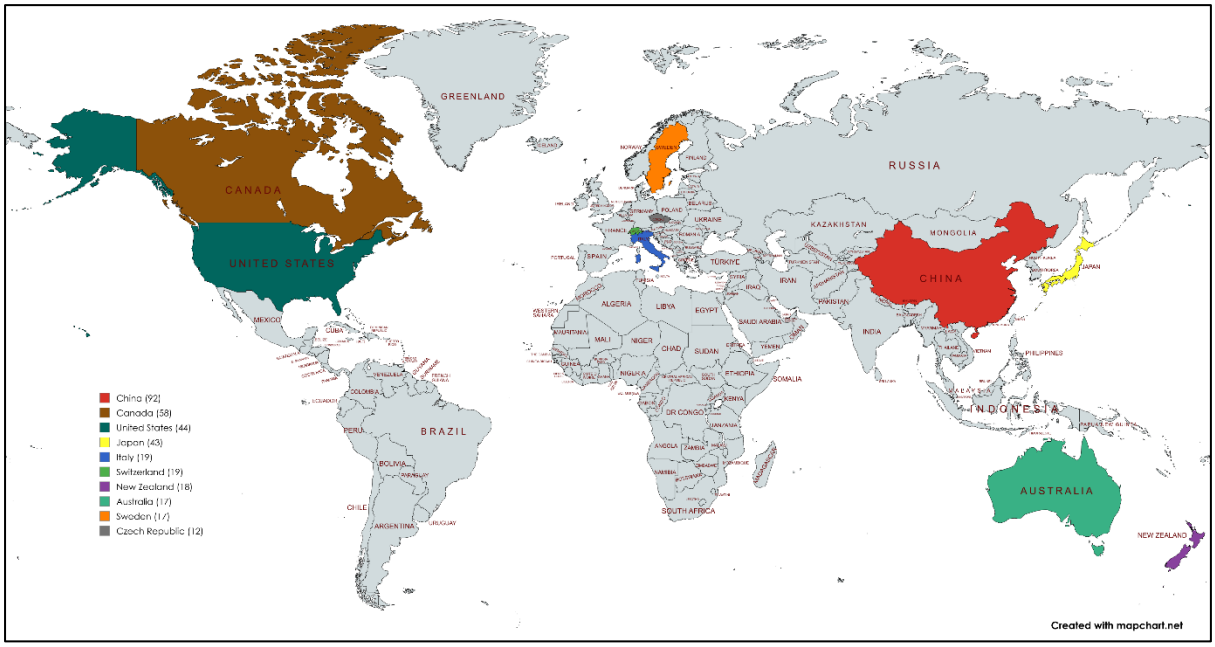

Figure 3: Top 10 Countries Ranked by The Number of Publications

Co-occurrence analysis of author keywords through VOSviewer (Figure 4) helps to identify research themes by grouping related terms into clusters. In this study, the analysis was based on the full counting method with a minimum threshold of five occurrences. Out of 1938 initial keywords, 244 met the criterion, and with a minimum cluster size of five, the software generated seven distinct clusters. These clusters represent different thematic directions in the study of fire resistance in timber. For example, the largest cluster revolves around "fire resistance," "timber," and "structural design," which indicates the strong emphasis on understanding the fundamental performance of timber under fire exposure and its implications on engineering design. Another cluster is formed around "flammability testing," "cone calorimeter," and "fire behaviour," reflecting a strong focus on experimental methods used to characterise material properties. Computational approaches such as "finite element method," "numerical models," and "fire dynamics simulator" emerge as a separate cluster, highlighting the growing importance of simulations in predicting fire performance. Meanwhile, terms like "cross-laminated timber," "glulam beams," and "mass timber" form a cluster dedicated to engineered wood products, showing the current trend of applying these materials in sustainable building construction.

The clustering also reveals niche but interconnected research areas. A cluster with keywords like "fireproofing," "protective coatings," "flame retardants," and "gypsum board" reflects the exploration of passive fire protection methods, while another with "load-bearing capacity," "mechanical properties," and "residual strength" points toward structural performance evaluation. Ecological and sustainability aspects appear in clusters containing "forestry," "sustainable construction," and "environmental protection," indicating how fire resistance studies of timber are connected to broader environmental and societal goals. These seven clusters collectively demonstrate how the field integrates different strands of research: from experimental testing and material science to numerical modelling, engineered timber

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applications, and sustainability considerations. By revealing these interconnected themes, the analysis shows that research on fire resistance of timber is not isolated but a multidisciplinary effort, contributing to safe and sustainable construction practices in line with international agendas such as the Sustainable Development Goals.

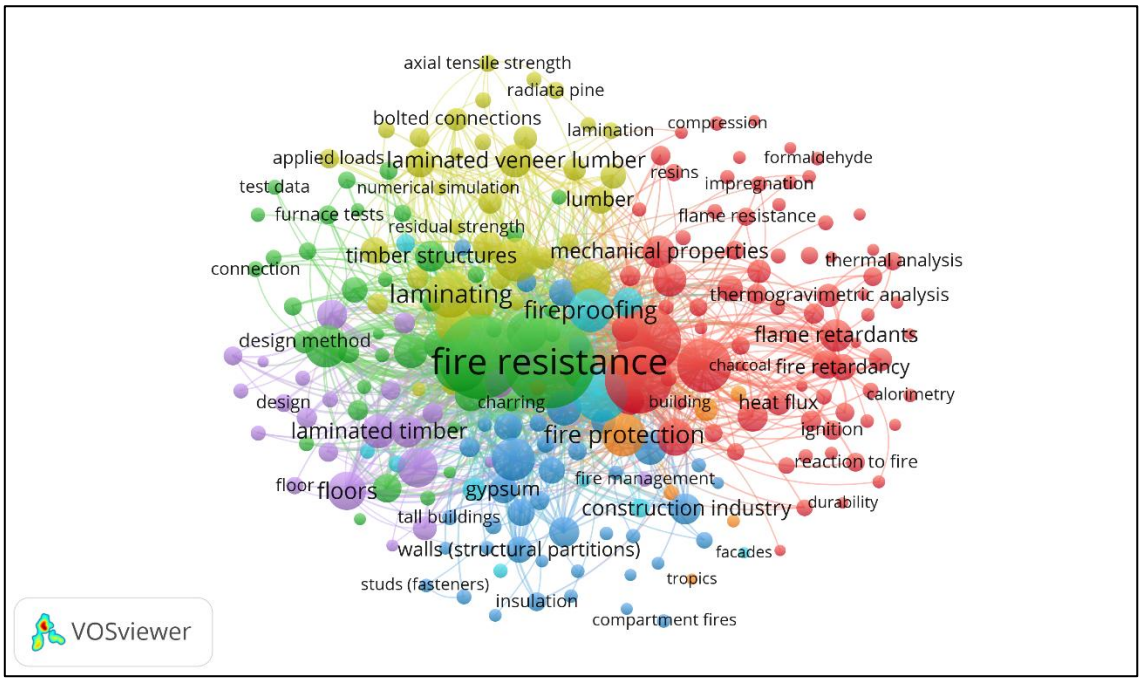

Figure 4: Network Visualization Map of Keywords' Co-Occurrence

Co-authorship analysis by countries using VOSviewer is a bibliometric technique that identifies how research collaborations are formed across nations. The concept is based on the co-occurrence of authors' affiliations, where each time researchers from different countries co-author a publication, a collaborative link is created. The strength of these links reflects the frequency and intensity of partnerships, allowing the mapping of international research networks. For this study, the full counting method was applied, meaning each co-authored paper was counted equally regardless of the number of collaborators involved. A minimum threshold of five documents was set to ensure only countries with consistent contributions were considered. From the total of 57 countries identified, 24 met this threshold, and with a minimum cluster size of five, the analysis generated five distinct clusters, each representing groups of countries that frequently collaborate in fire resistance of timber research.

The results (Figure 5) show that countries with high research output, such as China, the United States, and Canada, form the core of these clusters, reflecting their strong leadership roles and extensive collaboration networks. European countries, including Italy, Sweden, and Switzerland, are also central, supported by active participation in international projects and shared use of experimental facilities. Countries with smaller publication numbers, such as New Zealand and Australia, show relatively high link strengths, suggesting that they rely on strong collaborative ties to contribute to global research efforts. In contrast, some countries with moderate publication counts but low link strength highlight the potential for further international engagement. These findings contribute to the body of knowledge by demonstrating that global progress in timber fire safety research is driven not only by national productivity but also by international partnerships. The clustering of countries underscores the

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importance of collaborative networks in advancing testing methods, design models, and safety standards, which collectively strengthen the development of sustainable and fire-resilient timber structures.

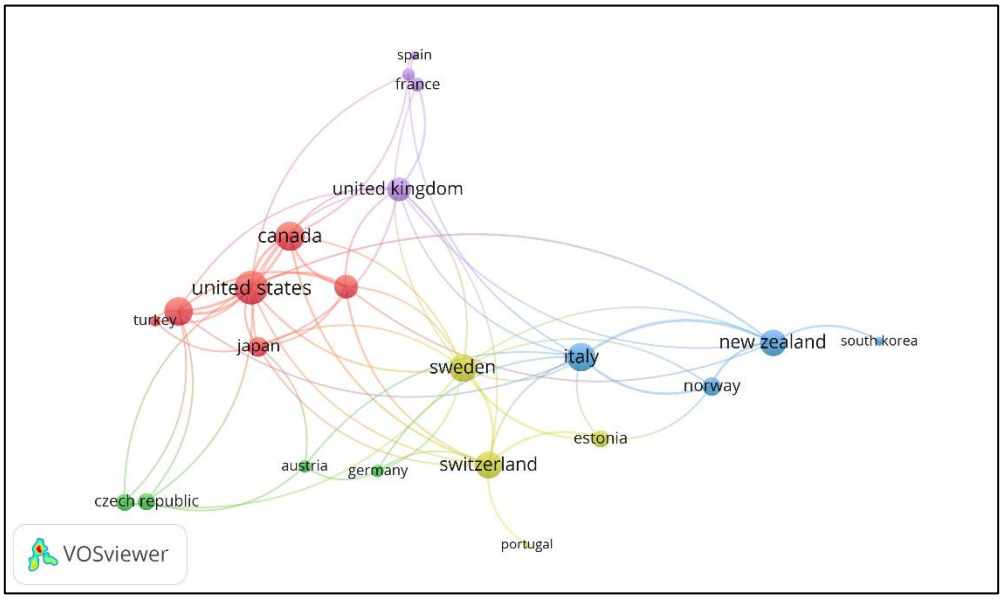

Figure 5: Co-authorship by Country

Conclusions

The purpose of this study was to examine the evolution and current state of research on fire resistance of timber structures through a bibliometric analysis, focusing on publication patterns, influential works, major contributors, and collaborative networks. The study aimed to answer key research questions on publication trends, highly cited articles, leading countries, recurring keywords, and global co-authorship patterns. The analysis of 402 documents from 2000 to 2025 revealed a consistent increase in publication output, particularly after 2015, reflecting the global shift towards sustainable construction and the need for safer timber applications. The most active contributors were identified from Asia, North America, and Europe, with China, Canada, and the United States leading the research output. Keyword analysis highlighted major themes such as fire resistance, charring behaviour, structural design, fire protection, and engineered timber systems, while co-authorship mapping showed extensive international collaboration among developed and emerging economies.

This study contributes to the field by presenting a clear overview of how scientific understanding of fire-resistant timber has progressed from fundamental material behaviour to advanced modelling and sustainable design strategies. The bibliometric mapping reveals that the research community has evolved from studying basic combustion characteristics to integrating modern analytical tools such as finite element modelling, artificial intelligence, and material modification techniques. The findings also emphasise the growing global interest in engineered wood products such as cross-laminated timber and glued laminated timber, which require continuous improvement in fire performance to support safe building applications. In practical terms, this research highlights the importance of collaboration between academia, industry, and regulatory bodies in developing reliable design standards and fire safety guidelines.

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Despite the comprehensive scope, the study is limited by its reliance on a single database and the exclusion of non-English publications, which may omit some regional insights. Future studies could expand coverage by combining multiple databases and conducting comparative analyses with other bibliometric approaches, including co-citation or thematic evolution studies. Further exploration of regional policy frameworks, experimental innovations, and real-scale testing would also strengthen the understanding of fire-safe timber applications. Overall, this bibliometric analysis provides a structured foundation for future research, supporting the advancement of knowledge and practice in fire performance of timber structures. It reinforces the relevance of bibliometric methods as a valuable tool for identifying knowledge gaps, guiding research directions, and promoting sustainable innovation aligned with global objectives such as SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

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