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Review

Evaluation of Timber Mechanical Properties Through Non-Destructive Testing: A Bibliometric Analysis

Marwa Brougui *, Krisztián Andor and Péter Szabó

Department of Wooden Construction, Faculty Wood Engineering and Creative Industries, University of Sopron, Bajcsy-Zsilinky, H-9400 Sopron, Hungary; soproniszakerto@gmail.com (K.A.); szabo.peter@uni-sopron.hu (P.S.)
* Correspondence: marwa.brougui@phd.uni-sopron.hu

Abstract

This study presents a comprehensive bibliometric analysis of research trends in evaluating the mechanical properties of timber structures, with a particular emphasis on the modulus of elasticity (MOE) assessed through non-destructive testing (NDT) methods, especially ultrasonic waves. Using VOSviewer software to analyze 129 Scopus-indexed publications, the analysis reveals a marked increase in research activity since the early 2000s and the formation of distinct thematic clusters. The keyword 'non-destructive examination' consistently emerges as the dominant term, underscoring a sustained and focused scientific interest in this field. Despite this growth, significant gaps remain, notably the lack of standardized methodologies and limited application of ultrasonic NDT techniques for in-service timber structures. This underscores the urgent need for targeted research efforts, including integrating machine learning with ultrasonic analysis, developing standardized testing protocols, exploring hybrid diagnostic approaches, and extending ultrasonic methods to aged and recycled timber. Furthermore, advancing portable, in-situ ultrasonic systems is essential to enable real-time, field-based assessments. This study not only maps the current research landscape but also highlights strategic opportunities to improve the accuracy, reliability, and sustainability of timber mechanical property evaluations, thereby supporting the advancement of timber engineering.

Keywords: non-destructive testing method[1]; timber[2]; mechanical properties[3]; ultrasonic waves[4]; elasticity modulus[5]; research map

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1. Introduction

With an increasing emphasis on sustainable construction practices, timber[2] has become a pivotal material in the architectural and construction industries. Within this evolution, a profound examination of the inherent mechanical properties[3] and intricacies of timber[2] becomes not only pertinent but imperative. At the forefront of these considerations lies the elasticity modulus[5]—a pivotal parameter governing how timber deforms under applied stress [1]. A nuanced understanding and accurate evaluation of this property are indispensable for the creation of buildings that not only showcase architectural brilliance but also embody robust structural integrity and enduring durability. A non-destructive testing method[1] using ultrasonic waves[4] plays a critical role in this evaluation.

In this context, the adoption of non-destructive testing (NDT) methods, specifically those employing ultrasonic wave[4] techniques, represents a significant technological advancement in the structural evaluation of timber[2]. Ultrasonic testing operates by emitting

high-frequency acoustic waves into the wood[2] and measuring the resulting wave propagation parameters, including velocity, attenuation, and reflection. These parameters provide valuable information about the material's internal structure. The mechanical properties[3] of timber[2]—such as stiffness, density, and elasticity modulus[5]—are inferred from the interaction of the ultrasonic waves[4] with the wood's microstructure, as wave speed and attenuation are sensitive to factors like grain orientation, moisture content, and the presence of defects or decay [2–8].

Ultrasonic waves[4] have the ability to detect internal defects—such as cracks, voids, or areas of decay, which may not be visible externally but could significantly affect structural integrity—without causing any physical damage [9–17]. Furthermore, ultrasonic wave[4] techniques have emerged as effective non-destructive testing methods[1] for evaluating moisture content and fiber orientation in timber[2], both of which critically influence its mechanical properties[3]. These techniques offer a non-invasive means of assessment, preserving the structural integrity of the material while providing essential insights into its properties [18–20]. By analyzing wave velocity and attenuation, ultrasonic wave[4] methods can detect variations in moisture content, as these parameters are highly sensitive to moisture variations [21–25]. The established relationship between ultrasonic wave velocity and moisture content allows for precise predictions of moisture levels in timber[2], making these methods valuable for quality control applications [26,27].

Moreover, the anisotropic nature of timber[2] results in directional variability in its mechanical properties[3], influenced by fiber orientation. Ultrasonic wave[4] techniques facilitate the evaluation of these variations by measuring mechanical properties[3] in different directions [28]. Studies have consistently demonstrated a strong correlation between ultrasonic wave[4] evaluations and the elasticity modulus[5] (MOE), which is significantly affected by fiber orientation [1,26,29–34]. Ultrasonic pulse velocity (UPV) techniques, a non-destructive testing method[1], have been effectively utilized to estimate MOE in various wood[2] species, achieving high correlation coefficients (R^2 up to 0.989) [32]. For instance, a study investigating oak wood[2] has illustrated that ultrasonic wave[4] evaluations correlate with the elasticity modulus[5], with temperature and time-dependent factors influencing this relationship. The study reported coefficients of determination ranging from 0.74 to 0.92 [29].

Despite the growing number of studies on non-destructive testing method[1] (NDT) of timber[2], there remains a lack of bibliometric synthesis specifically addressing the use of ultrasonic wave[4] methods to evaluate mechanical properties[3]—particularly the elasticity modulus[5]. This gap restricts a clear comprehensive understanding of research trends, focus areas, and potential future directions in this field. Accordingly, the present study seeks to address this gap by employing bibliometric methods to map and systematically analyze the existing literature, thereby supporting future research directions and enhancing evidence-based decision-making in timber[2] engineering.

Through the use of VOSviewer software, the study examines global research trends in ultrasonic wave[4]-based NDT for mechanical evaluation of timber[2], emphasizing the role of the elasticity modulus[5] as a key structural indicator. The analysis aims to identify dominant research clusters, influential contributions, and areas with limited exploration. In doing so, it advances a more nuanced and strategic understanding of the state of the art in non-destructive testing methods[1] within wood[2] science and structural engineering.

2. Materials and Methods

This section outlines the methodology employed to identify studies related to wood[2] engineering and non-destructive testing methods, with a specific focus on leveraging timber[2]'s mechanical properties[3] to enhance the material's resistance to deformation. It

explains the techniques used for conducting bibliometric analysis on document metadata and visualizing the growth of publications over a defined timeframe, serving the purpose of assessing whether research in this field is on the rise or decline. This methodology aligns with the information flow depicted in Figure 1.

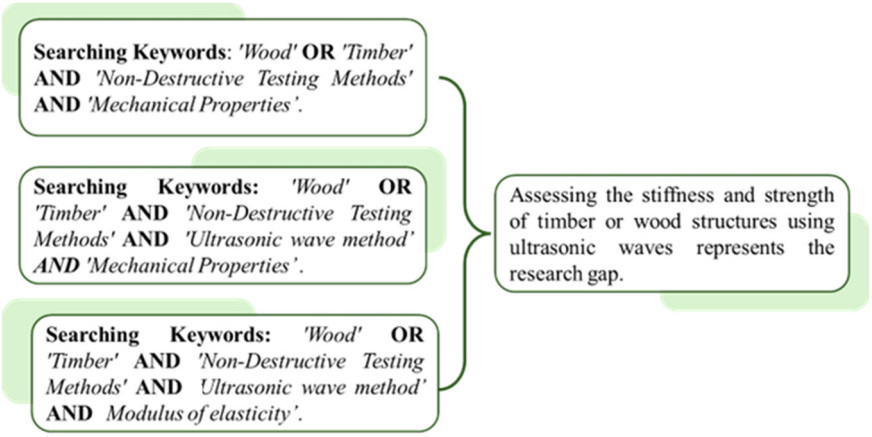


Figure 1. Literature selection from the Scopus database.

2.1. Literature Selection

We collected articles from the Scopus database on 16 November 2023. It is important to note that the Scopus database exclusively hosts articles from well-established and highly regarded scientific journals, ensuring a rigorous peer-review process [35]. Furthermore, Klapka & Slabý [36] have elucidated the comprehensive metadata features provided by the Scopus database. To retrieve the specific literature we sought, we formulated a keyword string, progressing from a general to a more specific scope, as depicted in Figure 1.

In our initial search, we utilized keywords such as 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'mechanical properties[3],' applying these criteria to titles, keywords, and abstracts. To capture the comprehensive timeline of publications from the inaugural release to the present, we intentionally omitted any time constraints, leading to the identification of 129 pertinent documents.

Subsequently, we refined our search by incorporating the keywords 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'mechanical properties[3].' Recognizing the ultrasonic waves[4] method as one of the non-destructive testing methods[1] for estimating wood[2]/timber[2] strength, we conducted a more targeted screening for related articles. This focused approach promises heightened precision in data analysis, yielding a total of 19 documents.

In our final exploration, our focus revolved around the elasticity modulus[5], a critical mechanical property[3] that defines a material's stiffness and characterizes its behavior under stress. This key indicator plays a pivotal role in evaluating the mechanical properties[3] of timber[2]/wood[2] structures. Employing the keywords 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'elasticity modulus[5]' led us to a comprehensive collection of 24 relevant documents, offering insights into determining the stiffness and strength properties of various materials.

The keyword selection was informed by a preliminary scoping review and aligned with the specific objective of this study: to present a comprehensive bibliometric analysis of research trends in evaluating the mechanical properties[3] of timber[2] structures—particularly the elasticity modulus[5] (MOE)—using non-destructive testing (NDT) methods, with a focused emphasis on ultrasonic wave[4] testing. General terms such as 'wood[2]' and 'timber[2]' were included to capture the broad material category. The phrase 'non-destructive testing

method[1]' reflects the overarching technique group, while 'ultrasonic waves[4] method' narrows the scope to a specific NDT technique. Finally, 'elasticity modulus[5]' was selected to isolate studies addressing a critical mechanical parameter. These keywords were chosen based on their frequency and relevance in highly cited literature, as well as their consistency with standard terminology used in Scopus indexing.

All searches were performed using the TITLE-ABS-KEY function in Scopus, which restricts results to documents containing the specified keywords in the title, abstract, or author keywords fields. To ensure topical relevance and methodological consistency, we applied the following filters: only documents in English, only peer-reviewed articles and conference papers, and only those categorized under the Engineering subject area. These constraints may explain the exclusion of certain publications that, while indexed in Scopus, may not include the keywords in searchable metadata fields or fall outside the engineering classification.

2.2. Visualization Using VOSviewer Software

The literature gleaned from the Scopus database has been meticulously organized and stored in two formats: *.ris and *.csv. The *.ris format is employed for visual representation in the VOSviewer software, while the *.csv format is dedicated to conducting comprehensive analyses of publication growth through Microsoft Excel 365. The primary aim of examining the growth of publications within a specified timeframe is to discern the trajectory of research development—whether it exhibits an upward trend or a decline.

This analysis not only unveils notable trends in researchers' preferences for specific topics related to timber[2], wood[2], non-destructive testing method[1], ultrasonic waves[4], and mechanical properties[3] but also provides a dynamic perspective on the evolving research landscape. Furthermore, the *.csv format is invaluable for extracting insights into the most impactful articles, distinguished by their substantial citation counts, reflecting their significant influence within the scientific community. This comprehensive approach not only enriches our comprehension of the dynamic research environment but also streamlines the identification of influential contributions within the academic discourse.

This research focuses on the latest version of VOSviewer, version 1.6.20, released on 31 October 2023, as noted by van Eck and Waltman [37]. VOSviewer is a powerful tool designed for constructing and visualizing bibliometric networks. It is used to create networks involving scientific publications, journals, researchers, research organizations, countries, keywords, or terms—such as non-destructive testing method[1], timber[2], wood[2], ultrasonic waves[4], mechanical properties[3], and elasticity modulus[5]—to determine the prominence of items within these networks. The connections between items in these networks can be established through co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links. Input sources include bibliographic databases (Web of Science, Scopus, Dimensions, Lens, and PubMed files) and reference manager files (RIS, EndNote, and RefWorks files).

3. Results

3.1. Research Trends of 'Wood[2]' or 'Timber[2]' and 'Non-Destructive Testing Method[1]' and 'Mechanical Properties[3]'

During the period from 1997 to 2024, our bibliometric analysis identified 129 articles pertaining to 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'mechanical properties[3].' The inaugural article on this subject within the Scopus database dates back to 1997. Surprisingly, for nearly three years, there was a dearth of articles addressing the evaluation of wood[2] mechanical properties[3] through non-destructive testing methods[1].

Notably, the publication rate remained relatively stagnant, hovering around 1–2 articles per year during the years 2002–2007 before experiencing a gradual increase until 2009.

Post-2009, the number of Scopus-indexed articles has consistently risen. A significant spike occurred in 2016, marked by gradual growth with 15 articles, followed by a dip in 2024, where only one publication is evident, as depicted in Figure 2.

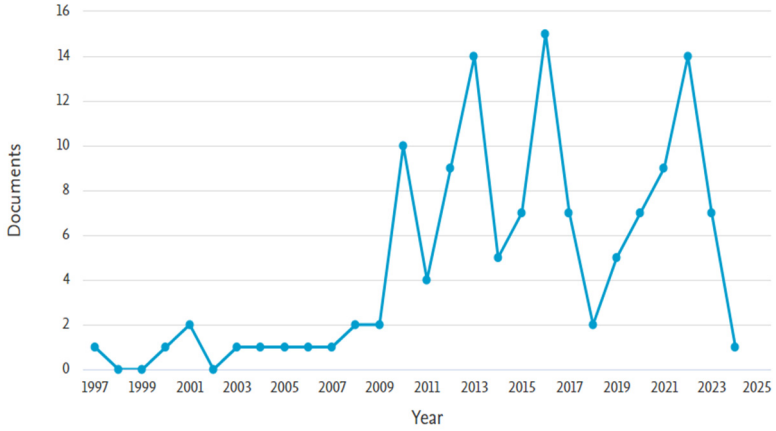


Figure 2. Number of articles on the topic of 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'mechanical properties[3]' in Scopus database.

In accordance with Xie et al. [38], research trends can be categorized into initial, rapid, and in-depth development stages based on annual publication numbers:

The initial phase spanned from 1997 to 2009, with a maximum publication rate of 2 articles per year.

The development phase encompassed the years 2009–2010, 2011–2013, 2014–2016, and 2018–2022, with publication numbers fluctuating between 2 and 10, 4 and 14, 5 and 15, and 2 and 14, respectively.

The rapid publication phase manifested in 2016, with 15 noteworthy publications.

Simultaneously, parallel trends unfolded beyond the engineering domain. Materials science experienced substantial growth, evidenced by a pronounced surge in publications totaling 55 papers between 2000 and 2023. The engineering sector, in parallel, displayed continuous development, supported by a total of 59 documents. It is crucial to note that in this bibliometric analysis, we did not undertake a systematic content analysis.

However, based on the retrieved database, it appears that the dominant subject in the field of evaluation of the mechanical properties[3] of wood[2] using non-destructive testing methods[1] is the development and application of non-destructive measurement system and testing techniques [39–41]). These techniques include acoustics, neutron imaging, and stress wave methods, among others [6].

While non-destructive tests (NDT[1]) can directly characterize materials, it is more effective to classify materials by strength values derived from empirical relationships between their mechanical properties[3] and physical characteristics [42]. The conventional approach involves applying direct empirical relationships between ultimate strength and non-destructive testing method[1] characteristics. However, results from non-destructive tests are influenced by various factors and are only stochastically related to ultimate strength values, making it necessary to evaluate the reliability of these methods. This reliability assessment requires analyzing the stochastic relationships between different property systems and their corresponding descriptive relationships [43–45]. Understanding these stochastic relationships and assessing test reliability are crucial when using non-destructive testing methods[1] for strength evaluation [46].The stochastic nature of defect parameters and their correlation with testing methods significantly impacts the reliability of strength

evaluations [47–49]. Statistical analyses of NDT[1] data reveal that the accuracy of predictions can be improved by incorporating probabilistic techniques [50]. Research indicates that while NDT[1] methods like Ultrasonic Pulse Velocity and the Schmidt Rebound Hammer are efficient, they may not always match the reliability of destructive tests [51]. Additional parameters, such as acoustic quality factors, can enhance the reliability of strength predictions in rock assessments [52]. While NDT methods[1] offer practical advantages, their reliability can vary, necessitating careful consideration of stochastic factors and supplementary parameters to ensure accurate strength assessments.

The focus is on estimating the mechanical properties[3] of wood[2], such as stiffness, modulus of rupture, and modulus of elasticity, using non-destructive, semi-destructive, and destructive tests [53]. There is growing interest in employing non-destructive testing methods to evaluate materials in existing and historic structures. Several countries have made substantial contributions to research on assessing wood[2]'s mechanical properties[3] through non-destructive testing method[1] techniques, with China leading (21 articles), followed by Canada (15), the Czech Republic (11), and Finland and Poland (7).

While destructive methods remain the most accurate for detailed mechanical characterization[3], they are often invasive and impractical for in-service assessments. The ultrasonic non-destructive testing method[1], in contrast, offers an efficient, rapid, and non-invasive alternative well-suited for in situ evaluations where preserving material integrity is critical. Based on our results, the tested ultrasonic waves[4] method provides a balance between efficiency and accuracy, making it a promising option for practical applications that require minimal material damage while delivering reliable mechanical property[3] estimations.

As we navigate the intricacies of assessing the mechanical properties[3] of wood[2] through non-destructive testing methods[1], an examination of the top 10 most-cited articles (refer to Table 1) offers valuable insight into the evolution of scholarly focus in this domain. The highest citation count—154 citations—was achieved by a 2013 article emphasizing the increasing relevance of Electromechanical Impedance (EMI) for structural health monitoring. This work highlights the potential for adapting smart materials and advanced monitoring techniques to evaluate mechanical properties[3] in materials such as wood[2] [54].

The top-cited articles span from 2007 to 2020, reflecting both the foundational role of earlier studies and the increasing scholarly influence of more recent work. Notably, Article 65, published in 2020, has already entered the top-cited list. This study, which combines guided wave propagation with machine learning to predict the mechanical properties[3] of wood[2], exemplifies a significant advancement in the integration of data-driven techniques within ultrasonic [4] NDT[1]. Its rapid accumulation of citations highlights its relevance and points to a shift in research priorities toward computationally enhanced diagnostic approaches.

The early impact of Article 65 is particularly striking when considered in light of the well-established phenomenon of citation lag, whereby newly published articles typically require several years to accrue substantial citations. That the 2020 article has already achieved high citation status by 2025 suggests accelerated dissemination and adoption of innovative methodologies, especially those aligned with broader trends in automation, digitalization, and sustainable materials assessment. This shift reflects a more dynamic and fast-moving research landscape in timber[2] engineering, emphasizing the need for ongoing bibliometric monitoring to capture and interpret emerging trajectories.

Since 1997, original research articles have overwhelmingly dominated publications in evaluating the mechanical properties[3] of wood[2] through non-destructive testing methods[1], accounting for approximately 69.21%. Categorized by document types, the corpus comprises 90 original research articles, 27 conference papers, 10 conference reviews, and 3 other

document types. Using VOSviewer, we mapped the bibliography and found 33 items in 7 clusters (Figure 3). A different color indicates each cluster. Meanwhile, the variation in the frame size indicates the links' different strengths. For example, the term 'non-destructive examination[1],' with the most enormous frame, has a total link strength of 333, with 32 links and 89 occurrences.

Table 1. Top 10 most-cited articles on the topics of 'wood'[2] OR 'Timber'[2] AND 'non-destructive testing method'[1] AND 'mechanical properties'[3].

Title	Journal	Cited by	Reference
Electromechanical impedance of piezoelectric transducers for monitoring metallic and non-metallic structures: A review of wired, wireless and energy-harvesting methods.	Journal of Intelligent Material Systems and Structures	154	[54]
In situ assessment of structural timber using the resistance drilling method—Evaluation of usefulness.	Construction and Building Materials	76	[55]
The relationship between standing tree acoustic assessment and timber quality in Scots pine and the practical implications for assessing timber quality from naturally regenerated stands.	Forestry	74	[56]
A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber.	European Journal of Forest Research	67	[57]
Measurement of dynamic modulus of elasticity and damping ratio of wood-based composites using the cantilever beam vibration technique.	Construction and Building Materials	66	[58]
In situ assessment of timber structural members: Combining information from visual strength grading and NDT/SDT methods—A review.	Construction and Building Materials	63	[59]
Chestnut wood in compression perpendicular to the grain: Non-destructive correlations for test results in new and old wood.	Construction and Building Materials	59	[60]
Prediction of the mechanical properties of wood using guided wave propagation and machine learning.	Construction and Building Materials	59	[61]
Finding fibres and their contacts within 3D images of disordered fibrous media.	Composites Science and Technology	52	[62]
Stress wave evaluation for predicting the properties of thermally modified wood using neuro-fuzzy and neural network modeling.	Holzforschung	41	[63]

Examining Figure 3, we observe that the 129 articles addressing the intersection of 'wood[2]' OR 'timber[2]' AND 'non-destructive testing methods[1]' AND 'mechanical properties[3]' have been systematically grouped into 7 clusters:

Cluster 1 (27 items/red): The three primary items, along with 'non-destructive examination[1],' encompass 'mechanical properties[3]' and 'timber[2],' totaling 43 occurrences. These are linked to 32 and 30 connections across 6 clusters. Additionally, the term 'wood[2]' appears 42 times with a total link strength of 142, distributed among 6 clusters. We have observed that 'compression strength,' located in Cluster 1 and appearing 5 times, exhibits the fewest links to other items (14 links). It is exclusively linked to only 2 clusters: 'hardness' and 'tensile strength.' Similarly, 'elastic waves[4],' also situated in Cluster 1 with 7 occurrences, displays 17 links to other items. However, it is linked solely to the 'hardness' cluster. This means that either compression strength or elastic waves[4] are potential research areas in the future, since only a few researchers have investigated this topic. For instance, 'elastic waves[4]' could be linked to various clusters, including 'tensile strength,' especially within the context of 'quality control' in non-destructive testing methods[1]. Quality parameters

are important for achieving sustainability and prosperity by improving the performance parameters of buildings throughout their life cycle. This ambition underscores the importance of rigorous non-destructive testing method[1] practices in maintaining structural integrity, optimizing operational efficiency, and prolonging the service life of constructions. Emphasizing quality control in non-destructive testing methods[1] is essential not only for meeting stringent regulatory standards but also for achieving long-term economic and environmental sustainability in infrastructure development [64]. Elastic waves[4], which propagate through a material in response to deformation or changes in stress, are closely tied to the elasticity modulus[5] and elastic properties of materials. In the context of non-destructive testing methods[1], elastic waves[4] are instrumental in evaluating the internal structure and integrity of materials without inducing any damage.

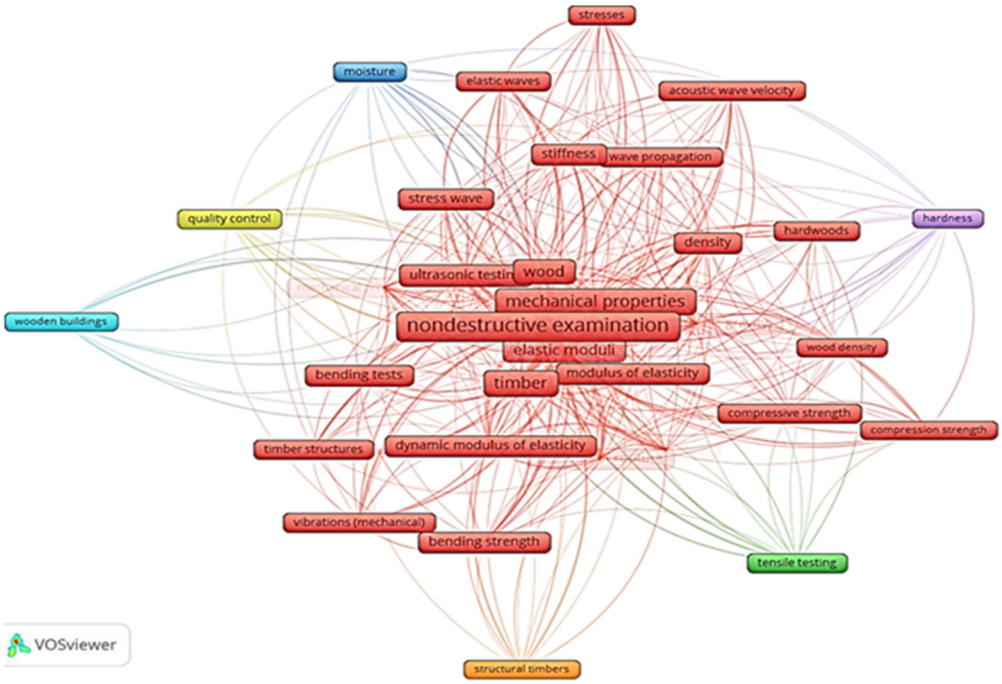


Figure 3. Visualization of VOSviewer on the topics of 'wood'[2] OR 'Timber'[2] AND 'non-destructive testing methods'[1] AND 'mechanical properties'[3].

Furthermore, within Cluster 1, the item 'acoustic wave velocity,' relevant to non-destructive examination[1], appears in 6 occurrences with 18 links. Interestingly, it stands as the only item without any links to other clusters.

Cluster 2 (1 item/green): Within this cluster, the only item is 'tensile testing,' observed 7 times and linked to 16 connections across 2 clusters. This presents numerous research possibilities, including potential connections to other clusters such as 'moisture.' For instance, one could investigate the impact of moisture content on transverse tensile strength.

Cluster 3 (1 item/blue): The predominant element is the concept of 'moisture,' which is iterated 7 times throughout the connected nodes. These nodes, in turn, form a network with a total of 16 links, distributing the influence and interrelation of 'moisture' across three distinct clusters.

Cluster 4 (1 item/yellow): Comprising a singular item, this cluster focuses exclusively on 'quality control.' This item is observed 6 times and is intricately linked to 14 connections, extending across two clusters: 'non-destructive examination[1]' and 'moisture'.

Cluster 5 (1 item/purple): This cluster centers around the singular item 'hardness,' observed 5 times and intricately connected to 18 links across three clusters: ' non-destructive examination[1],' 'moisture,' and 'tensile testing.

Cluster 6 (1 item/sky blue): Wooden buildings appear 6 times within 9 links. This cluster is scattered with weak links, making it the smallest both in occurrences and link count (less than 6 links to other items). Interestingly, it is exclusively linked to the ' non-destructive examination[1]' cluster.

Cluster 7 (1 item/orange): Structural timbers[2] appear 5 times within 14 links. Intriguingly, similar to Cluster 6, it is exclusively linked to the 'non-destructive examination[1]' cluster.

3.2. Research Trends of 'Wood[2]' or 'Timber[2]' and 'Non-Destructive Testing Method[1]' and 'Ultrasonic Waves[4] Method' and 'Mechanical Properties[3]'

In this section, we will provide a more in-depth exploration of the evaluation of wood[2]'s mechanical properties[3] using a non-destructive testing method[1], specifically the ultrasonic waves[4] method. As depicted in Figure 1, our search incorporated keywords such as 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'mechanical properties[3],' revealing 19 documents.

Navigating the intricacies of wood[2]'s mechanical properties[3] through the ultrasonic waves[4] method, our focus shifts to the top 10 most-cited articles (refer to Table 2). The peak, marked by 59 citations, occurred in both 2007 and 2020 for 'Chestnut Wood in Compression Perpendicular to the Grain: Non-destructive Correlations for Test Results in New and Old Wood.' This study employs non-destructive techniques, such as ultrasonic testing and Resistograph, to correlate compression strength and stiffness in chestnut wood.

Table 2. Top 10 most-cited articles on the topics of 'wood[2]' OR 'Timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'mechanical properties[3]'.

Title	Journal	Cited by	Reference
Prediction of the mechanical properties of wood using guided wave propagation and machine learning.	Construction and Building Materials	59	[61]
Chestnut wood in compression perpendicular to the grain: Non-destructive correlations for test results in new and old wood.	Construction and Building Materials	59	[60]
Lamb wave propagation method for nondestructive characterization of the elastic properties of wood.	Applied Acoustics	30	[64]
Experimental study for non-destructive mechanical evaluation of ancient chestnut timber.	Journal of Civil Structural Health Monitoring	28	[65]
Estimating mechanical properties of wood in existing structures—selected aspects.	Materials	18	[53]
Semi-destructive and non-destructive tests of timber structure of various moisture contents.	Materials	16	[66]
Evaluation of wood quality of Taiwania trees grown with different thinning and pruning treatments using ultrasonic-wave testing.	Wood and Fiber Science	15	[67]
Nondestructive assessment of cross-laminated timber using non-contact transverse vibration and ultrasonic testing.	European Journal of Wood and Wood Products	13	[68]
Application of nondestructive methods to evaluate mechanical properties of 32-year-old taiwan incense cedar (Calocedrus formosana) wood.	BioResources	11	[69]
Strength grading of hardwoods using transversal ultrasound.	European Journal of Wood and Wood Products	10	[70]

Another key article, 'Prediction of the Mechanical Properties[3] of Wood[2] Using Guided Wave Propagation and Machine Learning,' explores using guided wave propagation and

machine learning to predict wood[2]'s mechanical properties[3], offering a non-destructive testing method[1] and an efficient assessment of wood[2] quality [61].

Notably, the top 10 most-cited articles, spanning 2007 to 2020, significantly contribute to our understanding in this field.

Contrasting with the initial visualization, the bibliometric map of keywords 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'mechanical properties[3]' is more straightforward, identifying 3 clusters among 19 documents. However, both bibliometric maps share a commonality: the focal point of 'non-destructive examination[1]' as the largest item, intricately linked to other clusters.

According to Figure 4, there are 16 items divided into 3 clusters. In Cluster 1 (8 items/red), the items include ultrasonic testing[1], ultrasonic waves[4], ultrasonic frequencies, wave propagation, mechanical properties[3], acoustic wave velocity, mechanical properties[3] of wood[2], and elasticity modulus[5]. Within this cluster, the item 'ultrasonic testing[1]' has the highest number of links (15) and occurrences (11).

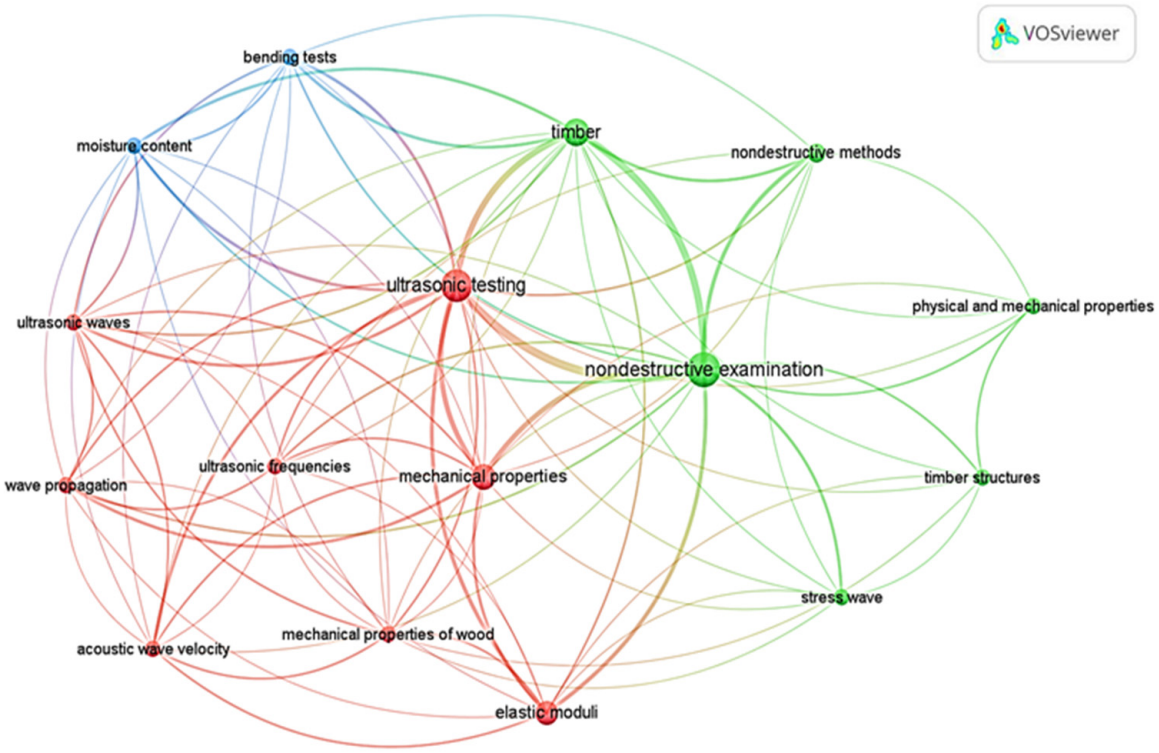


Figure 4. Visualization of VOSviewer on the topics of 'wood[2]' OR 'Timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'mechanical properties[3]'.

Cluster 2 (6 items/red) regroups non-destructive examination[1], timber[2], stress wave, timber[2] structures, non-destructive testing method[1], physical and mechanical properties[3] of wood[2].

Cluster 3 (2 items/blue) is relatively small, containing only 2 items (moisture content and bending test). These items are distributed in 3 occurrences and linked to other items 10 times.

Referring to Figure 3, researchers delving into the evaluation of mechanical properties[3] in wood[2] or timber[2] structures through non-destructive examination[1] have focused their studies on key aspects. These include quality control, tensile strength, compressive strength, compression strength, hardness, and bending tests, with consideration to how wood[2] density, moisture, and stress waves impact these factors. Moreover, a closer examination of the ultrasonic testing method [4], a prominent non-destructive examination[1] illustrated in

Figure 4, reveals a specific emphasis on the bending test concerning elastic moduli[5]. This analysis incorporates the influential factor of moisture content, which significantly affects the accuracy of results. Ultrasonic testing [4] serves as a crucial tool for evaluating material properties, particularly under varying environmental conditions such as moisture content.

The regularity with which ultrasonic waves[4] propagate provides valuable insights into materials. For instance, the speed of ultrasonic wave[4] propagation is influenced by the material's density, elasticity[5], and moisture content. Variations in moisture can significantly affect the velocity of ultrasonic waves[4] in wood[2], which can be used to estimate mechanical properties[3] like Young's elasticity modulus[5] and compressive strength [71–73]. However, the physical characteristics deduced from the propagation speed are not always precise. Thus, while the speed of ultrasonic waves[4] can be considered an independent characteristic, it closely correlates with other physical properties of materials.

This relationship underscores the critical importance of understanding how ultrasonic wave[4] propagation offers insights into the physics and structure of the materials studied [74]. Integrating practical testing methodologies with theoretical insights from wave propagation enhances our ability to accurately assess material properties[3] and their environmental dependencies.

A bibliographic coupling analysis in the VOSviewer network unveils those researchers contributing to review papers on the application of the ultrasonic testing method[1] for evaluating the mechanical properties[3] of wood[2] or timber[2] structures hail from diverse countries. This collaborative effort involves researchers from Canada, China, Iran, Italy, the Netherlands, Poland, Switzerland, and Taiwan. Such collaborative research across various countries is instrumental in fortifying the network and facilitating the exchange of information and best practices.

3.3. Research Trends of 'Wood[2]' or 'Timber[2]' and 'Non-Destructive Testing Method[1]' and 'Ultrasonic Waves[4] Method' and 'Elasticity Modulus[5]'

In this section, we focused on the elasticity modulus[5], a crucial mechanical property[3] characterizing the stiffness of a material. Our targeted search, using keywords such as 'wood[2]' OR 'timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'elasticity modulus[5],' yielded a comprehensive collection of 24 relevant documents.

Based on VOSviewer analysis for the keywords 'wood[2]' OR 'Timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'elasticity modulus[5]', there are 3 clusters and 14 items. Items in cluster 1 were non-destructive testing method[1], non-destructive examination[1], timber[2], ultrasonics, and ultrasound. Items in cluster 2 were dynamic elasticity modulus[5], elastic moduli[5], ultrasonic frequencies, wood[2], and ultrasonic testing[1]. Items in cluster 3 were elasticity modulus[5], moisture content, wave propagation, and ultrasonic waves[4].

Although this section has the smallest number of items (14 items), these items are linked to each other and displayed as a spider web pattern (refer to Figure 5).

Table 3 outlines the exploration of the modulus of elasticity[5] in wood[2] or timber[2] using the ultrasonic wave[4] method from 2005 to 2020. After reviewing articles from the Scopus database, the earliest relevant article, dated 2005 and titled 'Evaluation of wood[2] quality of Taiwania trees grown with different thinning and pruning treatments using ultrasonic-wave testing[4],' was published in the *Journal of Wood and Fiber Science*. This publication meticulously examines ultrasonic wave properties (Vt_{ree}, Vl_{umber}, MOE_{tree}, MOE_{lumber}) within these treatments. Going beyond mere analysis, the study reveals ultrasonic wave testing as a valuable, non-destructive method[1] for precisely appraising the wood[2] quality of Taiwania trees [68].



Figure 5. Visualization of VOSviewer on the topics of 'wood[2]' OR 'Timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'elasticity modulus[5]'.

Table 3. Top 10 most-cited articles on the topics of 'wood[2]' OR 'Timber[2]' AND 'non-destructive testing method[1]' AND 'ultrasonic waves[4] method' AND 'elasticity modulus[5]'.

Title	Journal	Cited by	Reference
MOE prediction in Abies pinsapo Boiss. timber: Application of an artificial neural network using non-destructive testing.	Computers and Structures	62	[75]
Prediction of the mechanical properties of wood using guided wave propagation and machine learning.	Construction and Building Materials	59	[61]
Lamb wave propagation method for nondestructive characterization of the elastic properties of wood.	Applied Acoustics	30	[65]
Comparative study on three dynamic modulus of elasticity and static modulus of elasticity for Lodgepole pine lumber.	Journal of Forestry Research	29	[76]
Experimental study for non-destructive mechanical evaluation of ancient chestnut timber.	Journal of Civil Structural Health Monitoring	28	[66]
Non-destructive ultrasonic testing method for determining bending strength properties of Gmelina wood (Gmelina Arborea).	Journal of Tropical Forest Science	25	[77]
The influence of cross-section variation on bending stiffness assessment in existing timber structures.	Engineering Structures	19	[78]
Estimating mechanical properties of wood in existing structures—selected aspects.	Materials	18	[53]
Non-destructive evaluation of bending strength of wood with artificial holes by employing air-coupled ultrasonics.	Construction and Building Materials	15	[79]
Evaluation of wood quality of Taiwania trees grown with different thinning and pruning treatments using ultrasonic wave testing.	Wood and Fiber Science	15	[67]

In scrutinizing the top 10 most-cited articles, a standout among them is the article titled 'MOE Prediction in *Abies pinsapo* Boiss. Timber[2]: Application of an Artificial Neural Network using Non-destructive Testing.' This influential study reached its zenith with a peak citation count of 62 in 2009, centering on predicting the modulus of elasticity (MOE) [5]

by considering parameters such as density, width, thickness, moisture content, ultrasonic wave[4] propagation velocity, and visual characteristics of the timber[2] [76].

4. Limitation of Study

The findings of this research provide a structured overview of current trends in the evaluation of mechanical properties[3]—particularly the elasticity modulus[5]—in timber[2] using non-destructive testing method[1] ultrasonic waves[4]. However, several methodological limitations must be acknowledged.

First, the bibliometric data were obtained exclusively from the Scopus database, using structured queries applied to the title, abstract, and author keyword fields (TITLE-ABS-KEY). As a result, documents in which relevant terms appear only in the full text—and not in indexed metadata—may have been omitted from the analysis. Additionally, to ensure consistency and methodological rigor, the dataset was filtered to include only peer-reviewed journal articles and conference papers, written in English, and classified under the Engineering subject area. These constraints, while ensuring a focused scope, may have excluded interdisciplinary or region-specific studies that fall outside these parameters.

Furthermore, while comparative searches in broader platforms such as Google Scholar suggest a much larger volume of potentially related content, these platforms index a wide range of document types—including theses, technical reports, and non-peer-reviewed material—which fall outside the scope of this analysis. Therefore, the relatively small number of documents identified in Scopus (e.g., 24 for the most specific search level) should not be interpreted as evidence of a lack of research in the field, but rather as a reflection of the strict inclusion criteria applied.

Future research may consider combining multiple bibliographic databases (e.g., Scopus, Web of Science, and Dimensions) and expanding search fields or language inclusion criteria to improve dataset comprehensiveness and capture a broader spectrum of relevant literature.

5. Conclusions

In summary, this bibliometric analysis has revealed meaningful patterns and trends in the evaluation of the mechanical properties[3] of timber[2], particularly the elasticity modulus[5] (MOE), using non-destructive testing methods[1]. A clear correlation was observed between the increasing volume of publications and the growth of research clusters. From an initial dataset of 129 documents, seven thematic clusters containing 33 items were identified. Subsequent, more focused searches involving 24 and 19 documents produced three clusters (16 items) and 14 items, respectively. Notably, the keyword non-destructive examination consistently emerged as the dominant term across all search levels, indicating a strong and persistent research focus in this area.

Despite these findings, a significant knowledge gap remains concerning the assessment of MOE[5] in timber[2] structures currently in service, particularly through ultrasonic wave methods. Although a small number of studies address this topic, they are limited in both scope and methodological standardization. This underlines the urgent need for further targeted investigations that advance the scientific and practical understanding of ultrasonic NDT[1] in timber[2] engineering.

Based on the gaps and trends identified, several key directions for future research are evident. First, the integration of machine learning with ultrasonic wave[4] analysis offers promising potential for predictive modeling of timber[2] properties yet remains underexplored. Second, there is a clear need to standardize ultrasonic NDT protocols, especially for MOE[5] evaluation, to improve reliability and comparability across studies. Third, future efforts should explore hybrid diagnostic approaches by combining ultrasonic testing with

other techniques such as acoustic emission or vibration analysis. Additionally, the application of ultrasonic methods[4] to the aged, recycled, or heritage timber[2] is an emerging area with practical implications for sustainable construction and conservation. Lastly, the development of portable, in situ ultrasonic[4] systems would significantly enhance field-based diagnostics, supporting real-time assessments in existing structures.

Addressing these areas will not only fill the observed bibliometric gaps but also contribute to the advancement of efficient, accurate, and sustainable non-destructive evaluation strategies in the field of timber [2] engineering.

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Abbreviations

The following abbreviations are used in this manuscript:

NDT	Non-destructive testing
MOE	Modulus of elasticity
UPV	Ultrasonic pulse velocity

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