Nondestructive Testing in Wood: A Systematic Review and Bibliometric Analysis Based on Scopus

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Nondestructive testing (NDT), also referred to as nondestructive evaluation/examination (NDE), applied to wood studies, has shown steady global growth driven by the development of innovative techniques and technologies that enable the characterization of wood pieces and structures while minimizing damage. The objective of this study was to analyze the development and recent trends of nondestructive testing in wood. To achieve this, a bibliometric analysis (1982-2025) and a systematic review (2020-2025) were conducted to identify the main research lines, commonly used techniques, and emerging approaches and future perspectives. A total of 303 Scopus-indexed scientific articles were analyzed using VOSviewer and Bibliometrix: Biblioshiny, and 137 recent articles were used for the literature review. The results revealed four main research lines: (I) NDE-NDT with computed tomography for defect detection; (II) NDT for the inspection of wooden buildings and structures; (III) ultrasound in forestry for the characterization of mechanical properties; and (IV) moisture content in wood products. Scientific output showed sustained growth, with China as the leading country and Northeast Forestry University as the most productive institution. Traditional NDT techniques prevail, while emerging approaches and artificial intelligence applications demonstrate that wood NDT research is an expanding field with diversified applications and increasing international relevance.

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INTRODUCTION

Nondestructive testing (NDT), which is also referred to as nondestructive evaluation/examination (NDE), comprises a set of techniques aimed at identifying the physical and mechanical properties of a material or component without altering its structure, characteristics, or suitability for final use. These methodologies have become key tools for characterization, classification, and diagnostics across multiple fields, experiencing continuous growth driven by technological advances (Ross and Pellerin 1994).

The formal development of NDT dates back to the discovery of X-rays in 1895 (Busch 2016), followed by radiography as one of the first nondestructive evaluation methods in the early 20th century. From the 1930s onward, techniques such as ultrasound, initially developed for medical applications (Newman and Rozycki 1998) and vibration analysis in metals and soils were later applied to the study of wood (Ide 1935). Pioneering studies on NDT applications in wood were conducted by McBurney (1943) and Kuenzi (1948), who used sonic waves and low-frequency vibrations to estimate elastic modulus and compare them with static tests, marking the beginning of NDT in this biomaterial.

The nondestructive evaluation of wood and its derived materials has evolved significantly in recent decades, moving from pioneering approaches in Europe—where publications more than 50 years ago appeared mainly in German in journals such as *Holz als Roh- und Werkstoff* and *Holzforschung*—toward a broader international scientific output in English and other languages (Brashaw *et al.* 2009). Historically, wood research has developed from two complementary but distinct perspectives: in academia, particularly in universities and research centers, analysis has focused on physical, mechanical, and durability properties, as well as structure, composition, processing, and the development of new derived materials (Hwang and Lee 2024). In contrast, the industrial sector has emphasized applied perspectives, prioritizing process optimization, product standardization, scanning, and innovation toward higher value-added products (Hurmekoski *et al.* 2018).

Subsequent decades saw specific advances, including studies on the vibrational properties of wood (Jayne 1959), prediction of dynamic modulus of elasticity (MOEd) through transverse vibrations (Pellerin 1965), application of stress waves for veneer selection in *Pinus taeda* L. (McAlister 1976), and correlations between stress wave velocity and static tensile and bending moduli in composite panels (Ross and Pellerin 1988). Since the 1990s, research has intensified due to technological advances, including the incorporation of computers in transverse vibration techniques (Ross *et al.* 1991), the development of ultrasound-based log scanning and artificial intelligence approaches (Han and Birkeland 1992), as well as the application of near-infrared spectroscopy (NIR) to evaluate density and strength in *Picea abies* (L.) H. Karst. (Hoffmeyer and Pedersen 1995).

In parallel, efforts to disseminate findings to the international research community have materialized in specialized symposia, beginning in 1964 with the *International Nondestructive Testing and Evaluation of Wood Symposium Series* organized by Washington State University and the USDA Forest Products Laboratory (Brashaw *et al.* 2009). This event, held biennially, has provided comprehensive perspectives that complement indexed literature in scientific journals, with recent editions in São Paulo (2024) and scheduled for Vicksburg, USA, in 2026.

In the last two decades, research has focused on predicting mechanical properties of wood (Mascarenhas *et al.* 2021; Arriaga *et al.* 2023), including the evaluation of MOEd in standing trees using acoustic and other NDT methods (Chuang and Wang 2001; Wessels *et al.* 2011; Llana *et al.* 2020; Rosas-Ramos *et al.* 2024), determination of MOEd with devices such as the rigidimeter (Launay *et al.* 2002), detection of internal knots in *Pinus radiata* D. Don logs via X-rays (Aguilera *et al.* 2002), and identification of decayed wood through computed tomography (Kim and Lee 2006). The effects of dimensional variables on MOEd, such as length (Osuna-Sequera *et al.* 2021), width (Liu *et al.* 2014), and cross-sectional area (Osuna-Sequera *et al.* 2020), as well as moisture content (Carreira *et al.* 2022), have also been investigated.

These techniques have further been applied to assess wood suitability for structural applications in the construction industry (Sales *et al.* 2011; Casado *et al.* 2012; Montero-González *et al.* 2013; Sotomayor and Ramírez 2015) and in the inspection of historic and cultural timber structures (Tan *et al.* 2022; Arriaga *et al.* 2023; López *et al.* 2023; Nocetti *et al.* 2024). Nevertheless, although a wide variety of information is available across journals, conference proceedings, anthologies, and books, the present work is based on searches conducted in Scopus and restricted to scientific articles published in English and Spanish. This implies partial coverage and the omission of relevant literature in other languages. Acknowledging these limitations allows situating the results in their proper context and appreciating the contribution of this review as an updated synthesis of recent trends in NDT applied to wood.

In this context, the objective of this study was to analyze the development and recent trends of nondestructive testing in wood by integrating bibliometric analysis (1982 to 2025) and a systematic review (2020 to 2025), identifying the main research lines, commonly used techniques, and emerging approaches.

EXPERIMENTAL

Data Collection

A systematic review was conducted following the PRISMA 2020 statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page *et al.* 2021). The bibliographic search was carried out in the Scopus database using a combination of keywords related to “nondestructive testing in wood” in the title, abstract, and keywords fields, connected with Boolean operators (AND, OR, AND NOT). The search string was: ((“Non-destructive testing” AND “wood” OR “Non destructive method” AND “wood” OR “Non-destructive evaluation timber” OR “Non destructive methods wood properties” OR “Non destructive evaluation wood properties” OR “Non-destructive testing lumber” OR “Non-destructive testing timber”) AND NOT (“biomass” OR “carbon” OR “concrete”)). The study identification and selection process following the PRISMA methodology is detailed in Fig. 1.

The initial search retrieved 524 articles, with a temporal range up to December 31, 2025.

Inclusion criteria included research and review articles published in English and Spanish. The temporal range covered publications up to December 31, 2025. With the application of these inclusion criteria, a total of 308 articles was obtained.

Exclusion criteria, applied after screening titles, abstracts, and keywords, were: a) documents without registered authorship (1 case) and b) contributions not directly related to nondestructive testing in wood (metals, ceramic materials and other polymers) (4 cases). Following these criteria, a total of 303 articles were included for bibliometric analysis, of which 8 were review articles.

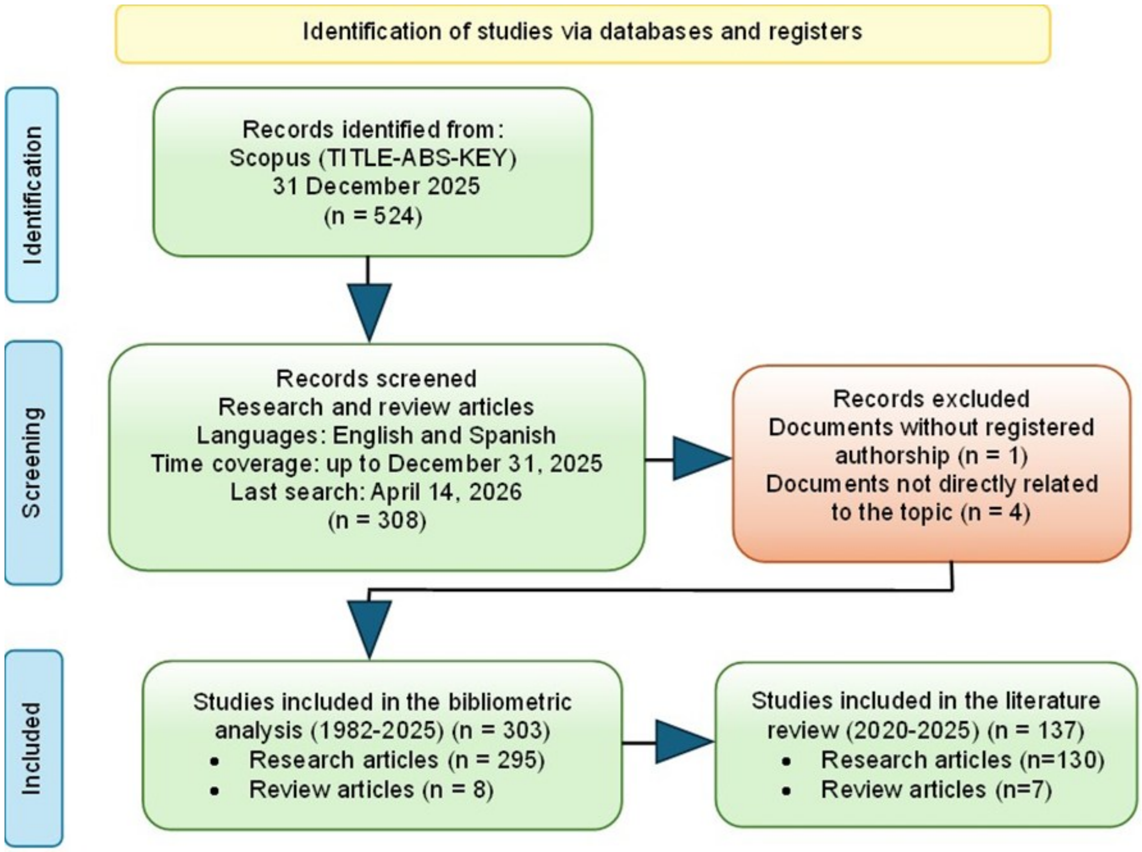

Fig. 1. PRISMA flow diagram of the study identification, screening, and selection process for the bibliometric analysis and literature review.

Determination of Bibliometric Indicators

Bibliometric indicators were selected based on the criteria proposed by Bordons and Zulueta (1999) and Maltrás (2003). Their characteristics are summarized in Table 1.

Table 1. Bibliometric Indicators Analyzed

Category	Indicators	Description
Production	Number of publications	Documents published in Scopus
	Authors	Number of authors publishing
	Institutions	Number of affiliated institutions
	Research lines	Study areas to which the topic of interest is applied
	Language	Publication language: English, Spanish
Collaboration	Countries	Countries of origin of publications on the NDT topic
Trend	Publications	Trend of publications per year

Processing and Analysis of Information – Bibliometrics

Production, collaboration, and trend indicators were analyzed using the Bibliometrix package (version 5.3.0) (Biblioshiny interface) in RStudio (R Core Team 2026). Cluster analysis (co-occurrence, co-citation, and bibliographic coupling) was conducted with VOSviewer software (Van Eck and Waltman 2010), applying the criteria shown in Table 2. The H-index (Hirsch 2005) was included to identify the most influential authors.

Table 2. Cluster Analysis Criteria

Type of analysis	Unit of analysis	Minimum criterion
Co-occurrence	Terms in the title, abstract, and keywords	20 occurrences
Co-citation	Journals and authors	34 citations
Bibliographic coupling	Countries of origin	5 documents per country 20 citations

Processing and Analysis of Information – Literature Review

In addition to the bibliometric analysis, 137 articles published between 2020 and 2025 were reviewed to identify the most commonly used NDT assays in the past five years. The contributions were organized according to the NDT technique employed, considering the principles of each method, practical applications, technological advances, and emerging methodological trends in the application of NDT's to wood studies.

Methodological Limitations

The methodological limitations of this review should be acknowledged. First, the bibliometric analysis relied exclusively on the Scopus database, which ensures consistency in information retrieval but limits the coverage of older publications and non-indexed literature. Second, the search was restricted to articles published in English and Spanish, excluding part of the scientific output in other languages, particularly German and Russian, which are historically relevant in the field of nondestructive evaluation of wood. Finally, the search terms focused on widely recognized techniques, which may have restricted the identification of studies addressing specific or less conventional methods.

These methodological decisions were necessary to maintain analytical coherence; however, they should be considered when interpreting the results, as they influence the representativeness of the panorama obtained. Within these boundaries, the review provides a consistent and updated synthesis of recent trends in NDT applied to wood, highlighting consolidated techniques, emerging methods, and future research perspectives.

The results of this study are organized into two sections: bibliometric analysis and systematic literature review. The first section characterizes the production, collaboration, and thematic evolution of research on nondestructive testing applied to wood, while the second analyzes the NDT techniques employed in the last five years.

RESULTS AND DISCUSSION

Bibliometric Analysis

Production

The bibliometric analysis identified 303 articles authored by 1027 researchers affiliated with 378 institutions, among which Universidad Politécnica de Madrid, Spain, stands out (Fig. 2). These articles were published in 131 journals (sources) during the period 1982 to 2025 (Fig. 3). Articles written in English accounted for 99.33%, confirming the consolidation of this language as the predominant medium of academic communication in the field of nondestructive testing in wood.

Among institutions, Universidad Politécnica de Madrid stood out for having the highest number of author affiliations in wood NDT/NDE research. The faculties with the most authors represented were the Department of Forest and Environmental Engineering and Management, with researchers Daniel F. Llana, Francisco Arriaga, and Ignacio Bobadilla.

In China, the Northeast Forestry University was particularly prominent, especially the College of Mechanical and Electrical Engineering, the College of Science, and the College of Computer and Control Engineering, with authors Jianfeng Chen, Hongbo Mu, and Dawei Qi. Additionally, the Beijing Forestry University, specifically the School of Technology, was notable, particularly researchers Yuan Wuang and Xiayang Xiao.

International open-access journals were the predominant sources, notably *BioResources*, which specializes in lignocellulosic material science and engineering, chemicals, and their applications, and *Forests*, which focuses on forestry and forest ecology. Other main sources included *Construction and Building Materials* and *Wood Research*, covering specialized topics in wood science (construction materials and their performance in civil engineering), biology, chemistry, wood physics and mechanics, mechanical and chemical processing.

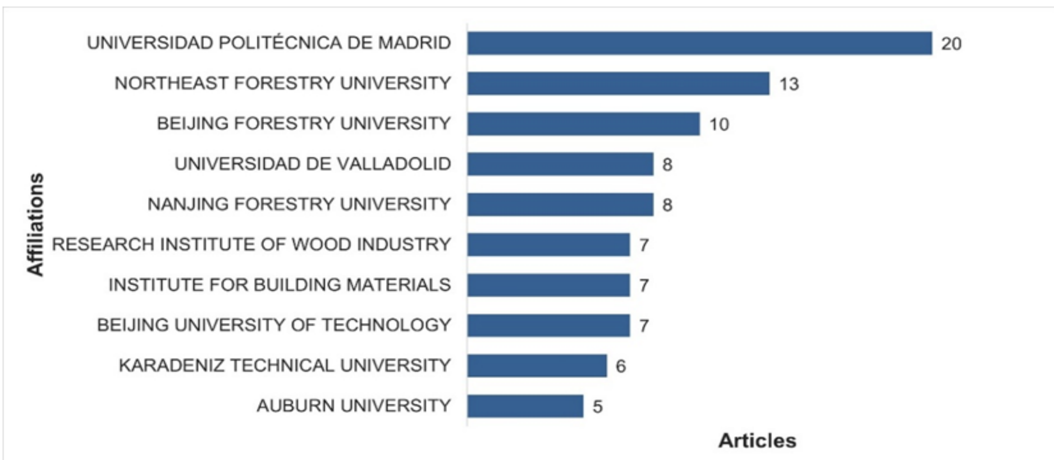

Fig. 2. Most frequent author affiliations related to nondestructive testing in wood for the period 1982-2025

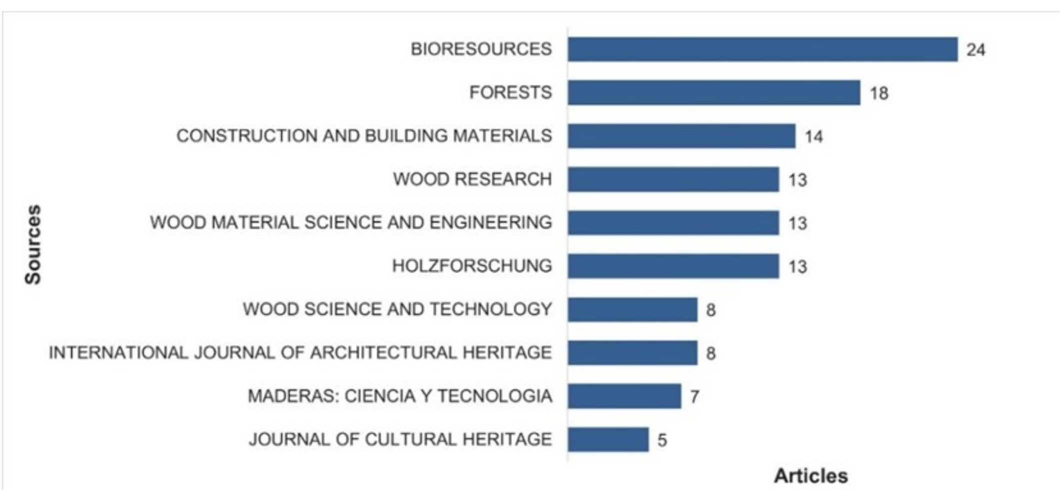

Fig. 3. Most frequent author sources related to nondestructive testing in wood for the period 1982-2025

Among authors (Table 3), Peter Niemz stood out for his focus on predicting mechanical properties such as bending strength, compressive strength, and MOEd using nondestructive techniques such as ultrasound and vibration. His work also includes evaluating the influence of moisture and temperature on NDT signals and the MOEd of wood.

In second place was David Mannes, whose contributions centered on the use and refinement of NDT techniques (neutron radiography, tomography, X-ray densitometry, synchrotron radiation) applied to wood characterization.

Another notable author was Daniel F. Llana, who has investigated the estimation of mechanical properties in standing trees and logs using acoustic and resonance methods, as well as comparisons between nondestructive and semi-destructive techniques (penetration resistance, core drilling, and drilling chip extraction) for estimating wood density, and the influence of moisture content and temperature on ultrasonic and vibration-based NDT measurements.

Table 3. Most Frequent Authors in Nondestructive Testing of Wood for the Period 1982-2025

Authors	Articles	Fractional Articles
Niemz, Peter	11	3.05
Mannes, David	8	2.52
Llana, Daniel F.	7	1.83
Acuña, Luis	5	1.24
Chui, Ying Hei	5	1.25
Gong, Meng	5	1.33
Müller, Ulrich	5	0.94
Tippner, Jan	5	1.08
Wang, Yuan	5	0.91
Adamopoulos, Stergios	4	0.95

Collaboration

The analysis of international collaboration revealed the participation of 47 countries in wood nondestructive testing research during the period 1982 to 2025. China was involved in 141 publications and 605 cumulative citations, followed by Spain with 533 citations (Fig. 4). This distribution confirms the role of Asia and Europe as leaders in wood NDT research.

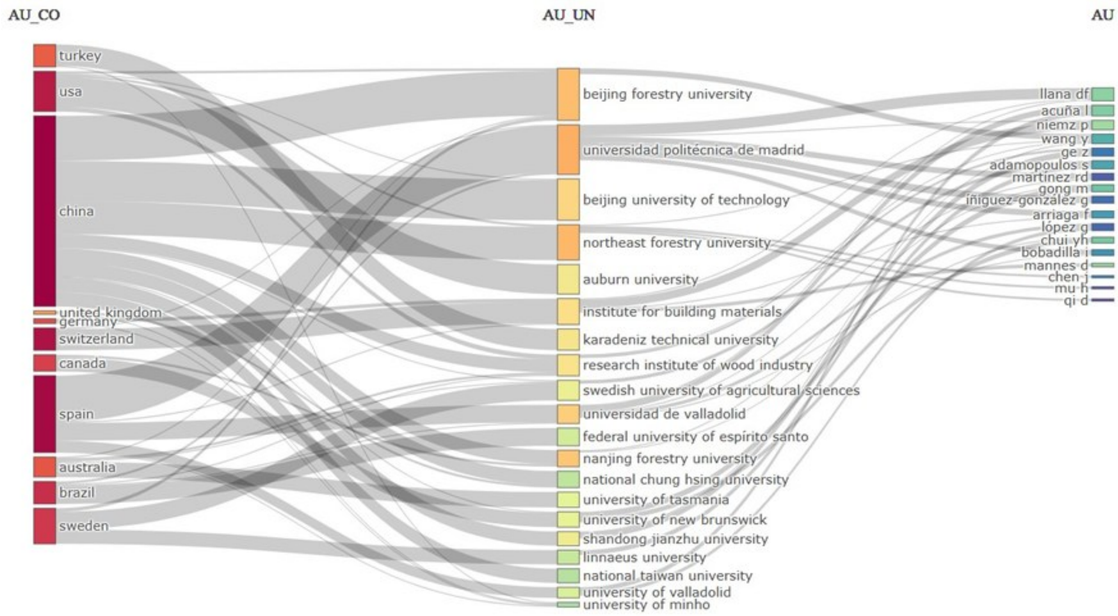

Fig. 4. Three-field plot of countries (AU_CO), institutions (AU_UN), and authors (AU) in wood nondestructive testing research for the period 1982-2025

Beijing Forestry University (China) stood out as the institution with the highest level of collaboration, with Yuan Wuang as a prominent contributor. In Europe, the Universidad Politécnica de Madrid (Spain) was notable, with Daniel F. Llana and Francisco Arriaga as key researchers, mainly in mechanical property prediction and structural evaluation using NDT.

The three-field plot (Fig. 4) revealed a pattern in which the majority of publications and citations have been concentrated in a few countries, while the participation of other countries has been limited. This result highlights the need to strengthen intercontinental cooperation.

Trends

The temporal analysis of scientific production on wood NDT for the period 1982-2025 showed a sustained upward trend, with a marked increase over the last 15 years (Fig. 5). During the early decades (1982 to 2000), production was limited and scattered, reflecting the exploratory nature of the research. From 2004 onwards, an expansion phase was observed, linked to the incorporation of new analytical technologies and the growing interest in non-destructive evaluation of wood materials.

The most notable growth occurred in the last decade, driven by the use and assessment of wood for structural applications and as a sustainable alternative, along with the integration of computational approaches. This pattern indicates that NDT applied to wood continues to be a steadily expanding research line.

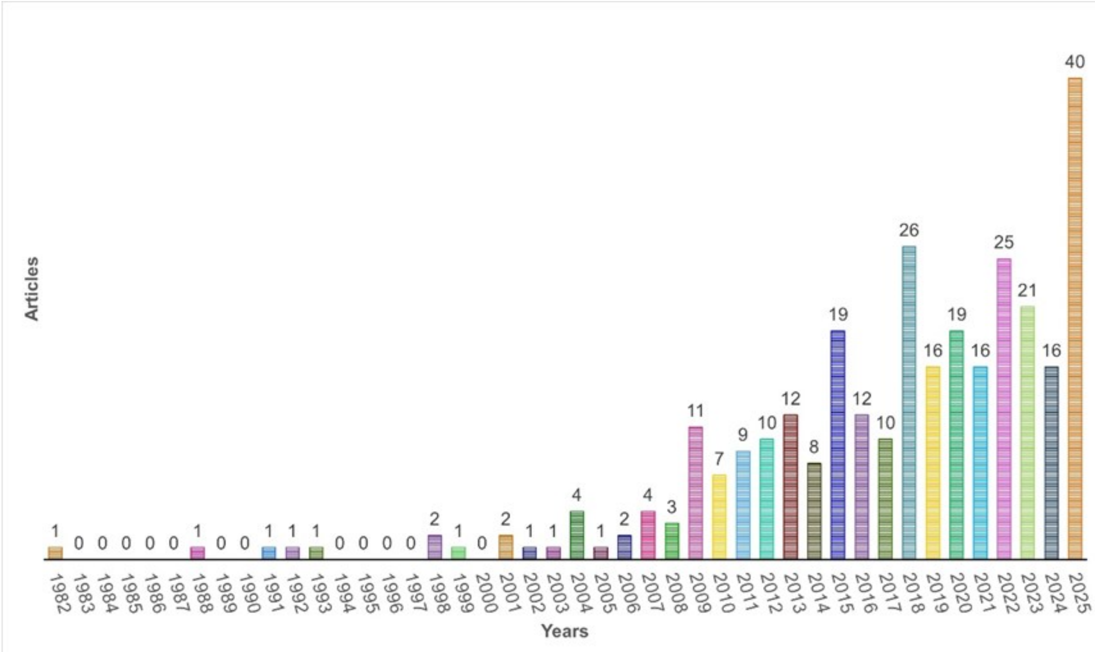

Fig. 5. Annual publication output on wood nondestructive testing for the period 1982-2025

Evolution of the topic nondestructive testing in wood

The thematic strategic diagram (Fig. 6) identifies the main research cores and their evolution during the period 1982 to 2025. The quadrants represent the degree of relevance (centrality) and development (density) of the themes, facilitating the recognition of which areas constitute the core of the discipline, which remain as basic topics, which are oriented toward specific niches, and which emerge as new trends.

Research located in the Motor Themes quadrant focuses on timber, the modulus of elasticity, and ultrasonic testing. These results confirm that the estimation of mechanical properties, such as the modulus of elasticity, through NDT/NDE occupies a central position in the field, guiding a significant portion of scientific production and supporting practical applications in construction and structural design. The high centrality and density of these themes indicate their strong development and their key role in structuring the research domain.

The Basic Themes quadrant included NDT/NDE in wood, reflecting its transversal role as a fundamental conceptual and methodological topic in research. This group also includes testing in wooden buildings, representing an expanding field linked to the evaluation of heritage and modern structures.

Specialized research lines focused on the evaluation of hardwoods and their density, located in the Niche Themes quadrant, showed a high density of these topics, indicating a solid level of internal development; however, their low centrality suggests that these are specialized lines with less impact or that are not strongly integrated with the main research lines of the NDT/NDE field.

The Emerging or Declining Themes quadrant includes topics such as forestry, nondestructive testing, and moisture determination, which exhibit low density and low centrality. These topics may represent either emerging research directions with potential for future growth or declining lines that have not yet consolidated within the NDT/NDE domain.

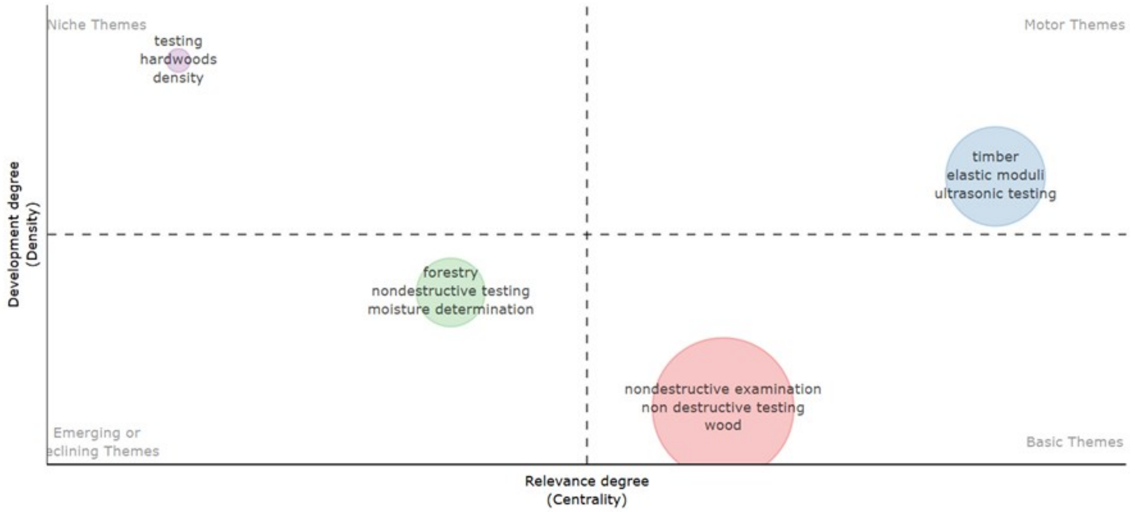

Fig. 6. Strategic diagram of themes in wood nondestructive testing for the period 1982-2025

Cluster Analysis

Co-occurrence of keywords

The bibliometric map, shown in Fig. 7, revealed the main research lines through four clusters that reflect the predominance and application of NDT techniques in wood: I. NDE/NDT with computed tomography for defect detection; II. NDT for the inspection of wooden buildings and structures; III. ultrasound in forestry for characterizing the mechanical properties of wood; and IV. moisture content in wood products. Additionally, Table 4 details the most frequently occurring keywords within each thematic cluster.

Cluster I is the most significant in terms of frequency, with seven terms associated with the application of nondestructive testing using computed tomography (CT) for defect detection in wood. Among the most notable contributions are studies by Zhao *et al.* (2021) and Yang *et al.* (2022), who used CT to identify internal defects such as cracks, holes, and degradations in wood products and structures; and by Křivánková *et al.* (2018), who compared medical and industrial CT equipment for measuring growth ring widths. This cluster reflects that CT is a reliable method for defect detection and non-destructive structural characterization of wood.

Cluster II groups together six terms related to the application of NDT in the characterization and diagnosis of wooden structures in buildings, especially those of historical and cultural value. Notable studies include the evaluation of beams in historic buildings using ultrasonic transmission tomography (Zielińska and Rucka 2023), the application of CT for heritage inspection (Ye *et al.* 2022), and the design of an NDT system based on ground-based synthetic aperture radar (GB-SAR) for post-earthquake damage assessment in wooden structures (Liu *et al.* 2016). This group highlights the importance of NDT in cultural heritage conservation and its expansion into civil engineering.

Table 4. Thematic Clusters of Co-occurrences

Cluster	Name	Terms
I (Red)	NDE/NDT with computed tomography for defect detection	Computerized tomography, defects, nondestructive examination, nondestructive tests, testing, tomography, wood
II (Green)	NDT for the inspection of wooden buildings and structures	Non destructive testing, non-destructive testing, nondestructive testing, timber, timber structures, wooden buildings
III (Blue)	Ultrasound in forestry for characterizing the mechanical properties of wood	Elastic moduli, elastic waves, forestry, mechanical properties, ultrasonic testing, wave propagation
IV (Yellow)	Moisture content in wood products.	Moisture, moisture determination, bridge decks, wood products

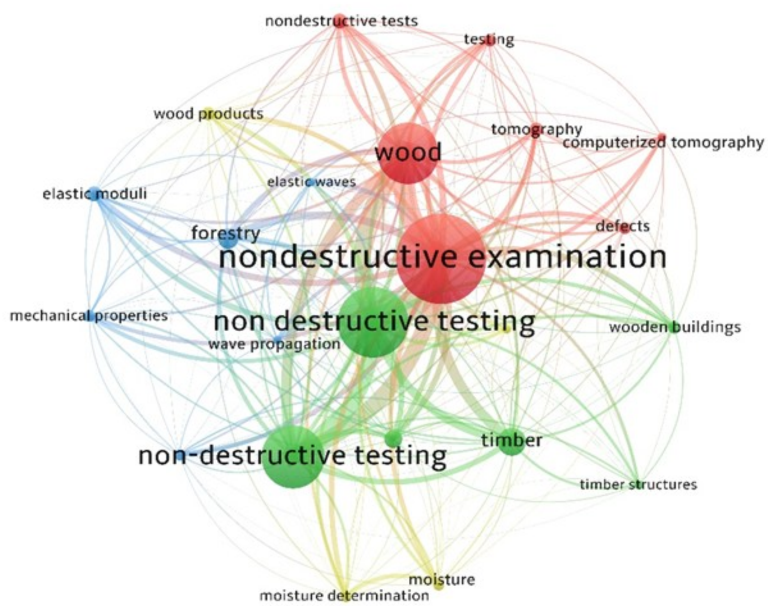

Fig. 7. Co-occurrence clustering of wood nondestructive testing for the period 1982-2025

Cluster III comprises six terms associated with the use of ultrasound and elastic wave propagation to assess the mechanical properties of wood, particularly the modulus of elasticity. Significant contributions include Llana *et al.* (2020), who used acoustic velocity to predict mechanical properties in standing trees and logs of hardwood species, and Acuña *et al.* (2023), who applied transverse vibration and ultrasound techniques in various coniferous and hardwood species to predict MOEd. This cluster reinforces the role of acoustic methods as a foundation for mechanical property prediction and their applications in forestry and the wood industry.

Cluster IV, containing four terms, addresses the estimation of moisture content (MC) as a key variable influencing wood properties. Notable studies include Sudakova *et al.* (2021, 2023), who applied ground-penetrating radar (GPR) and increment cores; Martínez *et al.* (2020b), who used drilling chip extraction in coniferous and hardwood species to estimate MC; and Duan *et al.* (2022), who explored terahertz time-domain spectroscopy (THz-TDS) for moisture content prediction.

Author co-citation

The analysis revealed a main co-citation core (red cluster) in the field of wood nondestructive testing (Fig. 8, Table 5), led by Xiping Wang, with studies focused on the use of acoustic techniques, including time-of-flight (TOF) methods to determine physical-mechanical properties and detect internal defects, mainly in standing trees and logs; and Robert J. Ross, with research on nondestructive evaluation of wood through acoustic methods, stress waves, and transverse vibrations aimed at assessing mechanical properties such as MOEd, modulus of rupture (MOR), and stiffness, and the detection of defects and deterioration in standing trees and logs, as well as structural analysis of in-service wood.

Together, these authors are the most influential and frequently cited, demonstrating high relevance, impact, and centrality in the literature on wood NDT. The blue and green clusters group together authors with lower reference frequency, whose research, while relevant, has had a more limited impact on the development of the field.

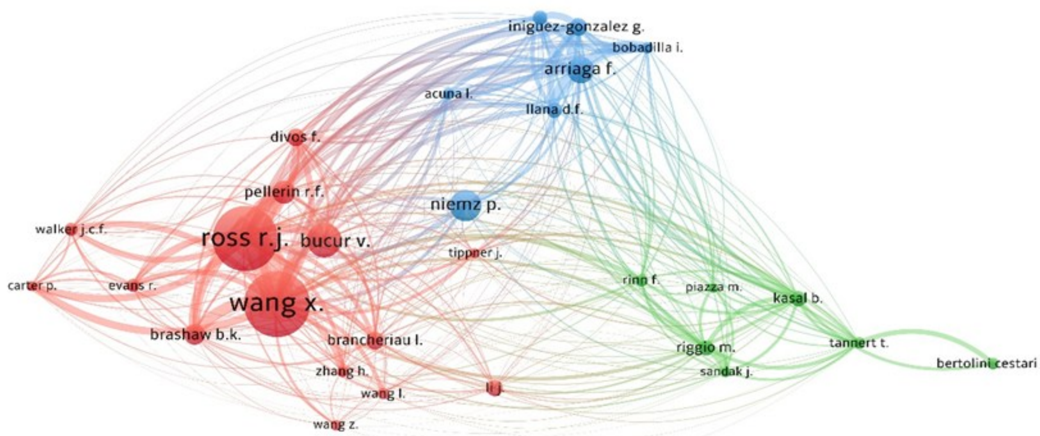

Fig. 8. Author co-citation network in wood nondestructive testing for the period 1982-2025

Table 5. Author Co-citation Clusters

Cluster	Co-citations per Author	Citations	H-index	Affiliation
(Red)	Brancheriau, L.	58	2	Agricultural Research Centre for International Development, France
	Brashaw, B. K.	68	1	USDA Forest Products Laboratory, USA
	Bucur, V.	113	2	INRA, Champenoux, France
	Carter, P.	34	1	Manager, Technology Commercialization, Carter Holt Harvey, fibre gen, New Zealand
	Divos, F.	60	2	Institute of Wood and Paper Technology, University of West Hungary, Sopron, Hungary
	Evans, R.	45	1	Silviscan Pty Ltd., Doncaster East, Victoria, Australia
	Li, J.	55	2	School of Resources, Environment and Materials, Guangxi University, China
	Pellerin, R. F	76	1	USDA Forest Products Laboratory, USA
	Ross, R. J.	214	2	USDA Forest Products Laboratory, USA
	Tippner, J.	35	4	Faculty of Forestry and Wood Technology Mendel University, Czechia
	Walker, J.C.F.	45	1	University of Canterbury, Christchurch, New Zealand
	Wang, L.	38	2	College of Engineering and Technology, Northeast Forestry University, China
	Wang, X.	218	3	USDA Forest Products Laboratory, USA
	Wang, Z.	36	2	College of Materials Science and Engineering, Nanjing Forestry University, China
	Zhang, H.	39	3	School of Technology, Beijing Forestry University, China
(Green)	Bertolini Cestari, C.	38	1	Department of Architecture and Design, Politecnico di Torino, Italy
	Kasal, B.	52	1	Fraunhofer Wilhelm-Klauditz-Institute WKI, Carolo-Wilhelmina University, Germany
	Piazza, M.	34	1	Department of Civil, Environmental and Mechanical Engineering, University of Trento, Italy
	Riggio, M.	52	1	CNR-IVALSA Wood Quality Laboratory, Italy
	Rinn, F.	41	1	Consulting Engineers, Heidelberg, Germany
	Sandak, J.	35	1	CNR-IVALSA Wood Quality Laboratory, Italy
	Tannert, T.	40	1	Department of Wood Science and Department of Civil Engineering, University of British Columbia, Canada
(Blue)	Acuña, L.	39	5	E.T.S. of Agricultural Engineering, University of Valladolid, Spain
	Arriaga, F.	88	3	Department of Forest and Environmental Engineering and Management, Universidad Politécnica de Madrid, Spain
	Bobadilla, I.	40	3	Department of Forest and Environmental Engineering and Management, Universidad Politécnica de Madrid, Spain

	Esteban, M.	50	2	Department of Forest and Environmental Engineering and Management, Universidad Politécnica de Madrid, Spain
	Iniguez-Gonzalez, G.	59	3	Department of Forest and Environmental Engineering and Management, Universidad Politécnica de Madrid, Spain
	Llana, D. F	51	6	Departamento de Ingeniería y Gestión Forestal y Ambiental, Universidad Politécnica de Madrid, Espain
	Niemz, P.	103	9	Institute for Building Materials, ETH Zurich, Switzerland

Bibliographic coupling and geographic distribution

The bibliographic coupling network (Fig. 9) identified 27 countries with the highest publication activity in nondestructive wood testing, representing 41% of the total global output. China led the list with 63 publications (21.7%) and 709 citations (11.3%), establishing this country as the main international reference (Table 6). In Europe, Spain, Germany, and Italy showed significant participation, while in North America, the United States and Canada stood out. This pattern highlights a strong concentration of research in developed countries, with lower representation in regions such as Latin America and Africa, reflecting the need to promote international scientific cooperation.

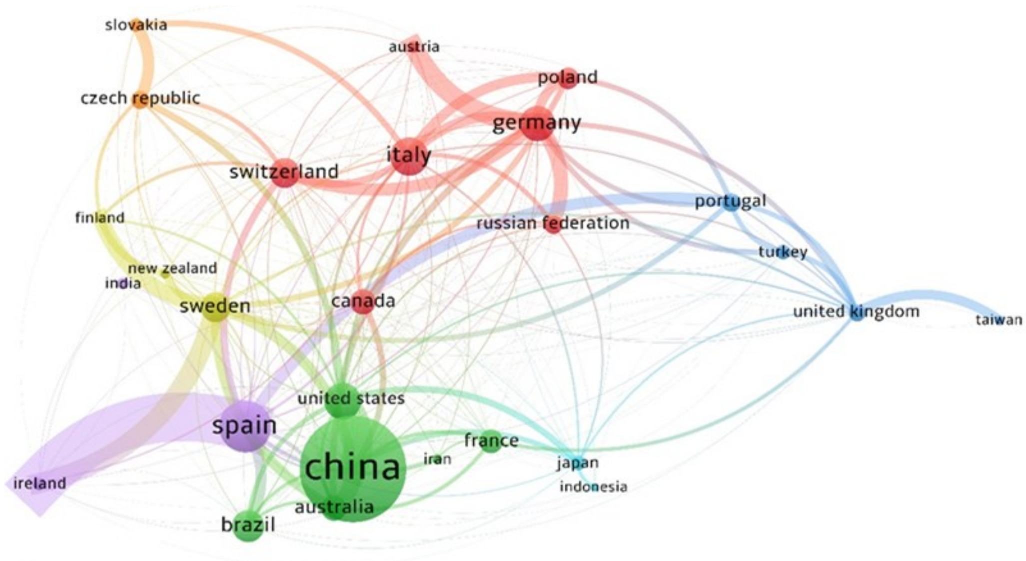

Fig. 9. Bibliographic coupling network by country on the topic of wood nondestructive testing for the period 1982-2025

Table 6. Bibliographic Coupling Clusters by Country

Cluster	Countries	Total Documents	Total Citations
(Green)	China	63	709
	United States	22	354
	Brazil	19	207
	Australia	15	329
	France	14	290
	Iran	6	43
(Red)	Italy	23	534
	Germany	21	546
	Switzerland	18	498
	Canada	15	247
	Poland	13	175
	Russia	11	98
	Austria	7	110
(Blue)	Portugal	11	390
	United Kingdom	10	194
	Türkiye	9	55
	Taiwan	5	36
(Yellow)	Sweden	18	224
	New Zealand	6	59
	Finland	5	99
(Purple)	Spain	31	623
	Ireland	8	82
	India	7	44
(Aqua)	Japan	9	68
	Indonesia	5	26
(Orange)	Czechia	11	110
	Slovakia	8	87

The bibliometric analysis confirms that research on NDT applied to wood chiefly revolves around established techniques such as acoustic and vibration methods, while emerging lines of research are focused on optical and computational technologies. The field is led by a small core of authors and institutions concentrated in China, Europe, and North America, indicating the importance of diversifying scientific production and expanding international collaboration to strengthen research in this sector. This geographic concentration of scientific output is not random but rather reflects underlying structural and technological conditions across regions.

The leadership of China, European countries, and North America in scientific output can be attributed to the high level of technological development in the forestry sector and to the widespread production and use of wood in structural applications within construction and engineering; this is driven by the adoption of sustainability-oriented regulations, as well as by a global shift toward sustainable building materials (Mensah *et al.* 2025). In contrast, in developing regions such as Latin America, the construction sector relies predominantly on concrete, steel, and masonry, thereby reducing demand for wood products for structural uses. This situation is associated with a lower degree of industrialization in the forestry sector, limited technology transfer, and underdeveloped technical capabilities—factors that collectively limit the use of wood for structural purposes and, consequently, restrict research development in this field (Fourier-Zepeda 2008).

LITERATURE REVIEW

The results of the literature review focus on nondestructive testing (NDT) applied to wood evaluation, with emphasis on studies published between 2020 and 2025. The fundamental principles and recent applications of the main techniques are described, encompassing consolidated methods such as acoustic, vibration, X-ray, and computed tomography techniques, as well as emerging approaches based on spectroscopy, optical technologies, and artificial intelligence, in order to highlight the most significant advances and current trends in the field of wood NDT. Additionally, Table 7 provides a comparative overview of the main NDT techniques applied to wood, summarizing their underlying principles, advantages, limitations, and typical applications.

Acoustic Methods

Acoustic testing is one of the most widely used methods for the nondestructive evaluation of wood, owing to its sensitivity and versatility in assessing various materials and fluids (Laugier and Haïat 2011). In wood, these techniques are based on wave propagation, whose behavior is influenced by density, anatomical structure, and hygroscopic state. In general, higher propagation velocity is associated with sound wood, while lower velocity indicates the presence of internal defects or deterioration. This relevance is also reflected in the bibliometric analysis, where ultrasonic testing and wave propagation form part of Cluster III, highlighting their central role in the characterization of mechanical properties, particularly in forestry contexts.

Pioneering contributions in this field date back to the 1980s, particularly through the work of Voichita Bucur, who has extensively advanced the scientific understanding of wood acoustics. Her contributions include seminal publications and reference books such as *Nondestructive Characterization and Imaging of Wood* (Bucur 2003) and *Acoustics of Wood* (Bucur 2025), which have significantly contributed to consolidating the theoretical and methodological foundations of acoustic-based nondestructive testing in wood. Other recent publications have evaluated MOE nondestructively, based on the dynamic modulus of elasticity using ultrasound. These include Beall (2002), Acuña *et al.* (2006), Hassan *et al.* (2013), Fang *et al.* (2017), Ettelaei *et al.* (2022), Balazs *et al.* (2025), Bencsik *et al.* (2025a,b).

Although acoustic tests are well-established methods, their accuracy can be affected by factors such as species, anatomy, anisotropy, engineered wood product type (cross-laminated timber (CLT) or glued laminated timber (glulam)), moisture content, sample size (field or laboratory), and sensor placement during measurements. Therefore, there is a high potential for innovation when these methods are combined or integrated with computational techniques, artificial intelligence, and predictive modeling (Nasir *et al.* 2022; Azzi *et al.* 2025).

Beyond their usefulness in detecting structural anomalies, acoustic techniques also enable the indirect estimation of mechanical properties, particularly the dynamic modulus of elasticity (MOEd), making them key tools for structural grading and design applications (Azzi *et al.* 2025). Among these techniques, time of flight (TOF), acoustic tomography, and acoustic emission stand out.

Time of Flight (TOF)

The time of flight (TOF) technique is based on the propagation of high-frequency elastic waves (ultrasonic >20 kHz) through an elastic medium (solid, liquid, or gas). Meanwhile, the propagation time and velocity are recorded as parameters to estimate physical and mechanical properties (Xu and Li 2024). In wood, direct transmission using piezoelectric transducers is commonly employed (Bucur 2006), with devices such as the Fakopp Microsecond Timer, Fakopp TreeSonic Timer (FAKOPP Enterprise, Ágfalva, Hungary), and Sylvatest (Trio, Duo, 4) (CBS-CBT, Lausanne, Switzerland).

In standing trees and logs, TOF has been widely used to estimate the dynamic modulus of elasticity (MOEd) and to assess mechanical properties associated with wood quality for structural applications (Cheng *et al.* 2020b; Llana *et al.* 2020; Stewart *et al.* 2021; Mvolo *et al.* 2022; Papandrea *et al.* 2022; Jones *et al.* 2023; Tippner *et al.* 2023). Recent examples include studies on the relationship between physical mechanical properties, age, and stem form in *Betula pendula* Roth and *Betula pubescens* Ehrh (Jones *et al.* 2024), as well as comparisons among trees, logs, and sawn timber of *Pinus contorta* Douglas ex Loudon to relate acoustic velocity with bending properties (Duchesne *et al.* 2025).

In wood products, TOF has been employed to estimate MOEd across a wide range of materials, including particleboards under different moisture conditions (Ahmed *et al.* 2020), sawn timber of *Pinus sylvestris* L. (Fundova *et al.* 2020) and *Eucalyptus globulus* Labill. (Derikvand *et al.* 2020), railing posts (Luo *et al.* 2020), thin birch veneers (*Betula pendula*) (Pramreiter *et al.* 2020b), solid and laminated wood of *Pinus pseudostrobus* Lindl. (Macedo-Alquicira and Sotomayor-Castellanos 2021), oriented strand boards (Chung and Wang 2022), composites made with coconut shell and pine residues (Hillig *et al.* 2023), glued-laminated timber (glulam) derived from hybrid *Eucalyptus urophylla* × *Eucalyptus grandis* (De Alcântara *et al.* 2024), and composites reinforced with hemp, flax, and wood chips (Nassar *et al.* 2025). It has also been applied for strength grading in cross-laminated timber (CLT) panels (Birinci *et al.* 2025).

In built heritage, this technique has been used to assess and inspect the structural integrity of timber elements in historical buildings (Madhoushi *et al.* 2021; Fu and Sugino 2024; Kang *et al.* 2025; Pranata *et al.* 2025), reinforcing its value for preventive conservation and risk management.

TOF has been combined with other techniques to expand its applicability. For example, it has been integrated with drilling resistance measurements in *Larix* sp. logs to determine density and MOEd (Cheng *et al.* 2020a), with heritage building information modeling (HBIM) in historical structures (Mol *et al.* 2020), in quantitative genetics studies to estimate the heritability of stem and wood traits of *Betula pendula* through genotypic and phenotypic correlations (Jones *et al.* 2021), and in analyses of the effect of initial planting density on ultrasonic velocity and drilling depth in *P. sylvestris* trees (Sharapov *et al.* 2024). In wood-based composites, it has been applied to evaluate aging and its effects on physical and mechanical properties (Bobadilla *et al.* 2025).

Acoustic Tomography

Acoustic or ultrasonic tomography generates images representing variations in the propagation velocity of sound waves emitted and received by transducers positioned around the analyzed area. As the waves travel through the wood, they are modified according to its internal properties, enabling the detection of voids, cracks, decay, and defects such as knots or reaction wood, especially in standing trees (Palma *et al.* 2018; Raabe *et al.* 2021). Common devices include USLab (Agricef, Paulínia, Brazil), ArborSonic 3D (Fakopp Enterprise Ltd., Sopron, Hungary), Pundit Pd 8000, and PiCUS 3 (Argus Electronic GmbH).

In urban trees, acoustic tomography has been applied to detect internal decay (Puxeddu *et al.* 2021), calculate the safety factor (FS), and evaluate stability against fungal degradation (Kobza *et al.* 2022). These applications reinforce its value as a preventive diagnostic tool for tree risk assessment and management in urban environments.

In the context of historical and cultural heritage, this technique has been used for structural assessment and damage detection in timber from ancient buildings, such as the Monastery of the Congregation of the Sisters of St. Catherine in Orneta, Poland (Zielińska and Rucka 2023) and All Saints Church in Sieroty, Poland (Nowogońska and Drobiec 2025), and for identifying the size and location of hollow and deteriorated sections in timber columns of renovated buildings in Beijing, China (Li *et al.* 2020).

Acoustic tomography has been established as an effective method for the nondestructive detection of internal defects in wood, with applications ranging from heritage conservation to urban tree management. Its main limitations stem from scan quality, as the technique requires strategic sensor placement, particularly in trees with highly irregular trunks (Gilbert *et al.* 2016), as well as from the need to account for the anisotropy of the material (Maurer *et al.* 2006), for which combined approaches (*e.g.*, TOF + ray tracing) have been employed, significantly improving the accuracy of predictions (Espinosa *et al.* 2017).

Acoustic Emission (AE)

The acoustic emission (AE) technique is based on detecting elastic waves within the ultrasonic range (50 kHz to 1 MHz) using piezoelectric sensors that convert mechanical vibrations into electrical signals (Ríos-Soberanis 2011). To ensure efficient transmission, a coupling agent is required between the sensor and the material, while the data are processed in real time through amplifiers, filters, and acquisition systems. With this procedure, parameters can be extracted, such as amplitude, energy, and frequency, which are useful for structural health monitoring and early damage detection in wood, particularly during machining processes (Nasir *et al.* 2022; Azzi *et al.* 2025).

AE has been applied in combination with other techniques to broaden its scope. Notable studies have integrated AE with digital image correlation (DIC) to evaluate crack propagation and damage behavior in wood plastic composites (WPCs) (Wang *et al.* 2023), and others have proposed improved source localization methods accounting for anisotropic wave propagation in finger-jointed laminated boards (Zhao *et al.* 2024a).

Recent studies have optimized AE to improve accuracy in detecting damage and surface fractures in wood, using energy attenuation analysis methods based on wavelet transforms (Du *et al.* 2025).

Acoustic emission has been established as a valuable technique for structural health monitoring, damage detection, and wood characterization, although its limitations depend on parameters such as species, geometry, orientation, moisture content, and temperature, as well as the frequency, position, and orientation of the transducers (Nasir *et al.* 2022).

Induced Transverse and Longitudinal Vibrations

Vibrational techniques consist of measuring the natural vibration frequency of wood, typically induced by impact with a hammer and recorded through a fast Fourier transform (FFT) spectrum analyzer (Carballo-Collar *et al.* 2009). The direction of wave propagation can be either perpendicular (transverse vibration) or parallel (longitudinal vibration) to the wood grain (Bube 1992). From the natural frequency, wood density, and specimen length, it is possible to estimate mechanical properties, particularly the dynamic modulus of elasticity (MOEd).

Transverse vibration methods have been used to inversely determine the bending and shear stiffness of three and five-layer CLT panels (Zhou *et al.* 2020), as well as to evaluate the mechanical characteristics of single and composite beams (Qi *et al.* 2024). When combined with ultrasonic testing, they have enabled the prediction of MOEd in species such as *Populus* × *euramericana* clone I-214, *Fagus sylvatica* L., *Quercus pyrenaica* Willd., *Paulownia elongata* S.Y. Hu, and *P. sylvestris*. (Acuña *et al.* 2023).

Longitudinal vibrations have been applied in the evaluation of wooden utility poles (Das *et al.* 2021), in the analysis of strength loss due to fungal degradation in *Fagus sylvatica* L. (Cristini *et al.* 2022), and in the mechanical grading of species such as *Pinus pinaster* ssp. *atlantica*, *P. radiata*, and *P. sylvestris* (Moltini *et al.* 2022), as well as in the estimation of tensile strength in *Eucalyptus globulus* Labill. (Martins *et al.* 2023). They have also been employed to evaluate the effect of specimen size and shape on dynamic and static bending in green wood (Zlámal *et al.* 2025).

These vibrational techniques have proven useful for assessing the structural viability of secondary wood sourced from the demolition sector for the manufacture of CLT panels (Llana *et al.* 2022; Dong *et al.* 2024), and for estimating MOEd in plywood made from *Betula* sp. and *Alnus* sp. (Pinchevska *et al.* 2020), mixed laminated timber of *Populus* × *euramericana* clone I-214 / *P. sylvestris* (Rescalvo *et al.* 2020), boards and individual layers of cross-laminated timber (CLT) from *P. radiata* (Maithani *et al.* 2023), and lamella-type panels manufactured from low-quality sawn timber of *Fagus sylvatica* and *Quercus* spp. (Lux *et al.* 2025).

In the field of musical instruments, vibrational techniques have been widely used to evaluate the effect of varnish on the vibrational properties of *Picea abies* (L.) H. Karst. and *Acer pseudoplatanus* L. wood used in violin making (Lämmlein *et al.* 2020), and for classifying and estimating mechanical properties of *Picea abies* wood intended for string instruments (Viala *et al.* 2020; Quintavalla *et al.* 2022).

Recently, with the development of mobile applications such as SMART THUMPER®, studies have assessed the accuracy and limitations of these applications for determining the stiffness properties of wood (Kumar *et al.* 2021).

Induced transverse and longitudinal vibrations represent a versatile and widely applicable method for estimating wood properties. Although their accuracy may be influenced by factors inherent to the anisotropic and heterogeneous nature of wood, sample size, and moisture content, innovations in digital applications have enhanced signal acquisition and analysis, expanding their potential for wood characterization and monitoring.

Penetration and Drilling Resistance Techniques

Drilling resistance techniques are based on measuring the resistance encountered by a rotating drill bit along its penetration path, generating a continuous profile associated with the internal structure of wood. The resistograph is the most representative instrument of this approach, as it provides a continuous resistance profile along the drilling path.

In contrast, penetration-based methods, such as the penetrometer (Pilodyn), rely on the depth reached by a needle driven by a spring mechanism, providing point-based measurements restricted mainly to surface layers. In both cases, drilling resistance and penetration depth can be used as indirect indicators of wood density, due to the negative correlation between this physical property and the depth reached (Schimleck *et al.* 2019).

These techniques have been applied to both standing trees and timber structures in service, owing to their simplicity and portability. However, in the case of penetrometers, a major limitation is their reduced penetration depth (2 to 3 cm), which restricts the evaluation of the transverse behavior of large timber elements and the characterization of the complete radial profile of trees (Fundova *et al.* 2018).

Recent applications include studies on the influence of drilling direction relative to grain orientation in Scots pine, beech, oak, and poplar wood (Sharapov *et al.* 2021); the estimation of wood density and mechanical properties in standing trees (Jones *et al.* 2023); and the inspection and technical evaluation of wood in historical structures (Ksit *et al.* 2022; Hernández-Oroza *et al.* 2022; Brunetti *et al.* 2023; Mackiewicz *et al.* 2024). Additionally, these methods have been used to assess the mechanical and biological resistance of boron-treated CLT under ground-contact conditions (Demir *et al.* 2025).

Penetration and drilling resistance techniques constitute accessible and highly useful approaches for wood evaluation; however, their limitations in penetration depth and sensitivity to grain orientation require their integration with other NDT methods to achieve a more comprehensive characterization of wood, encompassing mechanical performance, internal structural integrity, anisotropic effects, and the spatial distribution of material properties.

Drilling Chips and Increment Cores

The increment core technique involves extracting small-diameter cylindrical wood samples, mainly from living trees, using increment borers of various internal diameters and lengths. The drilling chip method was designed for estimating density and other physical parameters in timber structures in service, as both are low-impact semi-destructive techniques.

In this method, a wood extraction device coupled with an electric drill collects the chips generated during drilling in a disposable paper filter. The system operates with a drill bit of 8 mm in diameter and 47.7 mm in depth, resulting in a volume of 2.4 cm^3. It relies on the air flow generated by the drill turbine, which suctions and encapsulates the wood chips into the filter; these are then weighed to estimate wood density (Martínez and Bobadilla 2015; Zhao *et al.* 2025).

The extraction of increment cores and drilling chips has been applied for monitoring moisture content in *Tilia cordata* Mill. and *P. sylvestris* trees (Sudakova *et al.* 2023), and for estimating density in both softwood and hardwood species (Martínez *et al.* 2020a, 2020b).

Infrared Thermography (IRT)

Infrared thermography (IRT) is based on the principle that any object with a temperature above absolute zero ($T > 0$ K) emits electromagnetic radiation in the infrared region of the spectrum (0.75 to 1000 μm) (Meola 2012). For its application, thermographic cameras are used to record the radiation emitted by object surfaces and convert it into images known as thermograms (Jaramillo *et al.* 2019).

IRT is classified into two modalities: active and passive thermography. The active approach employs artificial stimuli to induce thermal gradients on the object, while the passive approach relies on natural sources such as solar energy and ambient temperature as the main heating agents (Rocha and Póvoas 2017; Pitarma *et al.* 2019).

In the context of wood, IRT has been applied to detect surface defects and deterioration, such as those caused by metallic contaminants in panels during the manufacturing process (Mnif *et al.* 2025), and to locate areas of moisture accumulation in glued-laminated timber (glulam) roofs, such as in the Corrales de Buelna Swimming Pool, Cantabria, Spain (Pinilla-Melo *et al.* 2024). These applications demonstrate its value as a nondestructive monitoring technique for wood in both field and laboratory settings.

Despite its practicality, IRT is generally ineffective for detecting deep-seated defects in wood unless they are located near the surface. This limitation is primarily associated with the inherently low thermal diffusivity of wood, which restricts heat propagation, as well as with the influence of environmental and material factors—such as temperature, moisture content, and fiber orientation—on thermal image interpretation. These factors can significantly constrain the reliability of damage characterization in wooden elements (Wyckhuyse and Maldague 2001a,b).

Near-Infrared Spectroscopy (NIR)

Near-infrared spectroscopy (NIR) is based on the excitation of vibrational modes of functional groups (O-H, N-H, C-H) present in wood through infrared radiation within the range of 1200 to 2500 nm. This phenomenon allows detection of changes associated with the reduction or attenuation of the main components (cellulose, hemicellulose, and lignin) through the presence of hydrogen-containing bonds (Zhao *et al.* 2024b).

Wood analysis using NIR relies on multivariate models calibrated with spectra obtained from different types of samples, such as solid wood, sawn timber, or even ground increment cores. These models reflect chemical and structural variations, enabling indirect prediction of wood properties (Schimleck *et al.* 2019).

Recent applications of NIR techniques include the characterization of mechanical properties in heat-treated wood through the detection of changes in functional groups (Hsieh *et al.* 2022), the microscopic morphology of defects in solid larch wood panels (Pan *et al.* 2021), and the prediction of air-dry density in black walnut (*Juglans nigra*) (Ren *et al.* 2023). Furthermore, advanced methods such as structural equation modeling (SEM) have been proposed to transfer calibrations between NIR spectrometers and improve the prediction of mechanical properties in solid wood panels (Jiang *et al.* 2023).

NIR techniques have demonstrated utility in determining the chemical composition of wood, including lignin, extractives, holocellulose, and ash content (Nörnberg *et al.* 2025). They have also been applied to the morphological characterization of fibers and tracheids, the evaluation of physical and mechanical properties, as well as wood identification and classification. Furthermore, their continuous evolution has led to the emergence of near-infrared hyperspectral imaging (NIR-HSI), which is considered to be one of the most advanced analytical technologies. This approach combines spectral reflectance measurements and image processing within a single system, facilitating the visualization of the spatial distribution of different chemical components in wood through three-dimensional datasets, also referred to as hypercubes (Deepa *et al.* 2024).

Nevertheless, although NIR techniques have significantly expanded the analytical and characterization capabilities in wood research, it is important to acknowledge certain limitations that constrain their adoption, particularly in field studies and industrial applications. Among the most relevant is the high sensitivity of NIR spectra to wood moisture content, as well as the requirement for controlled laboratory conditions and rigorous sample preparation protocols (Hein *et al.* 2017).

In response to these constraints, portable NIR spectrometers have been developed as rapid and easy-to-implement evaluation tools, especially targeted at industrial processes that require continuous monitoring of moisture content and defect detection. However, these devices typically operate within narrower wavelength ranges and at lower spectral resolution, which reduces their analytical precision for detailed chemical property assessment (Diniz *et al.* 2019; Toscano *et al.* 2022).

Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) is a technique that uses electromagnetic waves to investigate dielectric materials with low signal attenuation. The system consists of a transmitting, and a receiving antenna placed a fixed distance apart. The receiving antenna detects signals reflected at internal interfaces within the material and transforms the waveforms into images. In wood, this technology has been applied to detect and locate internal anomalies, estimate moisture content, and provide indirect information on structural anisotropy and fiber orientation (Ondrejka *et al.* 2021; Azzi *et al.* 2025).

Originally, GPR, also known as georadar, was used exclusively in geological material studies; however, its use has since expanded to materials such as wood, concrete, and asphalt (Annan 2009).

This versatility has promoted its adoption in the forestry and wood industries. GPR has been used to assess the health of trunks from *Quercus robur* L., *Picea obovata* Ledeb., *Castanea dentata* (Marshall) Borkh., and *Populus tremula* L., generating images of internal structures, locating decay zones, and quantitatively estimating moisture content (Sudakova *et al.* 2021). It has also been combined with 3D raster scanning to reconstruct the three-dimensional structure of standing trees and their growth-related characteristics (Jiang *et al.* 2021), as well as to reconstruct three-dimensional models of internal defects and decay in tree trunks (Li *et al.* 2022).

GPR has been applied experimentally to measure the refractive index and moisture content in wood chips (Choudhary *et al.* 2022), as well as to estimate and monitor moisture content in trunks of *P. sylvestris* (Sudakova *et al.* 2023) and Canadian softwoods (Duchesne *et al.* 2023).

In historical structures, GPR has proven useful for diagnosing the structural condition and conservation state of buildings such as the Cathedral of Foggia (Italy) (De Giorgi *et al.* 2024). More recently, GPR tomography based on multi-offset rays has been combined with displacement GPR to detect and characterize cavities and decay processes in living trees (Sudakova *et al.* 2025).

Although GPR offers advantages for wood inspection, including rapid scanning and *in situ* application with immediate data interpretation, it presents several limitations. Signal behavior and dielectric properties are strongly influenced by factors such as moisture content, density, temperature, object geometry (shape and size), and conservation treatments. Furthermore, the technique shows limited capability for accurately locating and identifying internal decay in wooden elements (Rodrigues *et al.* 2021). This reduced diagnostic performance is also observed in the inspection of living trees, particularly in individuals with small diameters and irregular trunks, where high false-positive rates have been reported in decay detection. Consequently, in some cases it is necessary to combine GPR with other nondestructive techniques—such as visual inspection, acoustic tomography, and resistance drilling—to enhance reliability and provide a more comprehensive assessment of the investigated element (Wu *et al.* 2018).

Microwave Methods

Microwave methods employ electromagnetic signals in the frequency range of 300 MHz to 300 GHz (wavelengths from 1 m to 1 mm) for nondestructive inspection of materials. The system consists of a source generating microwaves that propagate through antennas, waveguides, or probes. The propagation process is based on two main phenomena: reflection, where transmitted signals are reflected by the structure and return with amplitude and phase variations, providing information on the object's microstructural characteristics, and transmission, in which the signals pass through the sample and the recorded data are used to analyze dielectric behavior, material loss, and the interaction between porosity, permeability, frequency, and temperature (Saif ur Rahman *et al.* 2024; Ghattas *et al.* 2025).

In wood, applications have focused on detecting defects such as knots and voids in *P. radiata* beams (Radwan *et al.* 2021), as well as analyzing dielectric properties under different moisture conditions (Qin *et al.* 2025). These studies demonstrate the potential of microwave techniques to link the physical parameters of wood with its mechanical and durability properties.

However, several disadvantages limit the application of microwave methods in wood research. High-intensity microwave treatments can induce microstructural alterations, including tracheid collapse and fracture (Ganguly *et al.* 2021). Moreover, negative effects on density and mechanical performance have been reported, particularly reductions in shear and compressive strength associated with drying defects—such as cracks and voids—resulting from the degradation of rays and weak regions of the middle lamella (Balboni *et al.* 2018; Terziev *et al.* 2020). Therefore, careful control of microwave intensity is required when applying these treatments to avoid structural deterioration.

X-Ray Methods

X-rays comprise a technique based on ionizing radiation capable of penetrating materials and generating internal images from signal attenuation. Their operation follows the Lambert-Beer law, in which the transmitted intensity (I) decreases exponentially as a function of the material's density and the distance traveled by the radiation (Chen *et al.* 2012). In the resulting images, denser regions absorb more radiation and appear brighter or with higher contrast, revealing structural heterogeneities.

Common applications in wood include X-ray radiography, computed tomography (CT), and wide-angle X-ray scattering (WAXS). More specialized techniques, such as tomosynthesis, synchrotron X-ray microtomography, and X-ray fluorescence (XRF), have more limited and infrequent use in this field. Tomosynthesis has been employed to improve the early detection of termite damage in *Pinus densiflora* Siebold & Zucc. by evaluating the quality of reconstructed images based on the number of projections. Synchrotron X-ray microtomography has enabled the observation of microscopic anatomical features and identification of wood species used in kris sheaths (Cipta *et al.* 2022). XRF has been combined with Optical Coherence Tomography (OCT), FT-IR spectroscopy, and Nuclear Magnetic Resonance–Mobile Universal Surface Explorer (NMR-MOUSE), a portable low-field NMR device that enables non-destructive depth profiling of layered structures based on the principles of Magnetic Resonance Imaging (MRI), for studying the stratigraphy of wood treatments and varnish layers in historical violins (Invernizzi *et al.* 2020).

Conventional X-ray radiography, combined with computed tomography (CT), has been used to inspect sculptures made from wood, plastic, metal, and paper/cardboard (Reinhardt *et al.* 2023). However, a major limitation is the low contrast in radiographs, which is attributable to the low density of wood—similar to that of other soft tissues—as well as the inability of conventional radiography to provide depth information, particularly for locating defects and irregularities.

In addition, radiographic techniques generally require prolonged and careful sample preparation and often produce images with limited definition of wood structure, especially at growth ring boundaries. Likewise, medical CT scanners currently exhibit limited precision due to their relatively low spatial resolution, frequently exceeding 100 µm per pixel, which is insufficient for detailed ring-level or intra-ring analyses. Although advances such as X-ray microdensitometry allow substantially higher resolutions (1 µm, 3 µm, 8 µm, and 15 µm), enabling more detailed assessment of anatomical wood features, these systems involve longer acquisition and three-dimensional reconstruction times, thereby restricting their practical implementation (Jacquin *et al.,* 2017; Dierickx *et al.* 2024).

Computed Tomography (CT)

Computed Tomography (CT) employs ionizing radiation (X-rays) and electronic detectors to record density patterns and generate internal images of the material under evaluation. During scanning, the X-ray beam rotates around the object, producing multiple projections through the sample (Caldemeyer and Buckwalter 1999). The varying degrees of absorption and attenuation of X-rays by the object's tissues are processed and classified to produce maps of the internal structure, known as tomograms (Nasir *et al.* 2022; Ye *et al.* 2022). Technological development of CT scanners has been divided into four generations: the first two with parallel scanning systems, and the third and fourth with rotating fan-beam scanning, which significantly improves image resolution (Ondrejka *et al.* 2021). These innovations have expanded CT applications in the analysis of lignocellulosic materials, positioning it as an important technology in NDT, as previously verified through bibliometric analysis, in which computed tomography was identified within the most relevant cluster (Cluster I: NDE/NDT with computed tomography for defect detection), and has been considered since its early development as a fundamental nondestructive tool for wood studies.

In wood science, pioneering work by Jan Van den Bulcke and colleagues demonstrated the potential of CT for characterizing the anatomical structure of wood and analyzing growth rings (microdensity and ring width) in three dimensions, establishing a reference framework for subsequent studies (Van den Bulcke *et al.* 2009; Van den Bulcke *et al.* 2014). More recent advances highlight the advantages of high spatial resolution scanning and three-dimensional reconstructions, which allow detailed analysis of anatomical heterogeneity, ring-width series, and physical characteristics such as density profiles (Van den Bulcke *et al.* 2019). In parallel, CT has been applied to the detection and three-dimensional reconstruction of internal defects (cracks, holes, and degradations) in timber products (Zhao *et al.* 2021). It has also proven effective in assessing damage in historic timber structures (Yang *et al.* 2022; Ye *et al.* 2022; Yang *et al.* 2025) and in studying the effects and progression of fire on red spruce wood (Couceiro *et al.* 2023), enabling observation of heat-induced structural changes.

Despite these advances, CT application in wood evaluation remains limited due to high operational costs, the need for specialized equipment and software, and technical complexity. These constraints restrict its routine use in industrial environments, where faster and more economical techniques continue to predominate (Beaulieu and Dutilleul 2019). Furthermore, scanning is generally limited to small-sized samples, which hinders its application to standing trees, entire trunks, or large structural elements. Nevertheless, CT has proven useful for analyzing cross-sections and specific portions of trees (Espinosa *et al.* 2020), opening up possibilities for broader applications in wood characterization and diagnostics, particularly in research contexts where high-resolution anatomical and structural insights are required.

Wide-Angle X-Ray Scattering (WAXS)

Wide-Angle X-Ray Scattering (WAXS) analyzes Bragg peaks scattered at wide angles ($2\theta > 1°$), corresponding to sub-nanometric structures according to Bragg's law. Unlike small-angle X-ray scattering (SAXS), WAXS involves a shorter sample-to-detector distance, allowing diffraction maxima to be recorded at larger angles. In some instruments, both techniques can be combined. WAXS has become a reference tool for characterizing the crystalline structure of inorganic and organic polymer membranes (Lamba 2016).

In wood, WAXS has been applied to assess fiber deviation in and out of plane and the microfibril angle in thin veneers of *Betula pendula* Roth (Pramreiter *et al.* 2020a, 2021). However, its application is limited by the need for specialized, high-cost equipment such as high-resolution X-ray diffractometers, and by the requirement to work exclusively with thin wood sections that need prior conditioning, particularly moisture control. Consequently, as a strictly laboratory-based method, WAXS is not applicable *in situ* to trunks, beams, or standing trees.

Artificial Neural Networks (ANN)

Artificial neural networks (ANN) are employed in combination with NDT to process information and develop models aimed at analyzing, predicting, and classifying the mechanical and technological properties of wood. This computational tool simulates the human brain's processing capability through interconnected computing units ("artificial neurons") organized in layers and activated by mathematical functions that determine the output of each node (Zayegh and AI Bassam 2018).

The main ANN architectures are feedforward neural networks (FFNN), convolutional neural networks (CNN), and recurrent neural networks (RNN) (Makosso *et al.* 2025).

ANN have been applied to digital image processing for knot detection in wood (Gao *et al.* 2022), prediction of the modulus of rupture (MOR) of *P. sylvestris* (Fernández-Serrano and Villasante 2021), and estimation of the MOEd and MOR of composite panels from longitudinal vibrations and image segmentation (You *et al.* 2022; Wang *et al.* 2024). They have also been integrated with NIR spectroscopy to improve accuracy in defect detection, morphological description, and prediction of mechanical properties (Pan and Chang 2024).

Additionally, ANN have been combined with CT for defect localization in *Betula costata* Trautv. trunks and wood classification during sawing processes (Ji *et al.* 2023). Recent studies have proposed ANN models to identify optimal layer combinations in CLT panels based on strength class determination (Gezer *et al.* 2024). Moreover, multi-input residual network (MIRN) models have been developed to predict MOEd and MOR in *Picea sitchensis* (Bong.) Carrière (Ma *et al.* 2025).

Emerging Techniques in Nondestructive Testing (NDT) Applied to Wood

Although traditional NDT methods have proven effective for evaluating wood properties, characteristics, and defects, technological advances have driven the development of new techniques aimed at increasing precision and providing more detailed analysis of specific aspects of internal structure, physical-mechanical properties, and technological features of wood.

Among these emerging techniques are coded-pulse ultrasound, terahertz time-domain spectroscopy (THz-TDS), backscatter radiography, particle image velocimetry (PIV), and digital holographic interferometry (DHI). The integration of NDT with artificial intelligence methods, such as decision trees and support vector machines, also appears to be a promising strategy for advanced wood studies.

Effective applications of air-coupled coded-pulse ultrasound with complementary Golay code sequences (GCCS) include enhanced ultrasonic penetration and increased axial resolution for defect detection (Wang *et al.* 2025). THz-TDS has demonstrated utility in predicting moisture content in *Pseudotsuga menziesii* (Mirb.) Franco by analyzing absorption spectra and refractive index in samples with varying moisture levels (Duan *et al.* 2022). Particle image velocimetry (PIV) has been used to determine the elastic modulus of beams from *Eucalyptus grandis* W.Hill ex Maiden and *Pinus oocarpa* Schiede ex Schltdl., by measuring particle displacement during conventional static bending tests (Lima *et al.* 2022).

Double-exposure digital holographic interferometry (DHI) has enabled detection and quantification of defects in plywood (Pensia *et al.* 2021). Backscatter radiography has been explored by Mueller *et al.* (2024) for detecting defects and degradation in railway sleepers, particularly in the section beneath the rail, using steel plate simulations.

Other complementary approaches have also been investigated. For instance, guided ultrasonic waves have shown agreement with values obtained *via* resonance and time-of-flight methods (Bakar *et al.* 2022). Thermomechanical analysis (TMA) has been applied to assess bending strength in waterlogged archaeological *Pinus* wood (Qin *et al.* 2023). More recently, photoacoustic (PA) signal processing combined with AI algorithms, including decision trees and support vector machines, has been employed for defect detection in various materials, including wood (Balci and Mert 2025).

In the field of electrical and capacitive methods, electrical resistivity tomography (ERT) has been used to characterize moisture profiles in *Pseudotsuga menziesii* (Mirb.) Franco (Hafsa *et al.* 2023). Coplanar capacitive testing (CCT) combined with Jacobian matrices (JM) has enabled calibration of detection depth for capacitive sensors (CCS) in wood samples (Li *et al.* 2023). A device has also been developed to measure stratified moisture content on the basis of electrical conductivity in *Populus × beijingensis* and *Pinus sylvestris* var. mongolica Litv. (Wu *et al.* 2025).

In the optical and spectroscopic domain, light scattering has been applied to identify optimal wavelengths for detecting fiber orientation, showing that near-infrared light produces greater scattering in *Fagus sylvatica* L., *Pseudotsuga menziesii* (Mirb.) Franco, *Populus* sp., and *Quercus* sp. (Boivin *et al.* 2024). Short-wave infrared (SWIR) radiation has been employed to analyze transparency, absorption, and polarization of various materials, including wood (Hamdoh *et al.* 2025). Complementarily, terahertz dark-field imaging systems exploit off-axis illumination to suppress specular reflection and selectively capture scattered or diffracted signals, thereby enhancing the detection of fine features in low-contrast materials such as growth rings in wood (Chung *et al.* 2025).

These emerging techniques have been characterized as offering advantages over traditional NDT methods, such as improved resolution in density and cell wall thickness measurements through THz Time-Domain (Lei *et al.* 2022), enhanced precision and efficiency in the estimation of mechanical properties—particularly the modulus of elasticity—*via* PIV (Hélio de Novais *et al.* 2022), and real-time visualization of thermal fields and heat transfer in wood using DHI (Hortobágyi *et al.* 2021). Nevertheless, their adoption still faces significant challenges, particularly the high cost of equipment, components, and specialized software, as well as the complexity of operation, implementation, and the need for advanced training (Petrov *et al.* 2022; Kojo Chaway *et al.* 2024).

Comparative Characteristics of Nondestructive Testing Techniques for Wood Assessment

The nondestructive testing (NDT) techniques most frequently reported in the scientific literature for wood assessment are summarized in Table 7. The table provides a comparative synthesis of these methods, including their operating principles, main advantages, limitations, and typical applications in wood and tree evaluation. This synthesis facilitates the identification of the most appropriate techniques for different assessment contexts, such as structural grading, defect detection, tree inspection, and monitoring of timber structures.

Table 7. Comparative Table of NDT Techniques Applied to Wood

NDT Technique	Principle	Advantages	Disadvantages / Limitations	Typical Applications
Time of Flight (TOF)	Measurement of ultrasonic wave propagation time and velocity through wood.	Portable; estimates MOEd; applicable to trees, logs, sawn timber, CLT, glulam.	Affected by species, anisotropy, moisture, geometry, and sensor positioning; indirect defect information.	Structural grading; MOEd estimation; tree and timber evaluation; heritage structures.
Acoustic tomography	Reconstruction of internal images from acoustic velocity variations using multiple sensors.	Visualizes decay, cavities, and cracks; suitable for urban trees and heritage structures.	Requires proper sensor placement; reduced resolution in irregular trunks; equipment cost.	Urban tree risk assessment; hollow detection; historical diagnostics.
Acoustic emission (AE)	Detection of elastic waves generated by active damage processes.	Real-time monitoring; sensitive to incipient cracking; compatible with AI-based processing.	Influenced by moisture, species, geometry; complex signal interpretation.	Structural health monitoring; crack propagation; machining analysis.
Induced vibrations (transverse and longitudinal)	Measurement of natural vibration frequencies induced by impact.	Rapid estimation of MOEd; simple equipment; applicable to a wide range of wood products.	Affected by anisotropy, moisture content, and specimen size; limited capability for defect localization.	Mechanical grading, evaluation of beams and CLT panels, reused timber, musical instrument applications.
Drilling resistance (Resistograph / Pilodyn)	Measurement of resistance or penetration depth of drill bit or needle.	Portable; indirect density indicator; suitable for in situ inspections.	Semi-destructive; limited penetration depth; grain orientation sensitivity.	Tree inspection; heritage assessment; biological degradation detection.
Drilling chips and increment cores	Extraction of small cores or drilling chips to estimate density and moisture content.	Representative radial information; accurate density estimation.	Semi-destructive; requires laboratory processing.	Density and moisture monitoring in trees and timber in service.
Infrared thermography (IRT)	Detection of infrared radiation emitted from material surfaces.	Rapid; non-contact; detects moisture and surface defects.	Limited to near-surface defects; influenced by environmental conditions and low thermal diffusivity.	Moisture detection; delaminations; roof and panel inspection.
Near-infrared spectroscopy (NIR)	Analysis of molecular vibrational modes (1200–2500 nm).	Rapid; predicts chemical and mechanical properties; compatible with ANN models.	Requires robust calibration; sensitive to moisture; controlled conditions preferred.	Prediction of density, MOEd, MOR; chemical characterization; wood classification.
Ground penetrating radar	Reflection of electromagnetic	Rapid in situ scanning;	Affected by moisture and	Tree health assessment; decay

(GPR)	waves at internal interfaces.	moisture and anomaly detection; 3D reconstruction potential.	geometry; possible false positives.	and cavity detection; heritage diagnostics.
Microwave methods	Reflection and transmission of microwave electromagnetic signals (300 MHz–300 GHz).	Sensitive to dielectric properties; detects knots and voids.	Potential microstructural damage at high intensity; mechanical property reduction; experimental stage.	Dielectric characterization; defect detection; research applications.
X-ray methods (radiography)	Attenuation of ionizing radiation as a function of material density.	Direct internal visualization; detection of density heterogeneities.	Low contrast in wood; two-dimensional information; ionizing radiation exposure.	Inspection of timber elements; artifacts; cultural heritage objects.
Computed tomography (CT)	Three-dimensional reconstruction from multiple X-ray projections.	High spatial resolution; precise defect localization; anatomical analysis.	High cost; limited sample size; laboratory-based; long acquisition time.	Advanced research; fire damage analysis; internal defect studies.
Wide-angle X-ray scattering (WAXS)	Computational modeling for prediction and classification using NDT data.	Integration of multiple NDT techniques; improved MOEd and MOR prediction.	Requires large datasets; model validation needed; limited physical interpretability.	Strength grading; defect detection; structural classification.
Artificial neural networks (ANN)	Advanced optical, electromagnetic, and AI-based diagnostic approaches.	Higher resolution; innovative diagnostic capability; real-time visualization potential.	Mostly experimental; high equipment cost; technical complexity.	Advanced research; fine defect detection; moisture and microstructural analysis.
Emerging techniques (THz, PIV, DHI, backscatter radiography, ERT, CCT, PA)	Measurement of resistance or penetration depth of drill bit or needle.	Portable; indirect density indicator; suitable for in situ inspections.	Semi-destructive; limited penetration depth; grain orientation sensitivity.	Tree inspection; heritage assessment; biological degradation detection.

Literature Reviews on NDT Techniques

In recent years, several literature reviews have focused on nondestructive testing (NDT) applied to wood, addressing topics ranging from the application of NDT technologies in the preservation of historic trees and ancient structures in China (Xu *et al.* 2021), to acoustic emissions (AE) used for monitoring micro and macro cracks in *P. sylvestris* (Boccacci *et al.* 2022). Pahnabi *et al.* (2024) compiled a state-of-the-art review on the most significant NDT methods in wood, with a detailed examination of ground-penetrating radar (GPR) and ultrasonic testing (UST). Zhao *et al.* (2024) addressed the application of semi-destructive and nondestructive testing in timber constructions. Bandara *et al.* (2023) also reviewed the use of semi-destructive and nondestructive techniques for assessing the condition of wooden utility poles used in the electricity and telecommunications industries. Uldry *et al.* (2024) evaluated the application of NDT in reclaimed structural timber to analyze its fire performance, and Shi *et al.* (2025) provided a brief review of vibration-based methods applied to wood performance testing.

The literature reviews highlight the continued use of well-established NDT approaches alongside the increasing incorporation of advanced and complementary methodologies. A key trend is the integration of artificial intelligence tools to model complex nonlinear relationships in NDT data, thereby improving defect detection, material classification, and property prediction.

However, a major challenge in the application of AI-based techniques lies in the high biological variability of wood, which limits the development of models with universal calibration capability (Hwang and Sugiyama 2021). Unlike synthetic materials, wood is a natural, hierarchical, and anisotropic polymer whose structure restricts the ability of models trained on one species to maintain predictive accuracy across different materials, given the inherent heterogeneity of its physical and mechanical properties, which further hinders standardization.

To address this limitation, species may be classified into broader categories, such as softwoods and hardwoods. In softwoods, standardization may be more feasible due to the greater similarity of their properties; however, in hardwoods, the challenge is considerably greater given their wide diversity, ranging from very soft to extremely dense materials with highly variable characteristics (Hwang and Sugiyama 2021). Although similarities can be identified within certain families, such as oaks, additional factors, including growth region, significantly influence their properties, further increasing the complexity of modeling and prediction using AI-based techniques.

CONCLUSIONS

1. The bibliometric and specialized literature analysis confirms that nondestructive testing (NDT) applied to wood is a growing research field characterized by sustained output and strong international participation, particularly from Asia and Europe. Furthermore, publication sources are mainly concentrated in open-access journals, which facilitates the international dissemination of knowledge.
2. The findings indicate a transition from traditional NDT techniques toward the incorporation of emerging methodologies characterized by higher resolution, advanced sensing capabilities, and integration with artificial intelligence, enhancing wood

characterization and defect detection, although their adoption remains constrained by cost and operational complexity.

3. The concentration of scientific production in China and Europe is associated with higher levels of industrial development and the structural use of wood, whereas in Latin America, the predominance of concrete-based construction systems limits the demand for wood and related research. This highlights the need to promote the industrial utilization of wood and strengthen international collaboration to reduce regional disparities in research development.
4. The findings should be interpreted within the methodological scope of this study, particularly the use of the Scopus database, language restrictions, and the defined search strategy, which may have influenced the representativeness of the analyzed literature.
5. Despite advances in NDT, important challenges remain, particularly in the standardization of methodologies and the adaptation of AI-based approaches, largely due to the high biological variability of wood associated with its anisotropic nature, which limits model generalization, universal calibration, and predictive reliability. Although grouping species (*e.g*., softwoods and hardwoods) may improve model generalization, the challenge may be greater among hardwoods due to their wide diversity and more pronounced physico-mechanical variability; therefore, future efforts should consider the development of family-level models to achieve robust predictions.

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Conflict of Interest

The authors declare no conflicts of interest.

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