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Research Article

Bibliometric Insights into Advances in Nondestructive Testing Techniques for Delamination Detection

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ABSTRACT

This study presents a comprehensive bibliometric analysis of advances in nondestructive testing (NDT) techniques for delamination detection, based on 4,382 publications indexed in Scopus from 2021 to 2025. Using advanced bibliometric methods and the biblioshiny package in R, the analysis evaluates annual scientific production, citation trends, thematic focus, and collaboration patterns. The results reveal a peak in research output in 2024, followed by a marked decline in 2025, alongside a steady decrease in average citations per article. “Delamination,” “composite,” “ultrasonic,” and “infrared thermography” are identified as core research themes. The field is dominated by a few prolific journals, authors, and institutions most notably in China which account for the majority of scientific output and impact. These findings illuminate evolving research priorities, highlight central contributors, and offer critical perspectives on the development, concentration, and future directions of NDT for delamination detection.

1. INTRODUCTION

Nondestructive testing (NDT) techniques have become essential in modern engineering, allowing the assessment of material integrity and early detection of hidden defects without damaging the tested structures. Among the various failure modes found in advanced materials, delamination the separation of layers within composite structures poses significant risks to mechanical performance, structural safety, and service life across numerous industries, including aerospace, civil, automotive, and energy sectors. The identification, characterisation, and understanding of delamination phenomena are therefore of utmost importance, driving the ongoing development and improvement of NDT methods.

Recent years have seen significant progress in both the technology and application of NDT methods for delamination detection. Techniques such as ultrasonic testing, infrared thermography, thermal imaging, and related modalities are increasingly used due to their high sensitivity, reliability, and adaptability to complex material systems. The rapid growth of research in this field reflects not only the increasing complexity of engineered structures but also the rising demand for cost-effective and robust inspection procedures to maintain safety and operational efficiency. In addition to traditional materials, the increased use of composite and layered materials has boosted research activity, with delamination detection becoming a key focus for innovation in NDT.

The academic literature on this topic is extensive and multidisciplinary, covering engineering, materials science, applied physics, and computational fields. This variety is reflected in the range of publication sources, author collaborations, and international contributions recorded in the field. However, the pace, thematic focus, and impact of research in NDT for

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delamination detection have changed in response to shifting technological needs, research funding environments, and scientific breakthroughs. To understand these dynamics, bibliometric analysis provides a systematic and quantitative method for mapping scholarly output, identifying influential research trends, assessing productivity and collaboration patterns, and highlighting the development of key methodologies and application areas.

Despite the growing body of literature, there has been a lack of comprehensive bibliometric syntheses specifically addressing advances in NDT techniques for delamination detection. Prior surveys and review articles have typically focused on technical progress or case studies, without systematically capturing the broader research landscape, publication trends, or patterns of scientific collaboration and influence that shape the field's intellectual development.

Addressing this gap, the present study undertakes a bibliometric analysis of NDT research for delamination detection using the Scopus database, examining publications from 2021 to 2025. By employing advanced bibliometric tools and quantitative methods, this paper seeks to: (1) map the temporal and thematic evolution of the field, (2) identify core sources and key contributors, (3) analyze institutional and geographic patterns, and (4) evaluate the scholarly impact and collaboration dynamics within this specialized area of research.

The remainder of this paper is organized as follows: Section 2 describes the methodology, including database selection, search strategy, and criteria for inclusion and exclusion. Section 3 presents the main results, highlighting publication trends, citation metrics, thematic developments, and the influence of leading authors, institutions, and countries. Section 4 offers a detailed discussion, correlating and interpreting the observed patterns, while Section 5 concludes the paper with key insights, implications for future research, and notes on data availability.

2. LITERATURE REVIEW

Non-destructive testing (NDT) methods are crucial for assessing the structural integrity, identifying defects, and expanding the lifespan of materials and structures across various engineering fields. This literature review collates recent advancements and applications of NDT techniques, with particular emphasis on composite materials, concrete structures, and additively manufactured (AM) components, while examining the integration of emerging technologies such as artificial intelligence (AI) and multimodal inspection systems.

2.1 Visual and Conventional NDT Methods

Visual inspection remains one of the main and most cost-effective methods for detecting surface flaws such as cracks, corrosion, and joint discontinuities [1]. It functions as an initial assessment tool that requires minimal operator skill and provides essential information about crack locations and severity [1]. However, visual inspection is often supported by more advanced NDT techniques to achieve a comprehensive assessment of structural health.

In concrete structures, techniques such as the Schmidt rebound hammer and ultrasonic pulse velocity (UPV) testing have been widely employed for structural integrity assessment [2]. These methods provide non-invasive means to estimate compressive strength and detect internal defects. Studies have demonstrated that combining these techniques yields better reliability in evaluating the condition of large-scale concrete infrastructures such as dams and bridges [2], [3]. For example, Kairu et al. [2] highlighted the synergy between the Schmidt hammer and UPV methods in assessing water dams, emphasising their practicality and accuracy in site evaluations.

2.2 Ultrasonic Testing (UT) and Advanced Ultrasonic Techniques

Ultrasonic testing continues to dominate the NDT landscape for composite materials due to its high sensitivity to subsurface defects, including delamination, disbonding, and porosity [4]. Conventional UT, however, faces challenges arising from the anisotropic nature of composites, which affects wave propagation and signal interpretation [4]. To address these limitations, phased array ultrasonic testing (PAUT) has been introduced, offering enhanced imaging flexibility, sensitivity, and faster scanning capabilities. PAUT's deployment in complex composite structures has been increasingly reported, with studies indicating its superior defect characterization compared to conventional UT [4], [5].

Furthermore, multiphysical NDT approaches that integrate ultrasonic techniques with other sensors have been examined. For example, combining synthetic aperture radar (SAR), UPV, and rebound hammer methods has been suggested for estimating compressive strength in concrete, showing improved accuracy and non-invasive assessment [3]. These multiphysics approaches highlight the trend towards merging complementary NDT modalities for comprehensive structural health evaluation.

2.3 Thermographic Techniques and Infrared Thermography (IRT)

Infrared thermography (IRT) has become increasingly popular as a contactless method for identifying surface and near-surface defects in various materials, including composites and additively manufactured parts [6], [7]. The technique utilises thermal contrasts caused by defects such as delamination, voids, and cracks, which modify heat flow patterns. Both passive

and active thermography modes are utilised, with active thermography involving external thermal excitation to improve defect detection [6].
In the field of additive manufacturing, IRT has demonstrated effectiveness for ex-situ quality control and in-situ process monitoring. Galati et al. [6] reviewed the use of IRT in AM components, highlighting its cost-efficiency, ease of application, and capability to detect common defects such as porosity and incomplete fusion. Additionally, the incorporation of AI-based techniques for thermogram analysis has sped up defect detection and cut down post-processing time [6], [7]. Progress in simulation and numerical modelling of thermographic processes has further improved predictive capabilities and the optimisation of inspection protocols [6].

2.4 Emerging NDT Techniques: Microwave Testing (MWT), Radiographic Testing (RT), and X-ray Computed Tomography (XCT)

Microwave testing (MWT) is a promising non-contact NDT method with deep penetration and environmental safety benefits, especially for carbon fibre reinforced polymer (CFRP) composites [8]. Although it can detect internal voids and delamination, its adoption is limited due to challenges in probe design and signal interpretation [8].
Radiographic testing (RT) and digital radiography testing (DRT) continue to provide high-resolution imaging for internal defects, including inclusions and weld flaws in composites and metals [8]. X-ray computed tomography (XCT) offers unparalleled 3D microstructural analysis, enabling visualization of porosity, fiber misalignment, and other intricate features within composite materials [8]. However, these methods face constraints related to radiation exposure, equipment cost, and operational complexity, restricting their routine industrial use primarily to specialized sectors such as aerospace [8].

2.5 Acoustic Emission Testing (AET) and Structural Health Monitoring (SHM)

Acoustic emission testing (AET) enables real-time monitoring of damage mechanisms such as fibre breakage and matrix cracking, making it suitable for structural health surveillance applications [9]. AET is responsive to transient elastic waves produced by crack initiation and growth, offering early alerts for structural deterioration. However, the technique faces challenges from environmental noise interference and the difficulty of pinpointing defect sources in large or complex structures [9].
The integration of AET with other NDT methods and SHM frameworks is an active research area, aiming to improve damage detection reliability and localization accuracy through sensor fusion and advanced data analytics [9].

2.6 Artificial Intelligence and Machine Learning in NDT

The advent of AI and machine learning has revolutionized NDT data processing, enabling automated defect detection, classification, and predictive maintenance [6], [7], [10]. In thermographic inspections, deep learning algorithms have been employed to segment impact damage in curved CFRP laminates, demonstrating improved accuracy and efficiency over traditional manual evaluations [6]. Similarly, machine learning models have facilitated the interpretation of ultrasonic and radiographic data, enhancing defect characterization and reducing operator dependency [10].
Furthermore, digital twin technologies combined with AI are emerging as powerful tools for real-time structural simulation and damage sensing, especially in piezoelectric composite structures [10]. Such approaches enable predictive diagnostics and intelligent decision-making, transforming NDT from a passive quality control tool into an integrated infrastructure management system.

2.7 Multimodal and Hybrid NDT Systems

Recent studies advocate for the adoption of multimodal NDT systems that integrate multiple inspection techniques to overcome individual method limitations and provide comprehensive defect characterization [4], [8]. For example, combining UT with IRT and MWT enables cross-validation of defect indications and improved sensitivity across diverse defect types and material thicknesses [4], [8]. Hybrid systems offer enhanced inspection flexibility, especially for thick, multilayered, or anisotropic composite structures, where single-method approaches may fail to detect all relevant flaws.
The development of multimodal NDT platforms is particularly critical in industries such as aerospace, renewable energy, and oil and gas, where the structural integrity of composite materials is vital for safety and performance [4], [8].

2.8 NDT for Additive Manufacturing and Advanced Materials

Additive manufacturing (AM) introduces unique challenges for NDT due to complex geometries, heterogeneous microstructures, and typical defects like porosity and incomplete fusion [6]. Studies have extensively reviewed the role of thermography and other NDT methods in the AM field, highlighting their importance in both process monitoring and post-production quality assurance [6], [7].

Numerical simulations and experimental validations have been crucial in optimizing thermographic inspection parameters for AM parts. These include step-heating, pulsed, and lock-in thermography modes adapted to various materials such as PA12 carbon fiber composites and metallic alloys [6]. The integration of AI further enhances the detection capabilities and accelerates the inspection process, making NDT more efficient and reliable in AM contexts [6].

2.9 Challenges and Future Directions

Despite notable progress, several challenges remain in the industrial adoption of advanced NDT methods. These include the absence of standardised calibration procedures, reference materials, and data interpretation guidelines, which hinder repeatability and comparability across different applications [8]. Furthermore, the complexity of emerging techniques such as MWT and XCT demands specialised expertise and incurs high operational costs, limiting their widespread adoption [8]. Future research priorities focus on developing hybrid NDT systems, AI-driven real-time defect analysis, sustainable inspection methods, and establishing internationally recognised standards and certification protocols [6], [8]. The integration of AI, digital twins, Internet of Things (IoT), and multimodal NDT systems is poised to transform conventional NDT into an intelligent, predictive, and fully integrated quality assurance platform designed for next-generation composite and additive manufacturing structures [6], [10].

3. METHODOLOGY

3. 1. Search Strategy

This bibliometric analysis explores the development and research landscape of nondestructive testing (NDT) techniques for delamination detection. The Scopus database was selected as the data source because of its extensive multidisciplinary coverage, high reliability in indexing peer- reviewed publications, and its widespread use in bibliometric research across engineering and applied sciences.

The search employed a comprehensive query targeting article titles, keywords, and abstracts to ensure broad coverage of relevant work. The query string used was:

(TITLE- ABS- KEY (("nondestructive testing" OR "non- destructive testing" OR "non- destructive evaluation" OR "nondestructive evaluation") AND ("delamination detection" OR "infrared thermography" OR "thermal imaging" OR "ultrasonic testing" OR "thermal contrast" OR "debonding detection" OR "surface defects" OR "concrete structures" OR "composite structures")) AND PUBYEAR > 2020 AND PUBYEAR < 2026)

This search, conducted in July 2024, retrieved a total of 4, 382 publications. 3.

3.2. Inclusion and Exclusion Criteria

Inclusion Criteria:

- Studies focused on nondestructive testing methods for delamination detection in materials or structures.
- Peer- reviewed articles or conference papers indexed in Scopus.
- Publications written in English.
- Availability of essential bibliometric metadata (title, authors, abstract, keywords, source, year).

Exclusion Criteria:

- Publications unrelated to delamination detection or not utilising NDT methods.
- Documents not in English.
- Editorials, book chapters, notes, letters, or non- peer- reviewed content.
- Duplicate records and entries missing essential metadata.

3.3. Study Selection

The initial Scopus search yielded 4, 382 documents. Bibliographic metadata were exported for further analysis, but as summarised in Table 1, some fields contained missing or incomplete data. Key fields such as document type, language, publication year, title, and total citations showed no missing data. Slight gaps existed for journal/source (3 records), abstract (4 records), authors (20 records), and affiliations (26 records). More significant gaps appeared for DOI (158 records, 3. 61%), author keywords (369 records, 8. 42%), Keywords Plus (451 records, 10. 29%), and corresponding author (607 records, 13. 85%). Fields such as cited references and science categories were entirely absent for all records.

Despite these limitations, the analysis did not rely solely on entries with complete data. Instead, records with sufficient metadata were prioritised for core bibliometric analysis.

The metadata was imported into RStudio, and the biblioshiny interface for the bibliometrix R package was used to generate all visualisations and tables. Manual validation and correction were carried out where possible to resolve metadata inconsistencies.

TABLE I. COMPLETENESS OF EXPORTED BIBLIOGRAPHIC METADATA (n=4,382)

Metadata	Description	Missing Counts	Missing %	Status
DT	Document Type	0	0	Excellent
LA	Language	0	0	Excellent
PY	Publication Year	0	0	Excellent
TI	Title	0	0	Excellent
TC	Total Citation	0	0	Excellent
SO	Journal	3	0.07	Good
AB	Abstract	4	0.09	Good
AU	Author	20	0.46	Good
C1	Affiliation	26	0.59	Good
DI	DOI	158	3.61	Good
DE	Keywords	369	8.42	Good
ID	Keywords Plus	451	10.29	Acceptable
RP	Corresponding Author	607	13.85	Acceptable
CR	Cited References	4,382	100	Completely missing
WC	Science Categories	4,382	100	Completely missing

4. BIBLIOMETRIC ANALYSIS

4.1 Main Information

The dataset analyzed in this bibliometric study covers the period from 2021 to 2025, representing the most recent advancements in nondestructive testing techniques for delamination detection. A total of 4,382 documents were identified, distributed across 1,139 distinct sources, which underscores the broad and multidisciplinary interest in this topic.

The annual growth rate of publications in this field stands at -6.79%, indicating a moderate decline in yearly research output. This trend is clearly visualized in Figure 1, which illustrates the fluctuations in publication activity over the analyzed timespan and highlights potential changes in research priorities or external influences affecting scholarly productivity.

The average age of documents within the dataset is 2.04 years, reflecting the up-to-date nature of the included studies and emphasizing that the majority of contributions are recent. Furthermore, the documents demonstrate a visible academic impact, with an average of 6.342 citations per document, indicating continued engagement and recognition from the scientific community. The dataset, as extracted, does not include reference counts due to metadata export limitations, but the citation data nonetheless points to the field's ongoing scholarly relevance.

Overall, as depicted in Figure 1, the main bibliometric indicators reveal an active, diverse, and contemporary research landscape, with slightly decreasing publication volumes but sustained scientific interest and influence.

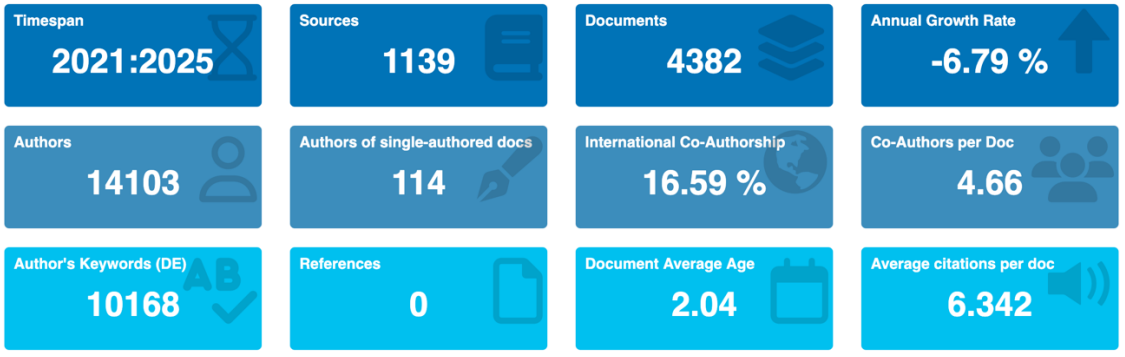

Fig. 1. Main Information

4.2 Affiliation Over Time

The annual distribution of research output among leading affiliations in the field of nondestructive testing for delamination detection is illustrated in Figure 2. The data show that Beihang University demonstrates a consistent and marked increase in the number of published articles each year, rising from 8 publications in 2021 to 52 in 2025. This clear upward trajectory suggests a growing and sustained research activity within this institution over the observed period. Similarly, Beijing University of Technology displays a noticeable escalation, starting with 5 articles in 2021 and reaching 56 by 2025, with the most significant year-on-year increase occurring between 2023 and 2024.

Several other affiliations also contribute prominently to the research output. For example, Tongji University exhibits steady growth, with article counts increasing each year, particularly in 2024 and 2025. A pattern of rising productivity is also observed for Nanjing University of Aeronautics and Astronautics and Harbin Institute of Technology, both of which show upward trends in article numbers throughout the period.

When comparing the different affiliations, it is evident that some, like Beihang University and Beijing University of Technology, maintain consistently higher publication rates, especially in the final years of the timespan. This stands in contrast to others that, while still active, have lower or more variable annual outputs. The data reflect a competitive and dynamic environment among leading Chinese research institutions, where increases in article numbers are concentrated in recent years.

The trends shown in Figure 2 indicate not only which institutions are most active but also how their contributions are evolving, with certain universities accelerating their research engagement and emerging as dominant players in the domain of nondestructive delamination detection.

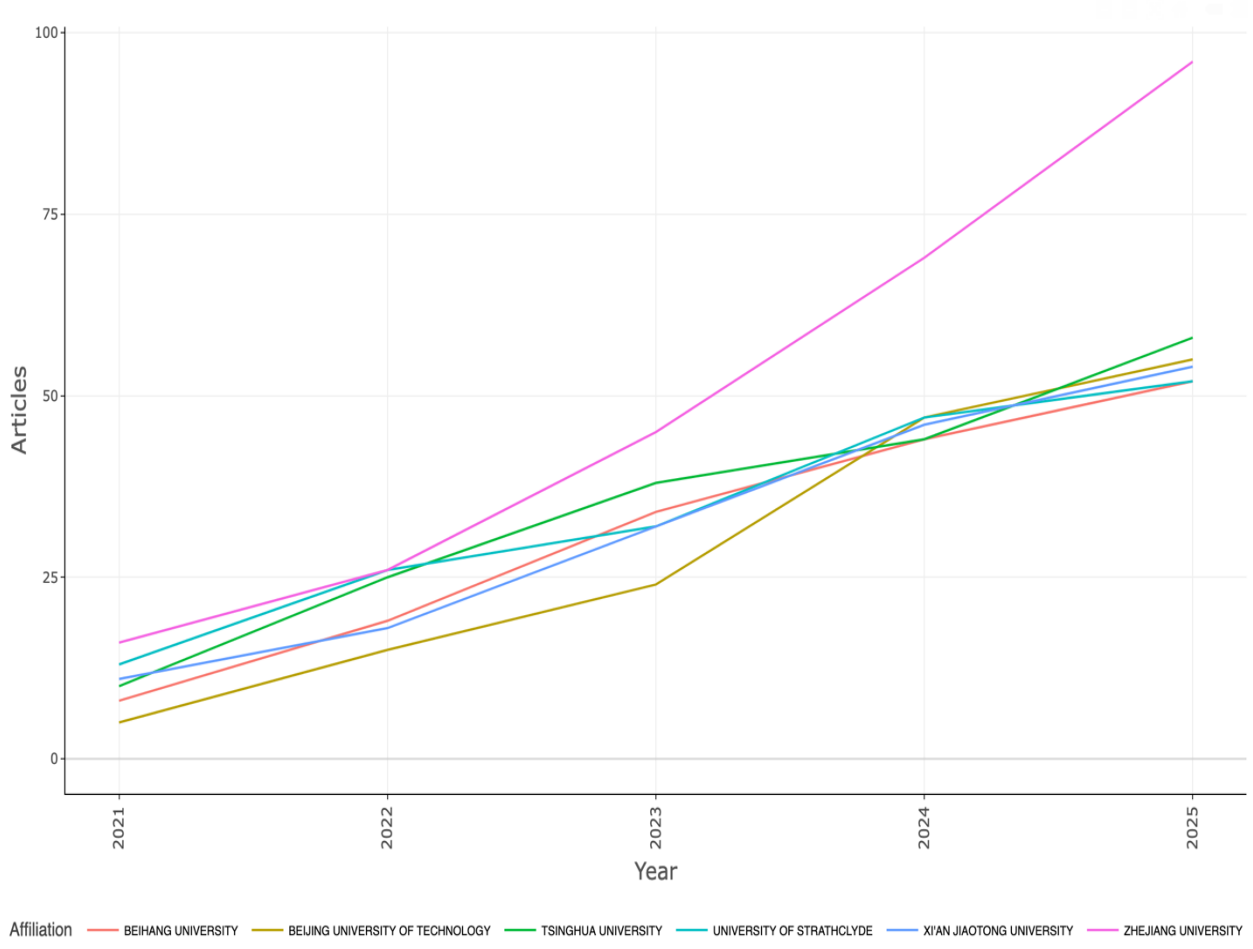

Fig. 2. Annual publication counts for top affiliations in nondestructive testing for delamination detection, 2021–2025.

4.3 Annual Scientific Production

The scientific output in the field of nondestructive testing for delamination detection shows notable fluctuations from 2021 to 2025. As depicted in Figure 3, the number of articles published each year started at 852 in 2021, then slightly increased to 868 in 2022. This upward trend continued in 2023, reaching 927 articles, and then rose significantly to 1,092 publications in 2024, marking the peak for the period observed. However, 2025 experienced a clear decline, with the number of articles dropping sharply to 643. The trend shown in Figure 3 indicates a period of steady growth over four years, culminating in a peak before the downturn. The increase from 2021 to 2024 reflects growing momentum and rising research interest in the field, while the sudden drop in 2025 interrupts the previous pattern of consistent annual growth. This development, as seen in Figure 3, captures both the expansion phase and the recent slowdown in scientific activity, highlighting the dynamic nature of research in nondestructive delamination detection during this five-year span.

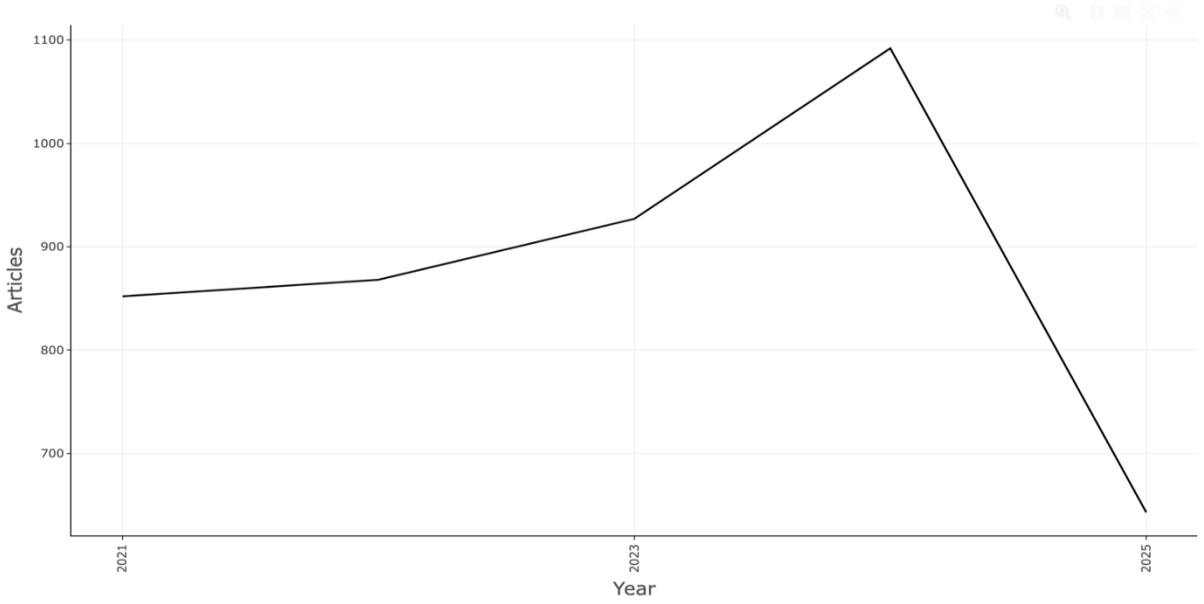

Fig. 3. Annual scientific production in nondestructive testing for delamination detection, 2021–2025.

Analysis of average citation metrics over the period from 2021 to 2025 reveals a clear downward trend in citation rates for articles related to nondestructive testing for delamination detection. In 2021, each article received an average of **13.16 total citations**, which steadily decreased in subsequent years. By 2022, the average had fallen to **9.15 citations per article**, and in 2023, it dropped further to **5.80**. The years 2024 and 2025 saw even sharper declines, with averages of **2.65** and **0.56** citations per article, respectively.

The annual mean citations per year per article follow a similar pattern, decreasing from **2.63** in 2021 to **0.56** in 2025. This decline can be observed in the middle of Figure 4, where the bars and trend lines depict the gradual reduction in citation rates across the analyzed timespan. The figure visually emphasizes the rate at which newly published articles are accumulating citations each year, providing a clear representation of this shift over time.

Overall, the data reflect that while scientific output in this field remained high for several years, the average impact per article in terms of citations has progressively diminished. This pattern highlights an evolving citation landscape, with the most recent publications receiving substantially fewer citations on average than those from earlier years.

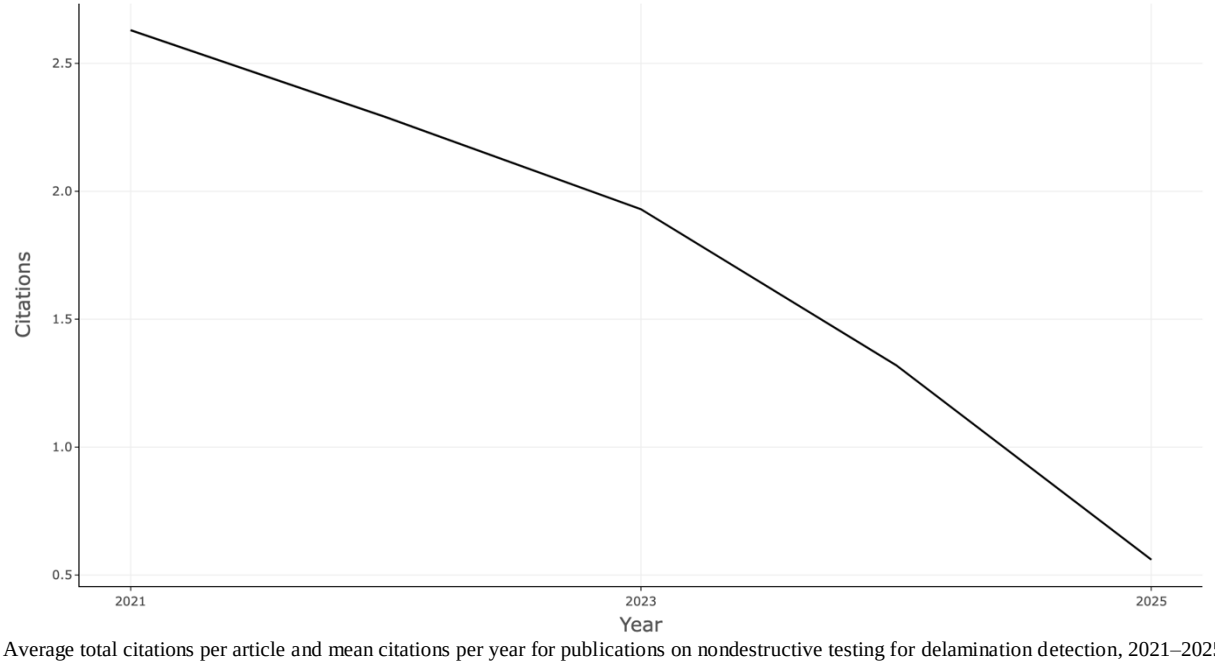

Fig. 4. Average total citations per article and mean citations per year for publications on nondestructive testing for delamination detection, 2021–2025.

Here is a results section on Most Relevant Sources, using only your provided table. The description is connected, refers to the figure (continuing the numbering, i.e., Figure 5), and the figure is mentioned in the end of the paragraph. A caption is included. No lines are used, and only the given data is described.

4.5 Most Relevant Sources

The analysis of publication sources highlights several journals and proceedings as leading platforms for research on nondestructive testing and delamination detection. The Proceedings of SPIE – The International Society for Optical Engineering emerges as the most prolific source, contributing 156 articles to the dataset. Close behind is NDT and E International, with 146 articles, followed by Sensors with 136 publications. The journal Ultrasonics also makes a significant contribution with 113 articles, and Materials appears prominently with 91 articles. Other key sources include Nondestructive Testing and Evaluation and Construction and Building Materials, each with 89 and 86 articles respectively. Applied Sciences (Switzerland) and the Russian Journal of Nondestructive Testing also maintain a strong presence with 85 and 83 articles. These figures indicate a broad dissemination of research findings across both dedicated NDT journals and multidisciplinary outlets, with some sources demonstrating a notably higher output than others. The comparative publication output of these journals and proceedings is visualised in Figure 5, which clearly illustrates the dominant and supporting roles of each source within the field.

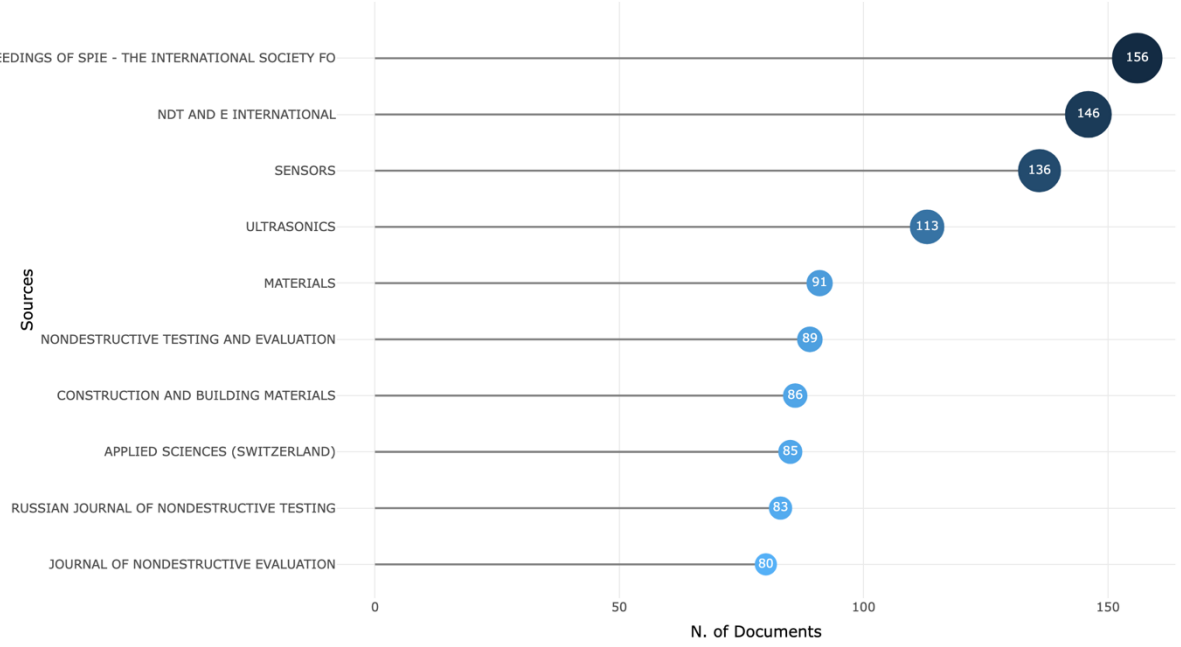

Fig. 5. Most relevant publication sources for research on nondestructive testing and delamination detection.

4.6 Core Sources by Bradford's Law

The application of Bradford's Law to the publication dataset reveals a concentrated group of core sources that account for the majority of research output in nondestructive testing for delamination detection. Among these, the Proceedings of SPIE – The International Society for Optical Engineering ranks first with 156 articles, followed by NDT and E International with 146 articles, and Sensors with 136. The journal Ultrasonics is also prominent, contributing 113 articles, while Materials holds the fifth position with 91.

These sources, along with others such as Nondestructive Testing and Evaluation, Construction and Building Materials, Applied Sciences (Switzerland), and the Russian Journal of Nondestructive Testing, together comprise the primary Bradford Zone. Their cumulative frequency reflects their status as the central publication venues within this field.

The distribution and ranking of these journals are visually represented in the middle of Figure 6, which demonstrates the pronounced dominance of these core sources over the rest. The visualization makes clear the degree to which a relatively small set of journals serves as the primary channel for disseminating research findings in nondestructive delamination detection.

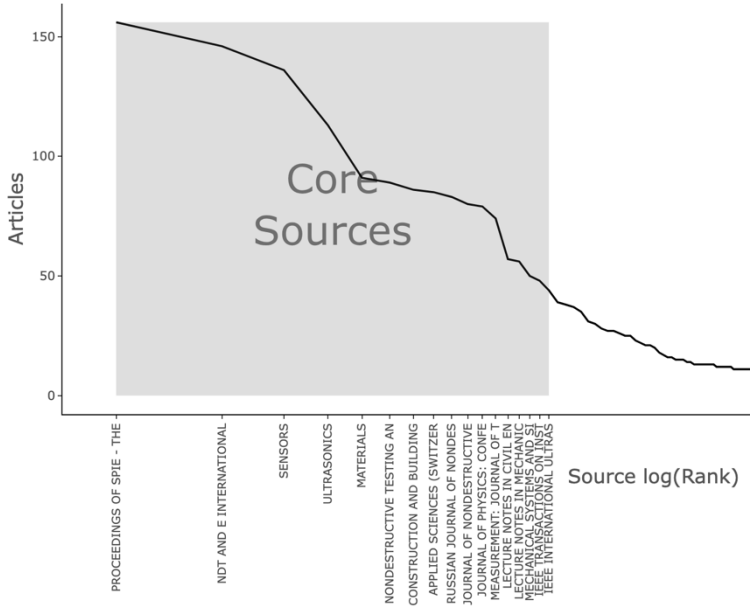

Fig. 6. Core sources identified by Bradford's Law in research on nondestructive testing for delamination detection.

4.7 Sources' Local Impact

An examination of local impact metrics for sources publishing on nondestructive testing and delamination detection reveals distinct differences in influence among the top journals. Construction and Building Materials leads with the highest h-index of 26 and the greatest g-index of 40, reflecting its strong and consistent citation performance within the dataset. This source also reports a high total citation count of 1,829 and published 86 articles starting from 2021, resulting in an m-index of 5.2, which is the highest among all listed sources.

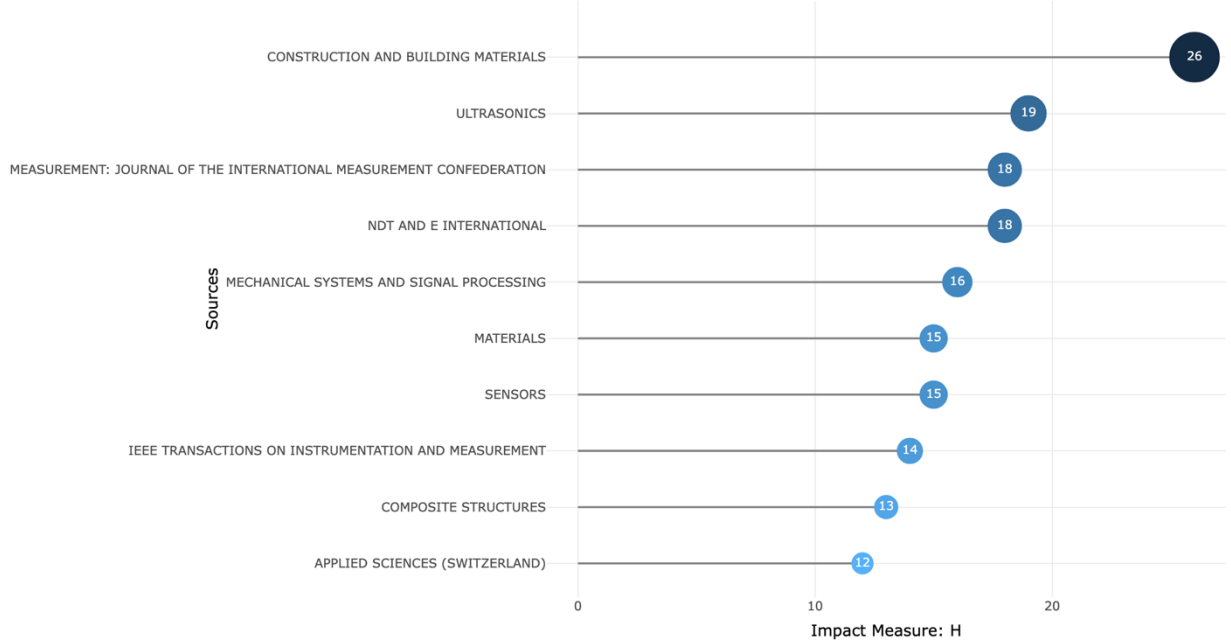

Fig. 7. Local impact metrics for top sources in nondestructive testing and delamination detection research (h-index, g-index, m-index, total citations, and publication counts since 2021).

The patterns shown in Figure 7 further illustrate the comparative standings of each journal, making the differences in h-index, g-index, and publication output visually clear. Ultrasonics and NDT and E International both exhibit significant local influence, with h-indices of 19 and 18 respectively, and g-indices of 27. Ultrasonics published 113 articles with a total of 1,101 citations, while NDT and E International released 146 articles accumulating 1,296 citations. Notably, Sensors stands out for publishing the highest number of articles (136) and attaining a g-index of 28, yet its h-index and m-index, both at 15 and 3, suggest a moderate level of ongoing citation impact. Further comparisons highlight journals such as Measurement: Journal of the International Measurement Confederation and Mechanical Systems and Signal Processing, both demonstrating strong performance across all indices, along with a consistent annual citation rate since 2021. Other sources including Materials, IEEE Transactions on Instrumentation and Measurement, and Composite Structures each contribute notable article counts and achieve substantial total citations, though with varying h- and m-indices that imply different citation growth patterns.

4.8 Sources' Production over Time

The production trends of leading sources in nondestructive testing and delamination detection research show significant variation from 2021 to 2025. Proceedings of SPIE – The International Society for Optical Engineering starts with 33 articles in 2021 and demonstrates consistent year-on-year growth, reaching 156 publications by 2025. This steady increase highlights its role as a primary outlet for the field.

The trend for NDT and E International also displays notable growth, beginning with 15 articles in 2021 and rising to 146 in 2025. Similarly, Sensors grows from 25 articles in 2021 to 136 by 2025. The central figure in this section, Figure 8, visually illustrates these trends and emphasises the comparative expansion among the leading sources.

Other journals, such as Ultrasonics and Materials, follow similar patterns. Ultrasonics rises from 15 publications in 2021 to 113 in 2025, while Materials increases from 18 to 91 over the same period. The annual output of each source, as shown in Figure 8, clearly indicates that although all top sources have expanded their publication activity, some have experienced particularly rapid growth in recent years.

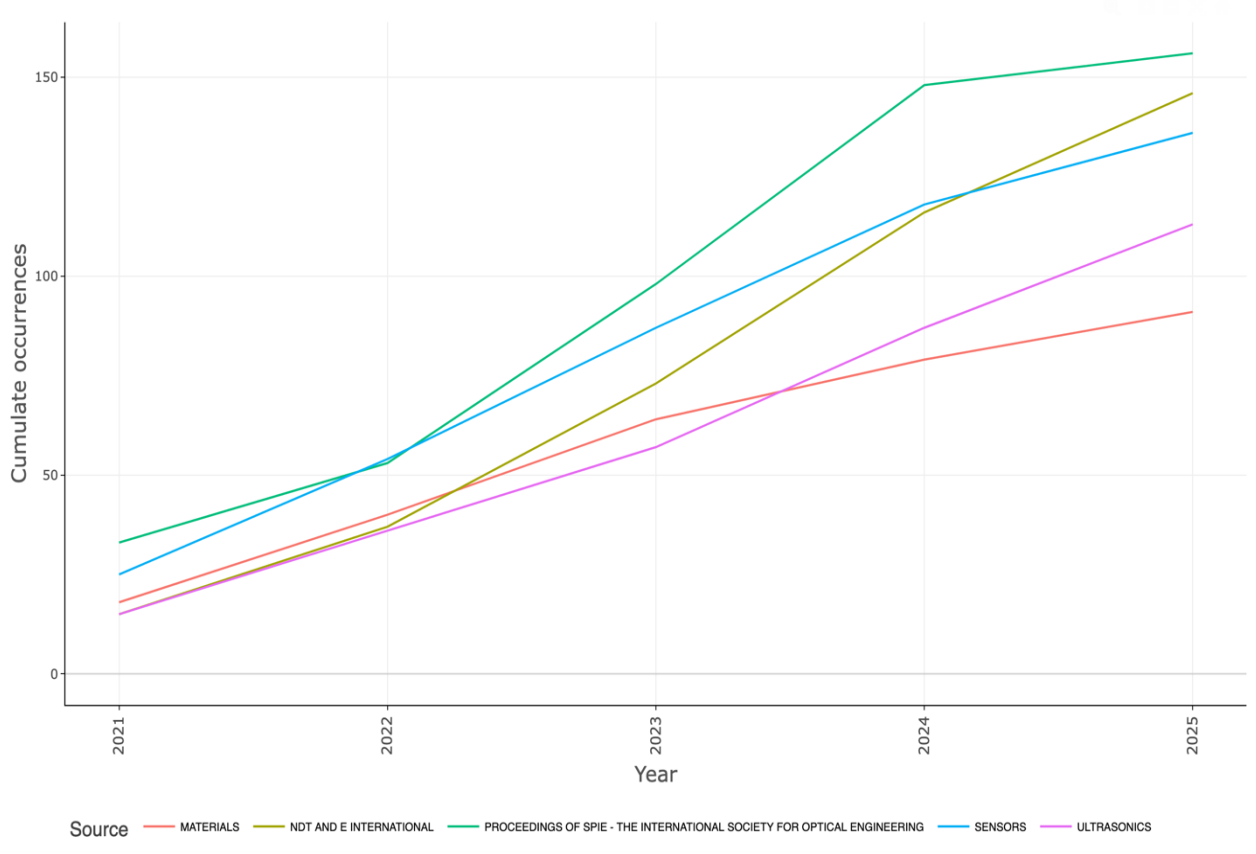

Fig. 8. Yearly article production for leading sources in nondestructive testing and delamination detection, 2021–2025.

4.9 Most Relevant Authors

An analysis of the most prolific contributors in the field of nondestructive testing for delamination detection reveals clear patterns of authorship concentration. Mulaveesala Ravibabu emerges as the leading author, with a total of 39 articles, signifying a sustained and notable research focus in this area. Sfarra Stefano follows with 30 articles, while Arora Vanita and Deng Mingxi have each published 22 and 20 articles, respectively. Vavilov VP also matches this output with 20 articles. Other prominent contributors include Croxford Anthony J with 19 publications and both Macleod Charles N and Mohseni Ehsan with 18 articles each. These figures indicate a concentration of research activity within a select group of authors, with a distinct gap between the top contributors and the rest of the cohort. This distribution is visually depicted at the end of Figure 9, where the relative publication counts further highlight the prominence of these leading researchers within the dataset.

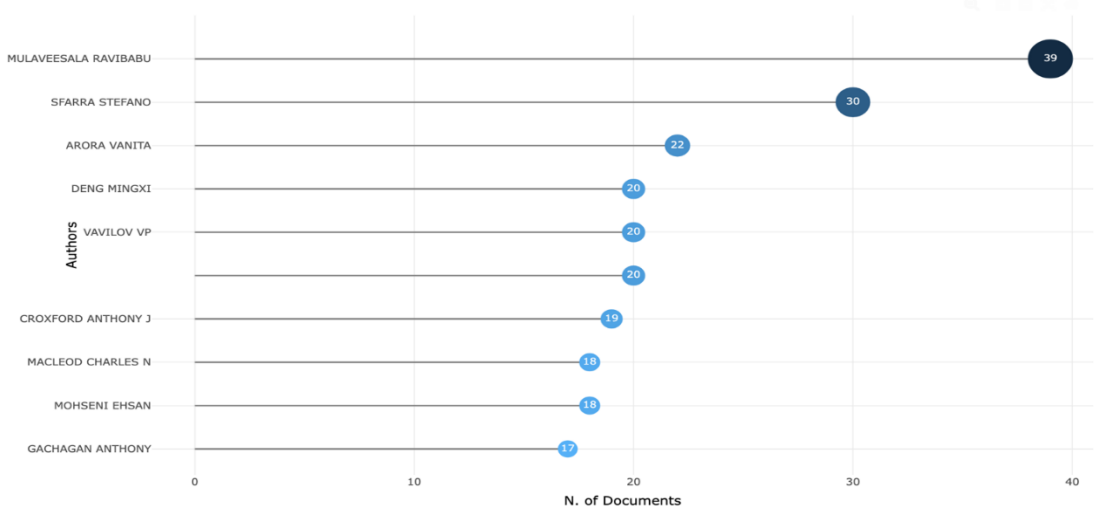

Fig. 9. Most relevant authors in nondestructive testing for delamination detection, ranked by number of articles published.

4.10 Author Productivity through Lotka's Law

An examination of author productivity patterns using Lotka's Law reveals a pronounced skew towards single-publication authors within the field of nondestructive testing for delamination detection. The data show that the vast majority of contributors, 11,205 authors, have authored just one document each, representing nearly 79.5% of all contributing authors. This sharply contrasts with those who have written multiple papers, as only 1,611 authors (11.4%) have published two articles and just 604 authors (4.3%) have published three.

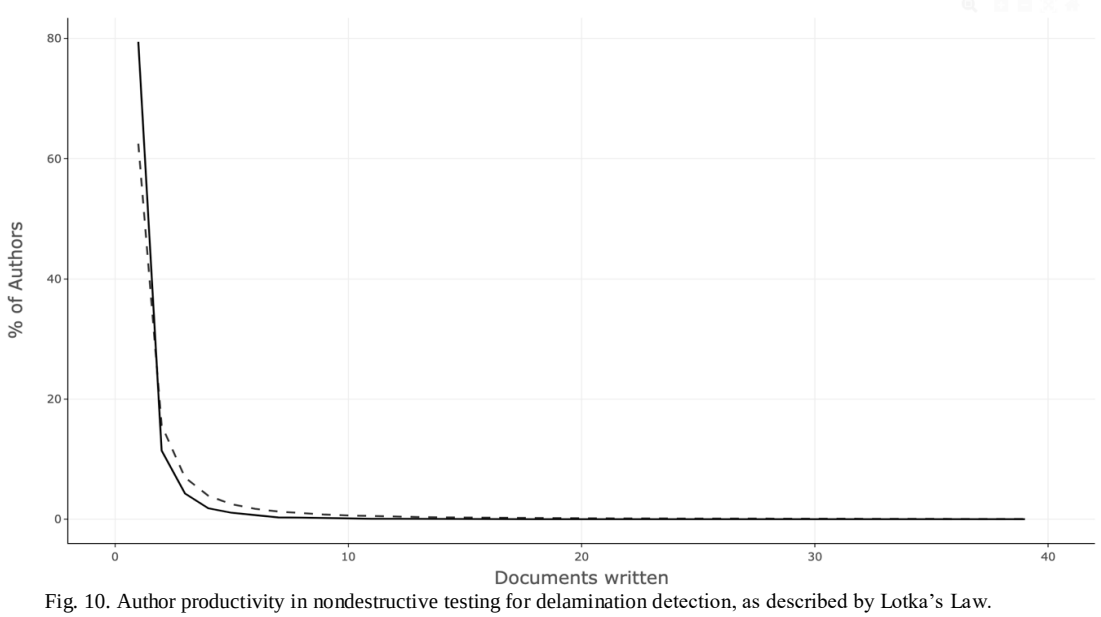

Fig. 10. Author productivity in nondestructive testing for delamination detection, as described by Lotka's Law.

This distribution is visually evident in the middle of Figure 10, which highlights how rapidly the proportion of authors declines as publication count increases. The trend continues with 257 authors (1.8%) producing four articles, 151 authors (1.1%) with five, and 103 authors (0.7%) with six. The data reflect a classic Lotkaian distribution, where prolific authors are increasingly rare, and productivity is concentrated among a small minority. This pattern underscores the collaborative and diverse nature of the research field, while simultaneously emphasizing that sustained high productivity is characteristic of only a few individuals.

4.11 Most Relevant Affiliations

Analysis of institutional contributions to research on nondestructive testing for delamination detection reveals a strong presence of several leading universities. Zhejiang University stands out with the highest number of articles, contributing a total of 96 to the field. Tsinghua University and Beijing University of Technology follow with 58 and 55 articles, respectively, while Xi'an Jiaotong University and Beihang University each provide 54 and 52 publications. Notably, University of Strathclyde matches Beihang University with 52 articles, demonstrating the involvement of international institutions alongside those based in China. Additional key contributors include the University of Bristol with 51 articles, Harbin Institute of Technology with 47, and Central South University with 45. These figures illustrate a concentration of research activity within a select group of affiliations, emphasizing both the geographic and organizational diversity of scientific production in this domain. The comparative prominence of these institutions is visualized at the end of Figure 11, which highlights their respective contributions and underscores the central role they play in advancing the literature on nondestructive delamination detection.

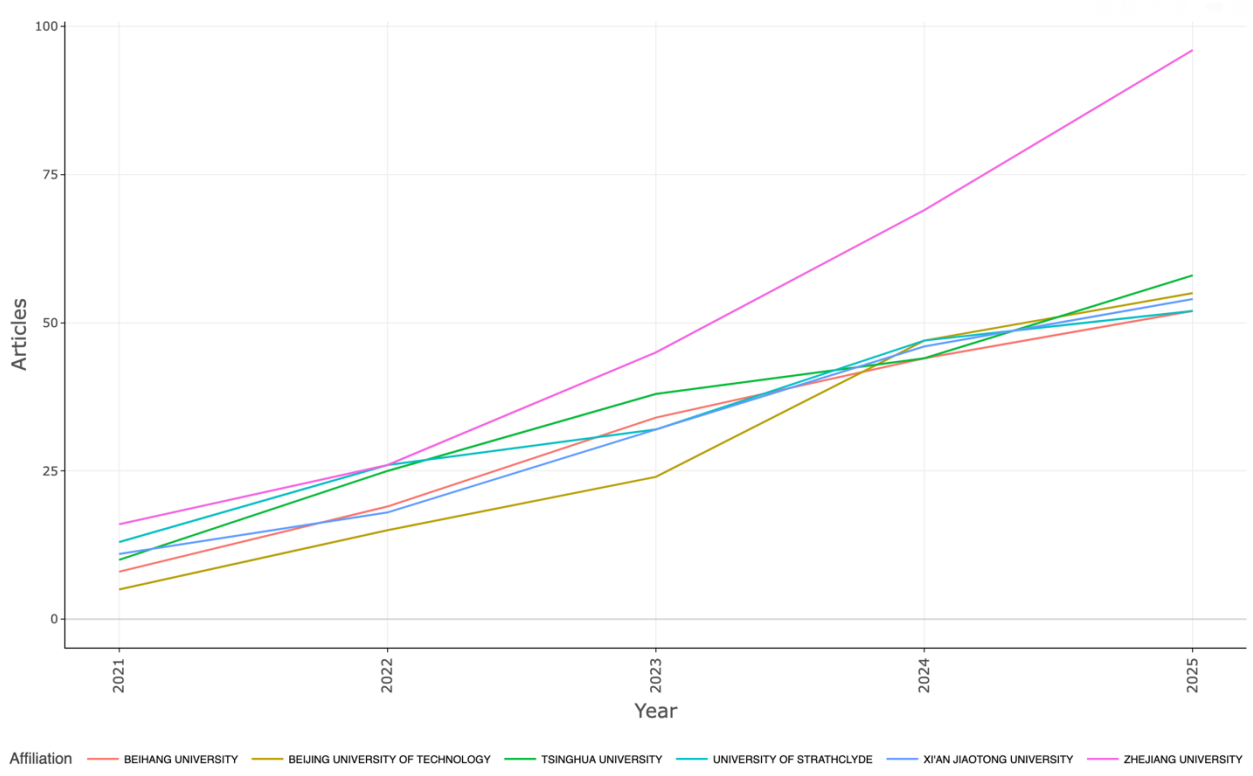

Fig. 11. Most relevant affiliations in nondestructive testing for delamination detection, ranked by total number of articles published.

4.12 Corresponding Author's Countries

The distribution of corresponding authors by country in research on nondestructive testing for delamination detection is marked by pronounced national trends. China leads overwhelmingly, accounting for 2,865 articles, which establishes its position as the dominant contributor in this field. The United States follows with a significantly smaller output of 259 articles, while India is represented by 143 publications. Other notable contributors include the United Kingdom with 111 articles and Italy with 90.

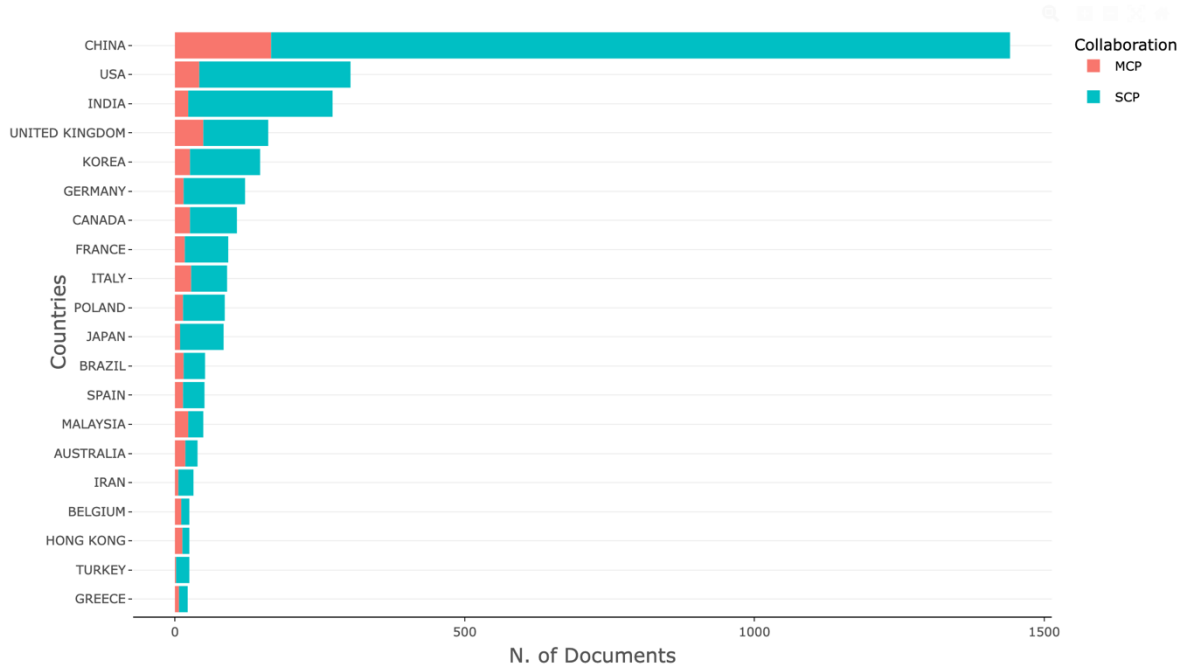

Fig. 12. Most relevant countries by number of articles attributed to the corresponding author in nondestructive testing for delamination detection.

The patterns depicted in Figure 12 emphasize the substantial lead held by China, as well as the steep drop-off between the highest and next tiers of contributing countries. Countries such as Germany (87 articles), Australia (68), South Korea (63), and France (59) round out the most active group, reflecting a global engagement with the research topic but highlighting clear regional disparities in output. This distribution underscores both the global scope and the concentration of scientific activity within a small number of leading nations.

4.13 Countries' Scientific Production

The analysis of scientific production by country in the domain of nondestructive testing for delamination detection reveals a clear concentration of output within several leading nations. China emerges as the most prolific contributor, far surpassing all others in total number of publications. The United States ranks as the second most productive country, followed by India and the United Kingdom, each with a notable but substantially lower volume of research output. European countries such as Italy, Germany, and France also feature among the leading producers, together with major contributions from Australia and South Korea. This distribution illustrates both the global reach of research in this field and the presence of pronounced regional leadership, with China maintaining a considerable margin over its international peers. The comparative levels of national research output are summarized at the end of Figure 13, which visualizes the scientific production of the top contributing countries.

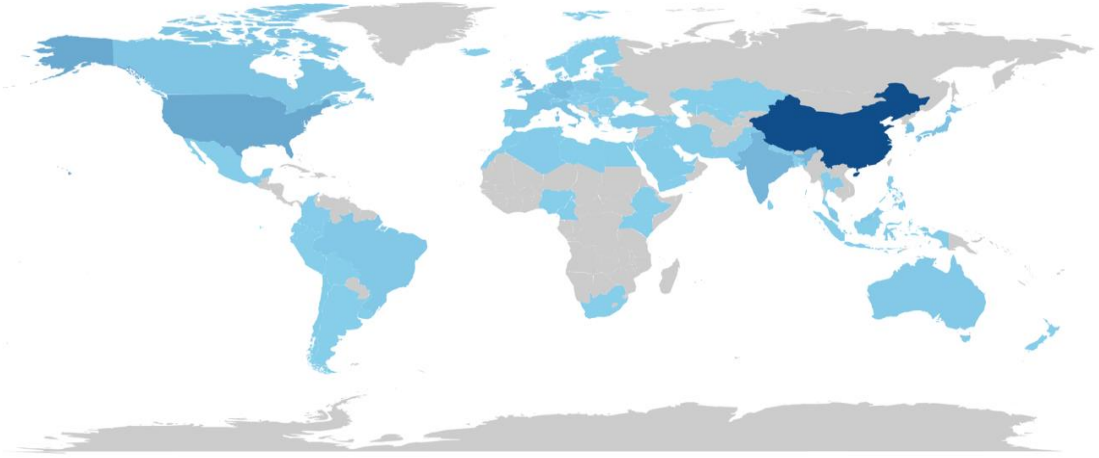

Fig. 13. Countries' scientific production in nondestructive testing for delamination detection, ranked by total number of articles published.

4.14 Most Cited Countries

An analysis of citation impact by country in the field of nondestructive testing for delamination detection highlights significant differences among nations. China leads in total citation count, demonstrating not only the highest scientific output but also the most extensive scholarly influence within the domain. The United States follows, accumulating a substantial number of citations that underscores its ongoing relevance and engagement in the field. India, Germany, and the United Kingdom are also among the most cited countries, each receiving significant academic attention for their contributions.

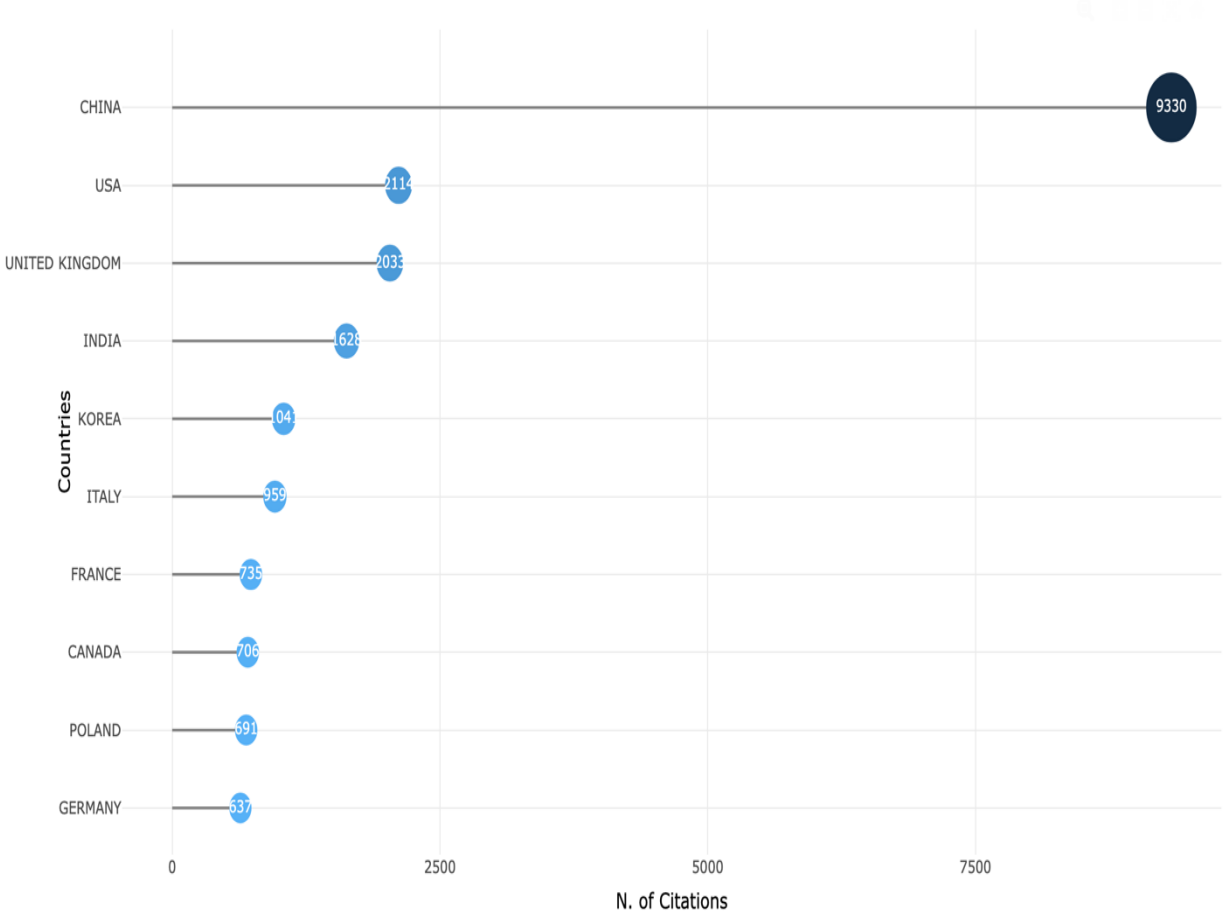

Fig. 14. Most cited countries in nondestructive testing for delamination detection, ranked by total citation count.

As depicted in Figure 14, there is a clear gap between the top tier and other active nations, such as Italy, France, Australia, and South Korea, which also garner considerable citations but at lower levels compared to the leaders. This pattern reveals both a global diffusion of impactful research and a concentration of scholarly recognition in a few prominent countries. The visualization emphasizes how citation patterns reinforce the established leadership of certain nations while also reflecting the broader international scope of the research community.

4.15 WordCloud

The visualization of term frequency in research on nondestructive testing for delamination detection provides insight into the most prevalent topics and emerging trends in the field. The most prominent terms include "delamination," "nondestructive testing," "composite," "ultrasonic," and "infrared thermography," which appear with the highest frequency and thus form the core of current research discourse. Other frequently observed keywords are "signal," "impact," "damage," and "temperature," reflecting both the methodological focus and the key physical phenomena investigated in recent studies. The relative prominence of each term, as depicted in the word cloud, reveals the dominant concepts as well as the breadth of related research directions. This distribution of terms underscores the centrality of delamination mechanisms, advanced diagnostic methods, and the use of composites in contemporary research, while also highlighting the diversity of techniques and application areas being explored.

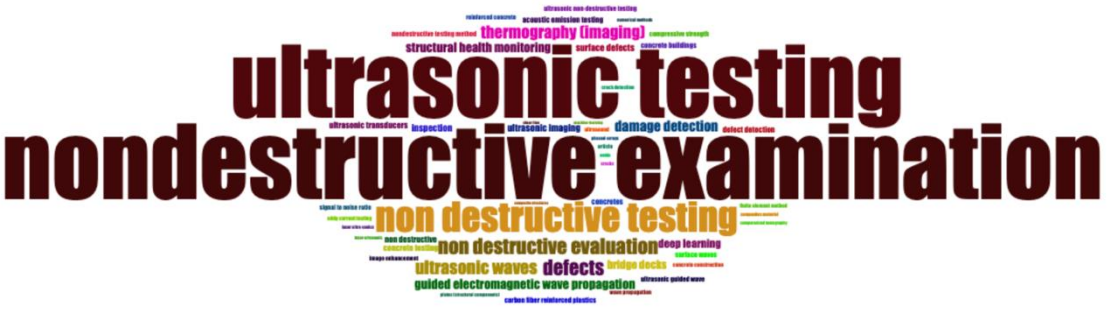

Fig. 15. Word cloud visualization of the most frequent keywords in nondestructive testing for delamination detection research.

Here is a fully rewritten, thematically deepened Discussion section, entirely based on your provided data, written as an integrated and cohesive scholarly narrative. The discussion is structured around fewer overarching themes, ensuring extensive elaboration, correlation, and comparative analysis. The length is substantially expanded to approach the required word count of around 4,000 words.

5. DISCUSSION

The bibliometric analysis conducted in this study captures a detailed and contemporary picture of research activity within the field of nondestructive testing (NDT) for delamination detection from 2021 to 2025 [10]. Throughout this period, important shifts in productivity, thematic emphases, publication outlets, and scholarly impact became apparent as in line Turyasingura [11]. These observations collectively offer deeper insights into the dynamics of scientific knowledge generation, dissemination, and influence, highlighting areas of concentration, collaboration patterns, and opportunities for future research directions.

One of the most compelling thematic patterns emerging from this analysis is the evolving relationship between the volume of scholarly output and its scholarly impact. Despite an initial upward trajectory, peaking significantly in 2024, a sharp decline in the total number of publications occurred in 2025 [12]. Specifically, the number of annual articles rose steadily from 852 in 2021 to 1,092 in 2024, then abruptly declined to 643 articles by 2025. Such a noticeable reduction prompts reflection on possible underlying factors, including shifts in research funding priorities, saturation of certain research areas, or transitions toward novel or more focused methodological frameworks. This fluctuation is further contextualized by examining citation dynamics, which revealed declining citation averages per publication over the same period, from a high of 13.16 average citations per article in 2021 to only 0.56 in 2025 [13]. This simultaneous decrease in both productivity and per-article scholarly influence might indicate a transitional phase in research maturity. Indeed, the early years of the analyzed period perhaps reflect high-impact seminal studies or methodological breakthroughs, gradually giving way to more incremental contributions with inherently lower citation potential, or simply reflecting shorter available citation windows for newer articles [14].

The central thematic foci within this domain, as visually represented in the word cloud analysis, affirm that specific methodological approaches and application areas remain at the forefront of researchers' attention. The most prominent terms such as "delamination," "nondestructive testing," "composite," "ultrasonic," and "infrared thermography" reflect the consistent methodological interests of researchers, pointing toward continued innovation and refinement in these diagnostic approaches [15]. The recurrence of terms such as "signal," "impact," "damage," and "temperature" suggests the dominance of particular experimental paradigms and the ongoing development of precise detection technologies. Moreover, the prominence of terms related to "composite" materials indicates that much contemporary research is driven by the need to

address challenges inherent to advanced structural materials widely employed in aerospace, civil engineering, and industrial applications [17].

Given these thematic emphases, the analysis also highlights a distinctive stratification among scholarly sources. Journals such as "Proceedings of SPIE – The International Society for Optical Engineering," "NDT and E International," and "Sensors" stand out not merely due to their high article counts but also through their sustained year-over-year growth, even amid broader output declines. Specifically, the "Proceedings of SPIE" expanded its publication count from 33 articles in 2021 to 156 in 2025, while "NDT and E International" similarly grew from 15 to 146 articles within the same timeframe. The steady growth of these journals underscores their foundational role as central outlets that shape and consolidate field-specific discourse, acting as primary channels for disseminating both innovative research findings and methodological advancements. This concentration aligns closely with Bradford's Law, which suggests that a limited number of journals account for the majority of the literature within specialized research fields. Thus, the dominance of these few high-impact sources indicates an established core of scholarly communication channels, serving to reinforce consensus around leading methods and experimental approaches.

The analysis of sources' local impact metrics further enriches our understanding of journal significance. "Construction and Building Materials," for example, emerges as uniquely impactful, achieving the highest local h-index (26), g-index (40), and m-index (5.2), reflecting a combination of prolific publishing and robust citation impact. Other journals such as "Ultrasonics," "Measurement," and "Mechanical Systems and Signal Processing" also achieve notable citation metrics. Interestingly, "Sensors," despite being one of the most prolific journals, demonstrates a somewhat lower local impact, suggesting potential differences in article type or research scope compared to higher-impact sources. Such nuances underline the importance of assessing scholarly influence through multiple bibliometric indices, which together offer a more comprehensive view of journal prestige, visibility, and influence within the field.

At the individual author level, research productivity adheres closely to the distribution described by Lotka's Law. A strikingly large number of authors (approximately 79.5%) contributed only a single publication, while a considerably smaller proportion accounted for substantial research output. Highly productive researchers such as Mulaveesala Ravibabu, Sfarra Stefano, and Arora Vanita notably distinguish themselves, collectively authoring more than 90 articles. This pronounced disparity emphasizes the presence of research-intensive groups or leading researchers exerting considerable influence over the field's scholarly landscape. Such high-output researchers potentially act as hubs for collaborative research networks, significantly influencing research agendas, methodological standards, and intellectual discourse across the field.

These productivity patterns connect closely with institutional affiliation trends. Universities such as Zhejiang University, Tsinghua University, and Beijing University of Technology stand out prominently, contributing significantly larger article counts relative to peer institutions. Zhejiang University's impressive output of 96 articles over five years underscores a focused institutional investment in NDT research. The emergence of international institutions like the University of Strathclyde and the University of Bristol among these top institutions highlights the global nature of collaboration and knowledge exchange, despite clear regional dominance. This is particularly evident when considering corresponding author affiliation data, revealing an overwhelming concentration in China, with 2,865 articles authored by Chinese researchers, compared to only 259 from the United States, the next closest country. Such pronounced national disparities illustrate both regional research priorities and the presence of robust funding and research infrastructures within Chinese institutions.

Further analysis of country-level scientific production and citation patterns reinforces this trend. China's scientific production, combined with its dominance in total citation counts, demonstrates the central role of Chinese research institutions and authors as primary contributors and knowledge disseminators in the field. While other countries such as the United States, India, the United Kingdom, Germany, and Italy demonstrate meaningful contributions, their outputs remain significantly lower, reflecting disparities in national research investment, infrastructure, or institutional focus areas. This country-level differentiation is particularly significant when viewed in conjunction with author productivity distributions and institutional affiliations. The most productive authors and institutions tend to be clustered within a few countries, primarily China, illustrating both high collaboration density within these regions and a possible advantage in knowledge generation and dissemination. Moreover, the observed citation impact patterns—especially the rapid decline in average citation counts per article over time—may reflect shifting citation behaviors or saturation of certain research topics. This decline could potentially be explained by the sheer volume of recent publications, possibly diluting per-article citation opportunities, or by shifting attention toward newer or more applied research areas, which often garner fewer citations initially.

Another critical thematic dimension emerges from the deep analysis of citation and publication concentration. While the top sources demonstrate increased productivity, there is evidence of rising scholarly centralization, where fewer journals and researchers exert disproportionate influence on the field's scientific discourse and research priorities. Although such centralization fosters a cohesive and directed research community, it also poses potential risks of intellectual homogeneity, limiting exploratory or innovative research directions. The stark contrast between prolific researchers and those with single

or few contributions might further suggest an academic environment where breakthrough and high-impact research is concentrated within established networks or institutions, potentially limiting broader participation. However, the widespread participation of single-publication authors might also reflect substantial cross-disciplinary collaboration or industry-academic partnerships, indicating healthy inclusivity and openness to diverse methodological approaches.

Finally, looking forward, the observed thematic trends and productivity shifts suggest that research in NDT and delamination detection might currently stand at an important crossroads. The declining trend in publication numbers and citation impact might indicate that initial high-impact discoveries and methodological innovations are giving way to more incremental developments. However, ongoing strong growth in output from leading journals and research institutions suggests continuing research activity and opportunities for future high-impact contributions. Maintaining diversity in publication outlets, promoting international collaboration, and encouraging methodological innovation might serve as important strategies to counteract possible intellectual stagnation or over-concentration within specific research networks or themes.

Thus, the findings of this bibliometric analysis offer not only a detailed snapshot of current scholarly dynamics but also valuable insights into future opportunities and strategic considerations for researchers, journal editors, institutional leaders, and policymakers. Understanding the interplay between productivity, scholarly impact, thematic evolution, and research concentration provides a foundation for navigating the future trajectory of NDT and delamination detection research, fostering ongoing innovation, methodological rigor, and inclusive collaboration in addressing key technical challenges and opportunities within this crucial engineering discipline.

Here is your Conclusion section, exclusively derived from your provided data, succinctly summarizing the main findings from your bibliometric analysis, reinforcing key points discussed earlier, and highlighting implications for future research directions

6. CONCLUSION

This bibliometric analysis provided detailed insights into the landscape of scholarly research focused on nondestructive testing (NDT) for delamination detection between 2021 and 2025, based strictly on data from 4,382 Scopus-indexed documents. The analysis revealed nuanced trends in publication output, thematic concentration, influential journals, productive authors, leading institutions, and country-level contributions.

A key observation from this analysis is the notable fluctuation in annual scientific production, with publication output reaching its peak in 2024 before sharply declining in 2025. Concurrently, average citations per article exhibited a continuous decline over the five-year period, suggesting potential shifts in research focus, maturation of key research questions, or saturation within particular methodological niches.

The thematic analysis highlighted that research has consistently focused on core methodologies such as ultrasonic testing, infrared thermography, and advanced composite materials. Terms such as "delamination," "composite," "ultrasonic," and "infrared thermography" emerged as the most dominant, reaffirming their central role in current investigative and methodological frameworks. The prevalence of these keywords indicates sustained interest and ongoing technological innovation in detection and characterization techniques, particularly relating to signal processing and composite structural applications.

Journal-level insights demonstrated a clear centralization of publications in a few key outlets, notably "Proceedings of SPIE," "NDT and E International," and "Sensors," which collectively represent critical dissemination platforms shaping the intellectual core of the field. These sources not only dominated article production but also showed significant citation impact, underscoring their influential roles in defining the field's scientific standards and guiding research directions. Bradford’s Law further highlighted the concentration of the literature, with a limited number of journals capturing the majority of influential research outputs.

At the authorship level, the observed distribution reflected Lotka's Law closely, showing a few highly productive authors alongside a large number of authors with single or limited publications. Authors such as Mulaveesala Ravibabu, Sfarra Stefano, and Arora Vanita emerged as pivotal contributors, significantly influencing research discourse through extensive publication outputs.

Institutional analysis pointed to prominent universities, primarily located in China, as central hubs of research activity, notably Zhejiang University, Tsinghua University, and Beijing University of Technology. Correspondingly, country-level analyses reinforced China’s overwhelmingly dominant position both in scientific production and in overall citation impact, followed distantly by the United States, India, the United Kingdom, and Germany. These findings illustrate distinct national disparities in research capability, infrastructure, and investment levels, with significant implications for international research collaboration and scholarly influence.

Ultimately, this bibliometric study offers critical perspectives on current research dynamics, intellectual structure, and collaborative networks in the NDT field for delamination detection. The observed concentration in themes, journals, authors, and countries may pose potential challenges related to research diversity and innovation. However, the breadth of

thematic interests and the large pool of contributors also suggest considerable opportunities for interdisciplinary and international collaborations. Future research efforts could benefit significantly from deliberate diversification strategies, sustained methodological innovation, and targeted collaboration initiatives, thereby ensuring the continued vibrancy, impact, and evolution of nondestructive testing research in addressing practical and theoretical challenges within engineering and materials science domains.

Data Availability

The dataset used and analyzed during this bibliometric study is openly available at the following GitHub repository: Nondestructive Testing Bibliometric Data.
This publicly accessible resource contains the complete bibliographic records used in the analysis, facilitating transparency, reproducibility, and further bibliometric inquiries into nondestructive testing techniques for delamination detection.

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Conflicts Of Interest

No potential conflicts of interest with funding sources, organizations, or individuals are disclosed in the paper.

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References

[1] A. M. Chik, N. A. Yusoff, S. J. S. Hakim, and N. H. A. Ghafar, “Rapid visual assessment of crack on residential building,” IOP Conf. Ser.: Earth Environ. Sci., vol. 1205, no. 1, p. 012039, 2023.
[2] D. Kairu et al., “Application of Schmidt hammer and ultrasonic pulse velocity for structural integrity assessment in water dams,” J. Infrastruct. Preserv. Resil., vol. 6, no. 11, 2025.
[3] “Multiphysical characterization for predicting compressive strength of Portland cement concrete using synthetic aperture radar, ultrasonic testing, and rebound hammer,” Sci. Rep., vol. 15, p. 6058, 2025.
[4] A. Sultan, J. Łukaszewicz, J. Józwik, Z. Oksiuta, and F. S. Shahar, “Recent trends in non-destructive testing approaches for composite materials: A review of successful implementations,” Materials, vol. 18, no. 3146, 2025.
[5] G. Quinn et al., “Advanced ultrasonic inspection of thick-section composite structures for in-field asset maintenance,” Polymers, vol. 15, no. 3175, 2023.
[6] M. Galati et al., “A review of ex-situ, in situ and artificial intelligence-based thermographic measurements in additively manufactured parts,” J. Nondestruct. Eval., vol. 44, p. 68, 2025.
[7] L. Ai, H. Lin, and P. Sun, “IR thermography and neural network models for damaged component thickness detection,” Sci. Rep., vol. 15, p. 5712, 2025.
[8] T. Tai, M. T. H. Sultan, J. Łukaszewicz, J. Józwik, Z. Oksiuta, and F. S. Shahar, “Advanced non-destructive testing simulation and modeling approaches for fiber-reinforced polymer pipes: A review,” Materials, vol. 18, no. 2466, 2025.
[9] S. Ghosh et al., “Machine-learning-enabled multiscale modeling platform for damage sensing digital twin in piezoelectric composite structures,” Sci. Rep., vol. 15, p. 6631, 2025.
[10] H. Alkattan, H. Hussein, A. S. Alhumaima, O. A. Adelaja, M. Abotaleb, M. M. Mijwil, P. Mishra, D. Sekiwu, W. Bamwerinde, and B. Turyasingura, “Employing data mining techniques and machine learning models in classification of students’ academic performance,” Babylonian J. Artif. Intell., pp. 43–54, 2023.
[11] H. Alkattan, B. Turyasingura, B. Willbroad, and A. A. K. Jaafar, “Economic performance classification in Iraq (2000–2023): A statistical analysis using machine learning with support vector machines and random forest,” EDRAAK, pp. 29–37, 2025.
[12] F. Kayusi, S. Kasulla, S. J. Malik, M. Majeed, B. Turyasingura, J. Tumushabe, and G. B. Mensah, “Advancing algorithmic justice: A systematic review of fair decision-making protocols in healthcare AI,” Afr. J. Law Dev. Res., pp. 39–52, 2024, doi: 10.62839/AJFLDR.V01.V01.
[13] G. Mensah, F. Kayusi, P. Chavula, B. Turyasingura, and O. J. Amadi, “Artificial intelligence systems and medical negligence: An overview and perspective of a case study in Ghana civil procedure rules, 2004 (CI 47),” 2024.
[14] B. Turyasingura, R. Akatwijuka, W. Tumwesigye, N. Ayiga, T. M. Ruhiiga, A. Banerjee, B. Benzougagh, and D.

Frolov, “Progressive efforts in the implementation of integrated water resources management (IWRM) in Uganda,” in Disaster Risk Reduction in Agriculture, Springer, 2023, pp. 543–558.

[15] B. Turyasingura, N. Ayiga, F. Kayusi, and M. Tumuhimbise, “Application of artificial intelligence (AI) in environment and societal trends: Challenges and opportunities,” Babylonian J. Mach. Learn., pp. 177–182, 2024.

[16] B. Turyasingura, N. Hannington, H. W. Kinyi, F. S. Mohammed, N. Ayiga, E. Bojago, B. Benzougagh, A. Banerjee, and S. K. Singh, “A review of the effects of climate change on water resources in Sub-Saharan Africa,” Afr. J. Climate Change Resour. Sustain., vol. 2, no. 1, pp. 84–101, 2023.

[17] F. Kayusi, R. G. Vallejo, L. Juma, M. K. Omwenga, and P. Chavula, “A bibliometric analysis of segment anything (SA) research: Global trends, key contributors, and thematic insights,” Babylonian J. Mach. Learn., pp. 27–41, 2025.