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Critical Review with Scientometrics Approach on the Retrofitting Strategies for Reinforced Concrete Structures

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Abstract

Many reinforced concrete (RC) structures across seismic zones remain at high risk due to inadequate design, poor construction practices, and material degradation over time. This vulnerability necessitates systematic retrofitting strategies to enhance seismic performance and ensure public safety. The present study offers a comprehensive scientometric and critical review of global research on retrofitting strategies for RC buildings, emphasizing their evolution, key contributors, and emerging interdisciplinary directions. A systematic scientometric analysis was conducted using the Dimensions.ai database, covering publications from 2016 to 2025. Bibliometric mapping tools such as VOS viewer and Biblioshiny were employed to analyze co-authorship, citation networks, and keyword co-occurrence, complemented by qualitative assessments of research domains. The dataset comprised over 59,132 publications spanning engineering, materials science, and design disciplines. The study concludes that seismic retrofitting of RC buildings has evolved into a mature, data-driven, and globally collaborative research domain. It underscores the need for AI-integrated modeling, sustainable materials, and inclusive policy frameworks to promote resilient and low-carbon infrastructure worldwide.

Keywords: seismic retrofitting, strengthening, upgrading buildings, reinforced concrete, seismic performance, scientometrics

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Introduction

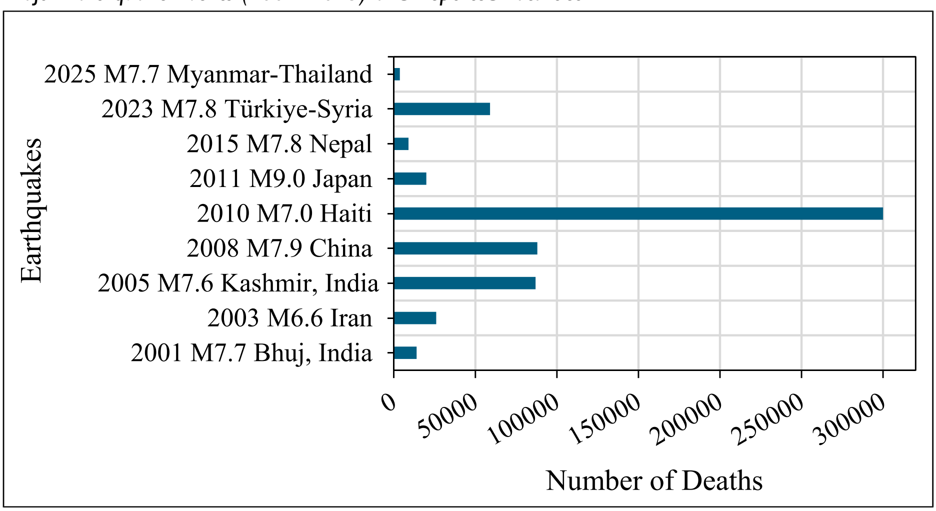
Earthquakes are among the most destructive natural hazards, posing serious risks to infrastructure, human life, and economic stability. Beyond the immediate ground shaking that causes structural collapse, earthquakes often trigger cascading effects such as landslides, liquefaction, tsunamis, fire outbreaks, and widespread service disruptions, all of which amplify disaster severity. Recent global analyses reveal that almost half (≈46%) of natural-disaster fatalities from 1995 to 2022 were caused by earthquakes (Tin et al., 2024). Figure 1 illustrates the number of fatalities associated with some major global earthquakes from 2001 to 2025, highlighting the varying scales of impact across different events (DesRoches et al., 2011; Dunham et al., 2024; Günay et al., 2025; Highland & Sun, 2013; Jain, 2004; Joshi & Kaushik, 2017; Liu et al., 2023; Nakahara & Ichikawa, 2013). These events triggered large infrastructural damage consequently leading to huge economic loss. Further, disaster statistics from over 130 major earthquakes indicated that more than 95% of casualties and losses resulted from building damage and collapse (Cao et al., 2021).

Throughout the world, RC buildings represent a large percentage of urban building types (Almeida et al., 2025). In India, too, RC construction is increasingly prevalent in urban areas, particularly in the form of masonry-infilled RC frames (Murty et al. 2012). However, many existing RC structures were constructed before the implementation of modern seismic design codes, such as IS 1893 (first introduced in 1962; latest revision 2016) and IS 13920 (first introduced in 1993; revised in 2016). In several regions, even recently constructed RC buildings lack compliance with prescribed design and detailing provisions, often due to the pressures of rapid urbanization and inadequate enforcement of construction standards.

Typical seismic deficiencies in such non-code-conforming RC structures include: widely spaced transverse reinforcement, discontinuity of positive reinforcement in beam and slab, inadequate number of reinforcing bars, short lap-splice, lack of shear reinforcement in the joints, inadequate anchorage of longitudinal reinforcement in the beam joints, and limited shear capacity of beams.

Figure 1

Some Major Earthquake Events (2001–2025) and Reported Fatalities



Over time, this building stock has further deteriorated due to environmental exposure and increasing functional demands, resulting in reduced serviceability.

While predicting the timing or magnitude of earthquakes is impossible, their recurrence in active seismic zones over long time scales is unavoidable (Takagi & Wada, 2019). Hence, to reduce the risk of such disasters, new RC structures should be designed to be earthquake-resistant, while existing vulnerable RC structures require systematic retrofitting, that is, upgrading the structure to meet new performance or safety standards. Using technically and economically feasible measures, retrofitting improves strength, stiffness, and/or ductility of the structure, thereby extending service life and reducing seismic vulnerability. Retrofitting is generally more cost-effective than demolition or reconstruction for most aging structures (Springfield, 2009; Sugano, 2000). In India, although seismic design provisions for RC buildings evolved through IS 1993 and IS 13920, dedicated retrofit guidelines emerged only with IS 15988 (2013). However, as the code remains advisory, its limited enforcement has restricted large-scale implementation. Moreover, high initial investment requirements, limited technical expertise, low public awareness, and inconsistent enforcement of seismic codes continue to impede the widespread adoption of retrofitting in India. Consequently, research and development on seismic retrofitting of RC buildings have intensified in recent years, aiming to address the vulnerabilities of existing structures. In this context, the present study conducts a scientometric review of research on seismic retrofitting strategies for RC buildings to trace their evolution, identify thematic trends, and emerging directions.

Scope and Objectives

Given the critical role of seismic retrofitting in enhancing the performance of existing RC structures, this study seeks to systematically assess the evolution of research in this domain. A scientometrics and critical review approach was adopted to achieve the following objectives.

(i) To analyze global research trends and growth patterns in seismic retrofitting of RC structures between 2016 and 2025 using scientometric techniques, identifying major publication surges, influential years, and evolving thematic directions.
(ii) To identify and categorize the dominant disciplines, countries, and institutions contributing to RC retrofitting research, emphasizing the role of engineering, design, and interdisciplinary collaboration in shaping the field's development.
(iii) To evaluate author and publication level influence through bibliometric indicators such as citation counts, link strength, and co-authorship networks, highlighting leading researchers, collaborative clusters, and intellectual structures within the domain.
(iv) To assess publication access models (open vs. closed) and their impact on visibility, citation performance, and knowledge dissemination, with particular focus on the transition toward open-access frameworks in civil and structural engineering research.
(v) To identify emerging research gaps and future directions by mapping material innovations, sustainability integration, and computational advancements thereby recommending strategies for data-driven, and sustainable retrofitting approaches aligned with global resilience goals.

Methodology

To address the research objectives, the study follows a structured scientometrics workflow as illustrated in Figure 2.

The systematic review process begins with the literature search phase, which involves defining the research question and selecting keywords such as "seismic," "retrofitting," "techniques," and "existing structures." These are applied using *Boolean operators* (AND, OR, NOT) to the title, abstract, and keyword fields in the *Dimensions.ai* database, selected for its comprehensive indexing of multidisciplinary publications, citations, and grants (Hook et al., 2018). Following filtering and quality assessment, the final dataset (2016–2025) comprising journal articles, conference papers, and reviews was compiled and exported in CSV format. A total of 59,132 publications were retrieved for evaluation and interdisciplinary nature of research on retrofitting of RC structures.

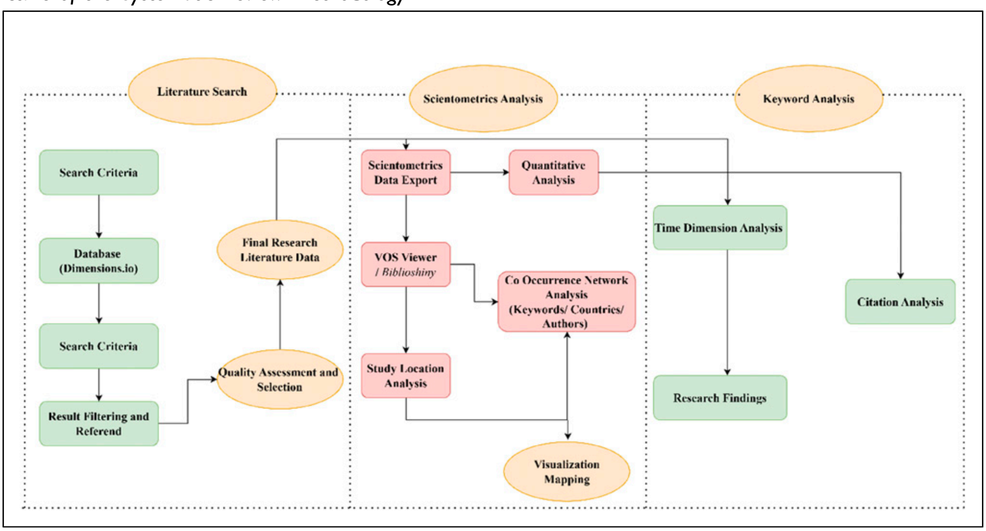
In the scientometric analysis stage, the data are cleaned and normalized to remove duplicates and harmonize author, institution, and country names. The refined dataset is then processed using *VOS viewer* and *Biblioshiny* (R-Tool) to perform co-authorship and co-occurrence network analyses, which visualizes collaboration patterns and thematic associations among authors, countries, and keywords. Citation and cluster analyses are further employed to identify key publications, research clusters, and intellectual structures within the field (Van Eck & Waltman, 2010).

Data Interpretation

The scientometrics analysis of the literature on retrofitting of RC buildings reveals an evolving and multidisciplinary research landscape that has expanded significantly over the past two decades. The growth trend in publications reflects the increasing global concern for the safety, durability, and sustainability of existing structures, especially in earthquake-prone regions. Between 2016 and 2025, research output related to structural retrofitting exhibited a steady rise, with major surges following catastrophic seismic events such as the 2004 Indian Ocean earthquake and the 2011 Tōhoku earthquake. These disasters stimulated a wave of studies on seismic strengthening, performance-based design, and material innovations such as FRP and high-performance concrete (HPC) (Akgüngör & Akgüngör, 2020; Bournas, 2018a, 2018b).

Figure 2

Structure of the Systematic Review Methodology



Categories

Figures 3 and 4 present the scientometric categorization of publications under the Australian and New Zealand Standard Research Classification (ANZSRC, 2020), illustrating the disciplinary engagement in the research of retrofitting of RC buildings.

Engineering (40) dominates with 33,105 publications, followed by Built Environment and Design (33) with 11,075 records, together accounting for nearly 70% of the total research output. This dominance underscores the pivotal role of civil and structural engineering in advancing retrofitting methodologies and performance-based design for existing structures. As shown in Figures 2 and 3, contributions from other disciplines such as Chemical Sciences (4,555) and Human Society (3,049) reflect the field's growing interdisciplinarity, supported by inputs from a few other fields. Chemical sciences advance innovative bonding agents, corrosion inhibitors, and self-healing materials that improve RC structure performance and durability, while human and social sciences address socio-economic and policy aspects, including safety, cost efficiency, and sustainability (Kumar & Sharma, 2022). This interdisciplinary approach reflects a growing emphasis on both structural performance and societal impact in modern research in the field of retrofitting of structures. The specific fields were considered because they collectively represent the core technological, environmental, and societal drivers shaping the evolution of retrofitting research. By integrating engineering sciences with design thinking, material chemistry, and social frameworks, the study

Figure 3

Category Wise Distribution of the Data (2016–2025)

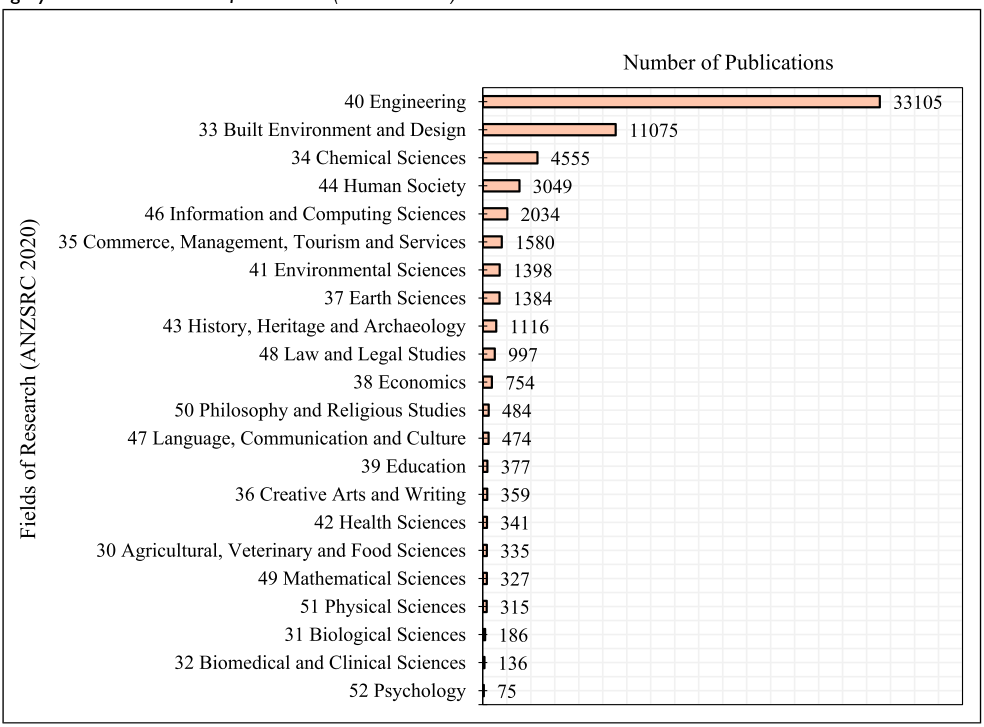
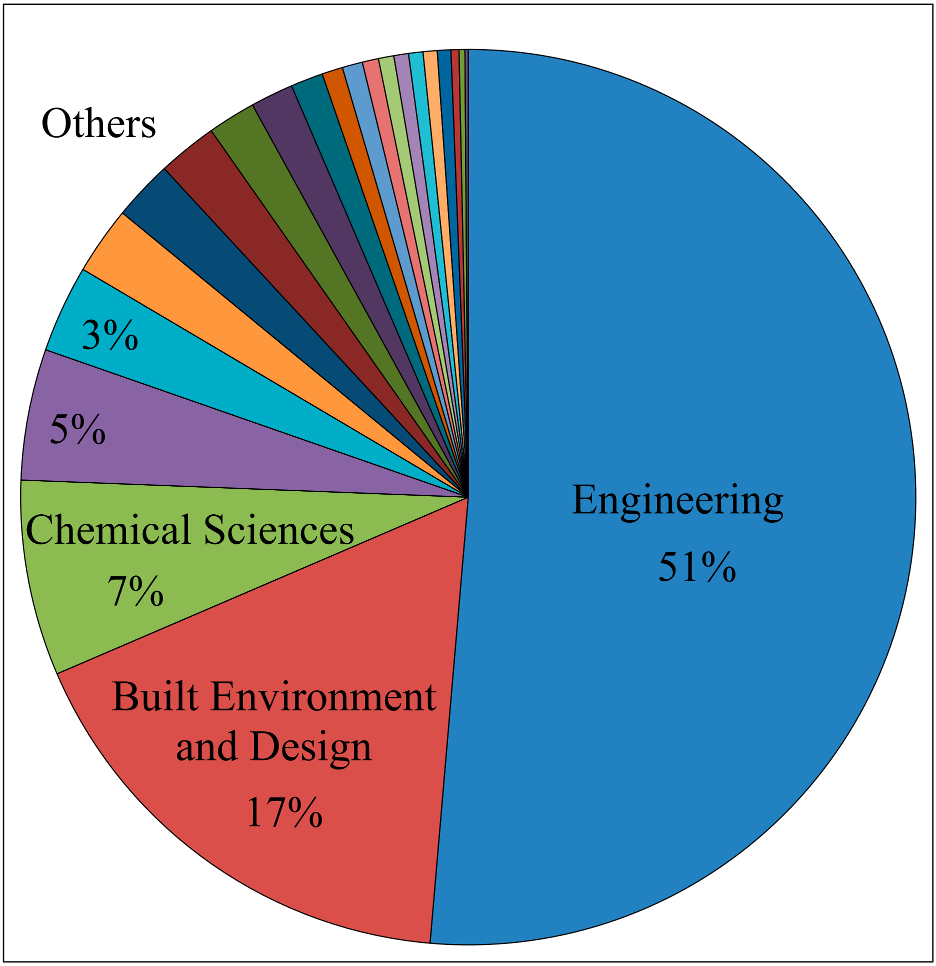


Figure 4

Category Wise Distribution of the Data (2016–2025)

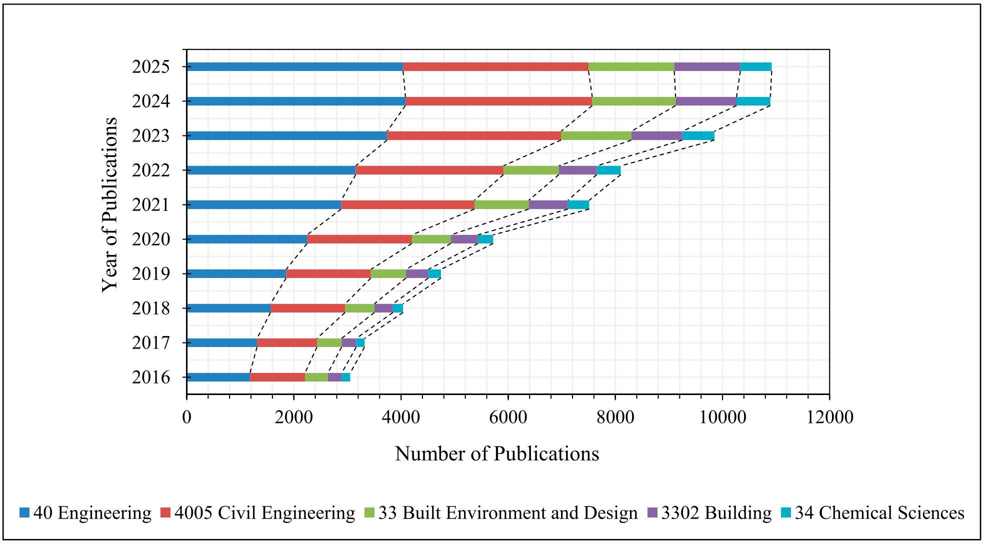


captures the holistic transformation of retrofitting research in alignment with Sustainable Development Goal 11 - Sustainable Cities and Communities (Li et al., 2022; Rao et al., 2023).

As an extension of the analysis, Figure 5 depicts the year-wise progression of research publications in the selected categories from 2016 to 2025, revealing both quantitative growth and thematic evolution. Engineering (40) demonstrates steady growth, peaking at 4,083 publications in 2024, reflecting greater integration of computational modeling and sustainability principles. Within this domain, Civil Engineering (4005) category shows the steepest increase, from 1,026 to 3,460 papers, signifying intensified efforts in seismic safety and structural rehabilitation. Built Environment and Design (33) and its subcategory Building (3302) display parallel upward trends associated with adaptive and performance-based design. In contrast, Chemical Sciences (34) reflects slower yet consistent progress, highlighting emerging material innovations but limited interdisciplinary integration. Overall, Figure 4 highlights the field's evolution from conventional

Figure 5

Year-wise Distribution of Research Publications (2016-2025) Classified by Specific Subject Area Under the ANZSRC 2020 Fields of Research



strengthening methods to data-driven, material-efficient, and sustainability-oriented frameworks, underscoring its growing contribution to resilient and sustainable urban infrastructure.

Publication Access

The distribution of open- and closed-access publications indicates varying levels of research activity and citation impact in the studies of retrofitting of RC buildings (Figure 6).

The analysis reveals that closed-access publications dominate the field, with 43,799 papers generating 812,461 citations, yielding a mean citation rate of 18.55. This indicates that traditional subscription-based journals continue to play a major role in disseminating high-impact research in civil engineering domains. Among the open-access (OA) models, Gold OA (9,997 publications) accounts for the largest share but records a comparatively lower mean citation of 11.46, suggesting that while openness enhances accessibility, the citation influence remains modest. Notably, Green OA demonstrates the highest mean citation value (27.69), highlighting the growing academic preference for repository-based dissemination and preprint sharing in enhancing visibility and scholarly engagement. Hybrid and Bronze OA categories exhibit intermediate impact levels with mean citations of 19.38 and 20.15, respectively. Overall, the dataset underscores a gradual shift toward open-access dissemination in the considered research area, emphasizing the role of transparent, freely accessible knowledge systems in accelerating innovation and promoting equitable global participation.

Countries

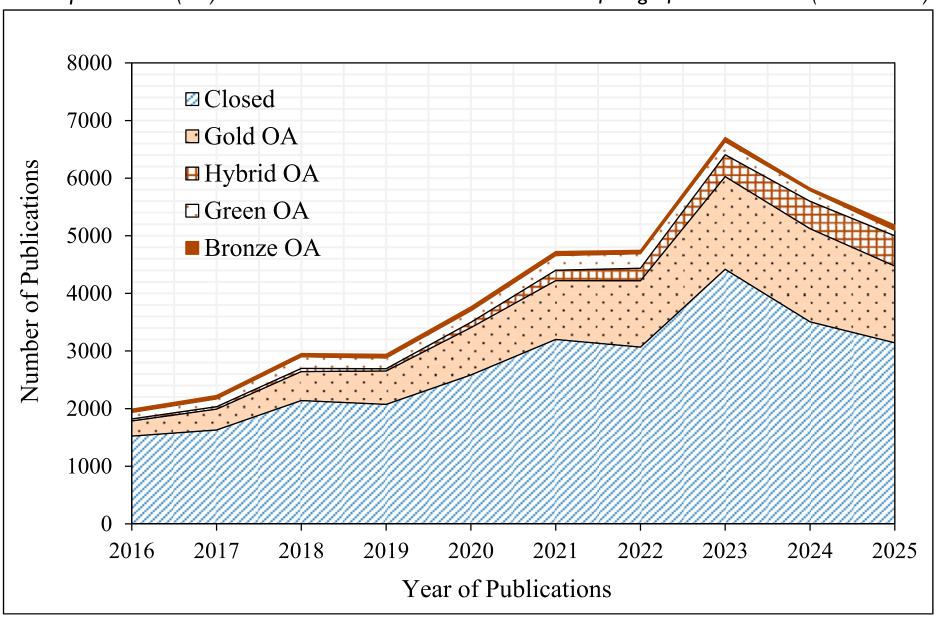
The comparative scientometric mapping highlights the leading countries contributing to research on retrofitting strategies for RC buildings, considering document count, citation volume, and total link strength, as shown in Figure 6.

The data (Table 3) clearly show that China leads the global research landscape with 6,818 publications, 139,410 citations, and the highest link strength 5,640,866, indicating its central role in global collaboration networks and consistent research output in the field. Italy and the United States follow closely, with 4,902 and 3,545 documents respectively, reflecting their strong academic foundations and well-established seismic retrofitting programs. Countries such as Iran, India, and the United Kingdom exhibit substantial participation, demonstrating growing regional engagement and expanding international collaboration. India's high citation count (37,772) and strong link strength (2,295,126) highlight its rising influence in low-cost retrofitting and sustainable structural strengthening research. Meanwhile, Australia, Turkey, and Canada contribute significantly to interdisciplinary studies integrating material science and performance-based design. Overall, the bibliographic coupling network reveals a highly interconnected research ecosystem dominated by Asia, Europe, and North America, illustrating that knowledge production in RC retrofitting has evolved into a truly global endeavor characterized by strong cross-border collaboration and technological innovation.

The visualization (Figure 6) generated using *VOS viewer* illustrates the international collaboration network among countries engaged in research on retrofitting strategies for RC structures. The map reveals a dense web of global interconnections, emphasizing the increasing globalization of scientific efforts in civil and structural engineering. The clustering pattern highlights four major collaborative groups. The green cluster, dominated by China, India, Saudi Arabia, Australia, and Malaysia, represents strong partnerships in Asia and the Middle East, focusing on experimental methods, sustainability, and material-based studies. The blue cluster, led by Italy, Portugal, Turkey, and Greece, reflects the European research focus on seismic strengthening, energy efficiency, and heritage conservation. The red cluster, anchored by Germany, Spain, and the United Kingdom,

Figure 6

Closed and Open Access (OA) Research Publication Distribution in Retrofitting of RC Structures (2016-2025)



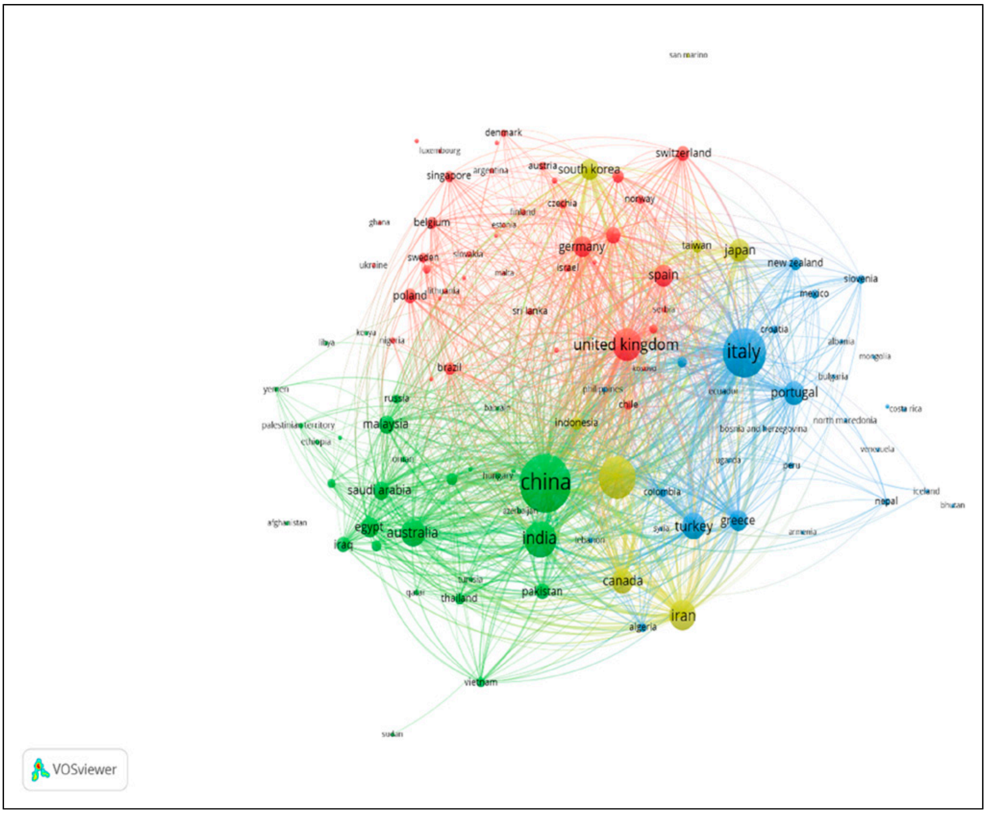
showcases extensive academic integration across Europe, emphasizing computational modeling and life-cycle performance analysis. Meanwhile, Iran and Japan bridge the Asian European collaboration spectrum, contributing to hybrid retrofitting technologies and smart material applications. Overall, the network demonstrates robust cross-border academic engagement. It underscores that research on retrofitting strategies for RC structures has transcended regional priorities, evolving into a globally shared pursuit aimed at improving resilience, sustainability, and innovation in the built environment.

Authors and Publishers

The publication trajectories of five eminent researchers—*Gabriele Milani, Andrea Prota, Paulo José Brandão Barbosa Lourenço, Antonio Formisano, and Humberto Salazar Amorim Varum*, who have made significant contributions to the domain of retrofitting strategies for RC buildings, is shown in Figure 7. Their research outputs demonstrate not only individual productivity but also reflect evolving global interests in seismic strengthening, heritage conservation, and sustainable rehabilitation practices.

Figure 7

Country Network in the Research of Retrofitting of RC Structures



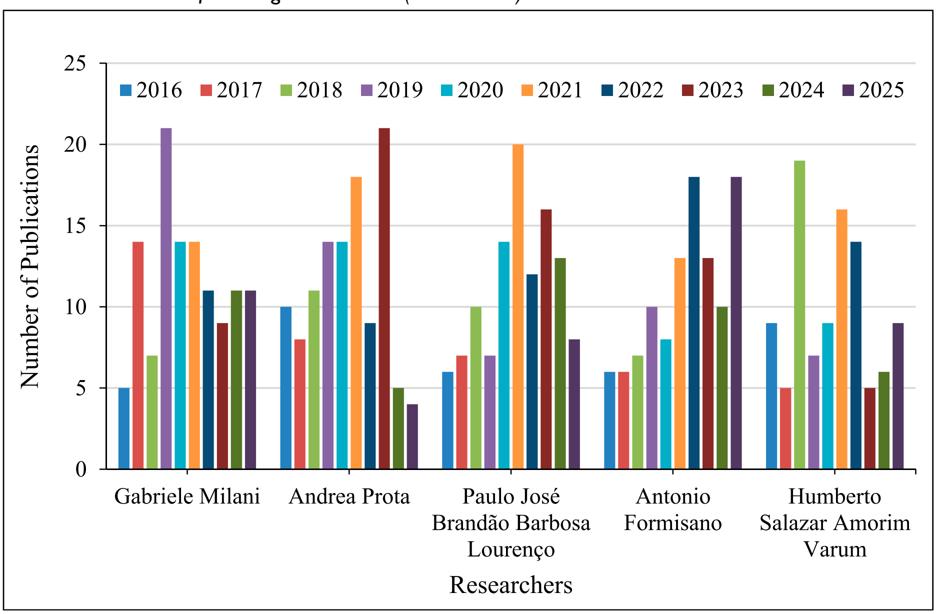
Among them, *Gabriele Milani* exhibits the most consistent research productivity, reaching a notable peak of 21 publications in 2019, indicative of his leading role in numerical modeling and advanced material applications in masonry and RC retrofitting. *Andrea Prota* also shows a strong upward trend, with a peak in 2023 (21 publications), largely associated with his pioneering work on FRP-based seismic strengthening and experimental retrofitting methodologies. *Paulo José Lourenço*, known for his expertise in historical and masonry structures, displays a steady increase until 2021, followed by a slight decline, reflecting the stabilization of output in mature collaborative research. *Antonio Formisano* and *Humberto Varum* reveal fluctuating publication patterns, yet their peaks in 2018 and 2021 respectively signify significant research activity within European collaborative projects focused on resilience assessment and performance-based design. The overall trend highlights dynamic scholarly engagement, with recurrent peaks aligned with major international research initiatives and European Union funding cycles. Thus, the figure underscores the growing intellectual synergy among these leading scholars, whose collective contributions have shaped the scientometric core of global research in retrofitting of RC structures bridging computational modeling, experimental validation, and sustainable engineering innovation.

Figure 8 illustrates the temporal distribution of publications from major academic publishers—*Springer Nature, Elsevier, Taylor & Francis, MDPI*, and *Wiley* in the field of retrofitting strategies for RC buildings. The data reveal an upward trajectory in research dissemination, demonstrating how publishers have increasingly prioritized topics related to sustainability, resilience, and seismic rehabilitation.

Among the analyzed publishers, *Springer Nature* emerges as the dominant contributor, exhibiting a strong upward trend from 2016 to 2023, peaking at approximately 2,750 publications in 2023. This surge corresponds with Springer's emphasis on open-access proceedings and special issues in

Figure 8

Annual Publication Trends of Leading Researchers (2016-2025)



structural engineering and construction materials. Elsevier follows closely, maintaining consistent growth, particularly after 2020, reflecting its focus on high-impact journals such as *Engineering Structures*, *Construction and Building Materials*, and *Cement and Concrete Composites*. *Taylor & Francis* maintains moderate but stable output, emphasizing heritage conservation, sustainable building systems, and computational modeling. Meanwhile, *MDPI* shows a rapid rise after 2019, attributed to the proliferation of open-access platforms such as *Sustainability* and *Buildings*, which encourage interdisciplinary publication and faster dissemination cycles. *Wiley*, although comparatively modest in output, sustains niche scholarly contributions emphasizing experimental mechanics and advanced composite applications. Overall, the graph underscores a clear shift toward open-access and interdisciplinary publishing ecosystems, driven by global demand for resilient infrastructure solutions. The increasing dominance of *Springer* and *Elsevier* highlights the consolidation of retrofitting research in high-visibility academic channels, fostering greater international collaboration and accelerating knowledge diffusion in sustainable structural engineering.

Findings

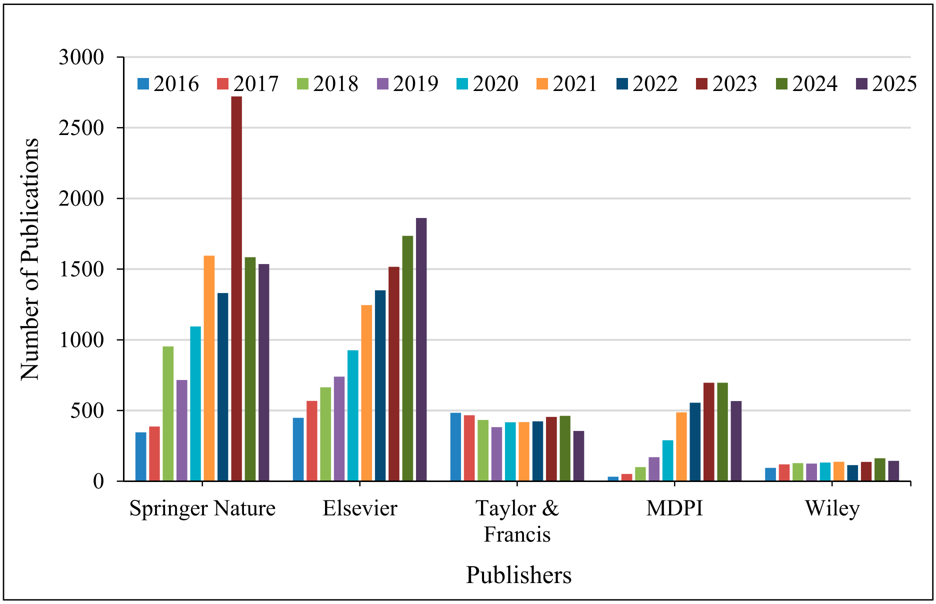
The scientometrics analysis of research on retrofitting strategies for RC buildings reveals a rapidly expanding, multidisciplinary, and globally collaborative domain. The study identifies a strong upward trajectory in publication growth from 2016 to 2025, demonstrating a shift from conventional seismic strengthening to data-driven, sustainable, and performance-based retrofitting approaches. The dominance of the Engineering (40) and Civil Engineering (4005) categories underscores the technical intensity of the field, while emerging integration with Built Environment and Design (33) indicates an expanding focus on urban resilience, heritage conservation, and adaptive reuse of structures (Figures 2, 3 and 4).

The bibliometric visualization and data analysis reveal a globally interconnected research ecosystem in retrofitting strategies for RC buildings, with China, Italy, and the United States leading the domain both in publication output and scholarly impact. China ranks first, contributing 6,818 documents with 139,410 citations and the highest total link strength (67,068), reflecting its dominant role in experimental retrofitting studies, seismic resilience modeling, and sustainable material innovation. Italy follows closely with 4,902 documents and 127,409 citations, demonstrating strong collaboration networks within Europe, particularly in performance-based design and heritage structure rehabilitation (Figure 9). The United States and United Kingdom emerge as key intellectual hubs with extensive international linkages, focusing on computational modeling, damage assessment, and hybrid retrofitting technologies. Their total link strengths (41,985 and 33,988, respectively) illustrate their influence in shaping global knowledge exchange. India and Iran, with growing research footprints and strong citation indices, represent the expanding contribution of Asian nations to cost-effective and sustainable retrofitting solutions, aligning with regional infrastructure resilience agendas.

The bibliographic coupling analysis of authors in the domain of retrofitting strategies for RC buildings reveals a highly cohesive and collaborative global research network. The visualization and tabulated data highlight Andrea Prota, Humberto Varum, and Gabriele Milani as the most influential authors, demonstrating both prolific research output and extensive co-authorship linkages across the international scientific community. Andrea Prota leads with 135 publications, 4,794 citations, and the highest total link strength (280,654), underscoring his pivotal role in advancing experimental and analytical methodologies for seismic retrofitting and FRP-based strengthening systems. Humberto Varum follows closely with 121 documents, 3,378 citations, and a link strength of 202,044, reflecting his contributions to performance-based retrofitting, post-earthquake reconstruction, and international joint projects in Europe and Latin America. Gabriele Milani, with 124 publications and 3,381 citations, demonstrates strong interdisciplinary engagement, particularly in finite element modeling, masonry retrofitting, and sustainable

Figure 9

Annual Publication Trends by Leading Publishers (2016–2025)



reinforcement approaches (Figure 7). Other key contributors such as Paulo B. Lourenço, Davood Mostofinejad, and M. Shahria Alam play critical bridging roles, connecting thematic clusters focused on structural rehabilitation, composite materials, and hybrid retrofitting systems. The dense connectivity across color-coded clusters in the VOS viewer map representing European, Asian, and Middle Eastern collaborations illustrates a well-integrated research community, where joint authorship and cross-national studies dominate knowledge creation.

The document-level citation and bibliographic coupling analysis provides a clear picture of the intellectual backbone underpinning research on retrofitting strategies for reinforced concrete (RC) buildings. The dataset reveals that a few seminal works serve as the conceptual foundation of the field, shaping subsequent methodological and experimental advancements.

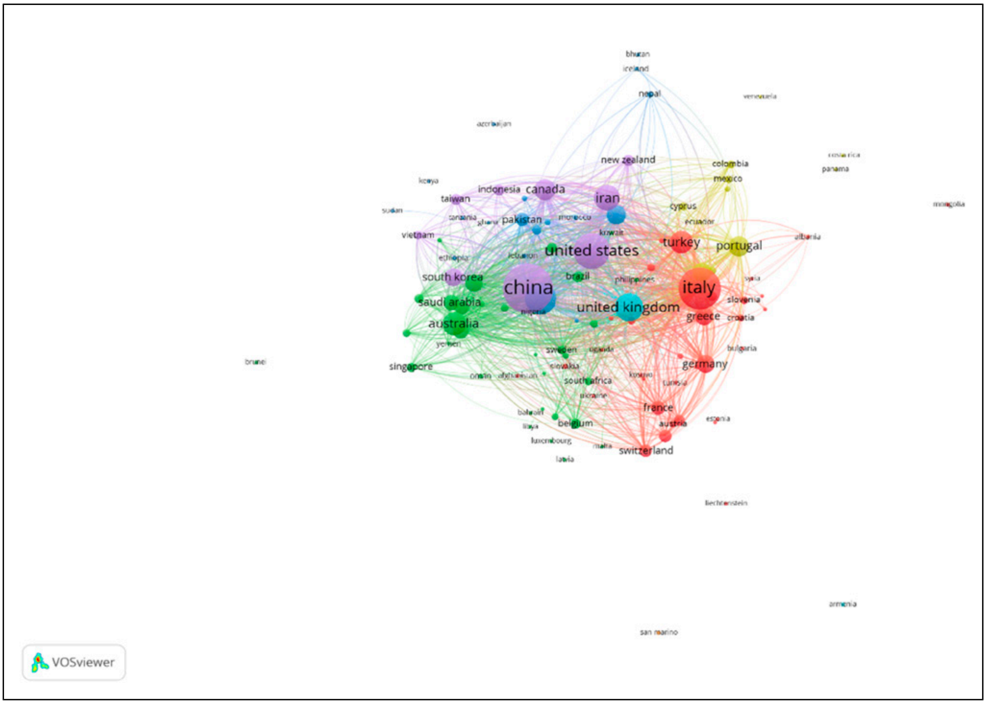
Among the most influential papers, Papanicolaou (2007) leads with 392 citations and a link strength of 86, highlighting its pivotal role in establishing the framework for fiber-reinforced polymer (FRP) confinement and structural retrofitting. This is followed by Kouris (2018) with 299 citations and Papanicolaou (2006) with 345 citations, both contributing to advancements in material-based retrofitting techniques. Koutas (2018) and Papanicolaou (2011) also exhibit strong link strengths (60–64), indicating their widespread integration into global retrofitting research networks (Figure 11).

Recent publications, such as Gkournelos (2021), though having fewer citations, show emerging connectivity within the research graph, reflecting evolving focus areas such as digital modeling, seismic performance simulation, and sustainability assessment. The co-citation network visualization demonstrates five distinct clusters.

- Red cluster centered on FRP and textile-reinforced mortars,

Figure 10

Country-wise Collaboration and Research Strength in Retrofitting of RC Structures



- Green cluster emphasizing seismic resilience and damage evaluation,
- Yellow cluster focused on computational modeling and finite element analysis,
- Blue cluster linking material innovation with hybrid retrofitting, and
- Purple cluster representing performance-based and heritage structure strengthening.

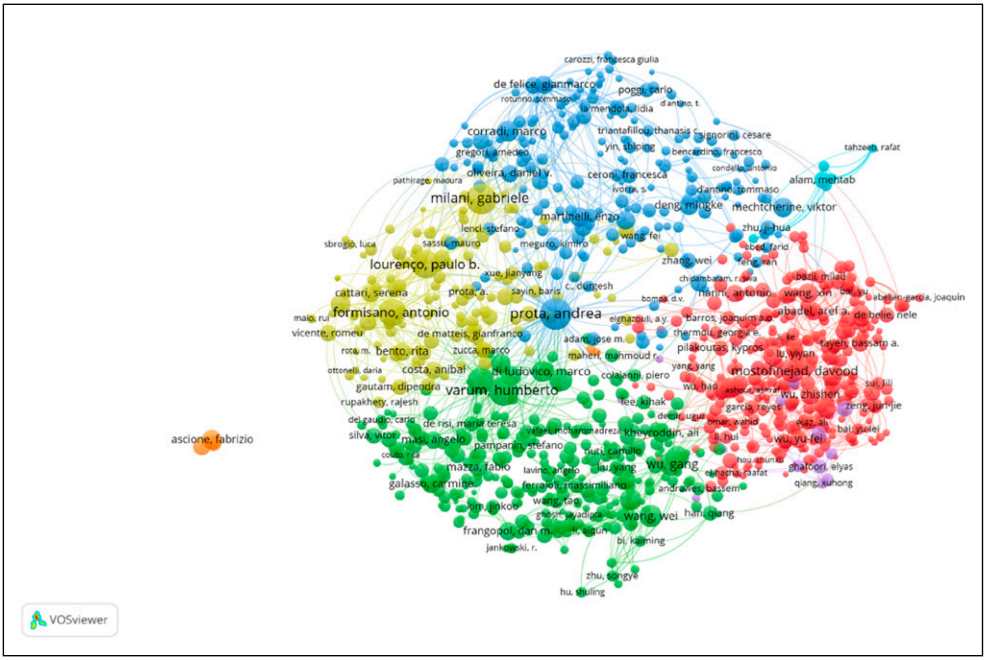
Overall, the findings underscore that RC retrofitting research is built upon a set of interlinked, high-impact studies that have progressively evolved from experimental validation to integrated digital and sustainable frameworks, positioning the field as a mature yet dynamically expanding discipline in civil engineering.

The co-authorship network map highlights strong institutional collaborations in retrofitting research (Figure 12). The University of Naples Federico II emerges as the central hub, extensively linked with the University of Minho, Sapienza University of Rome, and Polytechnic University of Turin, signifying European dominance in this field. Asian institutions such as Tongji University, Southeast University, and Beijing University of Technology show robust intra-regional partnerships, reflecting rapid scientific growth in seismic retrofitting. Meanwhile, Istanbul Technical University and Indian Institute of Technology bridge global collaborations, indicating a dynamic and interconnected academic ecosystem driving innovation in reinforced concrete retrofitting technologies.

The co-citation analysis of authors reveals Pitilakis K. as the most influential researcher, with 93 citations and the highest link strength (255), reflecting foundational work in seismic retrofitting and structural resilience. Crowley H. and Kaynia A.M. follow closely, each with 72 citations, emphasizing

Figure 11

Author-wise Bibliographic Coupling Analysis



their contributions to seismic vulnerability and performance-based engineering. The visual map highlights strong collaborative clusters among Varum Humberto, Belie Nele De, and Alexander Mark G., linking European research networks. These clusters illustrate a cohesive scholarly community integrating earthquake engineering, material durability, and retrofitting innovations to enhance reinforced concrete structure safety and global research connectivity.

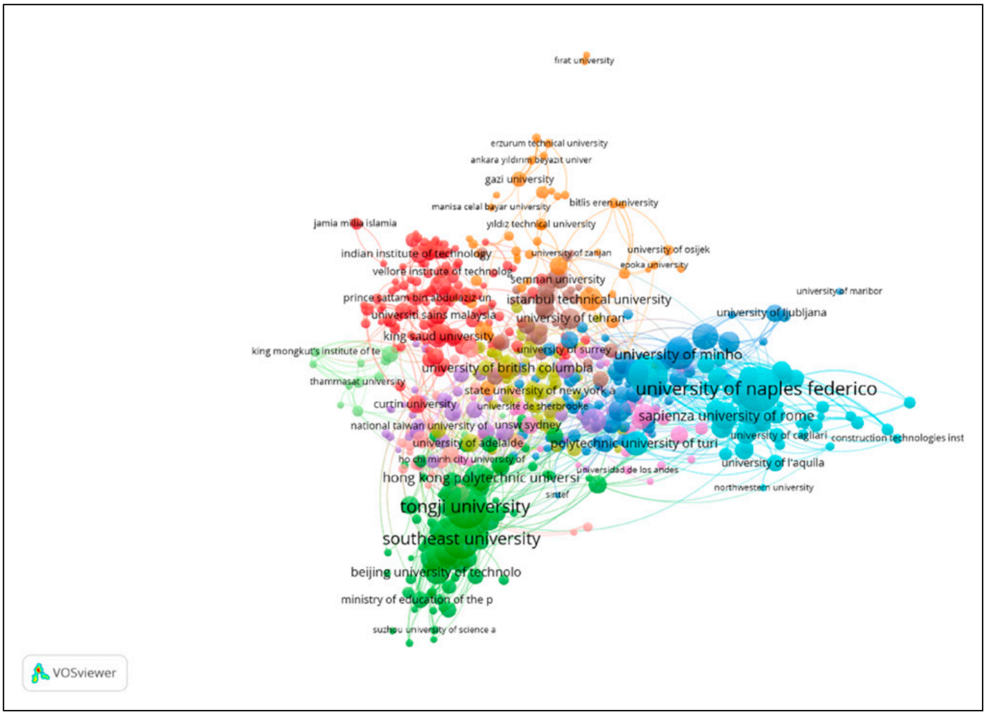
The international co-authorship map highlights Italy, China, and the United States as dominant contributors to retrofitting research on reinforced concrete buildings (Figure 13). Italy forms a strong collaboration network with Germany, Greece, and the United Kingdom, while China connects intensively with India, Malaysia, and Japan, emphasizing regional research synergy in Asia. The United States acts as a global intermediary, linking European and Asian clusters, fostering cross-continental knowledge exchange. These interlinked collaborations demonstrate a globally integrated research ecosystem focused on advancing seismic retrofitting, structural resilience, and innovative material applications in sustainable civil infrastructure development.

The co-authorship network of leading researchers in retrofitting reinforced concrete structures reveals Andrea Prota, Humberto Varum, and Gaetano Manfredi as central figures with the highest citation counts (4,794; 3,378; and 3,377 respectively) and strong collaborative link strengths. Their interconnectedness with Rodrigues Hugo, Di Ludovico Marco, and Milani Gabriele demonstrates a dense European research cluster focused on seismic retrofitting, structural resilience, and experimental strengthening methods (Figure 14).

The visualization indicates that Italy and Portugal dominate the scholarly network, fostering cross-border collaborations with Asia and the Middle East. Peripheral nodes like Wu Gang and Mostofinejad Davood reflect emerging Asian contributions, signaling global diffusion of expertise.

Figure 12

Co-Authorship Network Map Highlights Strong Institutional Collaborations



The dense interlinkages signify high research cohesion, promoting innovation and methodological standardization in sustainable retrofitting technologies.

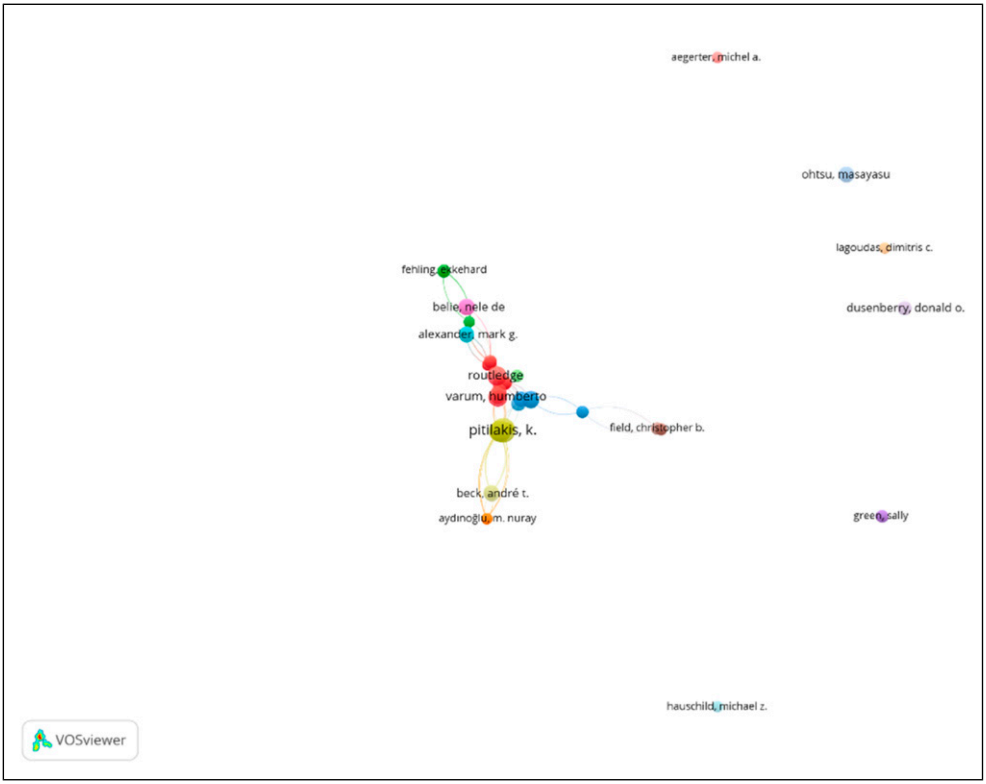
Discussion

The scientometric analysis of retrofitting strategies for reinforced concrete (RC) buildings offers a panoramic view of how this research domain has evolved over the last decade. A review of the subject categories (Figure 3) shows that Engineering (40) and Civil Engineering (4005) dominate the literature, together accounting for more than 33,000 publications. Built Environment and Design (33) contribute over eleven thousand articles and Chemical Sciences more than four thousand, revealing a strong but gradually broadening technical base that now incorporates materials science, architecture, and even social sciences. This diversity reflects the multifaceted nature of seismic retrofitting, which spans structural mechanics, material innovation and socio-economic considerations.

Temporal analysis underscores rapid growth. Figure 5 shows year-by-year publication counts in leading categories; Civil Engineering output climbed from 1 026 papers in 2016 to 3 460 by 2025, while Engineering publications peaked at over 4 000 by 2024. Built Environment and Design and Building followed similar upward trajectories, highlighting increased interest in urban resilience and heritage conservation. Chemical Sciences also showed steady growth, indicating sustained investment in advanced composites and bonding technologies. Collectively, these trends suggest that global seismic events and sustainability agendas have intensified scholarly attention to retrofitting.

Figure 13

Visualization of Co-citation Analysis of Authors



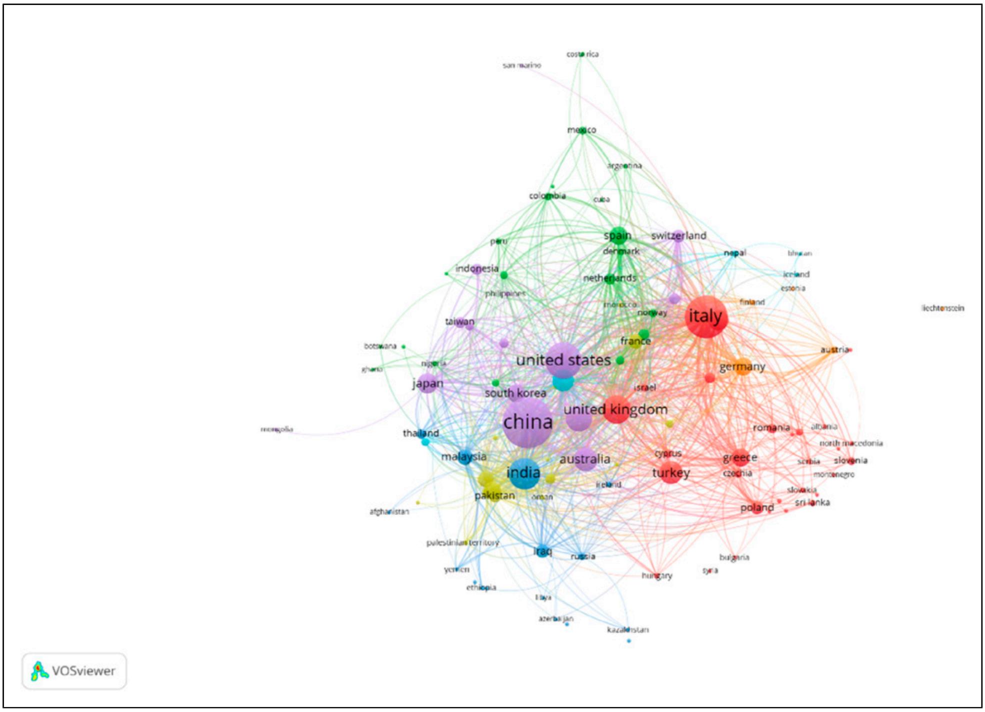
Evidence of open dissemination reveals mixed progress. Closed-access publications still generate most citations, but Green Open Access articles exhibit the highest mean citation rate. While Gold and hybrid models account for notable shares, their citation impact remains modest. Encouraging repository-based dissemination could thus enhance the reach and influence of retrofitting research (Figure 6).

Geographically, bibliographic coupling shows significant concentration yet growing inclusivity. Table 3 places China at the forefront, with 6818 documents and 139,410 citations. Italy and the United States follow, while Iran, India and the United Kingdom demonstrate strong citation impact relative to output. Collaboration networks depicted in the international co-authorship map (Table 1) reveal three major clusters: a European cluster led by Italy and Germany, an Asian cluster anchored by China and India, and a trans-Atlantic cluster connecting the United States and the United Kingdom. These clusters illustrate that retrofitting research has become a globally coordinated endeavor rather than a series of isolated national efforts.

At the micro level, author-level bibliometrics identify a handful of prolific researchers. Andrea Prota (135 papers, 4 794 citations), Humberto Varum (121 papers, 3 378 citations) and Gaetano Manfredi (72 papers, 3 377 citations) emerge as key figures, with extensive collaborative networks. Table 2 extends this view by mapping co-authorships: a dense European cluster centers on Prota, Varum and Milani, while peripheral nodes such as Wu Gang and Mostofinejad Davood indicate emerging Asian contributions. The

Figure 14

Visualization of International Co-Authorship Network on Retrofitting Strategies for Reinforced Concrete Buildings



co-citation analysis (Figure 10) further highlights Pitilakis K., Crowley H. and Kaynia A.M. as intellectual anchors whose works underpin contemporary methodologies.

Analysis at the document level reveals thematic convergence and divergence. The document-wise citation and co-citation network (Figure 16) show distinct clusters centered on fiber-reinforced polymers, seismic resilience and computational modeling. More recent papers on digital twins and sustainable materials occupy emerging clusters, signaling a shift towards integrating artificial intelligence and environmental considerations. Institutional co-authorship maps (Figure 12) position the University of Naples Federico II, University of Minho and Sapienza University of Rome as hubs of European collaboration, while Asian universities such as Tongji University and Southeast University form robust intra-regional partnerships.

Despite these positive trends, several limitations warrant attention. The study relies on a single bibliographic database, which may overlook regional journals and non-English works. Citation-based metrics inherently favor older publications, potentially underestimating the impact of recent innovations. Moreover, the predominance of engineering categories suggests that socio-economic dimensions of retrofitting such as cost benefit analysis, policy frameworks and community engagement remain underexplored. Future research should integrate multiple databases, incorporate qualitative assessments, and explore interdisciplinary frameworks that bridge engineering solutions with social resilience. Strengthening south–south collaborations and promoting open-access dissemination will be essential to ensure that innovative retrofitting strategies are globally accessible and tailored to diverse contexts.

Table 1

Country-Wise Bibliographic Coupling Analysis

Country	Documents	Citations	Total link strength
China	6818	139,410	5,640,866
Italy	4902	127,409	4,360,802
United States	3545	125,674	2,886,768
Iran	1849	34,958	2,302,385
India	2729	37,772	2,295,126
United Kingdom	2167	73,429	2,247,690
Australia	1542	63,990	1,750,975
Turkey	1383	23,871	1,490,890
Canada	1257	37,347	1,461,879
Portugal	1136	27,737	1,256,311
Greece	887	25,549	1,171,506
Saudi Arabia	667	16,079	923,708
South Korea	912	19,460	919,049
Spain	941	24,376	829,246
Egypt	835	14,527	800,751
Japan	1034	23,908	696,571
Pakistan	474	9046	694,409
Malaysia	679	18,692	684,537
Germany	926	26,072	646,450

Suggestions

The scientometric evaluation of retrofitting strategies for reinforced concrete (RC) buildings reveals significant progress yet exposes persistent research and implementation gaps that merit focused attention. Based on the insights drawn from Table 1 through Table 2 and Figures 1–16, several practical and scholarly recommendations are proposed to strengthen the global research and practice ecosystem.

1. Encourage Data-Driven and AI-Integrated Retrofitting Research.

Figures 8–11 demonstrate the growing convergence between computational modeling and collaborative design frameworks. Future studies should leverage artificial intelligence (AI), machine learning, and digital-twin technologies for predictive assessment of seismic vulnerability and real-time decision support (Van Eck & Waltman, 2010). Integrating big-data analytics with performance-based design codes will allow engineers to evaluate the dynamic response of RC buildings more efficiently, enabling adaptive retrofitting strategies tailored to site-specific risks.

2. Promote Open-Access and Knowledge-Sharing Mechanisms.

Figure 6 confirms that Green Open Access publications exhibit the highest mean citation rate, implying that free access enhances research visibility and societal uptake. Therefore, international agencies and publishers such as Springer Nature and Elsevier (Figure 5) should expand

Table 2

Author-Wise Bibliographic

Author	Documents	Citations	Total link strength
prota, andrea	135	4794	280,654
varum, humberto	121	3378	202,044
milani, gabriele	124	3381	182,507
rodrigues, hugo	95	2408	165,476
lourenço, paulo b.	109	2855	161,872
mostofinejad, davood	77	2380	159,916
ilki, alper	62	1551	152,261
alam, m. shahria	66	2515	151,117
cattari, serena	47	2665	142,664
wu, yu-fei	43	4044	142,647
wu, gang	77	2264	126,670
manfredi, gaetano	72	3377	125,484
di ludovico, marco	60	1661	122,477
lignola, gian piero	48	1379	118,909
hussain, qudeer	45	565	115,665
furtado, andré	53	1491	115,065
lagomarsino, sergio	38	3404	113,505
corradi, marco	61	1832	108,372
arêde, antónio	53	1529	108,167

repository-based dissemination models. Institutional repositories and national research portals could facilitate equitable access for developing nations, particularly across the Global South, thereby democratizing scientific knowledge (Hook et al., 2018).

3. Foster South–South and Trans-Regional Collaborations.

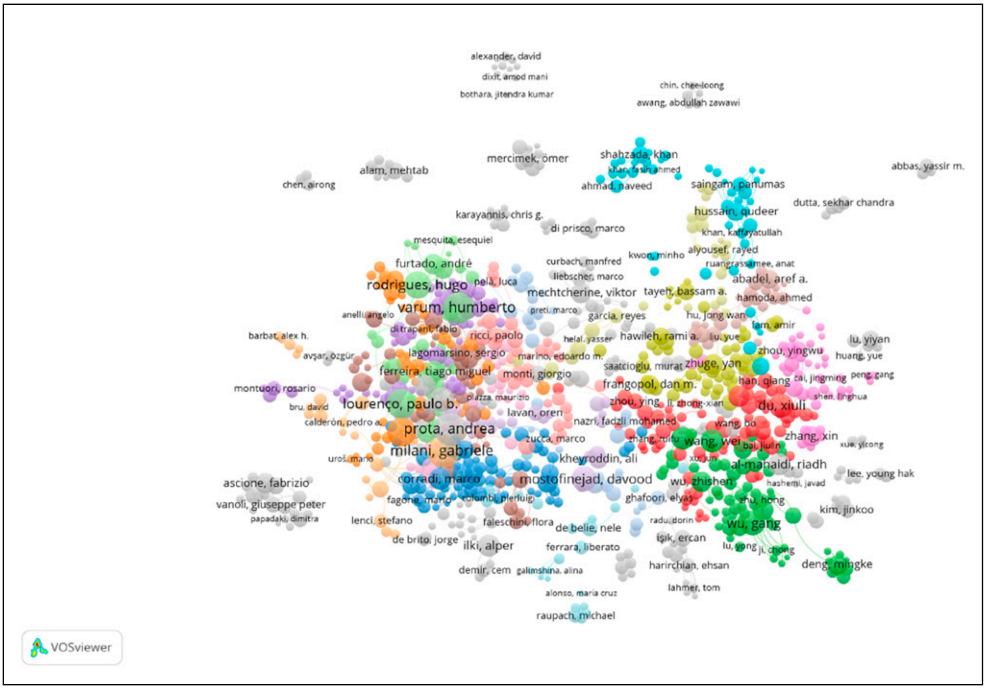
Country-wise and co-authorship networks (Figures 7, 10 and 13) show that while Europe and East Asia dominate output, collaborations between emerging economies remain limited. Establishing regional centers of excellence among Asian, African, and Latin-American institutions would diversify research perspectives and contextualize retrofitting solutions according to local materials, construction practices, and socio-economic constraints (Cao et al., 2021). India's increasing research footprint (Table 1) positions it as a strategic hub for such partnerships.

4. Strengthen Multidisciplinary Integration.

As revealed in Figures 2 and 3, most publications are concentrated within Engineering (40) and Civil Engineering (4005), while contributions from social sciences, policy, and economics remain low. Future studies should integrate cost–benefit analysis, behavioral modeling, and governance frameworks to ensure that retrofitting solutions are technically viable and socio-economically sustainable (Almeida et al., 2025). Collaborative projects uniting engineers, architects, and social scientists will advance holistic resilience frameworks aligning with the UN SDG 11 ("Sustainable Cities and Communities").

Figure 15

Visualization of Author Co-authorship Network in Retrofitting Strategies for Reinforced Concrete Buildings



5. Advance Experimental Validation and Sustainable Materials.

As illustrated in Figures 6, 7 and 12, global research activity demonstrates intensive experimental validation and material innovation in retrofitting strategies, with leading authors and countries focusing on sustainable composites such as FRP and textile-reinforced mortars (TRM). These figures collectively underscore the growing shift toward sustainable material development and validation under diverse environmental and seismic conditions.

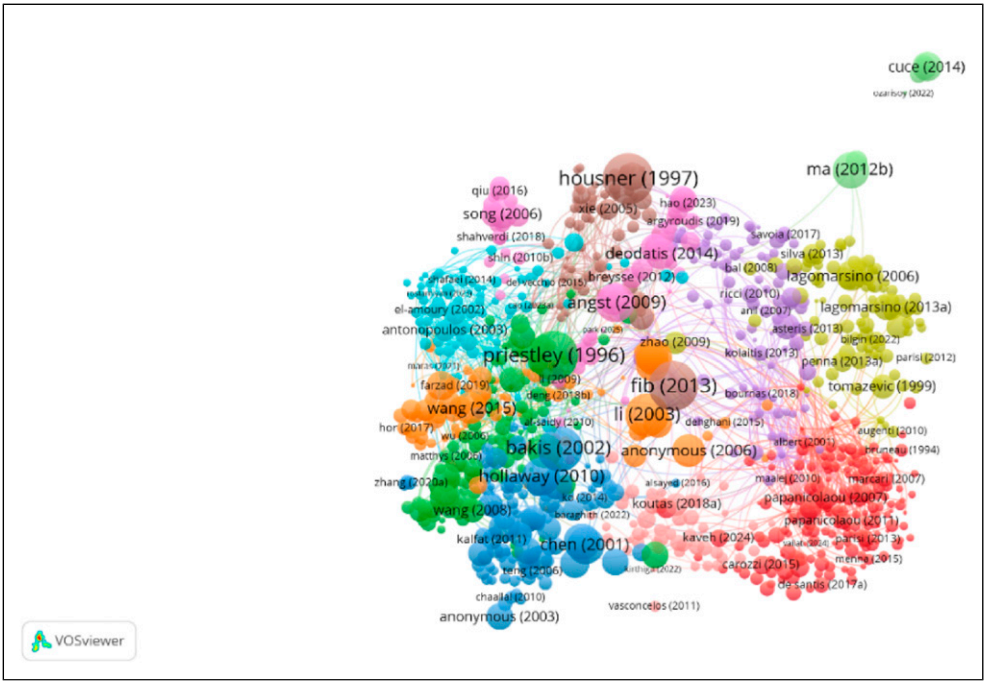
6. Develop Comprehensive Databases and Policy Frameworks.

As depicted in Figures 1, 4, 6 and 9, the rapid expansion of global research networks and publication trends underscores the necessity of developing comprehensive databases and standardized policy frameworks. These figures collectively emphasize the importance of integrating empirical data, international collaborations, and institutional contributions into unified repositories to guide future seismic retrofitting policies and code updates. Updating IS 15988 (2013) and equivalent international codes with digital monitoring guidelines will institutionalize evidence-based policy and accelerate practical implementation (IS 15988, 2013).

In essence, the next decade of retrofitting research must evolve toward intelligent, inclusive, and sustainable engineering. By bridging disciplinary, geographic, and accessibility divides, the scientific community can translate the insights reflected in Figures 1–16 and Tables 1–2 into real-world resilience for the built environment.

Figure 16

Document-Wise Citation and Co-Citation Analysis



Limitation

Although the present scientometric review provides valuable insights into the global research landscape of retrofitting strategies for reinforced concrete (RC) buildings, certain limitations must be acknowledged. First, the analysis is confined to data retrieved from the Dimensions.ai database, which, despite its extensive coverage, may exclude regional publications, non-English works, and conference proceedings not indexed within its scope. This selective dataset could lead to underrepresentation of emerging research from developing regions. Second, the reliance on citation-based indicators inherently favors older, well-cited publications while underestimating the impact of recent studies or innovative contributions that are yet to gain traction. Third, variations in author name formats, institutional affiliations, and keyword inconsistencies, even after normalization, may have introduced minor inaccuracies in mapping collaborations and thematic networks. Additionally, the study does not include field validation or experimental assessments to corroborate scientometric findings with practical engineering outcomes. Finally, the focus on quantitative bibliometric parameters limits the qualitative interpretation of research context, policy implications, and socio-economic dimensions. Future studies should address these gaps through multi-database integration, hybrid bibliometric–qualitative approaches, and expanded coverage of regional and open-access literature to ensure a more inclusive and comprehensive understanding of RC retrofitting research.

Conclusion

The present scientometric study provides a comprehensive evaluation of the global research trends, thematic evolution, and intellectual structure of retrofitting strategies for reinforced concrete (RC) buildings. The analysis reveals that seismic retrofitting has become an indispensable field of research and practice, bridging civil engineering, materials science, and sustainability studies. As the world continues to face frequent and destructive earthquakes, the retrofitting of existing RC structures emerges as a cost-effective and sustainable solution for mitigating structural vulnerability and ensuring public safety (Cao et al., 2021).

The results of the study demonstrate a robust upward trajectory in research output between 2016 and 2025, as observed in Figures 1–5 and Tables 1–2. The Engineering and Civil Engineering categories dominate the literature, supported by increasing contributions from Built Environment and Design disciplines, reflecting a strong interdisciplinary trend (Almeida et al., 2025). This growth is driven by global seismic events, technological innovation, and policy frameworks that promote performance-based seismic design. The increased focus on fiber-reinforced polymers (FRP), textile-reinforced mortars (TRM), and hybrid composite materials signifies a shift toward lightweight, durable, and sustainable solutions for structural strengthening (Bournas, 2018a, 2018b).

The country-wise bibliometric analysis (Table 3; Figures 6–8) identifies China, Italy, and the United States as global leaders in RC retrofitting research, characterized by prolific publications, extensive citation networks, and collaborative linkages. India, Iran, and Turkey also exhibit emerging prominence, contributing to low-cost retrofitting solutions suitable for developing economies. The institutional network (Figure 9) further illustrates Europe's central position, with the University of Naples Federico II and the University of Minho serving as major research hubs. These collaborations demonstrate how retrofitting research has evolved into a transnational endeavor grounded in shared innovation and knowledge transfer (Van Eck & Waltman, 2010).

At the author level, figures such as Andrea Prota, Humberto Varum, and Gabriele Milani have emerged as intellectual anchors, shaping global discourse through experimental validation, finite element modeling, and sustainable retrofitting frameworks. The co-authorship and co-citation networks (Figures 10–12) underscore an increasingly interconnected scholarly ecosystem, characterized by methodological diversity and thematic expansion. These developments have reinforced the role of scientometric mapping as a tool for identifying influential researchers, emerging technologies, and research gaps (Hook et al., 2018).

Despite this progress, several challenges remain. The study highlights underrepresentation of socio-economic and policy-oriented research, limited field validation, and uneven global participation. A disproportionate emphasis on quantitative engineering data often overlooks community resilience, cost-effectiveness, and social impact. Moreover, limited open-access dissemination (Figure 2) restricts the visibility of cutting-edge findings, particularly in developing regions. Overcoming these barriers requires an integrated framework that combines engineering innovation with social, environmental, and economic dimensions of resilience.

In conclusion, this study establishes that the global research on RC building retrofitting is advancing toward intelligent, sustainable, and performance-driven paradigms. Future research should emphasize data-driven modeling, artificial intelligence (AI)-based predictive assessment, and policy-driven implementation strategies. Encouraging open-access publishing, cross-disciplinary collaboration, and the adoption of low-carbon materials will enhance global knowledge exchange and contribute to safer, more resilient urban infrastructures. As the world transitions into an era of sustainable development and smart construction, seismic retrofitting stands as a cornerstone of disaster risk reduction and resilient built environments (IS 15988, 2013).

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