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Global Bibliometric Insights into Research Trends and Collaboration Networks in Risk Management of Reinforced Concrete Structures

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ABSTRACT

In civil engineering, the durability and sustainability of reinforced concrete structures have emerged as crucial issues, especially in light of growing needs for infrastructure around the world and heightened environmental threats. Risk management and sustainable development encounter numerous obstacles due to deterioration processes such corrosion, cracking, and mechanical fatigue, which are exacerbated by changing climate conditions and heavy resource use. This study offers a thorough bibliometric review of the body of research on environmental effect and risk management in reinforced concrete construction. Leading contributors, significant documents, key subject clusters, and new research avenues are identified by mapping co-authorship networks, institutional and national connections, citation patterns, and keyword co-occurrences. The findings highlight how integrative methods that incorporate environmental assessments-such as life cycle analysis, green building techniques, and digital monitoring technologies-into project risk frameworks have replaced traditional risk modelling. The work's conclusions guide future research directions and promote evidence-based policy and practice to improve the robustness, sustainability, and durability of reinforced concrete assets around the globe.

Keywords: Reinforced concrete, Risk management, Environmental impact, Life cycle assessment

INTRODUCTION

For decades, civil infrastructure has largely relied on reinforced concrete, underpinning buildings, transportation systems, and industrial facilities worldwide to ensure safety and operational efficiency. Maintaining safety, extending service life, and managing assets over the long term are complex tasks due to the interplay among concrete, embedded steel reinforcement, and environmental factors. Deterioration processes such as corrosion, cracking, and fatigue progressively compromise reinforced concrete structures, leading to increased repair costs, reduced service life, and potential safety risks for communities (Michel et al., 2016; Thoft-Christensen, 2003; Stewart & Rosowsky, 1998).

Mitigating these risks necessitates an integrated understanding of structural engineering, materials science, environmental studies, and project management. In recent decades, scholarly research in this domain has grown significantly, advancing new risk identification techniques, quantitative predictive models, portfolio management approaches, and reliability analysis frameworks. Advanced methodologies such as Monte Carlo simulation, probabilistic risk analysis, and machine learning have been integrated with traditional empirical methods to optimize prediction accuracy and decision-making (Nogueira, 20p12; Vořechovská, 2010; Beyhan, 2023).

Environmental impact is now a paramount concern in risk management. The concrete industry is a major consumer of natural resources and a significant emitter of greenhouse gases, exerting considerable environmental pressure throughout the material's entire life cycle. Techniques such as Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), and resilience evaluation are increasingly central to the renewal and sustainable development of infrastructure. The growing frequency and intensity of climate-related hazards have further spurred research targeting improved adaptability and risk reduction for concrete structures (SciELO, 2023; Rasheed, 2022; Azobuild, 2025).

Despite substantial advancements, literature points to persistent gaps: fragmented interdisciplinary integration, insufficient harmonization of global policies regarding risk and environmental stewardship, and a limited focus on life cycle sustainability within risk frameworks. Bibliometric analyses have mapped the growth of global research networks and the spread of innovative concepts in both risk forecasting and sustainable integration, yet understanding remains limited regarding topic structuring, knowledge transfer, and the practical influence of academic advances (Al Qudah, Qutaishat, Al-Ghamdi, & Al-Harthy, 2024; Sinarg, 2023; Azobuild, 2025).

This study addresses these deficiencies by conducting a comprehensive bibliometric analysis of academic research on risk management and environmental impacts in reinforced concrete infrastructure. Through network visualizations of authorship, institutional collaborations, country-level links, citations, and keywords, the study identifies leading contributors, key research clusters, and emerging trends. Its goal is to inform future research, support policy advancement, and establish best practices for enhancing the safety, durability, and sustainability of reinforced concrete structures, leveraging an evidence-based synthesis of scientific, collaborative, and thematic development (Al Qudah, Qutaishat, Al-Ghamdi, & Al-Harthy, 2024; Vořechovská, 2010; Beyhan, 2023).

LITERATURE REVIEW

The investigation into reinforced concrete has evolved from basic studies of material characteristics to a comprehensive exploration that emphasizes durability, risk management, and sustainability in complex infrastructure settings. Initial investigations laid the groundwork for understanding compressive strength, mix design, curing, and the hydration chemistry of cementitious materials (Mehta & Monteiro, 2014; Neville, 2012). The necessity for enduring durability has brought risk management to the forefront, with studies detailing various failure mechanisms such as the corrosion of steel reinforcements (Bertolini et al., 2013; Poursaee, 2016), sulfate attack (Taylor, 1997), alkali-aggregate reaction (Stark, 1975), and freeze-thaw cycling (Mindess et al., 2003; Li et al., 2016). Probabilistic analysis, reliability modeling, and life cycle assessment have gained significant attention in the literature, facilitating enhanced predictions of service life and the development of more efficient maintenance strategies (Dixit, 2019; Frangopol, 2017; Straub & Biondini, 2020).

The assessment of environmental impact and sustainability issues has gained significant importance, as numerous studies have employed life cycle assessment (LCA) methodologies to evaluate resource utilization, emissions, waste generation, and ecological risks (Bilec et al., 2006; Marinković, 2013; Zhu et al., 2025). Advancements in eco-friendly construction techniques—incorporating alternative binders (such as fly ash, silica fume, and slag), recycled aggregates, and polymer modifications—lead to decreased carbon emissions while maintaining or enhancing structural integrity (Tam & Tam, 2006; Zuo et al., 2019; Begum et al., 2009). International standards and shifts in regulations have emphasized the importance of environmental management and sustainability for those involved in infrastructure ownership and engineering (Li et al., 2005; Love et al., 2010). Technological innovation signifies a notable trend. The application of machine learning and artificial neural networks in predicting compressive strength, modeling degradation, and monitoring structural health is transforming both research and practice (Jang et al., 2022; Padgett & Soliman, 2022; Liu, 2021). Recent studies highlight the significance of digital monitoring, remote sensing, and data-driven maintenance (Yang, 2017; Dixit, 2019). Research indicates that networks of collaborative inquiry are enhancing innovation and the flow of information across various disciplines and global borders (Govindan et al., 2016; Petchrompo, 2019). Thematic mapping reveals future priorities, including high-performance fiber-reinforced concrete (Brahim et al., 2021; Andrić et al., 2019), nanomaterial modification (Chen et al., 2014), self-compacting and 3D printable mixtures (Song, 2024), and adaptive designs for climate-resilient infrastructure (Wang et al., 2017; Zhou et al., 2012). Despite notable advancements, reviews of existing literature indicate persistent shortcomings: the integration of environmental and operational risk models, the translation of laboratory findings into real-world applications, and the uniformity of evaluation protocols across different geographical areas (Tam et al., 2006; Biondini, 2016; Love et al., 2010; Wong & Chan, 2014). An extensive bibliometric examination of research output, key topics, and

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collaborative networks is essential for guiding continuous progress and ensuring resilient, secure, and environmentally sustainable physical infrastructure.

METHODOLOGY:

The essay utilizes a quantitative bibliometric methodology alongside network analysis to define and clarify the research domain related to risk management and environmental impact in reinforced concrete infrastructure. Here are the main steps:

Gettingdata

We use a systematic search strategy that combines controlled keywords like "reinforced concrete," "risk management," "structural reliability," "corrosion," "life cycle assessment," and "environmental impact" to find relevant publications in well-known bibliographic databases like Web of Science and Scopus. The search is limited to a certain time period (for example, 2000–2024) and only includes English-language journal articles, conference papers, and reviews that are relevant to civil or structural engineering. Preliminary results are sorted by title, abstract, and keywords to get rid of things that aren't relevant, like non-technical articles, research that isn't about infrastructure, or duplicate entries.

Cleaning and getting data ready

The databases export bibliographic information, such as authors, titles, abstracts, keywords, affiliations, references, and citation counts, in formats that work, such as CSV and RIS. The data are further cleaned up to fix errors, such as different author names, inconsistent institution names, and duplicate entries. Thesaurus files are made to bring together words that mean the same thing and make sure that spelling differences are the same (for example, "life-cycle assessment" vs. "life cycle assessment"). This preprocessing step makes sure that the counts for publication, citation, and co-occurrence are correct for future network development.

Metrics for bibliometrics

To describe the corpus, standard bibliometric indicators are used to find the yearly publishing output, the most important authors, institutions, nations, and journals. Citation-based metrics, such as total citations, average citations per document, and h-index, are used to highlight important papers and people who have made a big difference. These metrics give a numerical picture of how research on risk and sustainability in reinforced concrete infrastructure has grown and changed over time.

Using VOSviewer to build a network

VOSviewer is a tool made just for showing bibliometric connections, and it makes network maps. There are separate networks for:
Co-authorship (authors, institutions, countries): connections show collaborative publications and show how partnerships work.
Citation and bibliographic coupling (documents, authors): connections show how citations are linked and how common reference lists are, highlighting important works and how closely related they are to each other.
Keyword co-occurrence: linkages show how often terms appear at the same time, which points out important research questions and new topics.
To keep publications with multiple co-authors from having a big effect on cooperation indicators, the fractional counting method is often used. Minimum requirements, like the number of articles or citations needed to be included, are set to highlight the most important nodes and keep the maps easy to read.

Grouping and showing

VOSviewer's clustering algorithm sorts nodes into color-coded groups based on how strong their connections are. This makes groups of authors, organizations, countries, documents, or subjects that are closely related. For the following, visualizations of layout and density are made:
Networks of authors working together (Figure 1)
Institutional cooperation networks (Figure 2)
Figure 3 shows networks of cooperation between countries.

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Keyword co-occurrence (Figure 4)
Figures 5–8 show networks of citation and bibliographic links for documents and authors. The size of a node shows how productive or influential it is (for example, how many publications or citations it has), and the thickness of a connection shows how strong the cooperation or co-occurrence is. These pictures are the basis for the full interpretative results.

Looking at and putting together

The networks and indicators are examined to determine: m
Important authors, groups, and countries that work together to push scientific work forward.
Basic texts and important works that put together the knowledge framework on risk and environmental impact in reinforced concrete.
Current and emerging subjects (e.g..., corrosion, life-cycle assessment, machine learning, sustainability) and their interrelations among clusters.
Structural deficiencies, such as insufficient interdisciplinary connections and underrepresented locations and subjects, highlight opportunities for future research and policy development.
The quantitative bibliometric findings are subsequently integrated with qualitative insights concerning the risks and sustainability of reinforced concrete, aiming to examine their implications for research agendas, standards, and asset management practices, thereby establishing the methodological foundation for the article's interpretation sections and conclusions.

RESULTS AND DISCUSSION

Influence of Reinforced Concrete on Global Infrastructure

The best writers on infrastructure deterioration and structural reliability are linked and organized in Figure 1.The network sees "Frangopol, Dan M." as the most important node. His many partnerships show that he is an important person in making multiauthor research happen. People like "Biondini, Fabio" and "Akiyama, Mitsuyoshi" are in groups that are very close together. This could mean that they work together a lot on issues that are important to their region or theme. This could be because the institutions are connected or they have similar research goals. Smaller nodes and figures on the edges show areas of specialized study, knowledge, or new contributions. This map shows how different research communities are and how important scholars are. This could lead to more collaboration and integration across fields.

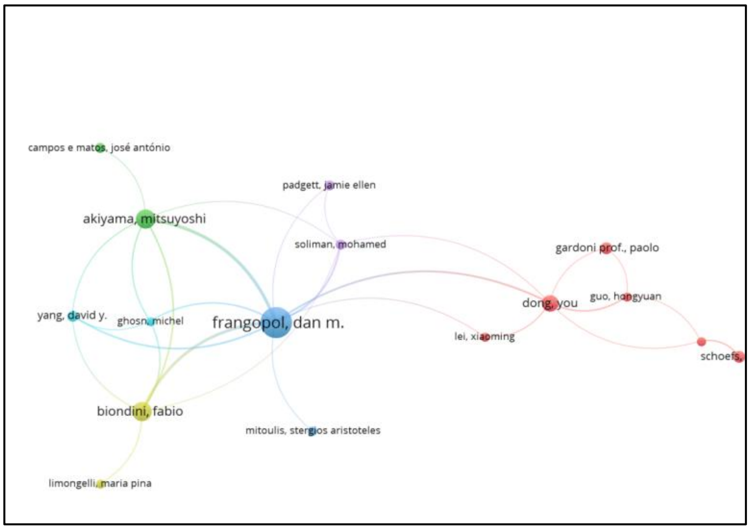

Figure 1: Co-authorship Network of Key Authors in Structural Reliability and infrastructure deterioration

Effects of Material and Environmental Interactions on Durability

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Figure2 shows how big organizations work together to make sure structures are safe. The "ATLAS Engineering Research Center" and other U.S.-based groups are at the center of the network. This shows that it has a lot of influence and output. "Politecnico di Milano" and "Tongji University, Shanghai" are examples of international nodes that highlight how far global relationships can go, even though they aren't as closely connected to the main core. This could be because the schools, money, or places are different. The « Department of Civil and Environment » connections to a number of international hubs indicate how it lets individuals communicate information across boundaries. The network displays major hubs, how institutions are ranked, and how to obtain greater research cooperation between continents. To fix problems with global infrastructure, all of these elements are important.

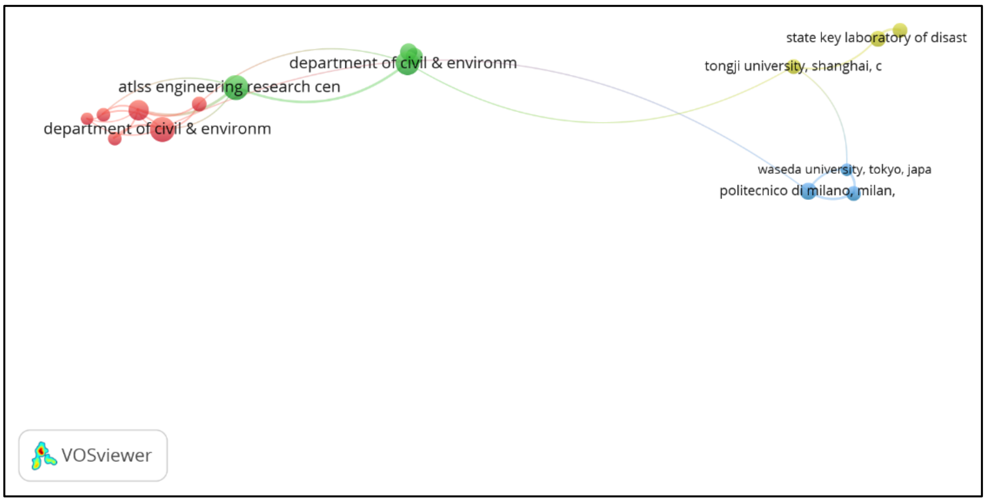

Figure 2: Institutional Co-authorship Network in Structural Reliability Research

Impact of Interdisciplinary Approaches on Risk Management

This figure shows how countries work together on a global scale. The US, China, and the UK are three major hubs with strong connections. This shows that they are the best places to do business and work with researchers. Asian and Oceanic countries connect continents, while dense networks in Europe show that goals are funded or matched locally. Peripheral countries are likely expanding their capacity or entering new domains of structural reliability research due to reduced connections. This graphic gives you a strategic view of international collaborations, which can help you find established networks and areas that could benefit from focused resource sharing and working together with people from other countries.

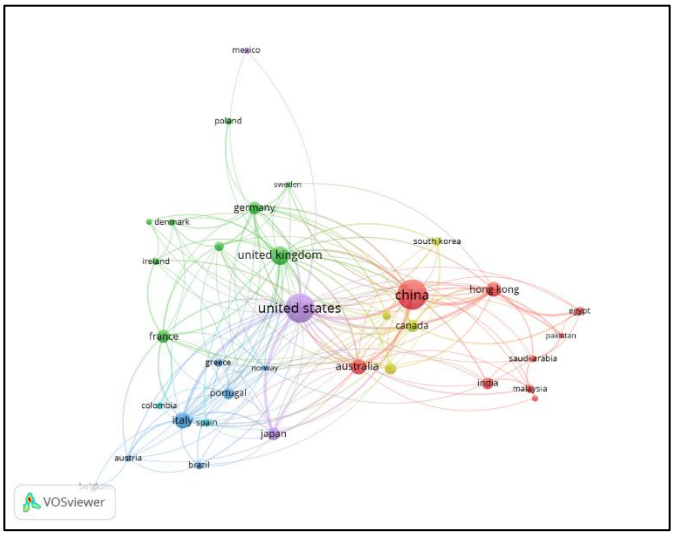

Figure 3: International Co-authorship Network in Structural Reliability and Deterioration Studies

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Environmental Impacts and the Drive toward Sustainability

Figure 4 uses keyword analysis to present a thematic landscape. The strong connections between essential terms like "deterioration," "corrosion," and "life cycle" emphasize their prominence as central study issues. The surrounding clusters pertaining to "machine learning," "forecasting," and "sustainable development" demonstrate the evolution of the discipline by demonstrating the integration of computational methods with environmental goals. The edge keywords, which have fewer connections, are either specialized fields or cutting-edge strategies that will expand as techniques change. Strategic planning for multidisciplinary studies and technological innovation is supported by the network's density and color-coded subdivisions, which make it possible to identify both established and emergent research areas

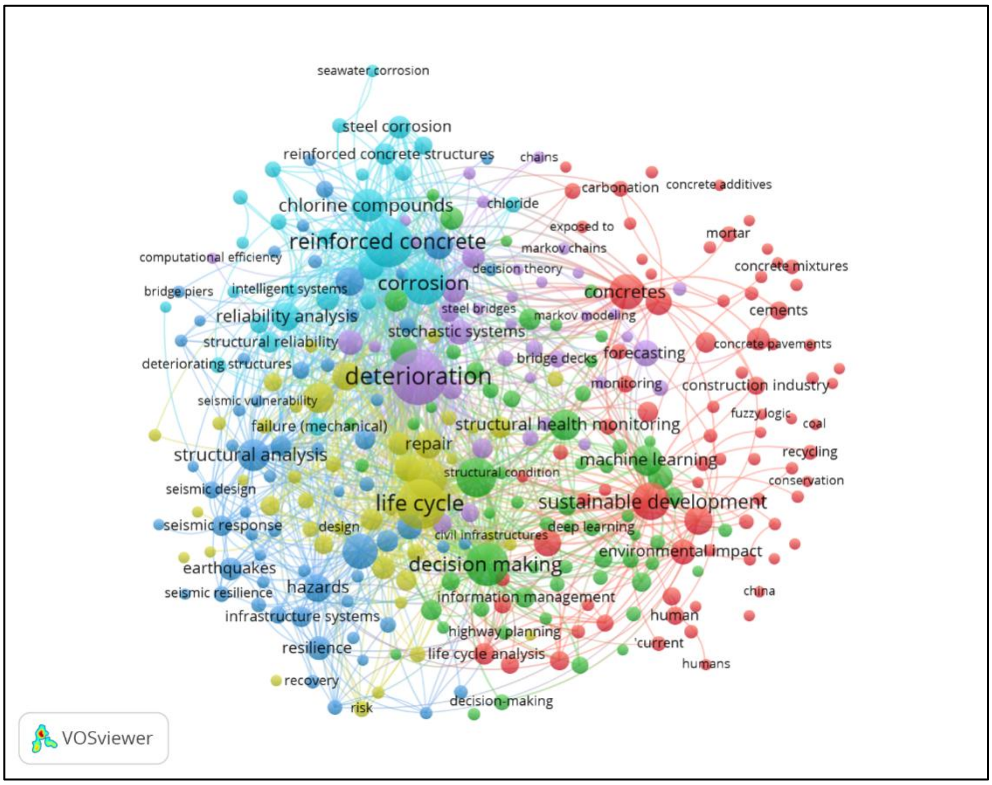

Figure 4: Keyword Co-occurrence Network in Structural Reliability and Deterioration Research

Knowledge Deficiencies and Their Influence on Research Progress

Figure5 shows how primary research papers affect academics. The big, core nodes, like "Mishra (2022)," "Frangopol (2017)," and "Bado (2021)," show that they have a big influence on citations, which shows how important they are and how widely they are used in later works. A lot of citations grouped together indicate how key ideas, methods, and empirical discoveries spread.

Documents that act as citation bridges show how they are different from other documents that bring together different research streams. This network makes it easier to find important research, lets scholars see how academic inquiry has changed over time, and points them to important works that will help them learn more about their field. On of important research, helps follow the development of academic research, and leads scholars to important works that are necessary for expanding domain knowledge.

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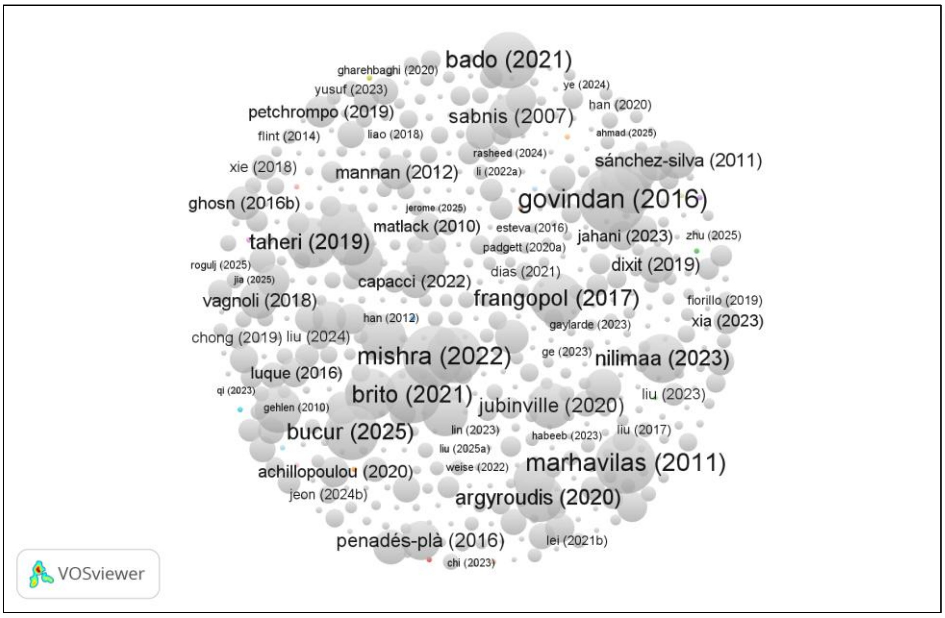

Figure5: Citation Network of Key Documents in Structural Reliability and Deterioration

Role and Potential of Bibliometric Analysis

Figure 6 shows the intellectual organization of the area by looking at how authors cite each other. "Frangopol, Dan M." and his closest colleagues have a lot of impact on citations, which affects the way others talk about and do research. Clustered writers indicate intellectual groups characterized by common emphasis or methodologies, while sparsely linked people signify specialized or emerging viewpoints. The citation trail among key people illustrates the spread of theories and the cross-pollination of ideas, essential for fostering academic leadership and mentorship within the subject.

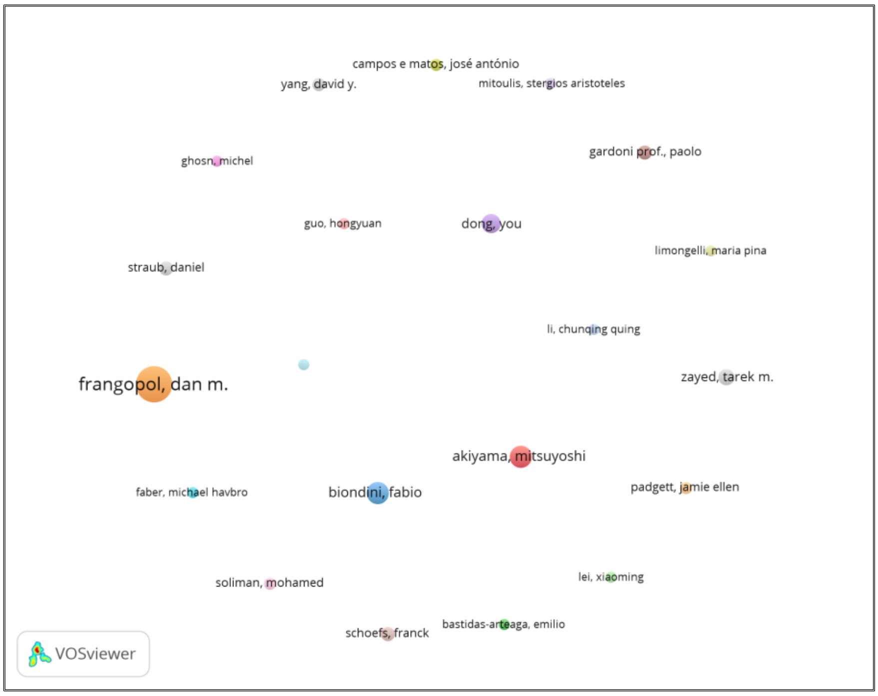

Figure 6: Citation Network of Key Authors in Structural Reliability

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Objectives and Scope of This Study:

Figure 7 shows how papers are related via common bibliographies. "Frangopol (2017)" and "Biondini (2016)" are two important works that show how often they are used as knowledge bases in many areas. The fact that certain publications are tightly grouped and often linked to one other suggests that specialized study lines and methodological schools are forming. The existence of peripheral papers suggests fresh ideas, specialist methods, or new ways of looking at things. This network structure helps both novice and experienced researchers find their way through the literature by pointing them to important works or holes that need to be filled.

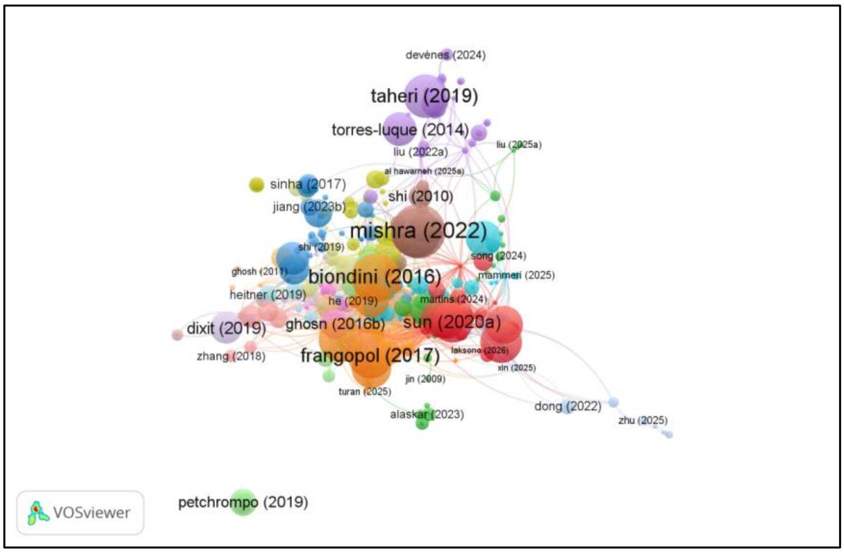

Figure 7: Bibliographic Coupling of Documents in Infrastructure Deterioration Research

Influence of Author Collaboration Networks on Knowledge Creation

Figure8 shows how authors are connected by shared citations, showing how intellectual communities grow around common research grounds. The prominent position of "Frangopol, Dan M." and the active clusters not only show intellectual leadership but also show how academic teams work together—groups that are connected by common interests, methods, or institutional ties. Peripheral writers may be knowledgeable in a certain field or new to the subject. The framework lets us see how research groups have developed and come together over time. This will enable them work together better in the future and make links across different fields.

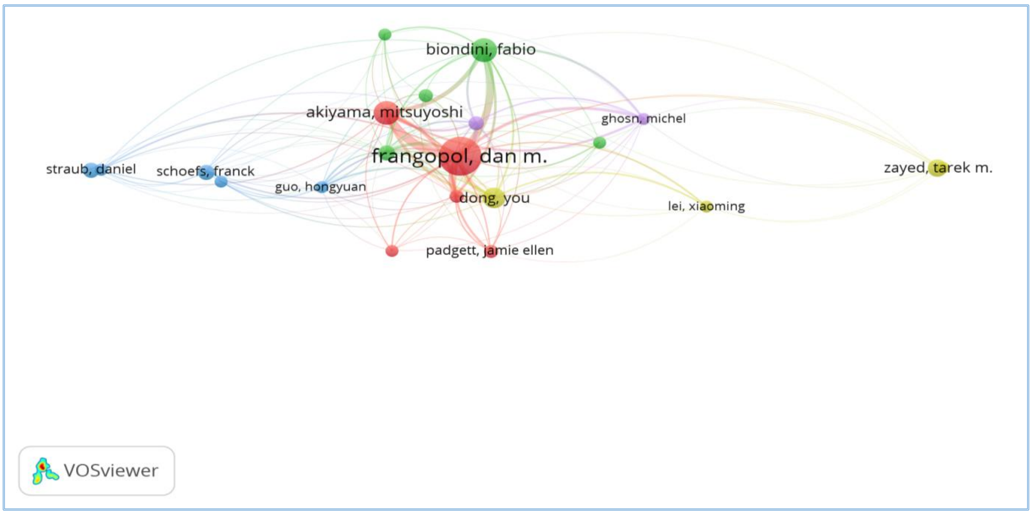

Figure 8: Bibliographic Coupling Network of Authors in Infrastructure Deterioration Research

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CONCLUSION

This analysis has uncovered the evolving trends in research focused on risk management and the environmental impacts associated with reinforced concrete structures. The analysis of co-authorship, institutional collaboration, and thematic clusters indicates a notable shift from traditional concerns regarding durability and performance to cohesive frameworks that align structural reliability with environmental sustainability.

The findings demonstrate that degradation mechanisms, particularly corrosion and fatigue, are essential to evaluating the risks associated with reinforced concrete structures. The choice of materials, design approaches, and operational conditions significantly influence the long-term durability of the infrastructure. The combination of life cycle assessment with environmental impact analyses is increasingly common in academic research and industrial practices, promoting progress in low carbon materials, resource-efficient design, and methods for prolonging service life.

Global collaborative initiatives, combined with advanced methodologies like machine learning, digital monitoring, and probabilistic risk modeling, are opening new research pathways, successfully linking environmental objectives with engineering approaches. However, challenges persist: variations in regional standards, the need for robust databases, and insufficient integration of durability metrics within life cycle assessment frameworks impede comprehensive risk and sustainability evaluation.

This study demonstrates that effective risk management in reinforced concrete requires a blend of technological innovations and data-driven decision-making, as well as a holistic approach that fully incorporates environmental factors. Subsequent research should highlight the significance of interdisciplinary collaboration, the uniformity of evaluation methods, and the transformation of scientific advancements into practical policy and design suggestions to promote robust and sustainable infrastructure globally.

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