INTERNATIONAL JOURNAL OF ACADEMIC RESEARCH IN BUSINESS & SOCIAL SCIENCES

Vol 16, Issue 3, (2026) E-ISSN: 2222-6990

Trending Methods and Advances in Prestressed Post-tensioned Concrete Structures and Sustainability: A Bibliometric Analysis

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DOI Link: http://dx.doi.org/10.6007/IJARBSS/v16-i3/27823

Published Date: 04 March 2026

Abstract

Recent advances in prestressed post-tensioned concrete structures have emphasized enhanced structural performance, resilience under extreme loading and thermal conditions. Additionally, its sustainability through innovative materials, hybrid systems, and data-driven modelling approaches in the years under review has not been adequately researched using bibliometric analysis research method. Therefore, this study presents a bibliometric and thematic review of research on prestressed and composite concrete systems, including ultra-high-performance concrete (UHPC), fiber-reinforced polymers (FRP), and steel fiber-reinforced concrete. Bibliographic data were retrieved from the Scopus database, covering peer-reviewed journals, articles, conference papers published between 1996 and 2026. A systematic screening process was conducted to remove duplicates and irrelevant records. VOSviewer software was employed to perform bibliometric analysis, including co-authorship analysis, keyword co-occurrence mapping, citation analysis, and bibliographic coupling. Author keywords and indexed keywords were analysed using a minimum occurrence threshold to identify dominant research themes and their interrelationships. Network visualization and density maps were generated to reveal knowledge clusters and emerging research trends. The results indicate strong thematic convergence toward prestressed UHPC and composite structural systems, FRP strengthening techniques, machine learning–based predictive modelling, and structural performance under extreme conditions such as fire and elevated temperatures. Additionally, sustainability-oriented studies focusing on economic and environmental performance are gaining prominence. Overall, the bibliometric findings demonstrate a growing interdisciplinary integration of advanced materials, prestressing technologies, and intelligent analytical methods aimed at improving safety, durability, and sustainability in modern concrete infrastructure. It also revealed that there is a need for similar research in Africa as there were few scholarly research from Africa and will be an easy source of research gaps for new postgraduate student's research thesis.

Keywords: Prestressed Post-Tensioned Concrete, Ultra-High-Performance Concrete, Fiber-Reinforced Polymers, and Steel Fibre-Reinforced Concrete, Sustainability, Bibliometric Analysis

Introduction

Prestressed post-tensioned concrete systems remain fundamental to modern civil infrastructure due to their superior load-carrying capacity, crack control, and serviceability performance (Naik et al. 2024). They are extensively used in bridges, railway sleepers, high-rise buildings, industrial floors, marine structures, and precast elements where structural efficiency and long-span capability are required. As infrastructure demands increase globally, particularly under rapid urbanization, climate change pressures, and sustainability. Which targets the need to enhance the performance, durability, and environmental efficiency of prestressed systems. Hence it has become more critical than ever. Despite their structural advantages, conventional prestressed concrete members depend heavily on longitudinal tendons for flexural resistance and transverse steel stirrups for shear capacity and confinement (Waqar et al. 2024). This traditional reinforcement strategy presents several technical and sustainability-related challenges. Reinforcement congestion complicates detailing and construction, increases labour intensity, and elevates project costs. Moreover, conventional steel reinforcement remains vulnerable to corrosion, particularly in aggressive environments such as marine, industrial, and transportation infrastructures. Corrosion-induced deterioration leads to reduced service life, increased maintenance frequency, and significant lifecycle economic and environmental burdens. These limitations highlight an urgent need for innovative reinforcement strategies that enhance structural performance while reducing material consumption, labour requirements, and environmental impact (Naik et al. 2024).

In this context, the integration of advanced materials, particularly steel fibre-reinforced concrete (SFRC), ultra-high-performance concrete (UHPC), and fibre-reinforced polymers (FRP), has emerged as a transformative approach. Steel fibers, through their crack-bridging mechanism, enhance post-cracking ductility, energy absorption capacity, shear resistance, and toughness of concrete composites. When combined with prestressing, a synergistic structural effect is achieved: prestressing reduces tensile stresses and delays cracking under service loads, while fibers control crack propagation and improve residual strength after cracking. This hybrid action has demonstrated the potential to partially or fully replace conventional stirrups in certain applications, thereby reducing reinforcement congestion and improving constructability.

The utility and effectiveness of these hybrid prestressed systems extend beyond mechanical performance. From a structural perspective, they improve flexural capacity, shear resistance, fire resilience, and impact performance. From a constructability standpoint, they simplify reinforcement detailing, accelerate production and particularly beneficial for precast industries. From a sustainability perspective, reducing traditional steel reinforcement lowers embodied carbon and energy consumption. Life-cycle assessment studies indicate that optimized fibre-reinforced prestressed members can significantly reduce global warming potential through material efficiency and structural optimization. Furthermore, the use of recycled steel fibers and industrial by-products promotes circular economy principles and waste reduction (Zia et al. 2022).

The importance of studying prestressed systems in combination with advanced materials is therefore multidimensional. Structural engineers benefit from improved design flexibility and enhanced reliability under extreme loading conditions such as fire, fatigue, and impact. Infrastructure owners and policymakers benefit from longer service life and reduced maintenance costs. Contractors and manufacturers benefit from simplified reinforcement layouts and improved production efficiency. Researchers and postgraduate scholars gain new interdisciplinary opportunities by integrating materials science, structural engineering, sustainability assessment, and artificial intelligence–based predictive modelling (Soltanzadeh et al. 2022).

However, despite the growing body of research on prestressed UHPC systems, FRP strengthening, steel fiber reinforcement, and machine learning-based prediction models, the literature remains fragmented. Most studies focus on isolated performance indicators such as flexural strength or compressive capacity, with limited integration of structural performance, durability, sustainability, and lifecycle considerations within a unified framework. Furthermore, bibliometric evidence reveals geographical imbalance in research output, with limited contributions from developing regions such as Africa. This fragmentation limits holistic understanding and hinders the development of comprehensive design guidelines for sustainable prestressed systems.

Therefore, there is a clear need for a systematic and integrative assessment of research trends, thematic evolution, and sustainability integration in prestressed and composite concrete systems. This study addresses this need through a comprehensive bibliometric analysis of prestressed post-tensioned concrete research, focusing on steel fibre reinforcement, advanced composite materials, and sustainability-driven innovations. By identifying dominant research clusters, emerging trends, knowledge gaps, and geographical imbalances, the study provides valuable insights for researchers, practicing engineers, policymakers, and postgraduate scholars. Ultimately, this research contributes to advancing high-performance, durable, and environmentally responsible prestressed infrastructure systems aligned with global sustainability objectives.

Structural Performance and Mechanical Behavior

The mechanical advantages of PSFRC are well-documented across various structural configurations. In terms of flexural performance, steel fibers contribute significantly to the residual tensile strength of the concrete, which is crucial for members subjected to high bending moments (Subramanian et al., 2024). For instance, research on geopolymer concrete sleepers reinforced with steel fibers demonstrated superior static behavior compared to traditional reinforced sections (Subramanian et al., 2024). Similarly, the use of ultra-high-performance concrete (UHPC) combined with steel fibers in prestressed I-shaped beams has shown exceptional structural efficiency and shear resistance (Harsányi et al., 2025).

Shear capacity remains a critical area of focus, as steel fibers can partially or entirely replace minimum shear reinforcement (stirrups) in certain applications (Almasabha et al., 2023). Hernandez et al. (2025) investigated the shear strength of prestressed SFRC hollow core slabs, finding that fiber inclusion significantly enhances the shear-carrying mechanism. Moreover, the crack-bridging effect of fibers reduces internal stresses and limits shear crack widths, facilitating a more progressive failure mode (Bhosale & Prakash, 2020; Yang et al., 2019). The

application of steel fibers in deep beams without stirrups has also been identified as a sustainable alternative that maintains structural integrity while reducing material complexity (Almasabha et al., 2023).

Sustainability and Environmental Impact

The construction industry is increasingly focused on reducing the embodied carbon of structural components. Conventional reinforced concrete is a major contributor to global CO emissions, primarily due to cement and steel production (Asare et al., 2024). Life Cycle Assessment (LCA) studies indicate that replacing a portion of conventional steel with steel fibers can reduce the total embodied carbon of concrete beams by approximately 37% (Asare et al., 2024). This reduction is attributed to the decreased requirement for secondary reinforcement and the potential for thinner, more efficient cross-sections (Yepes et al., 2017).

Sustainable PSFRC research has also explored the use of recycled materials. Recycled steel fibers (RSF) derived from waste tires have been proposed as an eco-friendly alternative to industrial steel fibers (Zia et al., 2022). Studies by Soltanzadeh et al. (2022) used an integrated environmental and mechanical index to show that RSF can provide comparable mechanical performance to industrial fibers while significantly lowering the environmental footprint. Furthermore, incorporating industrial by-products such as sawdust (Waqar et al., 2024) or nano-materials like CaCO (Wen et al., 2025) into the SFRC mix has been shown to optimize both durability and sustainability.

Bibliometric Trends and Research Landscape

The academic interest in sustainable PSFRC has seen an exponential rise over the last two decades. Bibliometric analyses of sustainable construction materials reveal that "durability," "life cycle assessment," and "innovative materials" have emerged as central thematic clusters (Alam Bhuiyan, 2024). The shift toward "green" concrete is reflected in the increasing volume of publications focusing on the optimization of prestressed members for both cost and CO emissions (Yepes et al., 2017). Recent trends also point toward the integration of advanced technologies, such as distributed optical fiber sensors for real-time monitoring of cracks in prestressed pipes (Liu et al., 2025) and machine learning models for predicting the eco-friendly performance of fiber-reinforced structures (Qin & Kaewunruen, 2023).

Despite these advancements, challenges remain in the standardization of design codes for PSFRC. While the Eurocode-2 (EC-2) Annex L now provides provisions for SFRC structures (De la Fuente et al., 2023), further research is needed to refine the long-term performance metrics, such as creep-fatigue interactions in fiber-reinforced prestressed girders (Kim et al., 2025) and the performance of hybrid systems involving fiber-reinforced polymers (FRP) (El Meski, 2026; Kodur et al., 2025).

Prestressed post-tensioned concrete systems remain fundamental to modern civil infrastructure due to their enhanced load-carrying capacity, crack control, and serviceability performance. The continuous demand for longer spans, reduced maintenance costs, and improved structural resilience has driven the development of advanced materials and hybrid structural systems, including ultra-high-performance concrete (UHPC), fibre-reinforced polymers (FRP), steel fibre-reinforced concrete, and UHPC steel composites. These

innovations have significantly improved mechanical performance, durability, and resistance to extreme loading and environmental conditions.

Recent studies have demonstrated the effectiveness of external FRP strengthening in improving the flexural behavior and deflection control of unbonded post-tensioned concrete members. Similarly, the integration of UHPC into prestressed beams, piles, and composite systems has shown notable improvements in stiffness, load capacity, and joint performance. In transportation infrastructure, advancements in concrete sleeper technologies and prestressed bridge girders have addressed increasing service demands and safety concerns, particularly under fire and thermal exposure scenarios.

In parallel with material and structural innovations, data-driven and machine learning-based approaches have emerged as powerful tools for predicting complex structural behaviours. Explainable artificial intelligence techniques, such as SHAP-based models, are increasingly being adopted to enhance prediction accuracy while maintaining interpretability for engineering applications. Moreover, sustainability considerations including economic efficiency and environmental impact have become integral to the evaluation of modern concrete systems, reflecting global efforts toward sustainable infrastructure development.

Notwithstanding these advancements, the rapidly expanding body of literature presents fragmented insights across materials, structural behaviour, predictive modelling, and sustainability assessments. A comprehensive synthesis that integrates experimental findings, analytical approaches, and bibliometric evidence is therefore essential to identify dominant research themes, assess current limitations, and guide future investigations in prestressed and composite concrete engineering. Based on the reviewed literature and bibliometric analysis, several critical research gaps are identified. These includes Limited Integration of Multi-Performance Criteria, where most existing studies focus on isolated performance aspects such as flexural capacity, compressive strength, or thermal resistance. There is a lack of integrated frameworks that simultaneously assess structural, thermal, durability, and sustainability performance of prestressed UHPC and composite systems. Similarly, Insufficient Long-Term and Serviceability-Based Studies, which shows that short-term mechanical performance has been extensively studied, long-term behaviour such as creep, shrinkage, prestress loss, fatigue, and time-dependent deflection remains underexplored, particularly for UHPC–steel and FRP-strengthened prestressed members. However, there Limited Post-Extreme Event Recovery Assessment. Although several studies examine fire or elevated temperature effects, few address post-event recovery, residual serviceability, and repair strategies for prestressed and composite concrete structures after extreme events. The review also revealed a fragmented application of artificial intelligence. Although, machine learning models have primarily been applied to strength prediction problems. Their application to serviceability, durability, fire response, and lifecycle performance of prestressed concrete systems remains limited. Furthermore, the integration of AI models with design codes is still largely unexplored. Additionally, economic and environmental evaluations are often conducted independently of structural performance analyses. Holistic life-cycle-based assessments that couple sustainability metrics with mechanical and durability performance are scarce. Notwithstanding extensive experimental research on UHPC, FRP, and composite members, standardized design guidelines for prestressed hybrid systems are still evolving, limiting practical implementation in large-scale infrastructure.

Prestressed Post-tensioned Concrete Systems

Prestressed post-tensioned concrete systems continue to play a critical role in modern infrastructure due to their superior load-carrying capacity, crack control, and serviceability performance. El Meski (2026) investigated the prediction of immediate deflection and flexural capacity of unbonded post-tensioned concrete members strengthened with externally bonded fiber-reinforced polymer (FRP) composites. The study highlighted the effectiveness of FRP strengthening in enhancing flexural performance while emphasizing the need for accurate predictive models to capture serviceability behavior. Similarly, Zhu et al. (2025) examined the thermo-structural response of prestressed bulb-tee girder bridges under severe fire exposure, revealing significant degradation in prestressing force and stiffness at elevated temperatures, which has important implications for bridge fire resilience design.

Ultra-High-Performance Concrete (UHPC) and Composite Structural Members

The integration of ultra-high-performance concrete (UHPC) with prestressing and steel components has gained increasing attention due to its exceptional mechanical properties. Zandi Lak et al. (2025) analysed the structural behaviour of precast prestressed H-shaped UHPC piles with steel spliced joints, demonstrating enhanced load transfer efficiency and joint performance. Harsányi et al. (2025) further explored prestressed I-shaped UHPC–steel composite beams with puzzle-shaped continuous shear connectors, reporting improved composite action and flexural performance. Yuan et al. (2025) investigated prestressed CAUHPC–normal concrete composite beams, confirming the compatibility of UHPC overlays with conventional concrete in achieving higher stiffness and load capacity.

Fiber Reinforcement and Innovative Materials

Fiber reinforcement has been widely adopted to improve ductility, crack resistance, and post-peak behavior of concrete structures. Nemati et al. (2025) studied the compressive behavior of prestressed steel fiber-reinforced concrete-filled steel tube (SFRCFST) stub columns after heating, emphasizing the beneficial role of steel fibers in retaining residual strength following thermal exposure. Ren et al. (2025) conducted an economic and environmental evaluation of steel fiber-reinforced concrete linings, concluding that fiber reinforcement can offer both cost efficiency and reduced environmental impact over the service life of infrastructure systems.

Structural Performance under Extreme and Specialized Conditions

Structural performance under extreme conditions remains a major research focus. Nemati et al. (2025) demonstrated that the fresh concrete compression technique significantly enhances the post-fire compressive capacity of prestressed composite columns. Zhu et al. (2025) performed parametric analyses on prestressed bridge girders under fire scenarios, identifying key parameters influencing thermal-induced damage. Additionally, Shen et al. (2025) proposed UHPC-based honeycomb protective structures with multi-scale mechanisms, showcasing their superior energy absorption and protective capabilities under impact loading.

Data-Driven Modelling and Machine Learning Applications

The application of artificial intelligence in structural engineering is increasingly evident. Jeong et al. (2025) formulated shear strength prediction models for concrete members using SHAP-based explainable machine learning combined with iterated local search algorithms. Their

approach not only improved prediction accuracy but also enhanced model interpretability, addressing a key limitation of black-box AI models in structural design.

Transportation Infrastructure and Sustainability Considerations

Transportation infrastructure remains a dominant application area. Yaghmour and Andrawes (2026) provided a comprehensive review of innovative material technologies for concrete sleepers in modern railways, highlighting advancements in durability, sustainability, and performance. Sustainability considerations were further reinforced by Ren et al. (2025), who demonstrated that steel fiber-reinforced concrete linings can significantly reduce life-cycle costs and environmental impacts. Subsequently, Table 1 shows the review of current literature in Prestressed concrete Steel fibre and its Sustainability.

Table 1
Literature Table on Sustainability Contribution

S/N	Reference (Author & Year)	Research Focus	Key Findings / Results	Sustainability Contribution
1	**Asare et al. (2024)**	Life Cycle Assessment (LCA) of SFRC beams.	Steel fibers reduced embodied carbon by up to 37% by minimizing traditional reinforcement.	Significant reduction in global warming potential through material optimization.
2	**Almasabha et al. (2023)**	Shear behavior of deep beams without stirrups.	Steel fibers can effectively replace minimum shear reinforcement while maintaining structural integrity.	Reduces labour intensity and material usage (steel stirrups) in complex members.
3	**Subramanian et al. (2024)**	Prestressed geopolymer concrete sleepers.	Geopolymer-based SFRC showed superior static behavior and crack resistance compared to OPC.	Lower carbon footprint by replacing Portland cement with industrial by-products.
4	**Harsányi et al. (2025)**	Prestressed I-shaped UHPC-steel composite beams.	High efficiency in load-carrying capacity and shear resistance using puzzle-shaped connectors.	Structural thinning and weight reduction lead to lower material consumption.
5	**Hernandez et al. (2025)**	Shear strength of PSFRC hollow core slabs.	Fiber inclusion significantly enhances shear-carrying mechanisms and ductility.	Optimization of slab thickness and reduction of conventional steel reinforcement.
6	**Soltanzadeh et al. (2022)**	Recycled steel fibers (RSF) from waste tires.	RSF provides comparable mechanical performance to industrial fibers when optimized.	Circular economy integration by repurposing industrial waste and reducing virgin steel use.
7	**Zia et al. (2022)**	Waste tire steel fiber applications.	Comprehensive review showing improved toughness and energy	Waste management and reduction of the

			absorption in cement composites.	environmental impact of tire disposal.
8	**Yepes et al. (2017)**	Optimization of precast-9prestressed bridges.	Hybrid evolutionary algorithms can optimize designs for both minimum cost and CO_{2} emissions.	Practical framework for sustainable engineering design and carbon reduction.
9	**Qin & Kaewunruen (2023)**	Eco-friendly design of high-strength fiber concrete.	Integrated assessment of mechanical and ecological metrics for structural design.	Promotion of "green" concrete standards through balanced performance-eco metrics.
10	**Wen et al. (2025)**	Nano-materials (Nano-$CaCO_{3}$) in SFRC.	Enhancement of durability and mechanical properties through matrix densification.	Extended service life of structures, reducing the need for frequent repairs or replacement.
11	**Liu et al. (2025)**	Smart monitoring of prestressed pipes.	Distributed optical fiber sensors allow for precise crack detection and health monitoring.	Enhances durability and safety, preventing catastrophic failures and associated environmental costs.
12	**Naik et al. (2024)**	Sustainable prestressed railway sleepers.	Laboratory investigation confirmed the performance of steel-fiber-modified sustainable mixes.	Improved durability and longevity for critical infrastructure under cyclic loading.
13	**Waqar et al. (2024)**	Sawdust and steel fiber in concrete.	Formulated sustainable mixes using organic waste and fiber reinforcement.	Utilization of agricultural/wood waste to lower the environmental footprint of concrete.
14	**Camille et al. (2024)**	Macro-synthetic vs. steel fibers in sleepers.	Macro-synthetic fibers offer a corrosion-resistant alternative with high post-cracking performance.	Improvement of service life in corrosive environments, reducing maintenance requirements.
15	**De la Fuente et al. (2023)**	Eurocode-2 design provisions for SFRC.	Standardized the structural use of fibers, facilitating wider industry adoption.	Enables the safe use of efficient, low-carbon fiber-reinforced designs in mainstream construction.

Research Methodology

The bibliometric analysis began with the download of dataset from Scopus database, being one of the best databases with high impact journal, book chapters, conference papers respected all over the word, using “Prestressed concrete Steel fibre AND Sustainability”. Before filtering, 2,204 documents were initially downloaded, where Subject area such as Engineering had1,464, Materials Science 647, Physics and Astronomy 84, Computer Science 59, Earth and Planetary Sciences 59 words respectively. Document type Article 95, Conference paper 517, Conference review 61, Review 38, and Book chapter 17. Hence, Keyword included are Prestressed Concrete 829, Concrete Beams and Girders 650, Reinforced

Concrete 588, Steel Fiber 510, Fiber Reinforced Plastics 434, however after the inclusion of only papers in English language and the years range included was from 1996 – 2026, 1,595 documents were used as the dataset from Scopus database. This dataset was imported into VOSviewer as seen below in figure 1 and was later used to carry out the bibliometric analysis.

Results and Discussions

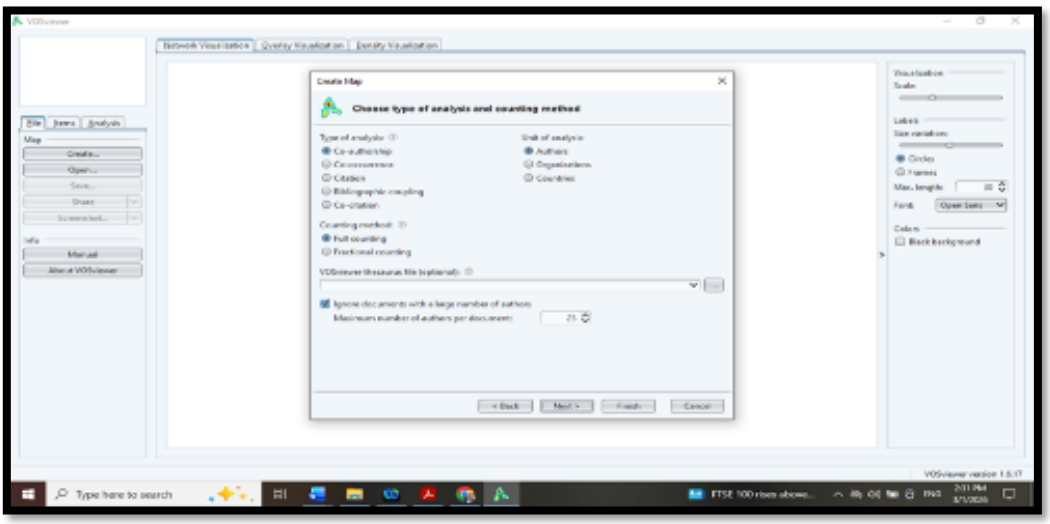

Figure 1. VOSviewer page for Visualization with Country and Author

Furthermore, figure 2 presents the country-level distribution of publications, citations, and collaboration strength in the dataset, highlighting the global landscape of research contributions. The United States and China dominate scholarly output with 309 and 291 documents respectively and also record the highest citation counts (4,501 for the United States and 4,045 for China), indicating both productivity and strong academic impact. These two countries further exhibit the strongest international collaboration networks, as reflected by their high total link strength values (129 for the United States and 106 for China). Other notable contributors include Canada, the United Kingdom, Australia, South Korea, Japan, Germany, Italy, and Switzerland, which show moderate to high publication volumes accompanied by substantial citation performance, underscoring their influential roles in the field. In contrast, several countries contribute relatively fewer documents and citations, suggesting emerging or niche participation. Largely, the table reveals a concentration of research activity and influence in a few leading countries, alongside a diverse set of nations contributing to the global knowledge network through varying degrees of collaboration and impact.

Overall, the distribution reveals a clear research gap, as African countries show little or no contribution in terms of publication output, citation impact, and international collaboration, highlighting an underrepresentation of the continent in the global scholarly landscape and a critical area for future research development.

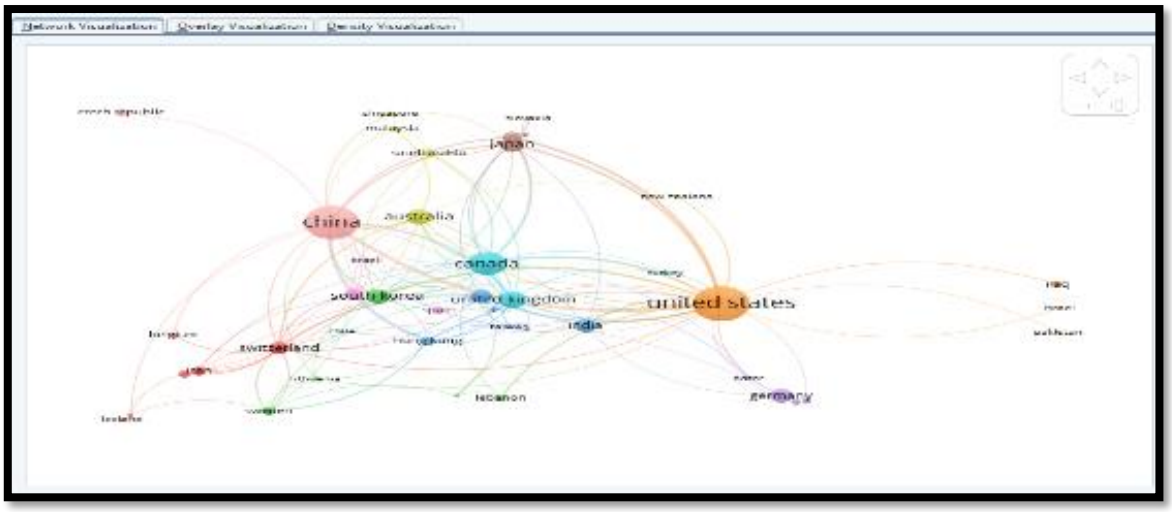

Figure 2. Visualization by Country

Similarly, figure 3 shows the organizational analysis that research output in the field is highly concentrated within a relatively small number of universities, research institutes, and industry-oriented organizations, predominantly located in China, North America, Europe, and parts of Asia. Chinese institutions, particularly universities and state key laboratories feature prominently in terms of document volume. Hence, reflecting their strong research capacity and sustained investment in this domain. North American and European organizations, such as major universities, national laboratories, and specialized research centers, exhibit comparatively lower publication counts but often achieve high citation impact. This suggests a focus on influential or foundational studies rather than volume-driven output. Industry-linked organizations and applied research centers also appear, though their contributions are sporadic and generally less integrated into international collaboration networks, as indicated by low total link strength values. Notably, African institutions are sparsely represented, with only a few organizations from Egypt appearing with modest document and citation counts, pointing to a significant geographic and institutional research gap. This uneven distribution highlights limited research capacity, visibility, and cross-institutional collaboration from most African regions, underscoring the need for broader inclusion, capacity building, and stronger international partnerships to balance the global knowledge structure in this field.

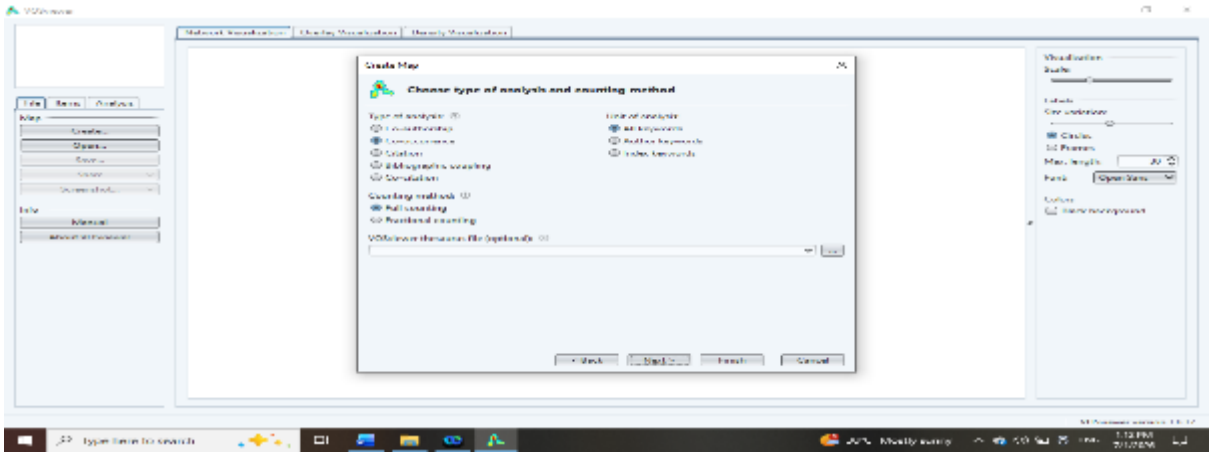

Figure 3. Cooccurrence of Author's Keywords

The co-occurrence author's keywords analysis as shown in figure 4 indicates that the research field is strongly dominated by structural engineering themes related to prestressed and reinforced concrete systems. With particular emphasis on prestressed concrete, prestressing, reinforced concrete, concrete beams and girders, and fiber-reinforced polymer (FRP) materials, which record the highest occurrences and total link strength. Keywords such as *prestressed concrete*, *prestressing*, *reinforced concrete*, *carbon fiber reinforced polymers*, *steel fibers*, and *finite element method* demonstrate dense interconnections, reflecting a mature and well-established research focus on material performance, structural behavior, strengthening techniques, and numerical modelling. Experimental investigations, flexural and shear behaviour, durability, fatigue, corrosion resistance, and strengthening methods also appear frequently, indicating that most studies prioritize mechanical performance and short- to medium-term structural response under controlled conditions.

However, comparatively lower occurrences are observed for keywords related to life-cycle assessment, sustainability, cost analysis, long-term monitoring, service life prediction, and environmental impact, suggesting that holistic and sustainability-driven evaluations remain underexplored. In addition, emerging areas such as smart sensing technologies, data-driven approaches, and performance-based design frameworks show weak link strength, indicating limited integration with traditional prestressed concrete research. Overall, the keyword structure reveals a clear research gap in long-term durability assessment, sustainability considerations, and advanced monitoring or decision-support approaches, highlighting opportunities for future studies to move beyond material-level and laboratory-focused investigations toward system-level, lifecycle-oriented, and context-sensitive research directions.

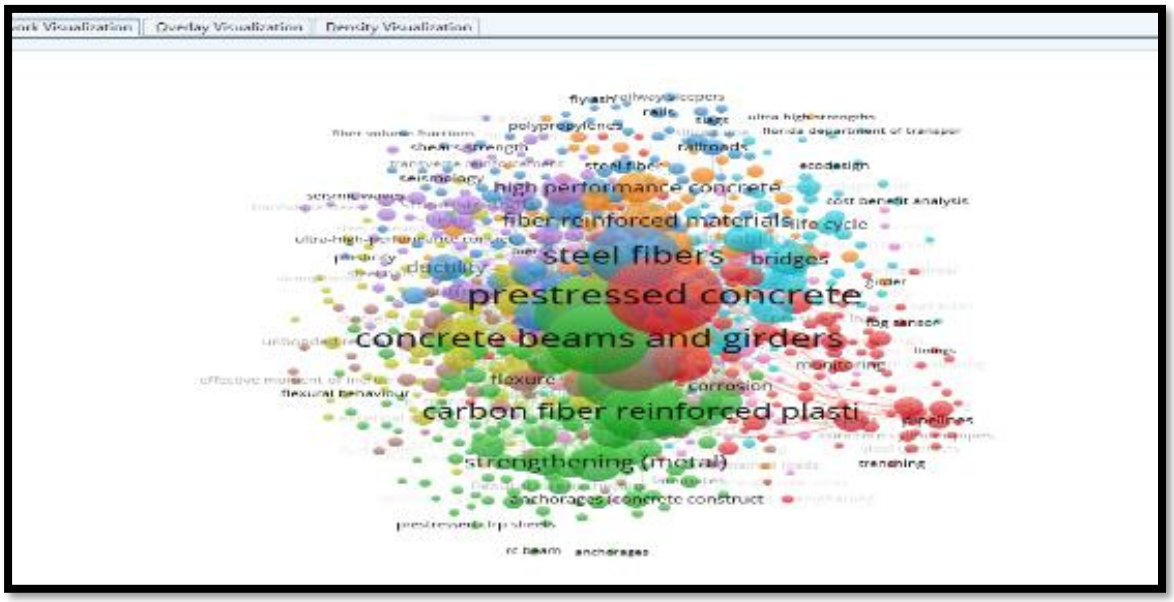

Figure 4. Cooccurrence of Author's Keywords

The bibliometric analysis of country contributions to prestressed research shows a clear imbalance in global research participation. As figure 5 shows that, the United States and China emerge as the most influential countries, leading both in publication output and citation impact, which highlights their strong research capacity and sustained investment in this area.

Other countries such as Canada, the United Kingdom, South Korea, Italy, Switzerland, and Australia also demonstrate substantial scholarly influence, as reflected in their relatively high citation counts despite lower publication volumes. Several Asian and European countries, including Japan, India, Iran, Germany, and Portugal, contribute consistently to the literature, although their overall impact remains moderate. In contrast, research output from Africa and most parts of South America is noticeably limited, with Egypt being the only African country showing a modest level of activity. Furthermore, the absence of link strength among countries indicates weak international collaboration, suggesting that prestressed research is largely conducted within national or regional boundaries. This lack of cross-country cooperation, particularly involving developing regions, points to an important research and policy gap where increased international collaboration could enhance knowledge exchange and promote more inclusive global research development.

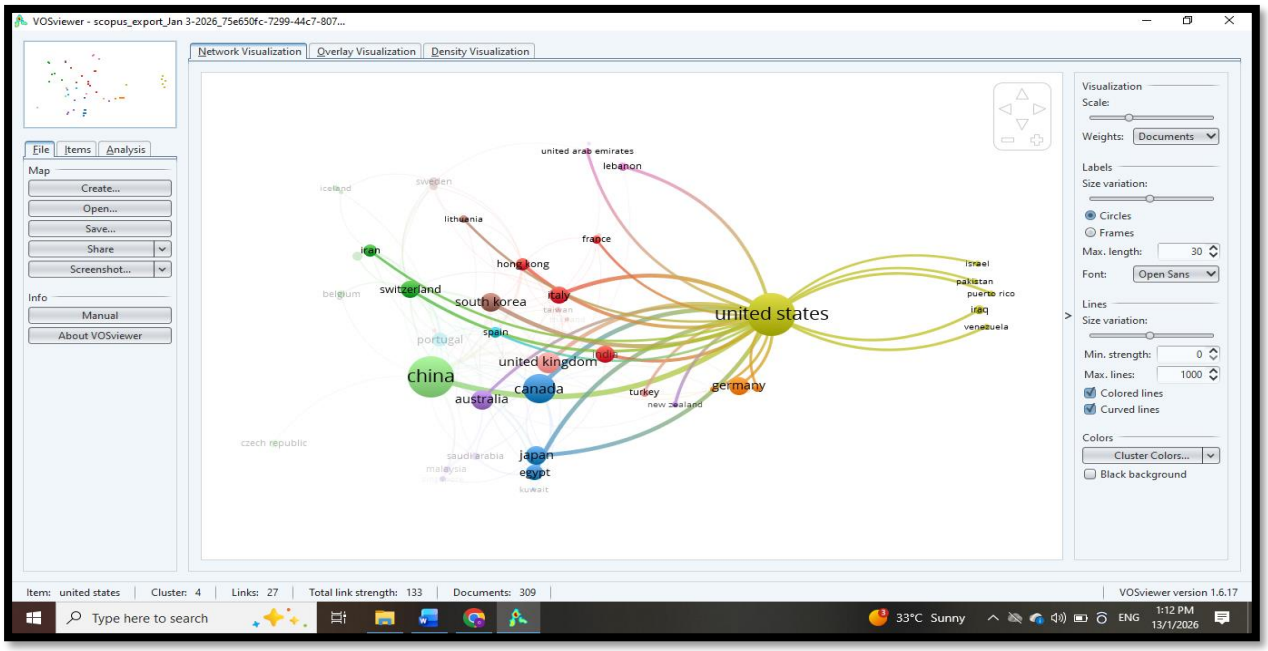

Figure 5. Citation by Country

The citation-by-document analysis reveals a mature and steadily expanding body of literature spanning nearly three decades, with foundational works published from early 1996 – 2026 attracting exceptionally high citation counts, indicating their role in establishing core theories, methodologies, and design frameworks within the field. Highly cited landmark studies (e.g., works with over 200 citations) dominate the intellectual base, while the period from 2010 onward shows a marked intensification of research activity, reflected in a dense cluster of moderately to highly cited publications that signal diversification into new materials, analytical techniques, and application contexts. More recent contributions (2023–2025) exhibit lower citation counts overall, which is consistent with citation latency, yet their growing frequency suggests sustained scholarly interest and incremental refinement of existing knowledge rather than paradigm shifts. The distribution of citations is highly skewed, with a small number of seminal papers accounting for a large share of total citations, while a long tail of recent studies contributes emerging insights with limited immediate impact. Collectively, this pattern indicates a field that is theoretically well grounded, methodologically stable, and evolving through cumulative advances rather than disruptive transformations

prestressed Citation by Document the breadth and longevity of the literature, the citation structure suggests an over-reliance on a limited set of seminal studies and a relative scarcity of highly influential recent works, pointing to a gap in innovative, integrative, and context-specific research capable of redefining or extending existing frameworks. Future research should therefore focus on generating high-impact, regionally grounded studies and comparative analyses that can both validate established theories and introduce novel perspectives relevant to developing economies, thereby broadening the global relevance of the field.

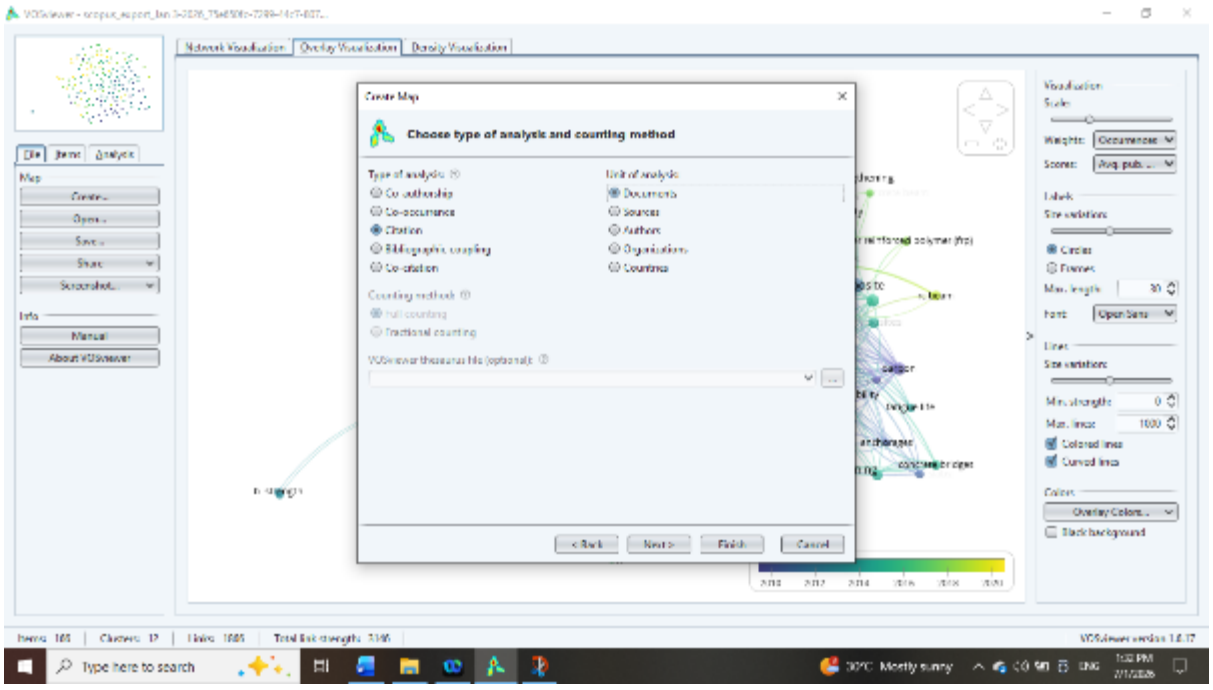

Figure 6. Citation by Document

Hence, the organization-level coupling analysis of the prestressed research domain indicates a strongly interconnected scholarly landscape dominated by a relatively small number of institutions that serve as central knowledge hubs. These leading organizations exhibit dense collaborative linkages, suggesting sustained research productivity, access to advanced experimental facilities, and long-term investment in prestressed concrete and structural engineering studies. In contrast, a larger proportion of institutions appear at the periphery of the network, characterized by weak or isolated coupling relationships, which reflects limited inter-organizational collaboration and narrower research scopes. The coupling structure further reveals that most influential organizations are concentrated in technologically advanced regions, reinforcing their visibility and citation strength, while collaborative ties across regions remain comparatively sparse. Overall, the pattern points to a field where knowledge production is institutionally concentrated, with incremental diffusion occurring through selective partnerships rather than broad, globally distributed collaboration in prestressed Citation by Document. Hence, the dominance of a few highly coupled organizations highlights a gap in inclusive and geographically diverse institutional participation, particularly from developing regions such as Africa, where organizational visibility and collaborative integration remain minimal. This imbalance suggests missed opportunities for contextualized research addressing region-specific materials, construction practices, and infrastructural challenges. Future studies should therefore emphasize inter-

organizational and cross-regional collaboration frameworks, capacity-building initiatives, and joint empirical projects that can strengthen contributions from underrepresented institutions and foster a more globally balanced and impactful prestressed research ecosystem.

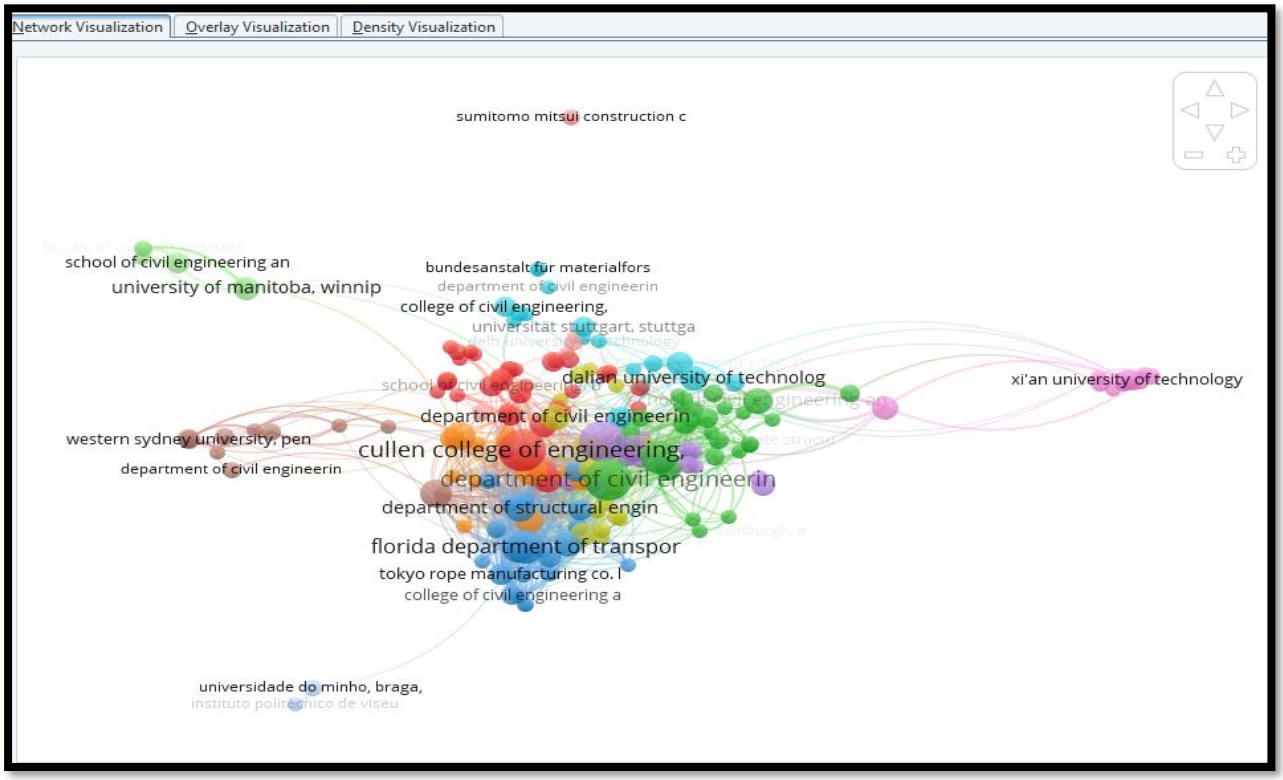

Figure 7. Coupling by Organisation

Conclusion

This study provided a systematic bibliometric assessment of research on prestressed post-tensioned concrete systems, with emphasis on steel fibre reinforcement, advanced composite materials, and sustainability-driven design. The analysis reveals sustained growth in scholarly output, reflecting increasing interest in improving structural performance, resilience under extreme conditions, and environmental efficiency. Dominant research themes include prestressed UHPC and composite systems, FRP-based strengthening techniques, fire and thermal performance, and the emerging use of data-driven and machine learning approaches for structural prediction. Despite these advances, the literature remains largely fragmented, with most studies focusing on isolated mechanical or material-level performance indicators. In addition, global research output is highly concentrated in a small number of developed countries, while contributions from Africa and other developing regions remain minimal. These findings indicate that, although the field is technically mature, critical gaps persist in integrated performance assessment, long-term behaviour evaluation, sustainability integration, and geographically inclusive research participation. Hence, it was observed that lower occurrences are observed for keywords related to life-cycle assessment, sustainability, cost analysis, long-term monitoring, service life prediction, and environmental impact, suggesting that holistic and sustainability-driven evaluations remain underexplored

Recommendations

To address the identified gaps, future studies should prioritize integrated evaluation frameworks that concurrently assess structural performance, durability, serviceability, economic viability, and environmental impact across the life cycle of prestressed systems. Strengthening international and cross-regional research collaboration is strongly recommended, particularly to improve the visibility and contribution of institutions from underrepresented regions such as Africa. Moreover, experimental and field-based studies focusing on long-term behaviour, including creep, shrinkage, prestress loss, fatigue, and durability under aggressive environment should be expanded. The application of artificial intelligence should also move beyond strength prediction to encompass serviceability, fire performance, durability assessment, and lifecycle optimisation, with greater emphasis on interpretability and alignment with existing design standards.

Future Works

Future research should focus on the development of holistic, lifecycle-oriented methodologies that integrate mechanical performance, durability, sustainability metrics, and cost efficiency in prestressed and composite concrete systems. Greater attention is required for post-extreme event behaviour, including residual capacity, repair strategies, and long-term serviceability following fire or thermal exposure. Further investigations should explore the field performance of UHPC–steel and fibre-reinforced prestressed members under diverse climatic and loading conditions. In addition, context-specific studies tailored to local materials, construction practices, and infrastructural needs in developing continents such as Africa, are essential to enhance global relevance and practical applicability. Finally, coordinated international research initiatives combining experimental testing, numerical modelling, and explainable artificial intelligence offer strong potential for advancing design guidelines and supporting the development of next-generation sustainable prestressed infrastructure.

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