Visualization Analysis of Concrete Incorporating Waste Tire Rubber: A Knowledge Graph Approach

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Abstract

The increasing disposal of waste tires presents a global environmental challenge, necessitating innovative recycling solutions. Incorporating waste tire rubber into concrete offers a sustainable approach to mitigating landfill accumulation while promoting eco-friendly construction materials. However, research on rubberized concrete remains fragmented, necessitating a systematic visualization of its evolution, key contributors, and emerging innovations. This study employs a knowledge graph approach to analyze bibliometric data on concrete incorporating waste tire rubber, identifying major trends, research clusters, and influential studies. Using VOSviewer and bibliometric techniques, the study maps the intellectual landscape, revealing a significant rise in publications between 2019 and 2024, with China, India, and Australia leading contributions. Keyword analysis highlights key challenges such as reduced compressive strength, durability concerns, and workability issues, while also identifying solutions like surface treatments and supplementary cementitious materials. Citation analysis indicates that research primarily focuses on mechanical performance and sustainability, underscoring the need for further exploration of long-term durability and large-scale applications. The findings offer valuable insights for researchers and industry professionals, supporting the optimization of rubberized concrete formulations and its broader adoption in sustainable construction.

Keywords

Waste tire rubber, Rubberized concrete, Knowledge graph, Bibliometric analysis, Sustainable construction materials

INTRODUCTION

The rapid expansion of the automotive industry has significantly increased the global production of waste tires, posing serious environmental and ecological concerns. Every year, approximately 1 billion waste tires are discarded worldwide, with estimates predicting this figure could rise to 1.2 billion by 2030 [1]. Improper disposal of these tires results in severe environmental challenges, including excessive landfill accumulation, toxic emissions from incineration, and the risk of fire hazards. Despite growing efforts, the global recycling rate for used tires remains inadequate, with some regions reporting a recovery rate as low as 5%, much lower than necessary to mitigate environmental damage [2]. Since rubber is a highly durable polymer that degrades very slowly under natural conditions, its disposal continues to be a long-term environmental burden. Traditional disposal methods, such as tire incineration, release hazardous pollutants, further exacerbating air pollution and ecological degradation [3].

In response to these concerns, researchers have explored innovative methods for repurposing waste tires, particularly within the construction sector. One of the most promising solutions is the integration of recycled rubber into concrete as a partial substitute for natural aggregates, addressing both waste management and sustainable construction challenges. Several studies indicate that incorporating rubber particles or rubber powder into concrete improves sustainability by reducing dependence on virgin raw materials [4], [5], [6], [7]. Additionally, waste rubber has been widely employed in road construction, embankments, and subgrade fillings, showcasing its versatility in infrastructure development [8]. However, while rubberized concrete provides significant environmental advantages, its mechanical properties remain a challenge. The hydrophobic nature of rubber, coupled with its lower stiffness compared to conventional aggregates, negatively affects bonding within the cement matrix, reducing compressive strength and impacting durability [9], [10].

Concrete remains one of the most essential materials in modern civil engineering, valued for its affordability, accessibility, and relatively simple production process. However, its large-scale usage contributes to the depletion of natural resources, particularly through the extensive mining of aggregates. The inclusion of rubber aggregates presents a sustainable alternative that not only lessens the environmental impact but also enhances certain performance characteristics of concrete. Compared to traditional concrete, rubberized concrete has demonstrated improved deformation capacity, enhanced crack resistance, superior energy absorption, and increased toughness. Additionally, it exhibits greater resistance to impact forces, fatigue cracking, freeze-thaw cycles, and sound transmission, making it suitable for specialized applications [11]. These properties make rubberized concrete an ideal material for use in pavements, bridge decks, railway sleepers, and airport runways. Research on the incorporation of rubber powder in concrete began in the 1980s, and since then, its applications have expanded significantly, particularly in Europe and North America, focusing on its mechanical properties, durability, and impact resistance [12].

Despite these advantages, multiple factors influence the performance of rubberized concrete, including the size of the rubber particles, rubber content, and surface pre-treatment methods. Research has shown that finer rubber particles tend to negatively affect workability and compressive strength, while chemical surface treatments, such as sodium hydroxide (NaOH) immersion, can enhance adhesion between rubber and the cementitious matrix [13]. Additionally, concerns regarding the long-term durability of rubberized concrete—such as carbonation, chloride ion penetration, and frost damage—necessitate further optimization of mix design to improve its structural integrity [10], [11]. Addressing these challenges is critical to advancing the application of rubberized concrete and ensuring its viability as a high-performance construction material.

Given the increasing interest in rubberized concrete and the vast body of literature on this topic, a comprehensive bibliometric analysis is essential to identify key research trends, influential studies, and emerging innovations. This study employs a knowledge graph approach to analyze the evolution of research on concrete incorporating waste tire rubber. By utilizing visualization techniques and bibliometric tools, this study aims to map the intellectual structure of this research field, highlight influential contributions, and provide insights into future research directions. The findings will serve as a valuable resource for researchers and practitioners seeking to advance the development and application of sustainable concrete materials.

LITERATURE REVIEW

The incorporation of tire rubber particles into concrete mixtures significantly affects workability due to water absorption and air-entraining effects. Rubber particles, being porous, absorb free water and reduce slump. They also increase air content within the mixture, which can improve liquidity. For instance, when the rubber admixture reaches 40% of the total volume, the slump is reduced by 185 mm [14]. Similarly, replacing 30% of sand with rubber reduced the slump by approximately 125 mm, which was 80% of that of the control group [15]. Impurities on the rubber surface, such as dust, further reduce workability by taking up free water during mixing [16].

The addition of supplementary materials, such as fly ash, silica fume, and glass powder, can mitigate the adverse effects of rubber on workability. Fly ash, with its spherical particle shape, enhances the flowability of self-compacting rubber concrete by reducing friction. For example, at a rubber replacement rate of 25%, the addition of fly ash significantly improved the slump [17]. Figure 1 illustrates this effect, showing how different fly ash (FA) replacement levels (0FA, 20FA, 40FA, and 60FA) influence slump flow at various rubber contents. It is evident that as rubber content increases, slump flow decreases, particularly in mixtures without fly ash. However, higher fly ash content helps retain better workability even at elevated rubber replacement levels.

Conversely, silica fume decreases compatibility due to its high specific surface area, which increases water demand [18]. Glass powder improves workability by filling voids between particles and forming a better pore structure, allowing water to be released from the voids [19]. High-efficiency water-reducing agents have also been shown to enhance workability; for instance, a 1.0% admixture increased slump by approximately 183% compared to concrete without a water-reducing agent [18]

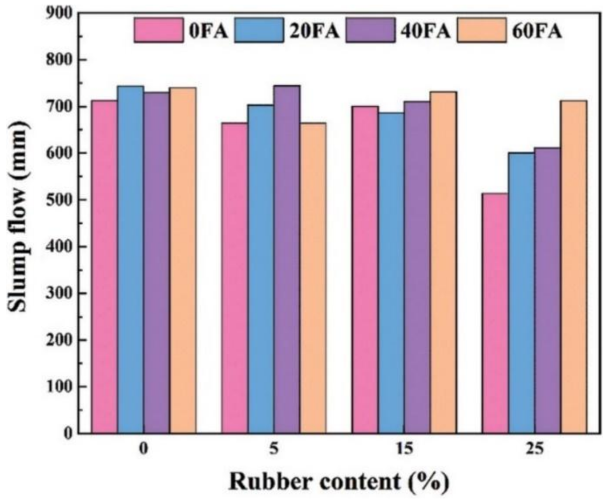

Figure 1 Effect of Rubber Content and Fly Ash on Slump Flow of Concrete [20]

Rubber particle size significantly influences workability. Larger particles generally improve workability due to their reduced surface area, which limits water absorption. For instance, concrete with rubber particles sized 1–3 mm exhibited a slump increase of approximately 33%, whereas finer particles, such as 40-mesh rubber powder, caused a 33% slump reduction [21]. Mixing methods also play a crucial role. Adding rubber to water at the beginning of the mixing process enhances workability compared to other methods. Surface treatments, such as NaOH treatment, further improve workability. For example, rubber concrete treated with a 50% NaOH solution exhibited a slump approximately 15% higher than that treated with a 10% concentration [22]

Rubber concrete generally exhibits higher water absorption compared to ordinary concrete. Adding 10% rubber granules (1–4 mm in size) increased water permeability depth by approximately 56% compared to concrete without rubber . This behavior is attributed to the poor adhesion between rubber particles and cement paste, which creates voids in the matrix [23]. Treatments with NaOH solutions enhance bonding between rubber and cement paste, reducing porosity and improving the microstructure. Figure 2 illustrates how water absorption varies with different treatments, such as water and NaOH at 15% and 30% replacement levels. It is evident that increasing the NaOH concentration results in the highest water absorption, indicating the significant role of treatment in altering the water retention properties of rubberized concrete. For example, at a 10% rubber substitution level, water permeability depth decreased by 58% with the use of a 1.0% water-reducing agent [18].

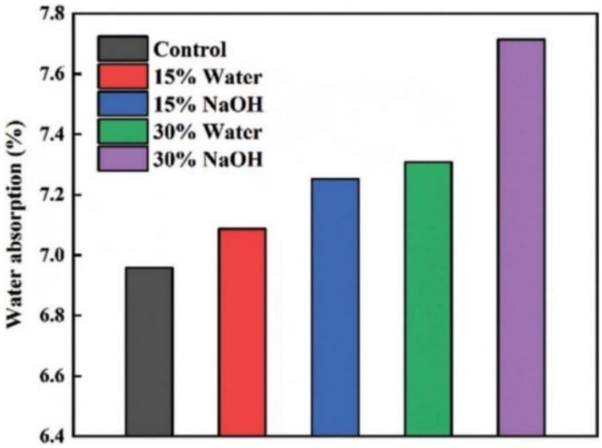

Figure 2 Effect of Water and NaOH Treatments on Water Absorption in Rubberized Concrete [24].

The carbonation resistance of rubber concrete is typically lower due to the increased void volume, which facilitates CO_2 penetration. For instance, a 30% rubber replacement level significantly increased carbonation depth, with NaOH-treated and water-treated samples showing depth increases of 329% and 414%, respectively, compared to control samples [18]. Figure 3 illustrates the carbonation depth progression over time for different rubberized concrete mixes, showing that higher rubber content generally results in greater carbonation depth. However, the inclusion of silica fume and eggshell powder improves carbonation resistance. Using 5% tire rubber powder combined with eggshell powder reduced carbonation depth by 40%, attributed to the filling effect of eggshell powder [25].

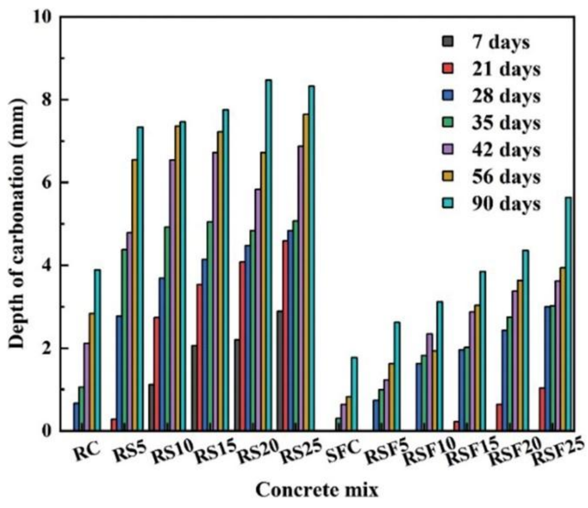

Figure 3 Carbonation Depth of Rubberized Concrete Over Time [25].

Rubber concrete shows improved resistance to chloride ion permeability. At a 20% rubber replacement level, the chloride ion diffusion coefficient decreased by approximately 26%, effectively reducing reinforcing steel corrosion [26]. Additionally, a mix of rubber powder (0.15–1.9 mm) and rubber fibers (2–5 mm in width, 20 mm in length) at a 25% substitution rate reduced the diffusion coefficient by 22% [27]

The freeze-thaw resistance of rubber concrete improves as rubber content increases. For example, increasing rubber content from 0% to 20% during 25 freeze-thaw cycles resulted in a 125% increase in the relative dynamic modulus (RDM) of elasticity and a 71.7% decrease in mass loss [28]. Styrene-butadiene copolymer-coated rubber aggregates further enhance frost resistance by reducing mass loss and improving mechanical properties [22]. Combining rubber powder with silica fume also improves frost resistance, although silica fume alone is more effective due to its densification of the microstructure [29].

Crumb rubber concrete has consistently shown reduced compressive strength due to the hydrophobic nature of rubber particles and their lower stiffness compared to natural aggregates. Figure 4 illustrates the decline in compressive strength over different curing periods (7, 28, and 90 days) as the percentage of crumb rubber increases. Untreated crumb rubber replacements of 15–25% reduced compressive strength by 9–20%. However, pre-treatment with NaOH enhanced compressive strength by 15–20% due to improved interfacial bonding between rubber particles and the cement matrix [30]. Similarly, increasing the NaOH concentration from 10M to 14M during pre-treatment resulted in a 49% increase in compressive strength for rubberized geopolymer concrete (CRGPC), demonstrating the effectiveness of chemical surface modifications [31]. Wet mixing processes also ensure better integration of rubber particles, enhancing compressive strength in rubberized sulfur concrete (RSC) [32].

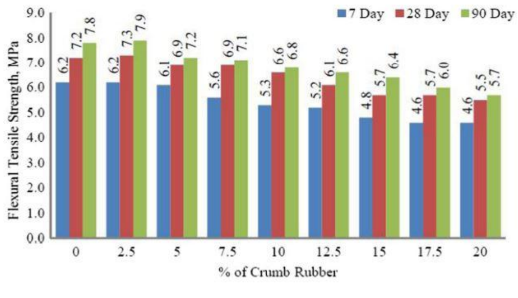

Figure 4 Effect of Crumb Rubber Content on Compressive Strength Over Time [1].

Dynamic performance, such as impact and energy absorption, is significantly enhanced by rubber addition. For instance, using 30-mesh rubber particles at a 10% rubber replacement level improved energy absorption capacity by 25% while maintaining acceptable reductions in compressive and tensile strengths [33]. Tire-derived aggregates (TDA) used in rigid pavements demonstrated a 20% improvement in impact resistance, highlighting the suitability of rubber for high-impact applications [34]. In addition to mechanical advantages, the use of crumb rubber presents significant environmental and economic benefits. Integrating waste tires into Portland cement concrete reduced landfill dependency by 20% and significantly decreased CO_2 emissions, aligning with global sustainability goals [34]. Furthermore, cost reductions of 10–15% were reported in concrete production when using recycled materials, supporting ecological and financial sustainability [35]. Crumb rubber concrete has also demonstrated enhanced performance under elevated temperatures when combined with nano additives. Steel-fiber- and nano-silica-modified crumb rubber concrete exhibited a 10% increase in compressive strength and a 15% reduction in mass loss at 600°C [36]. The combined effects of rubber's thermal stability and nano-silica's ability to densify the matrix make rubberized concrete a viable option for fire-resistant applications. These findings are consistent with the broader comparison of rubberized and normal concrete summarized in Table 1, which highlights the trade-offs between reduced mechanical strengths and improved impact resistance, ductility, thermal stability, and environmental performance.

Table 1 Comparison of Performance Characteristics of Rubberized Concrete and Normal Concrete

Performance Characteristic	Rubberized Concrete	Normal Concrete
Compressive Strength	Lower than normal concrete; decreases with higher rubber content	Higher compressive strength
Flexural Strength	Generally lower, but can be improved with additives like steel fibers	Higher flexural strength
Tensile Strength	Lower, but improved with steel fibers; better ductility and energy absorption	Higher tensile strength
Impact Resistance	Higher impact resistance and energy absorption	Lower impact resistance
Durability	More susceptible to water, chloride, and chemical attacks; higher carbonation depth	Better durability; lower water absorption and chloride penetration
Thermal Properties	Improved thermal insulation; better performance at elevated temperatures	Lower thermal insulation; significant strength loss at high temperatures
Ductility and Deformation	Higher ductility and deformation capacity; better crack resistance	Lower ductility and deformation capacity
Noise and Vibration Reduction	Better noise and vibration reduction	Lower noise and vibration reduction
Service Life	Shorter service life; estimated over 50 years with up to 15% rubber content	Longer service life
Environmental Impact	Utilizes recycled materials; reduces waste	Higher environmental impact

RESEARCH SIGNIFICANCE

The aim of this study is to analyze and visualize global research trends on the use of waste tire rubber in concrete through a bibliometric and knowledge graph approach. This research is significant as it highlights the growing academic and industrial interest in rubberized concrete as a sustainable alternative, addressing both environmental concerns and construction challenges. By identifying key contributors, influential publications, research clusters, and thematic focuses, the study provides a comprehensive overview of the field's evolution from 2019 to 2024. It also reveals critical gaps such as limited studies on long-term durability and life-cycle assessments while offering insights for future innovations. The findings support researchers, engineers, and policymakers in optimizing rubberized concrete formulations, encouraging practical applications, and advancing sustainable construction practices globally.

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METHODOLOGY

A bibliometric analysis was conducted to examine and visualize the current state of research on concrete production using rubber particles, identify gaps in the literature, and anticipate future trends in this area. Bibliometric methods, which employ systematic, computer-aided reviews, are widely used across scientific disciplines to assess, map, and analyze existing research [37], [38]. Two common algorithms used in bibliometric network construction are full counting and fractional counting. Full counting, known for its simplicity and ease of interpretation, was selected for this study. The VOSviewer software, recognized for its robustness in bibliometric analysis, was employed to generate knowledge graphs and visualize key trends [39]. Additionally, the bibliometrix package in R software was used to create network visualizations of research entities and their interconnections. In these visualizations, nodes represent entities such as articles, journals, authors, institutions, countries, or keywords, while links illustrate their relationships.

A systematic review of scientific literature was performed to identify documents focusing on concrete production using rubber particles. The primary research question driving this study was: "What are the trends, current approaches, and innovations in the use of rubber particles in concrete production, and how can these shape sustainable practices in construction?" Selecting an appropriate database was critical for achieving comprehensive and accurate results. The Scopus database, which offers a vast repository of scientific literature primarily in English, was chosen for its extensive coverage of relevant topics [40].

The search strategy utilized Boolean operators in two sets. The first set targeted terms directly related to concrete and rubber particles, such as “rubber particles,” “concrete production,” “waste rubber,” and “sustainability in concrete.” The second set incorporated related concepts, including “recycled materials,” “rubberized concrete,” and “mechanical properties of rubber concrete.” These keywords reflected core themes in the dataset, ensuring a thorough and detailed exploration of the subject. The Boolean search in Scopus yielded an initial dataset of 698 documents. To refine the dataset, filters were applied to include only journal articles and reviews published in English. All publication years were considered to ensure comprehensive coverage. After removing duplicates following the method described by Echchakoui using R software, the final dataset consisted of 614 unique documents [41].

The bibliometric analysis revealed valuable insights, such as the most prolific authors, influential journals, and prominent keywords in the field. These findings provide a foundation for identifying research gaps, evaluating emerging innovations, and proposing future research directions in the field of rubber particle utilization in concrete production.

The study’s findings were derived solely from the analyzed data, reducing subjective bias and ensuring objectivity. An overview of the research steps is presented in Figure 5 illustrates the study framework, detailing the methods used for data collection, processing, and visualization in bibliometric analysis.

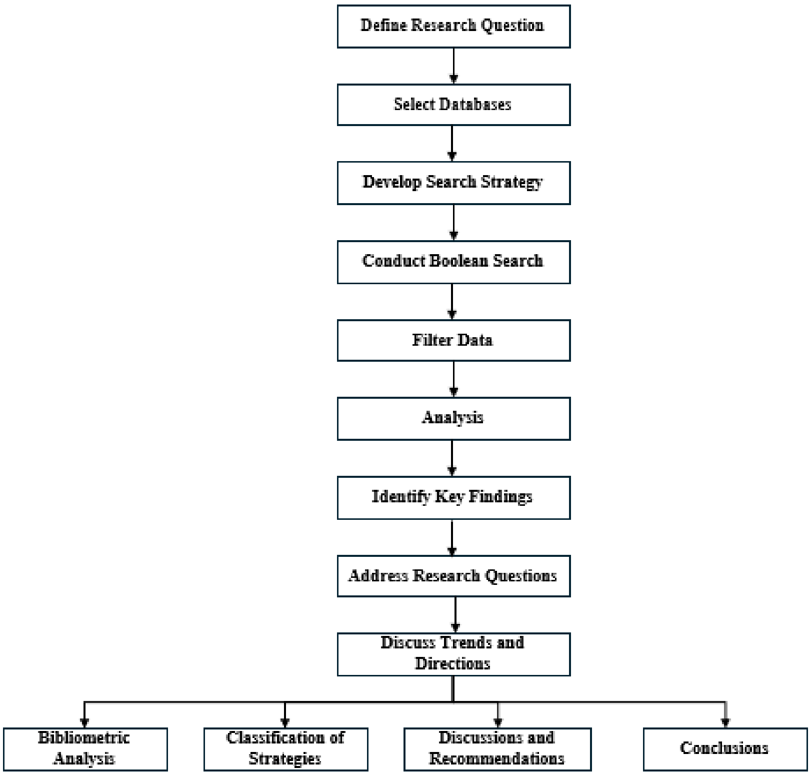

Figure 5 Research Methodology Framework for Bibliometric Analysis

DOCUMENT CHARACTERISTICS ANALYSIS

A. TREND OF RESEARCH

Analyzing the trend of research publications provides insights into the development and progression of a specific topic. It highlights the academic interest over time, showing whether a field is advancing or regressing [38], [39].

Figure 6 illustrates the annual and cumulative publication trends in research and developments from 2019 to 2024, highlighting the significant growth and increasing attention in this field. The annual publications show steady growth from 2019 to 2022, followed by minor fluctuations in 2023 and 2024. In contrast, the cumulative growth, represented by the dashed line, exhibits a sharp and continuous upward trend, reflecting sustained progress and expanding research interest. Notably, cumulative publications have surged by an impressive 958.6% over the six-year period, underscoring the accelerating pace of developments in this domain.

This trend underscores the growing prioritization of research and developments in sustainable construction, driven by the need to address key challenges such as resource conservation, cost reduction, and environmental sustainability. The slight decline in annual publications in the latter years may indicate a transition from rapid expansion to a phase of refinement, where researchers focus on optimizing existing techniques and tackling implementation challenges rather than exploring entirely new subfields.

The sharp rise in cumulative publications reflects both quantitative and qualitative advancements in this domain. This progress has been fueled by interdisciplinary collaborations that integrate expertise from materials science, environmental engineering, and construction technology. Key innovations include the development of sustainable concrete mixtures incorporating alternative materials and the evaluation of their effects on mechanical properties and long-term durability.

The sustained interest and investment in this area highlight its transformative potential in achieving sustainability goals within the construction industry. Integrating waste-derived materials in concrete production offers practical solutions for reducing raw material consumption, minimizing environmental impact, and enhancing the circular economy. As the field continues to evolve, future research will likely focus on improving material performance, scaling up practical applications, and assessing long-term structural impacts to support widespread industry adoption**.**

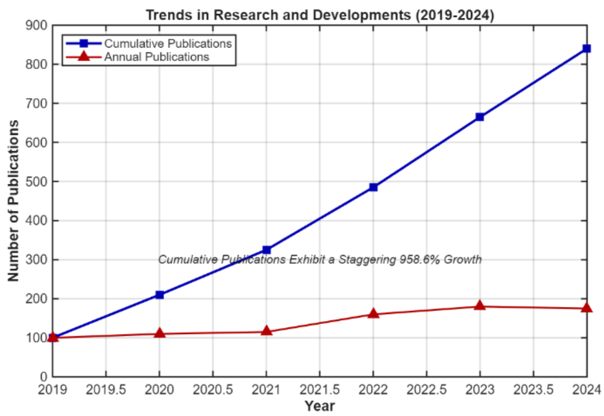

Figure 6 Trends in Research and Developments (2019–2024)

Identifying the key contributors in the domain of wastewater utilization for concrete production provides valuable insights into its global development and innovation trends. Table 2 summarizes the contributions of countries based on the number of documents (Figure 7) , citations (Figure 8), and the average year of publication, highlighting both prominent and emerging players in this sustainable research area.

China leads the global effort with 160 documents and 1,360 citations, underscoring its dominant influence and leadership in wastewater utilization research for concrete production. The country's average publication year of 2022.56 reflects its active involvement in recent advancements. The United States follows as a key player with 96 documents and 453 citations, demonstrating consistent contributions and significant impact, with an average publication year of 2021.93.

India ranks third, with 85 documents and 840 citations, showcasing its growing role as a major contributor among developing nations. Poland, with 37 documents and 224 citations, highlights its notable engagement in impactful research. Meanwhile, Australia (34 documents, 598 citations) demonstrates strong participation, blending quality-driven and innovative contributions.

Other significant contributors include Germany (33 documents, 200 citations), Canada (30 documents, 540 citations), and the United Kingdom (25 documents, 180 citations), reflecting their focus on advancing sustainable construction practices. Emerging contributors such as Spain (20 documents, 150 citations) and South Korea (18 documents, 120 citations) highlight their increasing commitment to quality-driven research in the field.

Countries with fewer publications, such as Saudi Arabia (10 documents, 95 citations), Switzerland (8 documents, 50 citations), and Singapore (7 documents, 78 citations), still indicate a focus on cutting-edge and recent research, as reflected by their average publication years ranging from 2021 to 2023. These contributions emphasize the increasingly collaborative and competitive nature of wastewater utilization research in concrete production, showcasing the efforts of both established leaders and emerging players.

This analysis demonstrates how established contributors like China and the United States dominate in terms of volume and impact, while countries such as India, Poland, and Australia are steadily advancing their influence through high-impact studies and innovative contributions. Emerging contributors like Saudi Arabia and South Korea further enrich the global knowledge base, reflecting the growing interest and potential of this sustainable approach in the construction industry.

The global distribution of research efforts, as captured in Figure 9, reflects the interdisciplinary and interconnected nature of advancements in wastewater utilization for concrete production. It highlights how countries with diverse technological priorities and academic strengths are collaborating to drive progress in this sustainable and transformative research area. By leveraging their unique expertise and addressing shared challenges, these nations are collectively contributing to innovations that promote resource conservation, environmental sustainability, and advancements in construction practices.

In addition to identifying the key contributing countries, leading organizations and authors were analyzed to highlight their pivotal roles in advancing the field of Waste Tire Rubber utilization in concrete production. These institutions and individuals have significantly contributed to the development and dissemination of knowledge through their research efforts, shaping the trajectory of this sustainable and transformative domain.

Table 2 Key Contributions by Countries

Country	Documents	Citations	Avg_Pub_ Year
China	128	2844	2022.141
India	85	596	2022.435
Australia	58	1849	2021.741
Malaysia	36	711	2021.306
Egypt	32	665	2022.656
Iraq	25	467	2022.28

Country	Documents	Citations	Avg_Pub_Year
United Kingdom	21	348	2022
Turkey	15	155	2022.467
United States	15	569	2021.067
Canada	13	118	2021.308
Indonesia	13	44	2021.308
Saudi Arabia	13	390	2022.692
Bangladesh	13	462	2022.462
Pakistan	12	284	2022.25
Italy	8	158	2020.875
Thailand	7	83	2021.571
Algeria	7	14	2022.429
United Arab Emirates	6	294	2022
Brazil	6	43	2021
South Africa	5	64	2020.4
Kenya	5	38	2022.6
Viet Nam	4	24	2023
Chile	4	29	2021.75
Croatia	4	94	2020.75
France	4	107	2022.75
Japan	3	69	2023.667
Nigeria	3	66	2022.333
Colombia	3	26	2021.333
Spain	3	77	2021
Cyprus	3	49	2021.333
Poland	3	14	2022

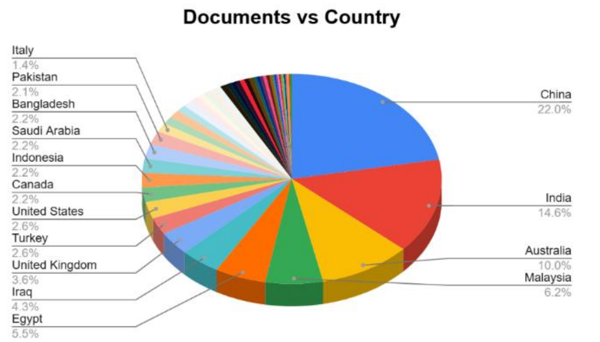

Figure 7 Documents by Country

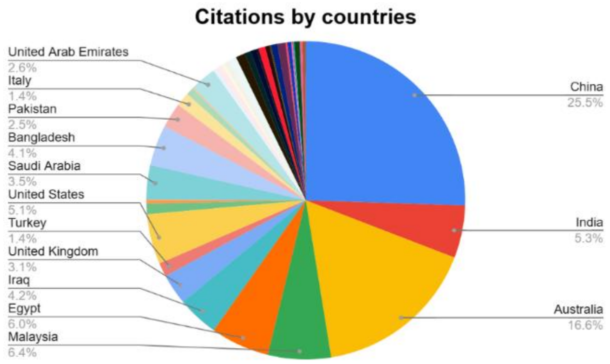

Figure 8 Citations by Country

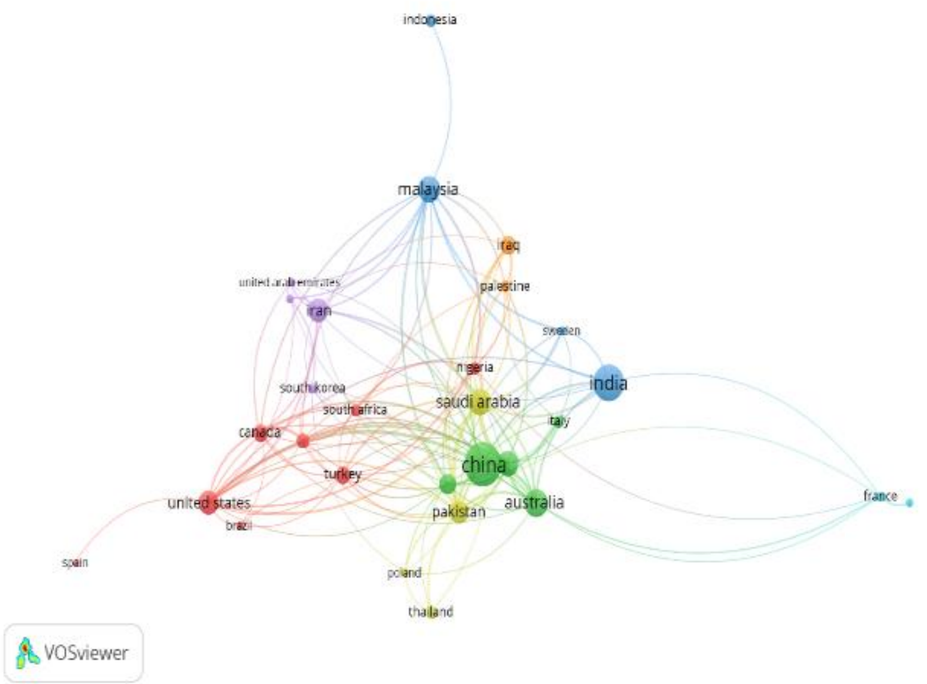

Figure 9 Global Collaboration Network in rubber concrete

The analysis of the most active organizations, as presented in Table 3, highlights the significant contributions of leading institutions to research advancements. The Ministry of Education of the People's Republic of China leads with 23 publications, showcasing its central role in promoting innovation in sustainable construction and engineering. Universiti Teknologi PETRONAS, Mansoura University, and the Faculty of Engineering follow closely, each contributing 15 publications, reflecting their strong commitment to advancing research in environmentally friendly and efficient materials.

Tianjin University and The University of Western Australia each contributed 14 publications, underlining their pioneering efforts in integrating interdisciplinary approaches to solve construction challenges. Similarly, RMIT University, with 13 publications, demonstrates its impactful research in optimizing construction materials and methods. Other notable contributors include Prince Sattam Bin Abdulaziz University, Zhengzhou University, Universiti Teknologi Malaysia, and the Islamic University of Gaza, each with 11–12 publications, further emphasizing the global collaborative effort toward innovative solutions in construction technology.

The contributions of individual researchers, as outlined in Table 4, are equally noteworthy. Wang J. and Li J. lead with 11 publications each, establishing themselves as key contributors to advancing sustainable practices in construction materials. Tayeh B.A. follows with 10 publications, while Youssf O. and Aslani F. have each contributed 9 publications, showcasing their active engagement in driving innovation in the field. Kumar R., Zhang Y., and Ahmed M.S. are also among the top contributors, with 7–8 publications each, reflecting their sustained impact on research trends.

From a global perspective, the evolving nature of the research landscape is evident. Figure 10 provides insights into the average publication year by country, showcasing emerging leaders such as China and Malaysia, with consistent contributions in recent years. Countries like Australia, Saudi Arabia, and Egypt also demonstrate substantial advancements, driven by interdisciplinary collaborations and innovative technologies.

In contrast, long-established contributors such as the United States and Germany continue to play a pivotal role, reflecting their sustained efforts and historical impact on the field. European countries, including Poland and the Netherlands, further contribute to the field's growth and diversification, emphasizing the global nature of these advancements.

Table 3 Leading Organizations in Rubber Concrete Research

Organizations	Articles
Ministry of Education of the People's Republic of China	23
Universiti Teknologi PETRONAS	15
Mansoura University	15
Faculty of Engineering	15
Tianjin University	14
The University of Western Australia	14
RMIT University	13
Prince Sattam Bin Abdulaziz University	12
Zhengzhou University	11
Universiti Teknologi Malaysia	11
Islamic University of Gaza	11

Table 4 Top Authors

Author	Number of Publications
Wang J.	11
Li J.	11
Tayeh B.A.	10
Youssf O.	9
Aslani F.	9
Kumar R.	8
Zhang Y.	8
Ahmed M.S.	7
Chen W.	7
Zhao X.	6

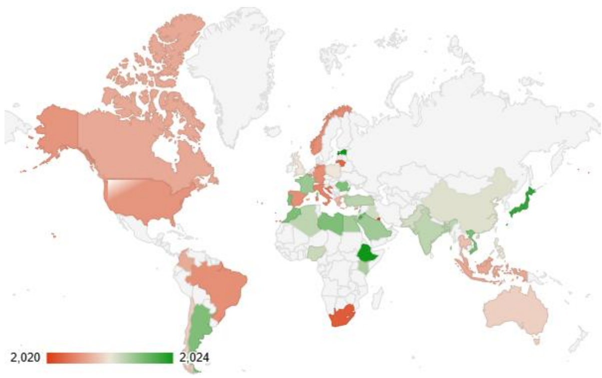

Figure 10 Average Publication Year by Country

B. CITATION ANALYSIS OF LITERATURE

Another essential aspect for researchers is identifying articles that have significantly contributed to advancing academic achievements in the domain of concrete incorporating waste tire rubber. Citation analysis plays a crucial role in determining which publications have had the greatest impact, offering insights into foundational works, emerging trends, and future research directions. Highly cited publications often represent groundbreaking studies that shape research discourse and uncover new opportunities in the field.

This analysis addresses influential articles and their relative contributions. Table 4 presents the most cited publications in this domain, showcasing key advancements in areas such as mechanical properties, durability, sustainability, and structural performance of rubberized concrete.

The publication titled "A Comprehensive Review on the Mechanical Properties and Durability of Concrete Containing Waste Materials" by Roychand et al. (2020) leads with the highest number of citations (305), reflecting its foundational importance in understanding the mechanical and durability aspects of concrete incorporating waste materials. Another highly influential article, "Properties and Utilizations of Waste Tire Rubber in Concrete: A Review" by Siddika et al. (2019), has 301 citations, providing an in-depth evaluation of rubberized concrete applications.

Other notable works include "Mechanical, Durability, and Microstructural Properties of Concrete with Waste Rubber Particles: A Review" by Wang et al. (2019) with 214 citations, which investigates the microstructural behavior of rubberized concrete, and "Engineering Properties of Sustainable Green Concrete Incorporating Industrial By-products" by Qaidi et al. (2021), with 193 citations, highlighting sustainable alternatives for green concrete production.

The study "Mechanical Properties of Recycled Aggregate Concrete Using Waste Tire Rubber as Fine Aggregate" by Hossain et al. (2019) (177 citations) further emphasizes the potential of waste tire rubber as a fine aggregate replacement. Additionally, Li et al.'s work on "Functions and Impacts of Plastic/Rubber Wastes as Filler in Sustainable Cementitious Systems: A Review" (2020) (175 citations) explores innovative approaches to using plastic and rubber waste for sustainable construction.

Further, "Fresh and Anisotropic-Mechanical Properties of Sustainable Green Concrete with Recycled Rubber and Plastic" by Ye et al. (2021) (159 citations) examines the fresh and mechanical behavior of rubberized concrete, while "Application of Polymer, Silica-Fume, and Crushed Rubber in Sustainable Concrete: A Multiscale Review" by Li et al. (2019) (152 citations) offers a broad overview of multiscale applications of waste materials in concrete. The article "Potential Use of Waste Tire Rubber as Aggregate in Green Concrete: Properties, Durability, and Structural Performance" by Li et al. (2019) (133 citations) further reinforces the importance of rubberized concrete in green construction.

The study "Research on Crumb Rubber Concrete: From a Multiscale Perspective" by Xu et al. (2020) (128 citations) presents insights into rubberized concrete at different scales, demonstrating its broad applicability in sustainable construction.

Figure 11 illustrates the publication trends in the five most productive journals in the field of waste tire rubber incorporation in concrete from 2019 to 2024. The graph highlights Construction and Building Materials as the leading contributor, consistently publishing the highest number of articles, with a peak in 2023 before experiencing a decline in 2024.

The Journal of Building Engineering shows an increasing trend, particularly from 2022 onwards, indicating its growing influence in publishing research on sustainable construction materials. Materials demonstrates a sharp rise in publications in 2022, reaching its highest point before declining in subsequent years. Lecture Notes in Civil Engineering and Journal of Cleaner Production have shown fluctuating trends, with a noticeable increase in 2023. These journals collectively contribute to advancing knowledge in sustainable construction, material innovation, and environmental impact reduction in concrete incorporating waste tire rubber.

C. KEYWORD ANALYSIS

The color coding in the VOSviewer co-occurrence network is a crucial element that helps visualize how related keywords cluster together (Figure 12, Figure 13). Each color corresponds to a specific research theme or cluster of keywords that are closely related based on their co-occurrence in the research articles. In the dataset, the keyword co-occurrence network is divided into three main clusters based on the color of the nodes. . The green cluster primarily focuses on the mechanical properties and structural integrity of rubberized concrete. It includes keywords such as "compressive strength" (308 occurrences), "rubberized concrete" (173 occurrences), "tensile strength" (153 occurrences), and "mechanical properties" (154 occurrences). The green color signifies that these keywords are often discussed together in research that examines the physical performance of rubberized concrete, particularly its strength and durability. These studies aim to understand how waste tire rubber influences the material's ability to withstand stress and load over time.

The blue cluster highlights the sustainability and environmental impact of rubberized concrete. Keywords such as "sustainable development" (66 occurrences), "eco-friendly" (frequently found in various studies), and "recycling" (146 occurrences) belong to this category. These keywords reflect the increasing emphasis on the environmental benefits of incorporating waste rubber into concrete mixes, reducing landfill waste, and promoting eco-friendly construction practices.

The red cluster focuses on material optimization and the improvement of concrete mixtures. Keywords like "concrete mixtures" (91 occurrences), "cement" (67 occurrences), and "aggregates" (92 occurrences) are prominent in this group. The red color highlights research centered on enhancing the performance of rubberized concrete by experimenting with different material compositions, including the use of alternative aggregates and advanced binders.

The technical concerns of rubberized concrete primarily revolve around its mechanical performance and structural integrity. Keywords such as "compressive strength" (308 occurrences; [42], [43], [44], "rubberized concrete" [45], [46], [47], and "tensile strength" (153 occurrences;[48], [49], [50], [51], [52]are closely linked, signifying the importance of understanding how the inclusion of waste tire rubber affects the material's strength and durability. Durability is a significant focus, as indicated by the keyword "durability" (149 occurrences; [53], [54], [55], [56], [57], which reflects ongoing research on the material's long-term performance, particularly under extreme environmental conditions. These technical concerns are critical to ensuring that rubberized concrete meets the structural standards required for real-world applications. Additionally, the use of "steel fibers" (82 occurrences;[58], [59], [60]) in rubberized concrete is a notable area of research aimed at addressing issues of brittleness and enhancing the material's strength and ductility. These efforts are essential for making rubberized concrete a more viable alternative for construction.

Despite extensive research into mechanical properties, there is still a noticeable gap in studying the long-term durability of rubberized concrete, particularly under extreme environmental conditions such as freezing temperatures and chemical exposure. More research is needed to assess how rubberized concrete behaves over prolonged periods and under various environmental stress conditions.

Sustainability is a key concern in rubberized concrete research. The use of waste tire rubber as an aggregate replacement offers significant environmental benefits. Keywords such as "sustainable development" (66 occurrences; [61], [62]) and "recycling" (146 occurrences; [63], [64]) highlight the importance of utilizing waste tire rubber to reduce landfill waste and the demand for natural aggregates.

Table 4 Highly Cited Publications.

Ref	Title	Authors	Year	Total Citations	Source
[65]	A comprehensive review on the mechanical properties of waste tire rubber concrete	Roychand R.; Gravina R.J.; Zhuge Y.; Ma X.; Yousuf K.; Zhang M.	2020	305	Construction and Building Materials
[65]	Properties and utilizations of waste tire rubber in concrete: A review.	Siddika A.; Mamun M.A.A.; Alyousef R.; Amran Y.H.M.	2019	301	Construction and Building Materials
[66]	Mechanical, durability, and microstructural properties of macro synthetic polypropylene (PP) fiber-reinforced rubber concrete	Wang J.; Dai Q.; Si R.; Guo S.	2019	214	Journal of Cleaner Production
[67]	Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review	Qaidi S.M.A.; Dinkha Y.Z.; Haido J.H.; Ali M.H.; Abdul Ghani M.F.	2021	193	Journal of Cleaner Production
[68]	Mechanical properties of recycled aggregate concrete containing crumb rubber and polypropylene fiber	Hossain F.M.Z.; Shahjalal M.; Islam K.; Tiznob D.	2019	177	Construction and Building Materials
[69]	Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete – A review	Li X.; Ling T.-C.; Hung Mo K.	2020	175	Construction and Building Materials
[70]	Fresh and anisotropic-mechanical properties of 3D printable ultra-high ductile concrete with crumb rubber	Ye J.; Cui C.; Yu J.; Yu K.; Xiao J.	2021	159	Composites Part B: Engineering
[71]	Application of polymer, silica-fume and crushed rubber in the production of Pervious concrete	Li D.; Toghroli A.; Shariati M.; Sajedi F.; Bui D.-T.	2019	152	Smart Structures and Systems
[72]	Potential use of waste tire rubber as aggregate in cement concrete – A comprehensive review	Li Y.; Zhang S.; Wang R.; Dang F.	2019	133	Construction and Building Materials
[73]	Research on crumb rubber concrete: From a multi-scale review	XU J.; Yao Z.; Yang G.; Han Q.	2020	128	Construction and Building Materials

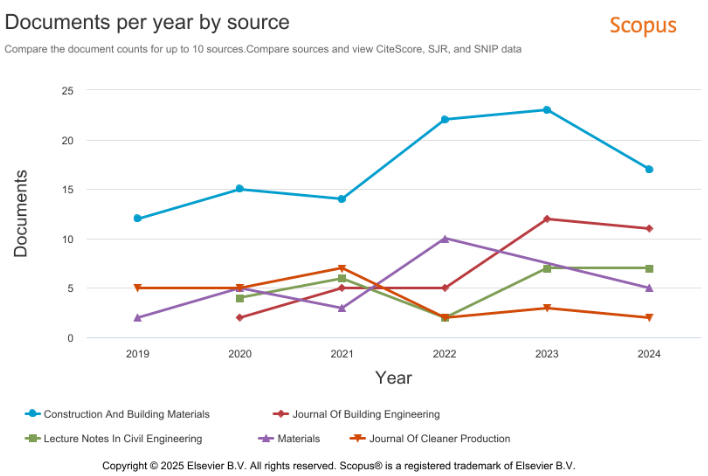

Figure 11 Trends of Articles Published in The 5 Most Productive Journals (2019–2024)

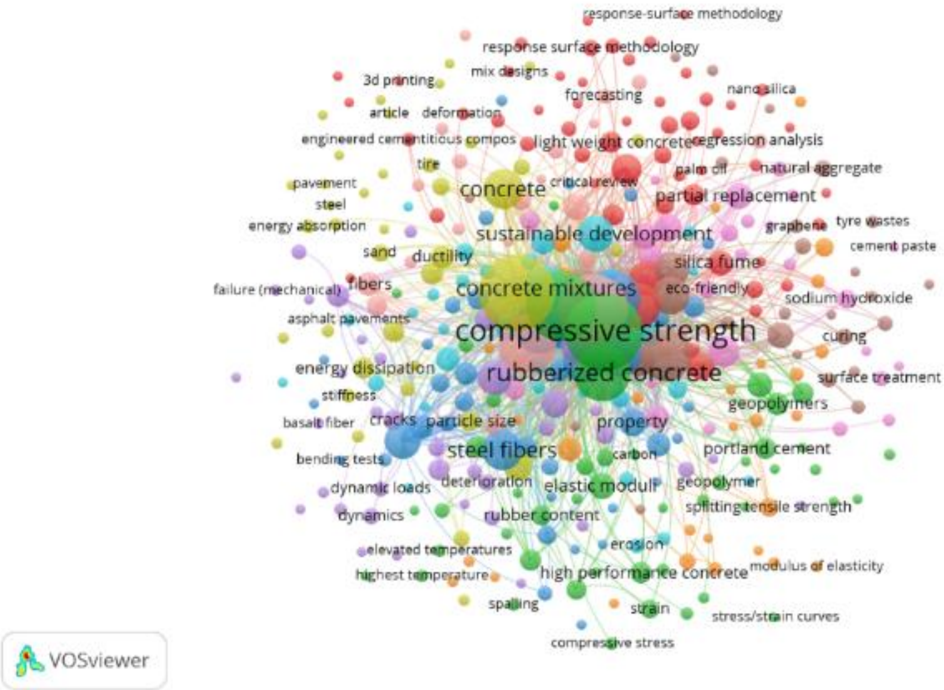

Figure 12 Co-Occurrence Network of Keywords.

Sustainability is further enhanced through the incorporation of alternative binders and advanced materials. Keywords such as "graphene," "silica fume," and "geopolymers" frequently appear, indicating their potential to improve the mechanical properties of rubberized concrete without compromising its sustainability. Research by [24], [74], [75], [76]supports the idea that these advanced materials can enhance performance while aligning with sustainability goals. The keyword "recycling" underscores the growing interest in waste tire utilization in concrete, which is essential for promoting green building practices and reducing the construction industry's carbon footprint.

While sustainability research is substantial, there is a lack of comprehensive Life-Cycle Assessment (LCA) studies on rubberized concrete. An LCA study could quantify the environmental impact of rubberized concrete throughout its life cycle, from production to disposal, and compare it with conventional concrete. Such studies would provide a more detailed understanding of its sustainability potential.

From a socio-economic perspective, research on rubberized concrete increasingly focuses on its economic viability and cost-effectiveness. Keywords such as "cost," "reduced maintenance," and "energy performance" reflect concerns regarding the economic impacts of using rubberized concrete, particularly in large-scale infrastructure projects. Advanced modeling techniques such as "response surface methodology," "regression analysis," and "mix designs" (91 occurrences; [44], [77], [78], [79], [80] are instrumental in optimizing concrete mixtures to achieve cost-effectiveness while maintaining performance. These techniques play a crucial role in expanding the use of rubberized concrete in infrastructure projects by ensuring that the material meets both strength and durability requirements in a cost-efficient manner. Although the cost benefits of rubberized concrete are gaining recognition, further research is necessary to develop economic models for large-scale infrastructure projects. Additionally, more studies should be conducted to quantify maintenance cost savings and the long-term financial viability of using rubberized concrete compared to traditional concrete.

Despite the growing body of research on rubberized concrete, several gaps remain that warrant further investigation. These gaps present opportunities for future studies and highlight areas that have been underexplored in existing literature. While substantial research has been conducted on the mechanical performance of rubberized concrete, there is a limited understanding of its long-term durability, particularly in harsh environments such as extreme temperatures or high humidity. A gap exists in comprehending how rubberized concrete behaves over extended periods of exposure to stress, fatigue, and weather conditions.

A significant gap also exists in the environmental assessment of rubberized concrete. While keywords like "recycling" and "sustainable development" are prevalent in the blue cluster, research on the life-cycle impact of using waste tire rubber in concrete remains sparse. More LCA studies are needed to evaluate the environmental footprint of rubberized concrete from production to disposal, comparing it to conventional concrete in terms of energy consumption, carbon emissions, and waste generation.

Furthermore, while material optimization is a key focus of the red cluster, advanced computational techniques such as machine learning for predicting optimal mix designs and artificial intelligence for analyzing rubberized concrete properties are still underrepresented. Exploring these modern tools could significantly enhance the efficiency and performance of rubberized concrete, paving the way for its broader adoption in construction applications.

Figure 13 Word Cloud of Key Terms

CONCLUSION AND RECOMMENDATIONS

The trend analysis of research publications from 2019 to 2024 highlights significant growth in academic interest in waste tire rubber utilization in concrete. The cumulative increase in publications demonstrates sustained progress in this domain, driven by the urgent need for sustainable construction solutions. However, the slight decline in annual publications in 2023 and 2024 suggests a shift from exploratory studies to practical refinement, focusing on optimizing existing methodologies rather than introducing entirely new concepts. This trend reflects the industry's transition toward implementing research findings in real-world applications. The growing prioritization of sustainable concrete materials underscores the need for continued innovation to address challenges related to resource conservation, environmental sustainability, and cost efficiency. Future research should explore large-scale applications, interdisciplinary collaborations, and policy frameworks that facilitate the adoption of waste-derived materials in construction.

The bibliometric analysis of global research contributions reveals that China, India, and Australia dominate in terms of both publication volume and citation impact, reflecting their leadership in sustainable concrete research. Emerging contributors such as Saudi Arabia, South Korea, and Malaysia demonstrate increasing engagement, signaling broader international participation in advancing sustainable construction practices. The geographic distribution of research indicates a growing network of collaborations between countries, emphasizing the interdisciplinary nature of innovations in waste material utilization. Strengthening global partnerships and promoting knowledge exchange between established and emerging contributors can accelerate progress in this domain. Furthermore, increased investment in research funding and industry collaborations in developing nations could enhance the impact and applicability of sustainable construction technologies.

Citation analysis highlights the most influential studies in rubberized concrete research, focusing primarily on mechanical properties, durability, and sustainability. Highly cited publications indicate that the integration of waste tire rubber into concrete has been extensively examined, particularly in terms of compressive strength, tensile behavior, and long-term durability. However, gaps remain in assessing the performance of rubberized concrete under extreme environmental conditions and in real-world applications. Researchers should prioritize studies on advanced additives and treatments that enhance the mechanical and microstructural properties of rubberized concrete. Additionally, systematic reviews and meta-analyses consolidating findings from various studies could provide a more comprehensive understanding of material behavior, helping bridge the gap between laboratory research and practical construction applications.

The keyword analysis provides insights into three primary research clusters: mechanical performance, sustainability, and material optimization. Studies have predominantly focused on evaluating the compressive strength and durability of rubberized concrete, but challenges related to long-term performance and environmental exposure remain underexplored. Sustainability research emphasizes the potential of rubberized concrete in reducing landfill waste and promoting circular economy principles. However, comprehensive life-cycle assessments (LCA) are needed to quantify its environmental benefits throughout its life span. Furthermore, the application of computational modeling and machine learning techniques in optimizing mix designs and predicting material performance remains limited. Future research should integrate these advanced methodologies to enhance the efficiency and reliability of rubberized concrete formulations.

Despite significant advancements, challenges persist in the widespread adoption of rubberized concrete. Issues related to workability, strength limitations, and structural integrity under varying environmental conditions require further investigation. The lack of standardized testing methods and performance benchmarks for rubberized concrete limits its acceptance in construction regulations and industry codes. Addressing these challenges requires the development of standardized guidelines and testing protocols to establish confidence in the material's performance. Additionally, exploring the compatibility of rubberized concrete with emerging technologies such as self-healing materials and carbon capture techniques could further enhance its sustainability and functional properties. Strengthening collaborations between academia, industry, and policymakers will be critical in facilitating the transition from research to practical implementation.

The economic viability of rubberized concrete remains a crucial factor in determining its large-scale adoption. While the use of waste tire rubber offers cost-saving potential by reducing raw material consumption, additional research is needed to evaluate the financial trade-offs associated with its application in large infrastructure projects. Conducting cost-benefit analyses that compare rubberized concrete with conventional concrete in terms of production, maintenance, and long-term financial feasibility will provide valuable insights for decision-makers. Industry incentives and policy support could further drive the adoption of sustainable construction materials. Beyond traditional applications, exploring new commercial opportunities, such as noise-reducing pavements and energy-absorbing structures, could expand the scope and economic potential of rubberized concrete. Table 5 summarizes key recommendations for advancing rubberized concrete, focusing on research, collaboration, durability, adoption challenges, and economic feasibility. It highlights the need for large-scale studies, standardized testing, and policy support to enhance sustainability and practical application.

Table 5 Focused Recommendations for Advancing Rubberized Concrete Research and Implementation

Recommendation Area	Focused Recommendations
Research Development	• Conduct large-scale applications in infrastructure (roads, bridges). • Establish long-term performance monitoring programs. • Develop new mix design methodologies to improve strength, workability, and thermal stability.
Global Collaboration	• Promote international research and funding collaborations. • Support open-access data-sharing and global conferences. • Establish regional hubs for localized testing and innovation.
Citation Impact	• Explore microstructural behavior and degradation mechanisms. • Conduct systematic reviews and meta-analyses. • Study effects of rubber particle size and treatments on mechanical performance.
Keyword Insights	• Perform life-cycle assessments (LCA) for environmental impact. • Use machine learning to optimize mix designs. • Study the effects of supplementary materials (e.g., fly ash, silica fume).
Challenges in Adoption	• Standardize testing protocols across climates. • Examine rubber-reinforcement compatibility. • Run field trials and develop treatment methods to improve bonding.
Economic Viability	• Carry out cost-benefit analyses comparing rubberized concrete with conventional • Perform cost-benefit comparisons with conventional concrete. • Quantify long-term savings from reduced maintenance. • Explore new applications (e.g., noise barriers, impact-resistant surfaces) and promote policy incentives.

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