Bio-based solutions for concrete infrastructure: a review of microbial-induced carbonate precipitation in crack healing

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Review

Bio-Based Solutions for Concrete Infrastructure: A Review of Microbial-Induced Carbonate Precipitation in Crack Healing

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Abstract: Microbial-induced carbonate precipitation (MICP) is gaining attention as an eco-friendly and sustainable method for concrete crack repair. However, key challenges related to its large-scale implementation, regulatory approval, and integration into existing construction standards remain underexplored. This review examines recent advances in MICP, emphasizing its role in circular economy practices and sustainable building solutions. Traditional synthetic sealants contribute to environmental pollution and have limited long-term durability, highlighting the need for greener alternatives. Global research trends reveal an increasing focus on self-healing materials, biomineralization, and durability enhancement, alongside emerging innovations such as encapsulation technologies, marine applications, and bio-based composites. Unlike previous reviews, this study integrates bibliometric analysis to systematically assess research trends, identify key collaboration networks, and evaluate regulatory challenges that impact MICP adoption. While MICP offers significant advantages, including self-healing capabilities and compatibility with industrial by-products, barriers related to cost, scalability, and policy integration persist. This review identifies critical thematic clusters which include microbial action, sustainability, and engineering applications. This helps to provide actionable insights for researchers, engineers, and policymakers. By fostering interdisciplinary collaboration, MICP has the potential to become a transformative solution for resilient and environmentally sustainable infrastructure.

Keywords: bibliometric analysis; biomineralization; calcification processes; eco-friendly solutions; structural repair

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1. Introduction

Concrete remains the cornerstone of modern construction due to its versatility, availability, and strength. It is used extensively in critical infrastructure, including bridges, highways, and buildings, primarily due to its high compressive strength [1,2]. However, its inherent vulnerability to cracking poses significant challenges, compromising structural durability and increasing long-term maintenance costs (Figure S1A). These cracks compromise impermeability, allowing water, chlorides, and sulfates to penetrate the material, which accelerates reinforcement corrosion, freeze–thaw damage, and structural degradation [3–5]. Given these vulnerabilities, early intervention in crack sealing is crucial for extending the service life of concrete structures.

Historically, synthetic crack sealants such as epoxy resins and polymer-based materials have been the standard repair method (Figure S1B and Table 1), owing to their strong adhesion, mechanical strength, and durability under various environmental conditions. While effective in restoring structural integrity, these materials present several drawbacks, including high carbon footprints, environmental pollution, and performance deterioration under extreme conditions [6–8]. These sealants are often applied in injection or surface-coating techniques, preventing further water ingress and aggressive agents into the concrete matrix.

Synthetic sealants contribute significantly to environmental pollution at various stages of their lifecycle. The degradation of polymer-based materials releases microplastics into water systems, leading to contamination of aquatic environments [9]. Their production consumes large amounts of energy, with epoxy resins alone generating up to 2.5 kg CO_2 per kg of material produced [10,11]. Additionally, polymer-based sealants degrade into microplastics, contributing to water system contamination, and releasing harmful chemicals like bisphenol A and phthalates into soil and groundwater [9,12,13]. The economic impact of synthetic sealants is also a major concern. Moreover, their susceptibility to UV radiation, thermal expansion, and chemical exposure results in frequent maintenance cycles and increased lifecycle costs [14–18]. The combination of environmental concerns, performance limitations under extreme conditions, high maintenance costs, and complex application processes further underscores the need for self-healing and durable repair solutions that minimize maintenance and extend structural longevity [19]. These drawbacks underscore the urgent need for sustainable alternatives that align with circular economy principles and green engineering solutions.

Table 1. Summary of existing materials and techniques for crack repair in building structures.

Materials/Methods	Advantages	Disadvantages	Applications	Performance Characteristics	Key References
Epoxy resins	Strong adhesion, watertight seal, chemical resistance	High carbon footprint, non-biodegradable, environmental concerns	Used in structural repair of cracks in bridges, dams, and nuclear facilities.	Flexural strength increased by 357.14%, tensile strength by 272.77%, and compressive strength by 111.2% compared to ordinary concrete.	[15]
Asphalt binder	Durable, effective sealing	Susceptible to performance deterioration in extreme conditions, high lifecycle costs	Ideal for roads and high-stress applications prone to thermal expansion.	Increased 126 times with anti-rutting additive, excellent adhesion (74.7 mJ/m^2), and cohesion properties.	[20]

Table 1. *Cont.*

Materials/Methods	Advantages	Disadvantages	Applications	Performance Characteristics	Key References
Polyurethane sealants	Flexible, durable, good for both interior and exterior repairs	May require repeated applications in high-movement areas	Sealing cracks and expansion joints in concrete pavements and other structures.	Improved shape recovery, tailored transition temperature (Tt), and 3% TiO_2 content for superior durability.	[17]
Non-shrink grouts	High strength, maintains volume during setting	Requires proper mixing and application	Filling voids, repairing cracks in masonry	10% Ordinary Portland Cement performs like commercial non-shrink grouts, with strong resistance to 5% $MgSO_4$ and excellent compressive and bond strength.	[16]
Ferrocement	High tensile strength, durable, flexible, and lightweight	Labor-intensive, requires skilled application	Structural repairs, thin-shell construction, water tanks, marine structures	Composite materials improve strength, crack resistance, and ductility.	[21]

In response to these challenges, microbial-induced carbonate precipitation (MICP) has emerged as a sustainable and bio-based solution for concrete crack repair (Figure 1). MICP utilizes urease-producing bacteria, such as *Sporosarcina pasteurii* and *Bacillus megaterium*, to catalyze urea hydrolysis, leading to the precipitation of calcium carbonate ($CaCO_3$) within cracks [22–24]. This biomineralization process not only restores structural integrity but also offers self-healing properties, reducing long-term maintenance demands [25,26]. Furthermore, MICP aligns with circular economy principles, as it can integrate industrial by-products like fly ash and slag, promoting resource efficiency and sustainability [18,27–29]. Studies have shown that MICP can successfully seal cracks up to 2.0 mm wide, significantly improving concrete durability and water resistance [30–32]. Moreover, integrating industrial byproducts such as fly ash and slag into the microbial growth medium aligns with circular economy principles, promoting sustainability and resource efficiency. MICP bacteria can be encapsulated in materials such as polyurethanes or lightweight aggregates, allowing them to survive within the concrete and precipitate calcite upon activation by water [33,34]. This process not only strengthens the concrete but also provides a sustainable repair solution by reducing reliance on synthetic chemicals commonly used in traditional repair materials [1]. Despite the potential of MICP, challenges persist, particularly regarding the scalability and mechanical robustness of the solidified materials. Research has primarily focused on optimizing bacterial strains, nutrient formulations, and environmental conditions to enhance the efficiency of carbonate precipitation. However, questions remain about the cost-effectiveness and integration of MICP into standard construction practices [27,35,36].

Although most literature reviews have focused on the technical aspects of MICP, such as biomineralization mechanisms, mechanical properties, and durability enhancements [2,37–42], this review takes a different approach. Prior reviews have primarily explored microbial impacts on material performance, bacterial selection, nutrient delivery systems, crack-healing efficiency, and niche applications like marine concrete repair and crack mitigation strategies. However, these works remain confined to specific areas within the broader MICP field. This bibliometric review builds on those foundational studies by providing a comprehensive overview of the global research landscape. It highlights cross-disciplinary collaborative efforts, showcasing how microbiologists, engineers, and material scientists are working together to advance MICP technologies. The review identifies trending research areas, such as encapsulation techniques, bio-based composites, and machine-learning applications for real-time crack detection. Furthermore, it explores potential real-world applications, offering actionable insights and proposing a future agenda for integrating MICP into standard building practices. By bridging the gap between academic research and practical implementation, this review aims to foster resilience and environmental sustainability in construction.

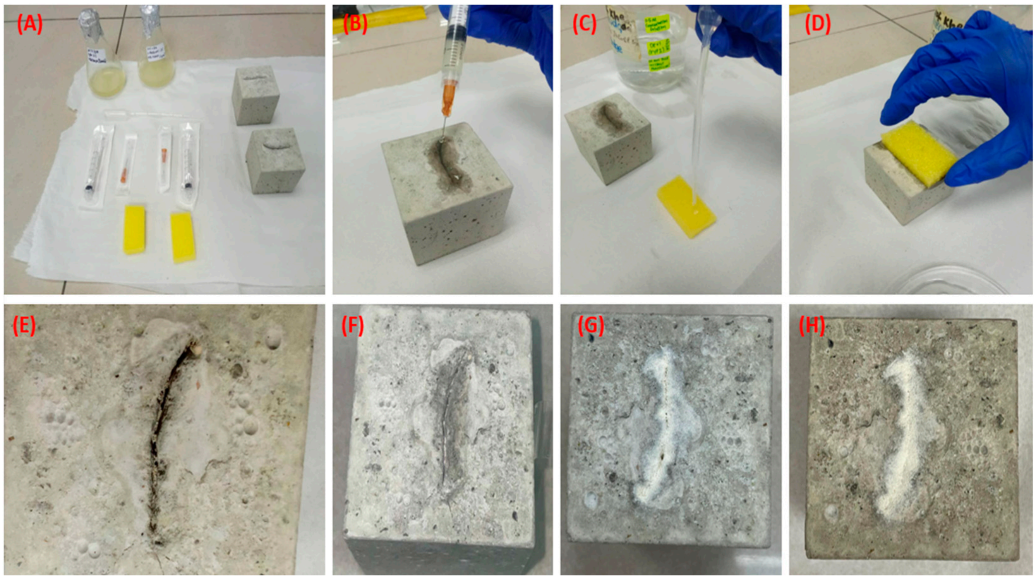

Figure 1. Stepwise demonstration of the MICP treatment process for repairing cracks in concrete specimens: (**A**) materials for the process, including ureolytic microorganisms, cementation solution, and tools; (**B**) application of cementation solution into an artificial crack; (**C**) sponge preparation with microbial culture; (**D**) placement of the microbe-enriched sponge on the crack; (**E**) specimen immediately after treatment, showing visible cracks; (**F**) partial crack filling after 1 day; (**G**) significant biomineral formation after 3 days; and (**H**) complete crack cementation after 14 days. This figure was created by the authors based on original, unpublished data.

To advance the practical application of MICP, it is essential to understand research trends and collaboration networks in this field. Bibliometric analysis is a powerful tool for systematically evaluating the evolution of the scientific literature, identifying influential studies, and uncovering emerging themes. Previous studies have established MICP's potential as an alternative to conventional methods, highlighting its ability to enhance mechanical properties, reduce porosity, and minimize water absorption [37,38]. However, recent advancements have broadened its scope, including applications such as marine concrete restoration [43], cost-effective grouting techniques [44,45], optimized calcium sources for high-temperature conditions [46], and machine-learning-based decision-making for real-time crack detection [47], these developments reinforce the need for a structured, data-driven analysis of how MICP research is evolving, which this study aims to provide

This review offers a comprehensive bibliometric analysis of MICP research from 2007 to 2024, identifying global research trends, intellectual contributions, and emerging collaborations. By analyzing data from Scopus and Web of Science (WoS), this study minimizes bias from variations in journal coverage and indexing criteria, ensuring a comprehensive and representative dataset [48,49]. Using visualization techniques via VOSviewer, this work seeks to advance sustainable concrete repair technologies by identifying key areas for innovation and development, bridging research gaps, and proposing future directions for MICP commercialization.

2. Methodology

2.1. Approach of Study

To investigate worldwide research trends in MICP for concrete crack repair, this study used a bibliometric method. Vast amounts of scholarly literature may be methodically examined using bibliometric analysis, which gives unbiased insights into research trends, significant contributors, and new developments [50]. This approach is particularly well-suited to MICP research, given the field's rapid growth and interdisciplinary nature, which spans engineering, material science, and sustainability studies. The bibliometric methods followed established protocols and focused on quantifiable metrics such as citation counts, h-index values, co-authorship networks, and keyword co-occurrences [51]. By identifying theme clusters and important contributions, these factors made it possible to gain a thorough grasp of the state of the field. Bibliometric analyses offer a macro-level viewpoint that facilitates trend predictions and reveals research gaps, in contrast to traditional literature assessments, which are usually qualitative.

2.2. Data Extraction and Search Strategy

The bibliometric dataset was generated from two leading academic databases, Scopus and WOS, selected for their extensive coverage and rigorous indexing. These databases provide complementary strengths, with Scopus offering broad coverage and advanced citation tools, while WOS emphasizes high-impact, peer-reviewed literature. Search queries were designed to include a comprehensive range of terms related to MICP and its applications in concrete crack repair. The Boolean queries applied are provided in Table 2. No additional refinements were applied to the queries, such as limiting by document type, language, or year of publication. This decision ensured inclusivity and minimized biases that might exclude relevant work. Duplicates between Scopus and WOS were identified and removed using a cross-referencing approach. The search, conducted on 23 September 2024, yielded 372 documents from Scopus and 257 from WOS, including overlapping and unique entries. These results formed the foundation for subsequent bibliometric analysis. The exact search strings and database outputs are available in the Supplementary Materials for replicability. To ensure relevance, only studies that explicitly contained the exact keyword phrases used in the search queries were considered. Articles that did not specifically mention MICP in the context of concrete crack repair or those focusing on unrelated biomineralization processes were excluded. Additionally, duplicate articles retrieved from Scopus and WOS were manually identified and removed directly within the databases before exporting the results. After exporting the Comma-Separated Values (CSVs) files, a manual cross-checking process was conducted to ensure accuracy. Given the reasonable number of retrieved articles, this verification process was feasible and ensured a high-quality dataset for bibliometric analysis.

Table 2. Search queries and results from Scopus and Web of Science.

Database	Search Query	Number of Documents Retrieved
Scopus	TITLE-ABS-KEY ((“concrete self healing” OR “self-healing concrete” OR “crack repair” OR “crack sealing” OR “self-repairing concrete” OR “structural crack repair” OR “microcrack repair” OR “crack filling” OR “crack closure” OR “self-repair” OR “self-healing material” OR “autonomous crack repair” OR “concrete crack biogrouting” OR “biological crack repair”) AND (“microbial induced carbonate precipitation” OR “MICP” OR “ureolytic bacteria” OR “urease-producing bacteria” OR “microbially induced calcite precipitation” OR “biogenic calcium carbonate precipitation” OR “microbial calcite precipitation” OR “bacterially induced carbonate precipitation” OR “biomineralization” OR “bacteria-induced calcite precipitation” OR “microbially mediated mineralization” OR “biocementation” OR “bacterial induced mineralization”))	372

Table 2. *Cont.*

Database	Search Query	Number of Documents Retrieved
WOS	TS = ((“concrete self healing” OR “self-healing concrete” OR “crack repair” OR “crack sealing” OR “self-repairing concrete” OR “structural crack repair” OR “microcrack repair” OR “crack filling” OR “crack closure” OR “self-repair” OR “self-healing material” OR “autonomous crack repair” OR “self-repairing material” OR “concrete crack biogrouting” OR “biological crack repair”) AND (“microbial induced carbonate precipitation” OR “MICP” OR “ureolytic bacteria” OR “urease-producing bacteria” OR “microbially induced calcite precipitation” OR “microbial induced calcium carbonate precipitation” OR “biogenic calcium carbonate precipitation” OR “microbial calcite precipitation” OR “bacterially induced carbonate precipitation” OR “mediated calcite precipitation” OR “biomineralization” OR “bacteria-induced calcite precipitation” OR “microbially mediated mineralization” OR “biocementation” OR “bacterial induced mineralization”))	257

2.3. Rationale for Database Selection

Scopus and WOS were selected due to their complementary strengths. Scopus indexes a broad range of outputs, including journals, conference proceedings, and books, and provides advanced analytics tools for examining citation trends, author affiliations, and funding patterns [48]. WOS focuses on high-impact, peer-reviewed literature and offers robust citation metrics, ensuring a high-quality dataset [52]. Together, these databases provided comprehensive coverage of MICP research, capturing both breadth and depth. Other databases, such as PubMed or Google Scholar, were not included due to their limited focus on engineering and material science or their less rigorous indexing criteria. The dataset was analyzed to identify trends in research topics, geographic contributions, and interdisciplinary connections. Articles were grouped into thematic clusters based on keywords, titles, and abstracts, providing insights into research foci such as microbial action, durability enhancement, and sustainability.

2.4. Data Categorization and Analysis

Figure 2 illustrates the step-by-step process used to retrieve, filter, and analyze bibliometric data from the Scopus and WOS databases, ensuring a systematic and comprehensive evaluation of research trends. The extracted data were systematically categorized and analyzed to identify patterns and trends. Scopus indexed 120 open-access documents, including 70 gold, 26 hybrid gold, 8 bronze, and 35 green documents. WOS indexed 104 open-access documents, comprising 68 gold, 19 hybrid gold, 7 free-to-read, and 60 green documents, further classified into subcategories (e.g., green published, accepted, and submitted). Articles constituted the majority of publications, representing 72.58% of the Scopus dataset and 74.33% of the WOS dataset. Other document types included reviews, conference/proceeding papers, and book chapters, which resulted in 27.42% and 25.67%, for Scopus and WOS, respectively. Journals dominated the source types in both databases, accounting for 86.8% of Scopus documents and 80.1% of WOS documents, followed by conference proceedings and books. Language distribution showed English dominated both databases, accounting for 95% of Scopus documents and 99% of WOS documents. The remaining 5% of Scopus documents were in Chinese (24), and one each in French, Korean, and Turkish. In WOS, only one document each was indexed in Chinese and Turkish. The interdisciplinary nature of MICP research was reflected in subject areas: Scopus highlighted engineering, materials science, and environmental science, while WOS emphasized materials science multidisciplinary, construction technology, and civil engineering.

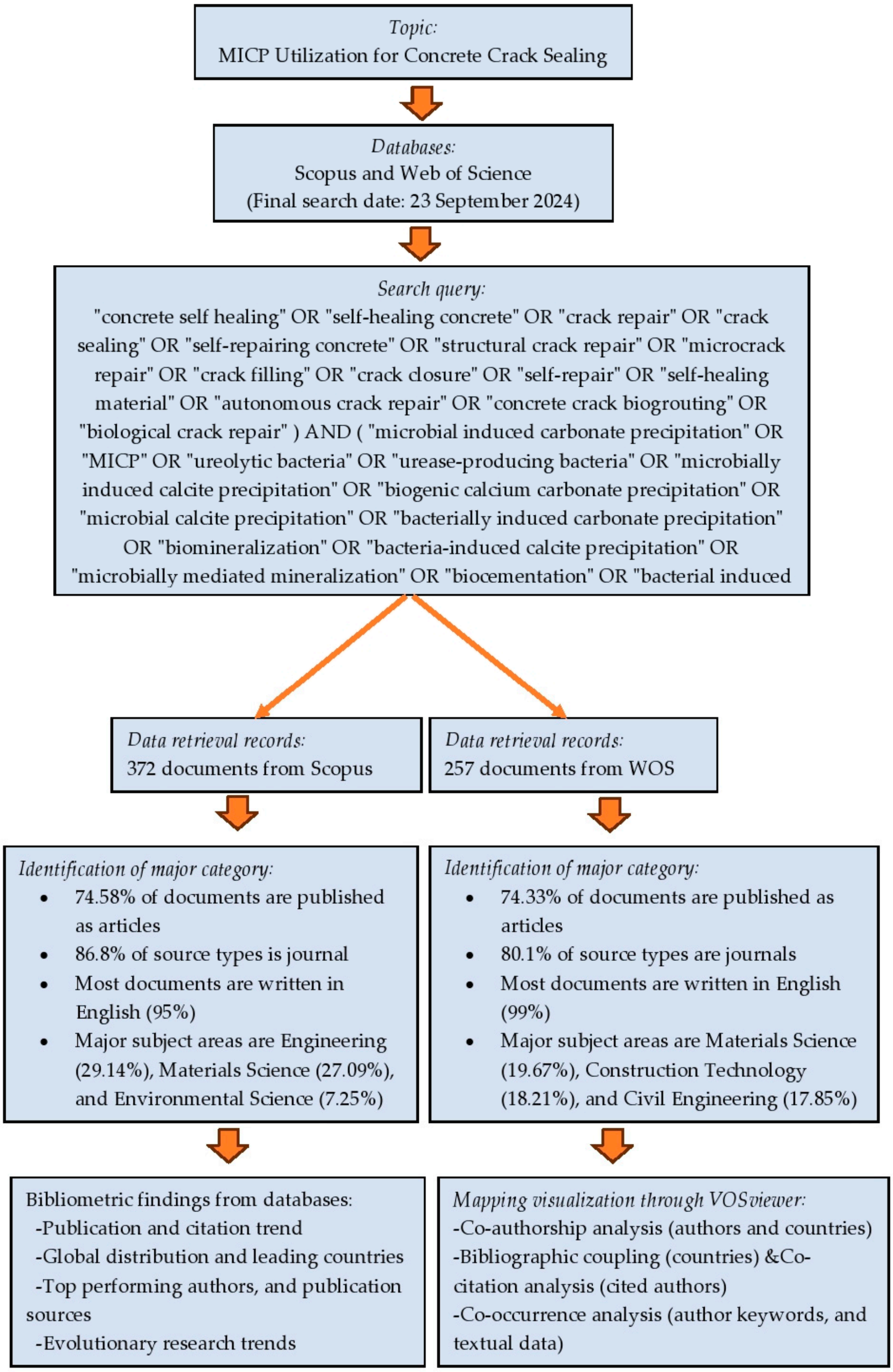

Figure 2. Flowchart illustrating the steps taken to retrieve and analyze bibliometric data from Scopus and WOS databases.

2.5. Visualization and Network Mapping

Visualization of bibliometric networks was performed using VOSviewer (version 1.6.17), a Java-based software developed by Leiden University. This tool generates graphical representations of co-authorship, keyword co-occurrence, bibliographic coupling, and co-citation networks, providing an intuitive means of analyzing complex relationships within the dataset. Nodes in VOSviewer maps represent entities such as authors, keywords, or countries, with their size reflecting prominence and lines indicating relationships. Thicker lines and larger nodes signify stronger connections and greater centrality, respectively. This approach facilitates the identification of thematic clusters and key contributors within the research landscape. Co-authorship analysis examined collaborative networks among authors and countries. Scopus identified 1275 authors, with 22 meeting the threshold of at least two documents, and 50 countries, with 37 meeting the threshold of at least one document. WOS identified 901 authors, with 13 meeting the threshold, and 47 countries, with 28 meeting the threshold. Bibliographic coupling highlighted interconnections based on shared references. Scopus identified 50 countries, with 27 meeting the threshold of at least three documents, while WOS identified 47 countries, with 25 meeting the threshold. Co-citation analysis measured relationships between documents based on shared citations. Scopus identified 23,518 cited authors, with 50 surpassing the threshold of at least 116 citations. WOS identified 5369 cited authors, with 50 surpassing the threshold of at least 36 citations. Keyword Co-occurrence revealed thematic trends. Scopus identified 904 keywords, with 53 surpassing the threshold of at least four occurrences. WOS identified 656 keywords, with 40 surpassing the same threshold. A co-occurrence analysis of text data (titles and abstracts) provided additional insights into thematic patterns. In Scopus, 8248 terms were identified, with 84 terms meeting the minimum threshold of 20 occurrences using the full counting method. In WOS, 6227 terms were identified, with 61 met the same threshold. By integrating advanced visualization tools, this analysis provided a clear, data-driven understanding of the MICP research landscape, emphasizing key connections, influential contributors, and emerging themes. These insights not only enrich the current understanding of the field but also inform future research directions.

3. Results and Discussion

3.1. Yearly Publication and Citation Trends

The publication trends in MICP research for concrete crack repair/sealing reveal significant growth as shown in Figure 3. Scopus recorded 321 publications, while WOS documented 257 during this period. Early research activity (2007–2012) was minimal, with single-digit publication counts, reflecting the field's nascent stage. A notable surge began in 2013, gaining momentum in 2015 when Scopus documented nine publications and WOS recorded three, as shown in Figure 3A. This upward trajectory continued, reaching 22 publications in Scopus and 17 in WOS by 2019. The most significant growth occurred after 2020, culminating in a peak in 2024 with 67 publications in Scopus and 36 in WOS. These trends highlight the accelerating pace of research output and the increasing recognition of MICP applications, driven by advancements in microbial techniques, sustainable construction practices, and interdisciplinary collaborations. Citation trends parallel this growth, underscoring the rising academic impact of MICP research as illustrated in Figure 3B. Total citations reached 9323 in Scopus and 6077 in WOS, with sharp increases observed from 2016 onwards. By 2024, average citations per publication climbed to 36.57 in Scopus and 37.81 in WOS, reflecting substantial academic recognition and influence. The h-index values of 51 for Scopus and 44 for WOS, further highlight the research impact. Differences between Scopus and WOS in publication and citation counts reflect variations in indexing scope, with Scopus offering broader coverage, while WOS publications tend to achieve higher average citation rates [48,49]. Scopus demonstrates extensive dissemination, while WOS may maximize visibility through its focus on more prestigious journals. Both databases affirm the field's growing importance, regardless of publication count disparities.

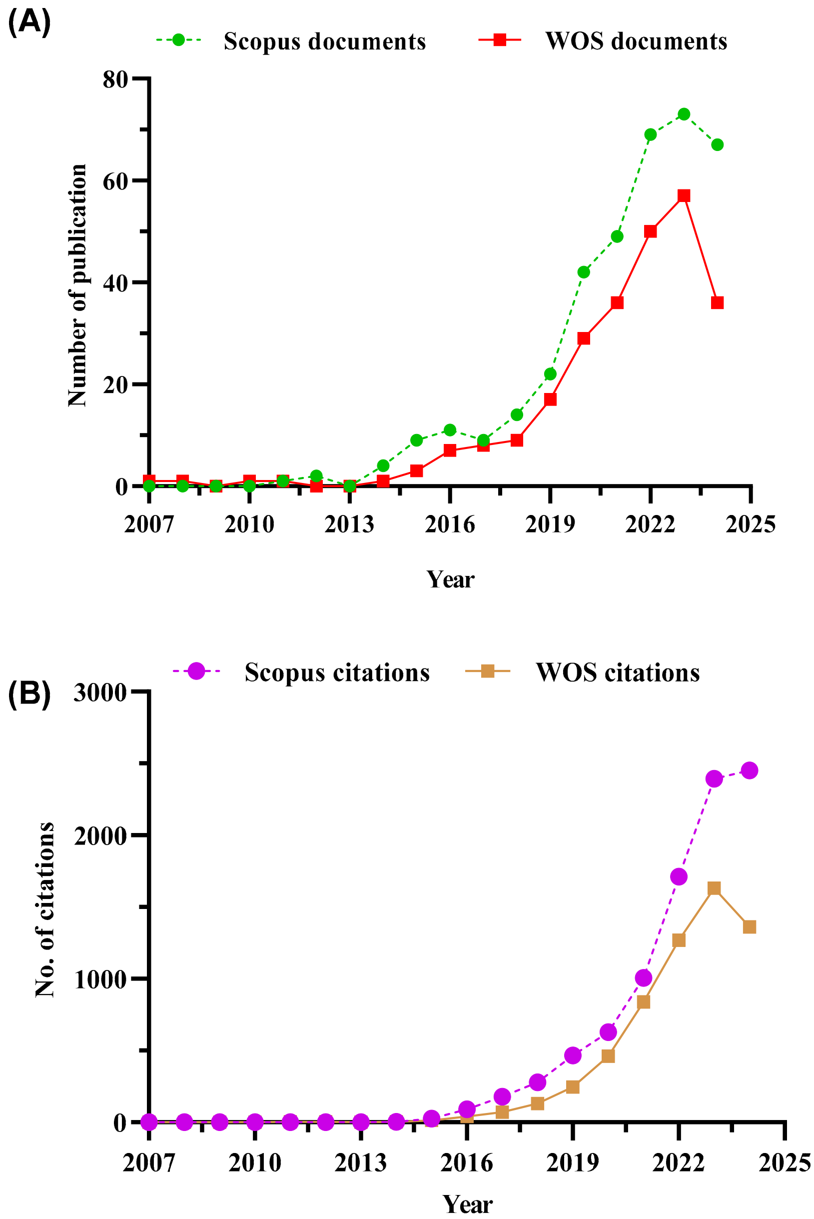

Figure 3. Publication and Citation Trends for MICP Applications in Concrete Crack Repair (2007–2024). (**A**) Highlights the significant increase in research activity over; (**B**) Reflects the growing academic impact of these studies through citation trends.

The growing interest in MICP for concrete crack repair can be attributed to several factors. Heightened awareness of sustainable construction practices and the pressing need for environmentally friendly solutions have increased attention to MICP technologies. These approaches align with global efforts to reduce carbon footprints and enhance infrastructure durability [53]. Advancements in microbial technology and biomineralization processes have refined procedures and expanded applications for crack repair and self-healing concrete [54]. Such technological improvements have streamlined research, enabling deeper exploration of biochemical mechanisms and practical MICP deployment. Collaborations between academia and industry have accelerated progress, translating lab findings into scalable, cost-effective, real-world solutions [55].

3.2. Global Distribution and Leading Countries

The geographical distribution of publications highlights significant regional contributions, as shown in Figures 4 and 5. In Asia, Scopus records 302 publications from

21 countries, led by China with 146 publications, followed by India with 57 publications. WOS, on the other hand, lists 199 publications from 18 countries, also led by China with 81 publications, followed by India with 45 publications. In Europe, Scopus reports 103 publications from 19 countries, with the United Kingdom leading with 26 publications. WOS lists 63 publications from 17 countries, also led by the United Kingdom, but with 19 publications. In North America, the United States dominates with 38 out of 39 publications in Scopus and 31 out of 32 publications in WOS. In South America, Brazil leads with two out of four publications in Scopus and five out of eight publications in WOS. In Africa, Egypt is the leading contributor, with 9 out of 12 publications in Scopus and 7 out of 9 publications in WOS. In Oceania, Australia leads with 8 publications in both Scopus (out of 13 total) and WOS (out of 11 total).

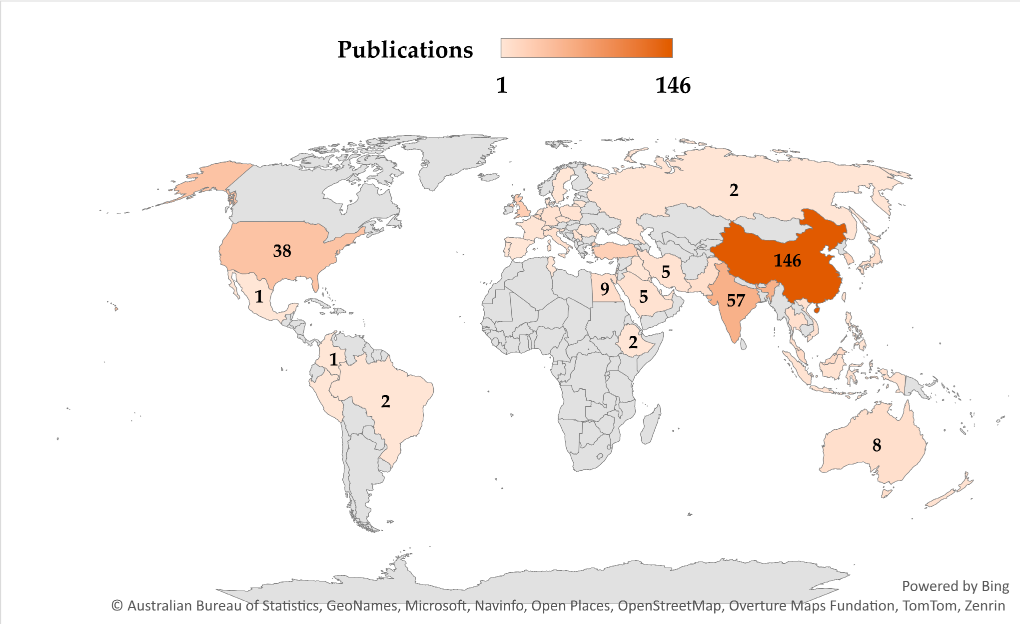

Figure 4. Global contributions of countries to MICP research in concrete crack sealing over the years from Scopus database. This figure illustrates the geographical distribution and research output of various countries, highlighting the leading contributors and regional research activity in the field. Different colours in the maps show the sum of publications per country.

For the top-performing countries overall, China, India, and the United States emerged as the leading contributors to the research field in both databases. In Scopus, China accounts for 146 publications (45.48%), India for 57 publications (17.76%), and the United States for 38 publications (11.84%). Similarly, in WOS, China contributes 81 publications (31.52%), India 45 publications (17.51%), and the United States 31 publications (12.06%). Notable contributors include the United Kingdom (26 publications in Scopus, 19 in WOS), Turkey (24 in Scopus, 12 in WOS), Republic of Korea (17 in Scopus, 13 in WOS), Malaysia (12 in Scopus, 13 in WOS), Egypt (9 in Scopus, 7 in WOS), Singapore (9 in Scopus, 5 in WOS), and Australia (8 in Scopus, 8 in WOS). There are also discrepancies in representation between the two databases. For example, countries like Pakistan (eight publications in Scopus) and Nigeria (four publications in Scopus) are not listed in WOS, while Spain (seven publications in WOS) and Italy (seven publications in WOS) do not appear in Scopus. This broader distribution of research activity underscores the diverse global participation in the field. Although the numbers differ, the contributions from various countries highlight the collective efforts toward advancing research in biocementation and related topics.

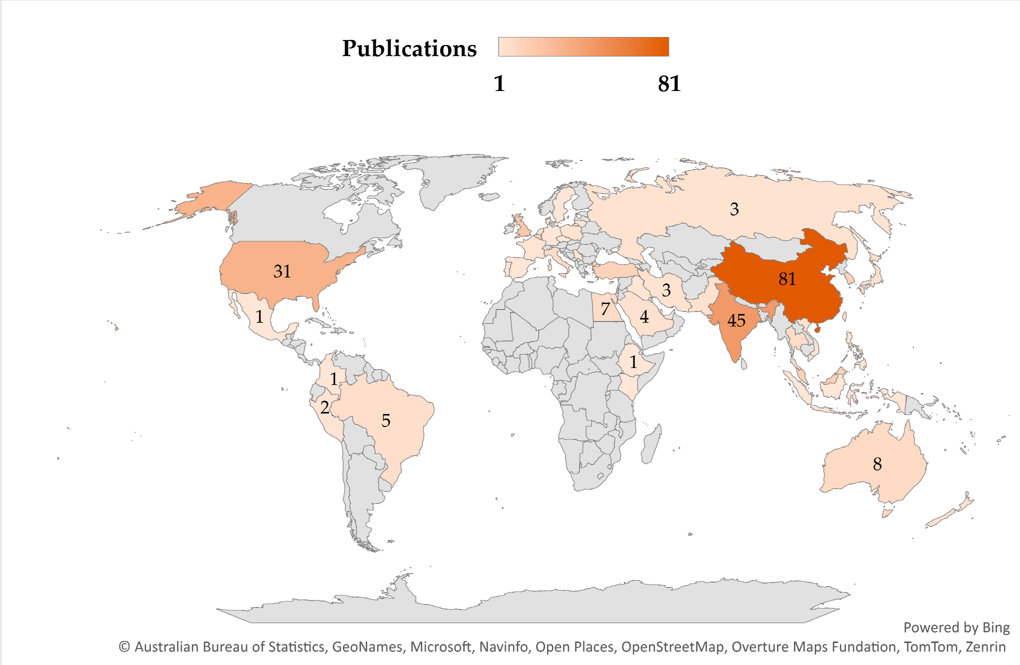

Figure 5. Global contributions of countries to MICP research in concrete crack sealing over the years from WOS database. This figure illustrates the geographical distribution and research output of various countries, highlighting the leading contributors and regional research activity in the field. Different colours in the maps show the sum of publications per country.

Countries actively pursuing research in MICP for concrete crack repair are motivated by unique regional challenges and infrastructure needs. China's leadership in MICP research stems from its rapid urbanization and aging infrastructure. The country is exploring innovative, sustainable methods to repair concrete cracks and extend the lifespan of critical structures. For instance, Wang et al., [56] introduced a soybean urease-induced calcium carbonate precipitation system integrated with crack-filling materials such as fiber additives (e.g., lignin, basalt, and polypropylene fibers) and lightweight aggregates like fine-silty sand.

This approach significantly improves unconfined compressive strength and crack-filling efficiency, with high-crystallinity calcite observed in repaired structures. In another study by Xiang et al., [57], a two-bacterial capsule system was developed to enhance the self-healing ability of cracked mortar. This system achieves 90% crack closure (50–600 μm width), demonstrating effective three-dimensional healing capacity, particularly in impermeability and strength recovery. These advancements position China as a leader in applying MICP for large-scale concrete rehabilitation. India's focus on MICP addresses infrastructure challenges posed by diverse climatic conditions like frequent monsoons and high humidity. Its cost-effectiveness and adaptability make MICP a practical solution for both urban and remote areas. Nain et al., [58] demonstrated the use of *Bacillus subtilis* and *Bacillus megaterium* for micro-crack management, achieving a 15% increase in compressive and tensile strength. These microbes enhance concrete's structural integrity and support self-healing of shrinkage-induced cracks. Anand et al., [59] showed that India has advanced field-scale MICP application by developing a mineral-based bacterial inoculum with a long shelf life.

The United States focuses on MICP to address aging infrastructure, emphasizing sustainability and cost reduction. Federal initiatives encourage biotechnological innovations like MICP for long-term infrastructure durability. Choi et al., [60] showed that MICP can repair cracks in mortar ranging from 0.15 to 1.64 mm, significantly reducing water permeability and restoring tensile strength. The study highlights the importance of the quantity and morphology of calcium carbonate precipitated on crack surfaces, providing insights into optimizing MICP applications for varying crack sizes. European countries prioritize MICP due to strict environmental regulations and commitments to sustainable construction. The method aligns with the European Green Deal and offers solutions for preserving historical structures. Reeksting et al., [61] explored the diversity of biomineralization mechanisms across ureolytic and non-ureolytic bacteria. While both mechanisms produced comparable amounts of calcium carbonate, non-ureolytic bacteria delivered more robust results for crack healing, offering new insights into optimizing MICP for specific applications. This research highlights Europe's emphasis on leveraging environmental bacteria to develop innovative, eco-friendly engineering solutions.

In addition to the top contributors, several other leading countries have made significant strides in MICP research for concrete crack repair. Research in Turkey has explored the use of corn-steep liquor as a carbon source to propagate microbial cells for biomineralization in cement-based materials [62]. This approach not only reduces costs but also enhances the environmental sustainability of MICP applications by utilizing industrial by-products. Belgium has concentrated on selecting bacterial strains and finding protection materials compatible with concrete to enhance the efficiency of biomineralization in self-healing concrete [63]. This work is critical for ensuring the compatibility and durability of MICP applications in diverse construction environments.

Researchers in Republic of Korea have examined the impact of various biomineralization conditions on the microstructural properties of cement mortar. Their findings offer valuable insights into optimizing MICP processes to enhance crack healing efficiency and improve material durability [1]. Malaysian researchers have created biological self-healing techniques using non-ureolytic bacteria encapsulated in alginate hydrogel capsules. This method has proven effective in repairing cracks in cement paste and mortar, offering a novel alternative to traditional ureolytic bacteria-based systems [64]. Research in Singapore has concentrated on the viability of bacterial spores and their capacity to heal cracks in bacteria-containing geopolymer. These studies investigate innovative applications of MICP in advanced materials, expanding the range of self-healing concrete technologies [65].

Furthermore, notable contributions from countries with fewer publications in the field underscore the global interest in MICP research. Researchers in Qatar have developed bio self-healing concrete using MICP facilitated by an indigenous *Bacillus cereus* strain isolated from Qatari soil. This study demonstrates the potential for region-specific bacterial strains to address local infrastructure challenges [66]. Experimental investigations in Ethiopia have shown the self-healing efficiency of mortar using *Bacillus subtilis* and *Bacillus cereus*, highlighting the adaptability of MICP technologies in resource-constrained environments [67]. Portuguese researchers have examined the use of biocementation techniques for sealing cracks in concrete water storage tanks. This research highlights the potential of MICP in improving the durability and water-tightness of essential infrastructure [68].

The network visualization of co-authorship among countries based on the Scopus database (Figure 6A) reveals that China has the highest total link strength (39) and the most links (18), indicating its central role in international collaborations. India and Belgium also show significant collaboration, each with a total link strength of 13, but India has more links (10) compared to Belgium (8). Countries are divided into clusters, with Cluster 1 including Egypt, Pakistan, Saudi Arabia, and Kuwait, showing strong regional collaborations. Cluster 5 includes China, Israel, and Macao, highlighting China's extensive network. Australia and Malaysia (Cluster 3) and Germany and France (Cluster 4) show regional collaboration trends. Brazil and Iran (Cluster 8) have minimal international links, suggesting a need for increased global engagement. Emerging collaborators such as Turkey (Cluster 7) and the United States (Cluster 7) show strong collaboration networks, with Turkey having a total link strength of 16 and the United States 29. The analysis from the WOS database (Figure 6B) provides a complementary perspective.

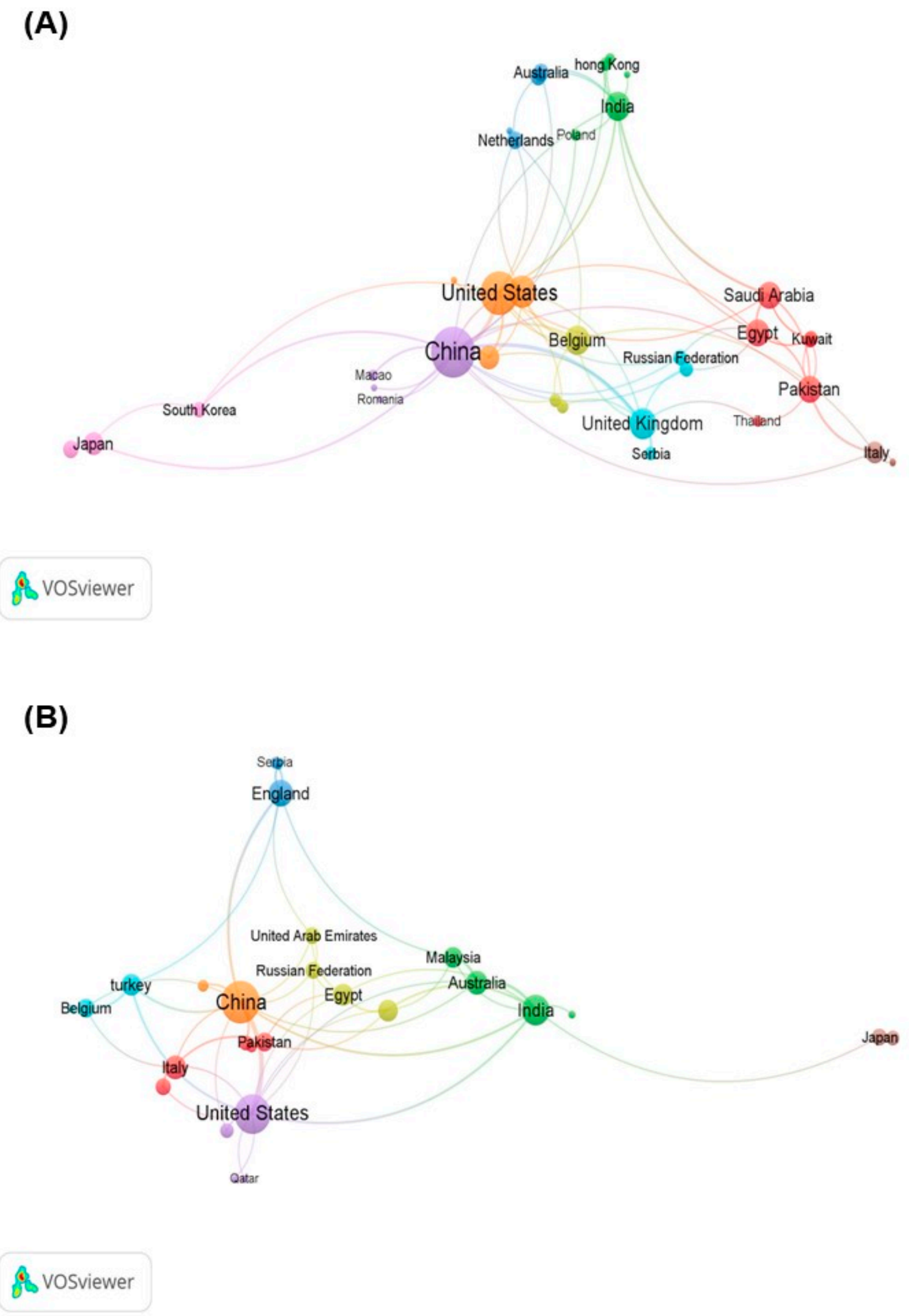

Figure 6. Network visualization of co-authorship among countries based on VOSviewer analysis from the Scopus (**A**) and Web of Science (WOS) (**B**) databases. This figure highlights collaborative relationships and link strengths among countries actively contributing to MICP research for concrete crack sealing. Node size represents the total number of publications, while link thickness indicates the strength of collaboration between countries. Different colors represent clusters of countries with stronger internal collaborations, reflecting regional and international research partnerships. The clusters and their corresponding colors are as follows: Cluster 1 is represented in red, Cluster 2 in green, Cluster 3 in blue, Cluster 4 in yellow, Cluster 5 in purple, Cluster 6 in turquoise, Cluster 7 in light brown, Cluster 8 in chocolate, and Cluster 9 in pink.

China again emerges as a leading collaborator with a total link strength of 25 and 12 links. The United States follows closely with a total link strength of 22 and 12 links, indicating its significant role in global research networks. Cluster 2 includes Australia, India, and Malaysia, showing strong intra-cluster collaborations. Cluster 4 features Egypt, Saudi Arabia, and the United Arab Emirates, highlighting regional cooperation in the Middle East. England (Cluster 3) and Italy (Cluster 1) show strong collaboration networks, with England having a total link strength of 10 and Italy 8. Turkey (Cluster 6) and Singapore (Cluster 5) also demonstrate significant international collaborations. Co-authorship analysis of countries is essential to evaluate and visualize the collaborative relationships between researchers from different countries. It helps to identify patterns of international collaboration, highlight leading countries in specific research areas, and understand the dynamics of global research networks [69]. In the context of MICP for crack repair or sealing, countries with less collaboration might face challenges such as limited research infrastructure, funding constraints, or less emphasis on this specific area of research [70]. For example, Brazil and Iran have minimal international links, which could be due to a lack of advanced research facilities, limited funding for international projects, or fewer researchers specializing in MICP. Countries with stronger collaboration such as China, the United States, and India, often have well-established research institutions, significant funding opportunities, and a larger pool of researchers working in this field. This is because regional scientific productivity and geographical proximity also play crucial roles in fostering strong collaborations [71].

The network visualization of bibliographic coupling among countries, based on VOSviewer analysis from both databases (Figure S2), further reinforces these findings. Bibliographic coupling identifies collaborative networks and shared research interests by analyzing how often researchers from different countries cite the same literature [72]. The analysis highlights China's dominant position with the highest total link strength (74,324 in Scopus and 56,231 in WOS) and extensive links (146 in Scopus and 81 in WOS). This is followed by India (45,988 in Scopus and 40,485 in WOS) and the United States (32,618 in Scopus and 27,518 in WOS), indicating their significant influence and interconnectedness in the research landscape. Comparing the two databases, China and the United States consistently appear as central nodes in the global research network. India and Australia also maintain strong collaborative ties across both databases, reflecting their active participation in international research.

Regional collaborations are evident, with clusters indicating strong intra-regional ties. For instance, the Middle East (Egypt, Saudi Arabia, United Arab Emirates) and Southeast Asia (Australia, Malaysia) demonstrate robust intra-regional partnerships. However, countries like Brazil and Iran exhibit minimal international links, which may hinder their ability to contribute to global advancements in MICP. To address this, targeted initiatives such as South–South collaboration networks or mentorship programs involving MICP leaders (e.g., China, India) could provide resource-sharing opportunities and enhance research capacity in underrepresented regions [69]. Additionally, the alignment of national research priorities with MICP's interdisciplinary nature could encourage institutional support and funding [70].

This analysis provides a foundation for understanding global research dynamics and identifying potential areas for fostering international collaborations. By leveraging bibliometric insights, policymakers and researchers can prioritize efforts to strengthen partnerships, particularly in regions with untapped potential, thereby advancing the field of sustainable concrete repair technologies.

In addition, Figure 6 offers a closer look at how these co-authorship patterns manifest. Each node corresponds to a country, with the node size reflecting its total publication count in MICP-related studies, while the thickness of the connecting lines signifies the strength of collaboration. Color-coded clusters highlight how geographic proximity, established research consortia, and funding priorities shape these networks. For instance, China's extensive links to nations like the United States and Belgium underscore its central role as a global research hub, whereas countries with fewer or thinner links might face challenges in building collaborative momentum. By comparing Figure 6A,B, it becomes clear that both Scopus and WOS data identify China, the United States, and India as dominant contributors. However, differences in total link strength and cluster compositions also reveal secondary research alliances, such as those between Australia, India, and Malaysia. Overall, these visualizations underscore the importance of international collaboration in accelerating MICP research, wherein diverse expertise from microbiology, materials science, and civil engineering can converge to advance sustainable concrete crack repair solutions.

3.3. Top Prolific Authors

Table 3 presents a detailed comparison of the top 10 most prolific authors contributing to MICP research for concrete crack repair based on Scopus and WOS databases. In Scopus, these authors account for 15.3% of the total 549 publications, while in WOS, they contribute 12.4% of 483 publications. This highlights the significant role of a small group of researchers in driving advancements in the field, while the majority of publications are distributed across a broader collaborative network.

Table 3. Contributions of the most prolific authors in MICP research in scientific databases.

Database	Author	Publication	Citation	H-Index	Affiliation	City and Country	Reference
Scopus	Xu, Jing	11	596	7	Tongji University	Shanghai, China	[73]
	De Belie, Nele	10	799	9	Ghent University	Ghent, Belgium	[63]
	Bundur, Zeynep Basaran	9	328	7	Özyeğin Üniversitesi	Istanbul, Turkey	[74]
	Gebhard, Susanne	9	266	7	Johannes Gutenberg-Universität Mainz	Mainz, Germany	[75]
	Boon, Nico	8	854	8	University of Bath	Bath, England	[76]
	Li, Zhu	8	249	5	Taiyuan University of Technology	Taiyuan, China	[77]
	Paine, Kevin	8	200	6	University of Bath	Bath, England	[75]
	Ferron, Raissa	7	368	7	The University of Texas at Austin	Austin, United States	[78]
	Jiang, Lu	7	225	5	Ningxia University	Yinchuan, China	[77]
	Park, Woojun	7	367	7	Korea University	Seoul, South Korea	[79]
WOS	Erşan, Yusuf Çağatay	13	646	8	Hacettepe University	Ankara, Türkiye	[63]
	Park, Woojun	7	321	7	Korea University	Seoul, South Korea	[79]
	De Belie, Nele	7	622	7	Ghent University	Ghent, Belgium	[63]
	Boon, Nico	6	593	6	Ghent University	Ghent, Belgium	[76]
	Xu, Jing	6	430	6	Tongji University	Shanghai, China	[73]
	Gebhard, Susanne	6	145	5	University of Bath	Bath, England	[75]
	Bundur, Zeynep Basaran	5	191	4	Ozyegin University	Istanbul, Türkiye	[74]
	Paine, Kevin	5	89	5	University of Bath	Bath, England	[75]
	Li, Zhu	5	201	4	Taiyuan University of Technology	Taiyuan, China	[77]
	Millra, Jose	4	32	3	Louisiana Transportation Research Center	Louisiana, United States	[80]

In Scopus, the most productive author is Xu Jing (Tongji University, Shanghai, China), with 11 publications, 596 citations, and an H-index of 7, followed by De Belie Nele (Ghent University) and Bundur Zeynep (Özyeğin University), both with notable contributions. In WOS, the leading researcher is Erşan Yusuf Çağatay (Hacettepe University, Ankara, Turkey), with 13 publications, 646 citations, and an H-index of 8, alongside other key contributors such as Park Woojun (Korea University) and Boon Nico (Ghent University). Several authors, including Gebhard Susanne, Li Zhu, Bundur Zeynep, and Park Woojun, appear in both databases, indicating their broad impact. However, some researchers are more prominent in one database due to differences in indexing criteria and journal coverage. For example, Ferron Raissa (The University of Texas at Austin) is recognized in Scopus but not in WOS, while Erşan Yusuf Çağatay is highly ranked in WOS but not in Scopus.

The research field has advanced significantly through the contributions of various authors. These studies have emphasized themes such as bacterial selection, nutrient carriers, protection methods, and sustainability, providing a holistic understanding of the potential of this technology. The publications by these prolific authors often explore similar themes, such as the application of MICP in concrete crack repair, the mechanical properties of self-healing concrete, and the development of innovative bacterial carriers for enhanced crack healing. For example, Xu Jing investigated non-ureolytic bacteria for calcium carbonate deposition as a strategy for self-healing concrete [73]. The study demonstrated that incorporating bacteria and calcium glutamate into the concrete matrix enhanced crack healing efficiency, resulting in significantly higher recovery ratios of flexural strength and modulus. Gebhard Susanne and Kevin Paine examined the molecular mechanisms of MICP, focusing on the biochemical interplay between bacterial metabolism and extracellular environmental changes [75]. This work addressed the knowledge gaps in the molecular drivers of biomineralization, essential for advancing the biotechnological exploitation of MICP.

Boon Nico explored an environmentally sustainable alternative to ureolytic MICP by employing *Methylocystis parvus* and calcium formate as a substrate [76]. This method reduced ammonia emissions while achieving high calcium carbonate precipitation yields, making it a promising approach for eco-friendly construction applications. De Belie Nele and Erşan Yusuf Çağatay co-authored a study evaluating protective materials for bacterial survival in a high-pH concrete environment [63]. Their research tested materials such as diatomaceous earth, metakaolin, and zeolite, highlighting the potential of novel self-protected bacterial agents. These agents did not compromise the compressive strength or setting times of concrete, paving the way for advanced microbial self-healing techniques. Bundur Zeynep examined ammonium salt-based air-entraining admixtures (AEA) as a protective measure for *Sporosarcina pasteurii* [74]. While AEA showed limited influence on bacterial viability, the findings underscored the challenge of maintaining microorganism activity in high-pH environments.

Li Zhu and Jiang Lu co-authored a study proposing sugar-coated expanded perlite (EP) particles as carriers for bacteria and nutrients [77]. The approach enhanced crack-healing capacity and water permeability resistance, demonstrating that EP particles are a cost-effective option for large-scale applications in self-healing concrete. Millra Jose explored calcium alginate beads as reservoirs for MICP enhancement [80]. This study revealed that the beads improved both stiffness recovery and crack-sealing efficiency, suggesting that encapsulation systems could maximize the effectiveness of MICP in concrete. Park Woojun reviewed the challenges and potential applications of MICP in construction, addressing biological factors such as bacterial survival, metabolic optimization, and calcite precipitation conditions [79]. This work offered valuable insights for overcoming the limitations of MICP in practical settings. Ferron Raissa investigated the impact of bacterial solutions on hydration kinetics and compressive [78]. Her findings indicated that while bacterial incorporation enhanced calcite precipitation, hydration retardation posed challenges requiring careful system optimization. The contributions of these authors have significantly advanced the understanding and application of MICP for self-healing concrete. Their collaborative and individual efforts have shed light on bacterial selection, nutrient delivery, protection methods, and environmental sustainability.

The co-authorship analysis from both Scopus and WOS highlights key researchers and their collaborative networks, as shown in Figure S3. In the Scopus analysis, the leading three authors are Nele De Belie with a total link strength of 22, Nico Boon with 19, and Raissa Douglas Ferron with 12. Similarly, in the WOS analysis, the leading three authors are Nele De Belie with a total link strength of 18, Nico Boon with 16, and Yusuf Cagatay Ersan with 16. These authors not only contribute a substantial volume of research but also collaborate extensively, enhancing the impact and dissemination of their work. The co-citation analysis of cited authors in Figure S4 highlights the most influential researchers based on Scopus and WOS data. In the Scopus analysis, Nele De Belie stands out with the highest total link strength of 80,993 and 1423 citations, followed by Nico Boon with a total link strength of 30,903 and 473 citations, and Henk M. Jonkers with a total link strength of 45,000 and 761 citations.

Similarly, in the WOS analysis, Henk M. Jonkers leads with a total link strength of 5900 and 248 citations, followed by Nele De Belie with a total link strength of 1899 and 71 citations, and Yusuf Cagatay Ersan with a total link strength of 4150 and 155 citations. This analysis shows key researchers who are central to the field of MICP for concrete crack repair and sealing. The high link strengths and citation counts of these authors reflect their important role in shaping the research landscape. The presence of overlapping key figures in both databases indicates their widespread recognition and influence. For instance, Nele De Belie and Nico Boon are consistently noted for their substantial contributions and strong collaborative networks across both Scopus and WOS. Similar research themes emerge from the works of these leading authors. Nele De Belie's research often focuses on microbial carbonate precipitation in construction materials, while Nico Boon's studies include bacterial self-healing cementitious composites. Henk M. Jonkers is known for his work on bio-concrete and self-healing concrete technologies. These themes show how researchers build upon each other's work to advance knowledge and innovation in the field. Several authors identified in the co-authorship and co-citation analyses are noted for their contributions across both Scopus and WOS databases, such as Nele De Belie, Nico Boon, and Yusuf Cagatay Ersan. However, some authors appear prominently in one database but not the other, due to differences in database coverage, indexing criteria, and the specific journals included in each database. For example, Raissa Douglas Ferron is more prominent in the Scopus analysis, whereas Yusuf Cagatay Ersan stands out more in the WOS analysis. These analyses demonstrate the interconnectedness of researchers and indicate potential areas for further collaboration and research development. Countries and researchers with lower link strengths may benefit from increased international collaboration to enhance their research impact.

3.4. Top Preferred Publication Sources

Table 4 provides an overview of the most frequently used publication sources in MICP research based on Scopus and WOS databases. Construction and Building Materials is the leading journal in both databases, reaffirming its prominence in disseminating research on MICP-based concrete repair. Other key journals, including Journal of Building Engineering and Cement and Concrete Composites, also contribute significantly to the field, highlighting their focus on materials science and sustainable construction technologies. A comparison of citation impact shows that Scopus journals generally exhibit higher H-index values and citation counts compared to those in WOS, indicating broader research visibility. However, WOS journals maintain high selectivity, emphasizing rigorously peer-reviewed studies. The CiteScore and impact factors of these top journals further underscore their influence on MICP research.

Table 4. Top Preferred Publication Sources in MICP Research Based on Scopus and WOS Databases.

Database	Journals	Publications	Citations	H-Index	Publisher	CiteScore 2023	Highest Cited Article
Scopus	Construction and Building Materials	44	2045	25	Elsevier	13.8	[39]
	Journal of Building Engineering	25	342	10	Elsevier	10	[40]
	Cement and Concrete Composites	15	557	10	Elsevier	18.7	[60]
	Materials Today Proceedings	15	211	7	Elsevier	4.9	[81]
	Materials	14	356	8	Multidisciplinary Digital Publishing Institute (MDPI)	5.8	[82]
	Applied Microbiology and Biotechnology	9	826	7	Springer Nature	10	[83]
	Journal of Materials in Civil Engineering	8	69	3	American Society of Civil Engineers	5.8	[84]
	Sustainability	7	45	5	Multidisciplinary Digital Publishing Institute (MDPI)	6.8	[85]
	Case Studies in Construction Materials	6	39	3	Elsevier	7.6	[86]
	Lecture Notes in Civil Engineering	6	10	2	Springer Nature	0.8	[87]
WOS	Construction and Building Materials	42	1937	24	Elsevier	7.4	[39]
	Journal of Building Engineering	13	141	5	Elsevier	6.7	[40]
	Cement Concrete Composites	12	457	8	Elsevier	10.8	[60]
	Materials	11	269	6	Multidisciplinary Digital Publishing Institute (MDPI)	3.1	[82]
	Applied Microbiology and Biotechnology	9	667	6	Springer Nature	3.9	[83]
	Materials Today Proceedings	9	140	5	Elsevier	nil	[81]
	Sustainability	8	38	5	Multidisciplinary Digital Publishing Institute (MDPI)	3.3	[85]
	Case Studies in Construction Materials	6	18	3	Elsevier	6.5	[86]
	Journal of Sustainable Cement Based Materials	6	66	4	Taylor and Francis	4.3	[41]
	European Journal of Environmental and Civil Engineering	4	22	3	Taylor and Francis	2.2	[59]

Notably, some journals are exclusive to either Scopus or WOS. For example, The Journal of Materials in Civil Engineering and Lecture Notes in Civil Engineering are indexed in Scopus but not in WOS, whereas The Journal of Sustainable Cement-Based Materials and European Journal of Environmental and Civil Engineering appear in WOS but not in Scopus. This indicates varying indexing criteria across databases. However, Construction and Building Materials, Journal of Building Engineering, and Cement and Concrete Composites are indexed in both databases, reinforcing their central role in MICP-related research. These insights are particularly valuable for researchers seeking to publish their work in high-impact journals. The Scopus database offers broader coverage, while WOS prioritizes select high-impact publications, making both databases essential for tracking developments in MICP research.

In recent years, the application of MICP in concrete has garnered significant attention as a sustainable and effective solution for crack repair and durability enhancement. Several high-impact journals have published studies focusing on this innovative technology. Vijay et al. [39] presented a comprehensive review of bacterial concrete in Construction and Building Materials, highlighting the potential of MICP to seal micro-cracks through the addition of urease-producing bacteria such as *Bacillus pasteurii* and *Bacillus subtilis*. Vijay et al. [39] emphasized the encapsulation method as superior to direct application, demonstrating significant improvements in concrete strength and durability. In the Journal of Building Engineering, Nodehi et al. [40] discussed thoroughly about biomineralization mechanisms, focusing on the precipitation of calcium carbonate through bacterial activity. The study also discussed the importance of application methods and environmental factors in optimizing bacterial performance for self-healing concrete.

In Cement and Concrete Composites, a study by Choi et al. [60] discussed their investigation of MICP to repair pre-existing cracks in the mortar. The study demonstrated reduced water permeability and enhanced splitting tensile strength, with a clear relationship between $CaCO_3$ precipitation and crack width reduction. Scanning electron microscopy revealed calcite and vaterite morphologies on repaired surfaces. Jena et al. [81] explored the impact of different concentrations of *Bacillus subtilis* on concrete properties—published in Materials Today Proceedings. Their results showed significant improvements in compressive, tensile, and flexural strength, with a 32% increase in compressive strength observed at an optimal bacterial concentration. SEM analysis confirmed calcite deposition within concrete pores, resulting in denser concrete. In Materials, a detailed review of bacterial strains for MICP was presented by Chuo et al. [82], emphasizing *Sporosarcina pasteurii* as the most studied bacterium. This article discussed factors affecting MICP efficiency, including bacterial strain, nutrient concentration, and distribution methods while proposing cost-effective and sustainable practices such as using plant or animal waste as media.

A study by Seifan et al. [83] in Applied Microbiology and Biotechnology highlighted the long-lasting and environmentally friendly nature of microbial self-healing techniques. The study compared microbial approaches with traditional chemical treatments, demonstrating superior bonding capacity, environmental safety, and compatibility with concrete compositions. In Journal of Materials in Civil Engineering, a study on the viability of *Sporosarcina pasteurii* in cement-based materials which was studied for over 330 days was reported by Bundur et al. [84]. The research demonstrated reduced porosity and increased strength recovery in bacterial mortar, suggesting extended durability and improved service life for bioconcrete. Chen et al. [85] reported their investigation of the use of lightweight aggregates as carriers for *Sporosarcina pasteurii* in concrete, which was published in Sustainability. Results indicated enhanced interfacial transition zones and significant improvements in compressive strength, chloride penetration resistance, and water permeability, contributing to stronger and more durable concrete.

In Case Studies in Construction Materials, Tanyildizi et al. [86] showed how different self-healing methods for metakaolin-based geopolymer mortars were compared. The injection method of MICP treatment was identified as the most effective for crack closure, achieving a 29.69% recovery in flexural strength. Shashank et al. [87], in Lecture Notes in Civil Engineering, discussed alternative bacterial colonies capable of growing in high-alkaline environments. They reported a 36% improvement in compressive strength and significant enhancements in other strength parameters, with SEM and EDX analyses confirming calcium carbonate deposition. Mutitu et al. [41] published their work in Journal of Sustainable Cement Based Materials, which provided an in-depth discussion of ureolytic bacteria, such as *Bacillus pseudofirmus* and *Bacillus subtilis*. They showed how MICP could in improve Portland pozzolana cement. The study also outlined the effects of pH, temperature, and nutrients on MICP, emphasizing its potential for repairing cracked cement-based structures. Lastly, Anand et al., [59] published in European Journal of Environmental and Civil Engineering. They utilized electromechanical impedance techniques to monitor crack healing in concrete using fly ash as a MICP-bacterial carrier. The study demonstrated the effectiveness of bacterial healing agents in restoring structural integrity and reducing water permeability. These publications collectively underscore the potential of MICP as a transformative approach to enhancing the sustainability, durability, and functionality of concrete. Future research may focus on genetic engineering of bacteria, cost reduction methods, and large-scale applications to further advance this field.

3.5. Keywords Co-Occurrence Analysis

The co-occurrence analysis of author keywords related to MICP for concrete crack sealing, based on publications indexed in Scopus (Figure 7) and WoS (Figure 8) from 2007 to 2024, was conducted using VOSviewer software. These keywords, chosen by the authors, represent research focusing on MICP technology for enhancing concrete durability. The leading keywords in both databases are found in Table 5. In the VOSviewer analysis from Scopus data, the prominence of "self-healing" is also notable, appearing 99 times with a link strength of 191, indicating a strong focus on MICP's potential for autonomously sealing cracks in concrete. This highlights the crucial role of microbial processes in producing calcite to heal cracks in concrete. The keyword "biomineralization" appears 67 times with a total link strength of 158. Keywords like "*Bacillus*" and "*Sporosarcina pasteurii*" are frequently mentioned, highlighting the microbial species responsible for calcite precipitation.

Table 5. Top occurring author keywords in MICP research on Scopus and WOS databases.

Database	Label	Cluster	Links	Total Link Strength	Occurrences
Scopus	self-healing	2	41	191	99
	self-healing concrete	4	35	126	72
	biomineralization	5	38	158	67
	micp	6	36	104	57
	bacteria	6	32	132	55
	concrete	5	30	97	41
	calcium carbonate	6	25	79	28
	compressive strength	7	25	48	23
	crack repair	5	22	45	21
	crack	9	13	44	18
WOS	self-healing concrete	2	25	84	59
	micp	4	27	89	50
	self-healing	1	33	107	48
	biomineralization	3	30	104	46
	bacteria	5	24	94	40
	concrete	3	21	68	29
	calcium carbonate	4	27	69	27
	compressive strength	2	17	27	16
	crack repair	4	17	35	15
	biocementation	1	17	28	12

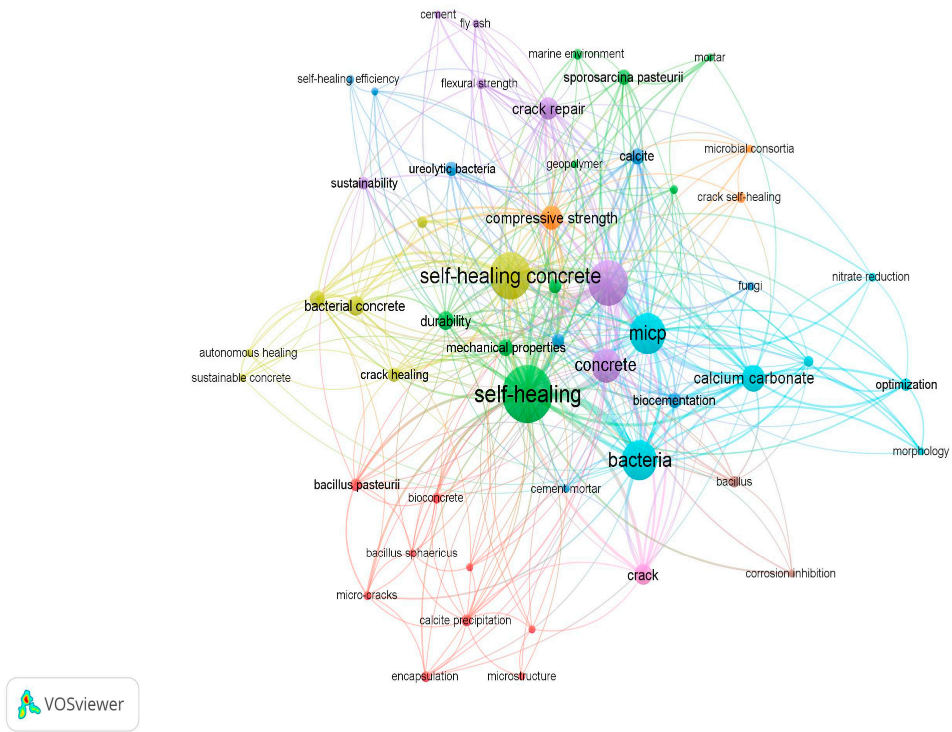

Figure 7. Co-occurrence analysis of author keywords in MICP research for concrete crack sealing (2007–2024) based on data from the Scopus database. Different clusters represent groups of closely related keywords, with each cluster assigned a specific color: Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), Cluster 4 (yellow), Cluster 5 (purple), Cluster 6 (turquoise), Cluster 7 (light brown), Cluster 8 (chocolate), and Cluster 9 (pink).

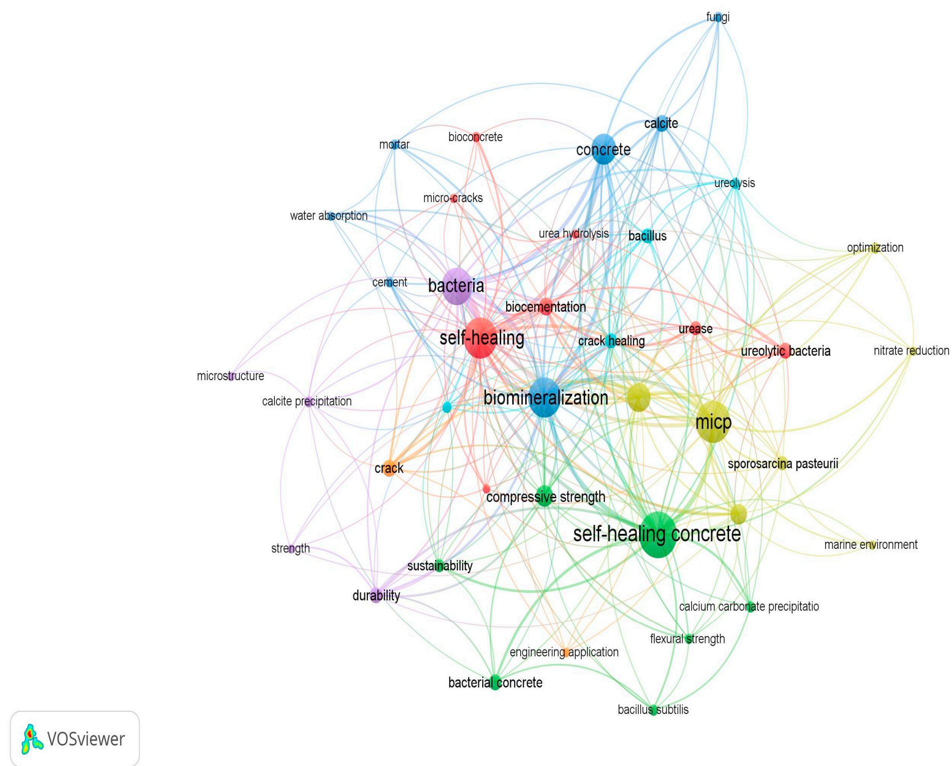

Figure 8. Co-occurrence analysis of author keywords in MICP research for concrete crack sealing (2007–2024) based on data from the WoS database. Different clusters represent groups of closely related keywords, with each cluster assigned a specific color: Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), Cluster 4 (yellow), Cluster 5 (purple), Cluster 6 (turquoise), and Cluster 7 (light brown).

For Cluster 1 (designated as Microbial Agents and Material Interactions) as shown in Figure 7, keywords such as "*Bacillus pasteurii*", "*Bacillus sphaericus*", and "bioconcrete" show a focus on specific microbial species involved in calcite formation. These results align with studies indicating the effectiveness of *Bacillus* species in enhancing calcium carbonate precipitation, thereby improving the healing potential of concrete [81,88,89]. Terms like "encapsulation", "microstructure", and "permeability" indicate a detailed examination of the material properties of MICP-treated concrete. Encapsulation technologies, particularly using silica gel or hydrogel, have been shown to enhance microbial viability under harsh conditions, thus optimizing crack healing efficiency [90–92].

In Cluster 2 (designated as Durability and Mechanical Performance), VOSviewer analysis from Scopus data highlights the "durability" of MICP-enhanced concrete in harsh environments, with terms like "marine environment" and "water absorption". Research emphasizes the potential of MICP to improve resistance to chloride penetration and sulfate attack, critical for marine applications [93]. The keyword "geopolymer" suggests interest in alternative materials, and "*Sporosarcina pasteurii*" highlights the use of specific bacterial strains. Geopolymer-based binders offer lower carbon emissions compared to traditional Portland cement, making them an eco-friendly choice when combined with MICP technologies [29]. In Cluster 3 (designated as Calcite Precipitation and Healing Efficiency), terms like "biocementation", "$CaCO_3$", and "calcite" were found, which focus on the biological process of calcite precipitation and its effectiveness in crack sealing. The efficiency of biocementation has been correlated with the availability of calcium ions and the metabolic activity of microbial strains used [29,94]. Furthermore, keywords like "self-healing efficiency" and "fungi" suggest exploring alternative healing mechanisms such as using fungi for crack repair. Recent studies highlight fungi's ability to survive in extreme conditions and secrete calcite, broadening the scope of self-healing concrete research [95,96].

Cluster 4 (designated as Sustainable and Autonomous Healing) emphasizes "autonomous healing" and "sustainable concrete". The integration of MICP with sustainable practices, such as the use of recycled aggregates or industrial by-products, is gaining attention for reducing environmental impact [27,97]. Keywords like "bacterial concrete" and "self-healing concrete" highlight microbial mechanisms used to create self-repairing materials. Terms like "crack healing" and "calcium carbonate precipitation" point to the importance of these processes in enhancing concrete durability. In Cluster 5 (designated as Biomineralization and Sustainability), keywords like "fly ash", "flexural strength", and "crack repair" suggest an interest in integrating sustainable materials and improving mechanical properties. Fly ash-based MICP systems have been demonstrated to enhance both the mechanical performance and sustainability of concrete products [98,99].

In Cluster 6 (designated as Microbial Action and Structural Properties), the focus was on "bacteria" and "calcium carbonate" formation, with keywords like "nitrate reduction" and "ureolysis" indicating interest in optimizing microbial action for crack healing. Ureolytic activity is a key driver in efficient calcite precipitation, with ongoing research exploring the impacts of varying nutrient concentrations and environmental conditions on this process [100]. In Cluster 7 (designated as Crack Healing and Engineering Applications), keywords like "compressive strength", "crack self-healing", and "microbial consortia" highlight how microbial communities can enhance the structural performance of MICP-treated concrete. The synergistic effects of mixed microbial consortia have shown promise in improving both healing rates and material compatibility [30]. In Clusters 8 and 9 (designated as Corrosion Inhibition and Crack Repair), the unique focus was on keywords related to "corrosion inhibition", extending MICP applications beyond crack healing to include durability enhancements in corrosive settings. MICP's ability to form protective biofilms and precipitate calcite layers is particularly valuable in mitigating steel reinforcement corrosion [101,102].

In the VOSviewer analysis from the WoS database as shown in Figure 8, "biomineralization" occurs 46 times with a link strength of 104, indicating its importance in the field. "Self-healing" appears 48 times with a link strength of 107, emphasizing the potential of MICP for autonomously sealing cracks. Keywords like "Bacillus" and "Sporosarcina pasteurii" are also frequently mentioned. In Cluster 1 (designated as Microbial Agents and Material Interactions), the focus was on broader concepts such as "biocementation" "self-healing", and "urea hydrolysis", indicating an emphasis on overarching processes that contribute to crack sealing. Research supports that the biocementation process is influenced by factors such as microbial type, pH, and nutrient availability [103,104].

In Cluster 2 (designated as Durability and Mechanical Performance), the emphasis was on the "mechanical properties" of MICP-treated concrete with keywords like "compressive strength" and "flexural strength." Experimental studies demonstrate that MICP-treated samples exhibit improved compressive strength and reduced porosity compared to untreated counterparts [105]. The inclusion of "self-healing concrete" and "sustainability" indicates a focus on structural performance and long-term benefits. In Cluster 3 (designated as Calcite Precipitation and Healing Efficiency), the focus centered on "calcite", "cement", reflecting an interest in mineral production and applications in concrete. The optimization of cementitious material compatibility with MICP remains a key area of study, particularly for enhancing adhesion and durability [106,107]. Keywords like "mortar" and "water absorption" indicate a more material-focused approach. In Cluster 4 (designated as Sustainable and Autonomous Healing), keywords like "calcium carbonate", "crack repair", and "MICP" reveal an interest in self-healing mechanisms, with additional focus on "nitrate reduction" and "optimization", suggesting detailed examination of biochemical pathways and improving MICP efficiency. Cluster 5 (designated as Biomineralization and Sustainability) focused on "calcite precipitation" and "microstructure", reflecting interest in enhancing material properties through MICP processes. Scholarly work suggests that improvements in microstructure, such as reduced pore size, directly correlate with enhanced durability and mechanical strength [108]. The term "durability" points to long-term performance.

In Cluster 6 (designated as Microbial Action and Structural Properties), the attention was on the impact of microbial processes on structural integrity with terms like "*Bacillus*", "mechanical properties", and "ureolysis". Studies emphasize that tailoring microbial strains to specific environmental conditions is crucial for optimizing self-healing outcomes [109,110]. Cluster 7 (designated as Crack Healing and Engineering Applications) identified keywords like "crack" and "engineering application" suggesting a broader view of practical engineering applications of MICP. The scalability of MICP for large-scale engineering applications is an area requiring further interdisciplinary collaboration [111]. The analysis identified nine clusters in Scopus and seven clusters in WoS, with Scopus focusing more on specific microbial species and material properties, while WoS emphasized broader concepts such as mechanical properties and practical engineering applications. By comparing these clusters, it is clear that while Scopus and WoS share significant overlaps in key themes like microbial action, calcium carbonate precipitation, and self-healing, they differ in their focus. Keywords found in Scopus but not in WoS include "autonomous healing", "encapsulation", "*Bacillus sphaericus*", "fungi", "geopolymer", and "self-healing efficiency". On the other hand, keywords found in WoS but not in Scopus include "engineering application", "bioconcrete", and "urea hydrolysis".

3.6. Co-Occurrence Analysis of Textual Data

The textual analysis of titles and abstracts from the Scopus and WOS databases using VOSviewer highlights the key terms and themes in MICP research for concrete crack repair. The leading outcomes of this analysis are found in Table S1. The most frequently occurring keywords in Scopus are “self-healing” (99 occurrences), “mortar” (191 occurrences), and “process” (201 occurrences), as illustrated in Figure 9. These terms highlight a focus on the self-repair mechanisms of concrete, the use of mortar as a key material, and the various processes involved in MICP [86,100,112]. Key themes include “compressive strength” (145 occurrences), which indicates the importance of structural integrity, and “biomineralization” (100 occurrences), emphasizing the role of biological processes in concrete repair. Other notable terms include “bacterial concrete” (45 occurrences), “crack repair” (57 occurrences), and “calcium carbonate precipitation” (98 occurrences), illustrating the scientific interest in using microbial action and calcium carbonate deposition for enhancing concrete durability. Keywords with fewer occurrences such as “fungi” (23 occurrences), “encapsulation” (25 occurrences), and “*Bacillus megaterium*” (27 occurrences) suggest emerging or niche areas within the research field. These indicate ongoing exploration into alternative microbial agents and innovative material treatments.

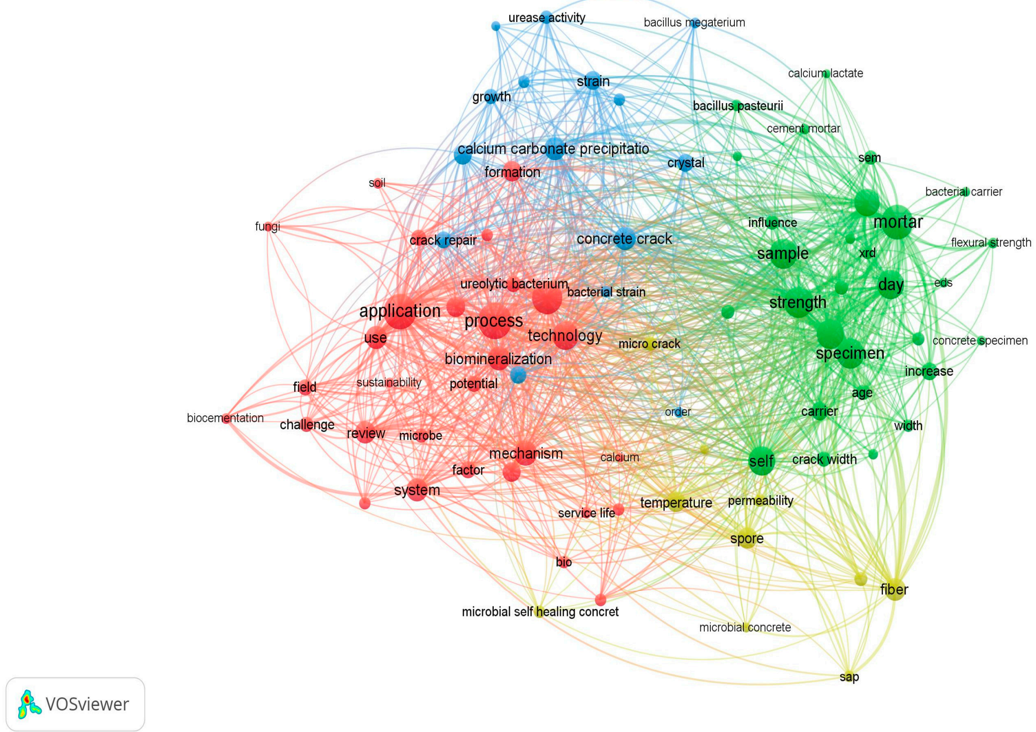

Figure 9. Co-occurrence analysis of textual data (title and abstract) MICP research for concrete crack sealing (2007–2024) based on data from the Scopus database. Different clusters represent groups of closely related keywords, with each cluster assigned a specific color: Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), and Cluster 4 (yellow).

In WOS, “MICP” (231 occurrences), “healing” (192 occurrences), and “property” (144 occurrences) are among the most common keywords, indicating a strong interest in the processes and outcomes of MICP technology as shown in Figure 10. The frequent mention of “mortar” (118 occurrences) and “self-healing” (48 occurrences) aligns with the focus on improving concrete materials and autonomous repair systems [18,63,113]. Significant themes include “strength” (137 occurrences) and “mechanism” (65 occurrences), reflecting the research interest in understanding and enhancing the mechanical properties of MICP-treated concrete [40]. Other important terms are “calcium carbonate precipitation” (101 occurrences) and “compressive strength” (92 occurrences), underscoring the critical role of microbial processes and structural integrity in MICP research. Keywords with fewer occurrences, such as “X ray diffraction” (21 occurrences), and “microbial self-healing concrete" (32 occurrences), highlight emerging research areas and specific methodologies being developed.

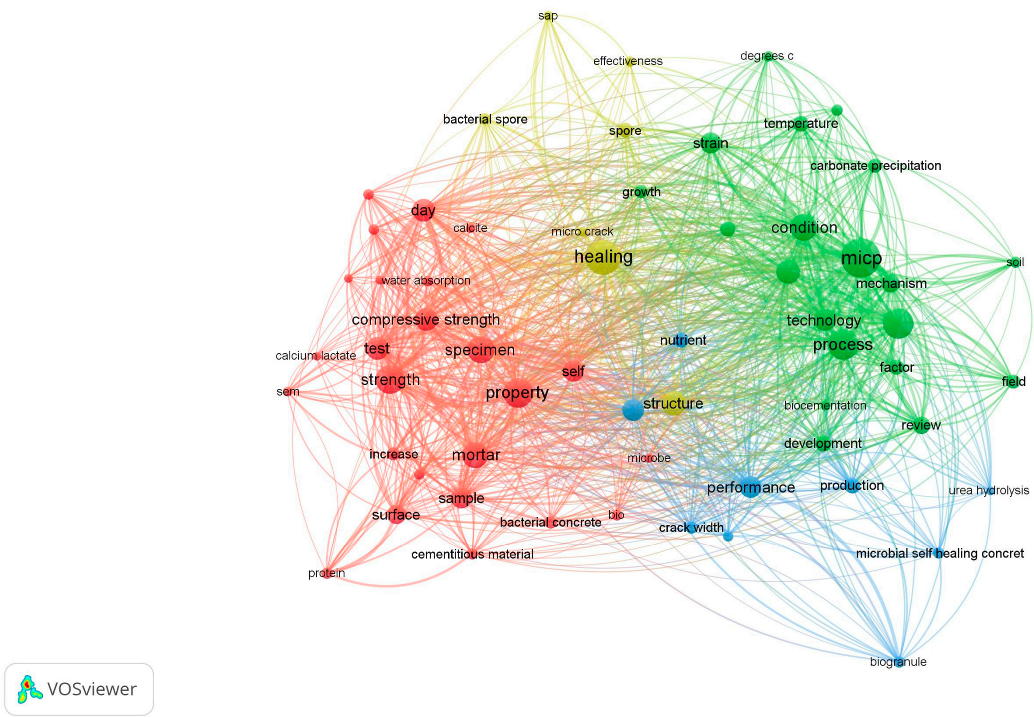

Figure 10. Co-occurrence analysis of textual data (title and abstract) MICP research for concrete crack sealing (2007–2024) based on data from the WoS database. Different clusters represent groups of closely related keywords, with each cluster assigned a specific color: Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), and Cluster 4 (yellow).

Both databases show a strong focus on "self-healing", "compressive strength", and "biomineralization", highlighting these as central topics in MICP research. Scopus places more emphasis on specific microbial strains and material properties, such as "*Bacillus pasteurii*" and "calcium carbonate precipitation". In contrast, WOS features broader concepts like "MICP" and "mechanism", suggesting a wider scope of inquiry into the processes and effects of MICP. This divergence reflects the different indexing and focus criteria of each database, with Scopus favoring detailed, application-driven research and WOS emphasizing conceptual and theoretical advancements. Future studies can leverage the combined insights from both databases to explore interdisciplinary approaches, such as integrating microbial concrete repair with green building technologies.

4. Implications of the Bibliometric Analysis

This analysis provides an overview of the research landscape on MICP for concrete crack repair, using Scopus and Web of Science databases. Combining insights from both databases ensures a comprehensive understanding of the field, reducing bias. The findings reflect publication trends, geographical contributions, and thematic changes in MICP research. The growing interdisciplinary nature of MICP highlights its potential across microbiology, materials science, civil engineering, and sustainable construction. These fields see MICP as both a practical solution for infrastructure issues and a path toward environmental sustainability. The geographical analysis shows alignment with countries focused on green construction and resilient infrastructure, reflecting global efforts to cut construction-related carbon emissions. A key contribution of this analysis is mapping collaboration networks, highlighting prolific researchers and active regions. These insights encourage targeted collaborations, resource allocation, and strategic investments by funding agencies. The bibliometric findings guide MICP research and its practical applications, offering policymakers and industry stakeholders a framework to prioritize future efforts.

This analysis has identified several key applications of MICP in concrete repair. These include crack sealing, where MICP autonomously repairs cracks up to 0.8 mm wide and enhances durability by reducing water permeability and improving resistance to chloride and sulfate attacks. The analysis also highlights MICP's effectiveness in marine environments, enhancing corrosion resistance, and its role in promoting sustainability by using eco-friendly microbial agents and recycled materials. Additionally, MICP can be customized for specific conditions, with specialized microbial strains tailored for environments like high alkalinity or salinity. Hybrid approaches that combine MICP with traditional methods further enhance its effectiveness, with innovations such as encapsulation and nutrient delivery systems improving long-term performance.

5. Challenges and Considerations for Large-Scale Implementation

5.1. Cost Challenges in MICP Implementation

One of the biggest hurdles preventing the large-scale adoption of MICP is its high operational cost, particularly for bacterial cultivation and cementation media. Traditional laboratory-grade nutrients, such as yeast extract and synthetic growth media, significantly drive up expenses, making MICP less economically viable compared to conventional repair methods [114]. To address this, researchers have been exploring more affordable alternatives. For example, food-grade yeast extract has been found to cut bacterial cultivation costs by up to 99.80%, while still maintaining high urease activity, a key enzyme for calcite formation [115]. Likewise, agricultural waste products such as corn steep liquor and chicken manure effluent have proven to be effective nutrient sources, reducing costs by 88.2%, while sustaining bacterial growth and biocementation efficiency [116,117]. Additionally, industrial by-products like fertilizer urea, snow-melting agents, and beer yeast have emerged as low-cost cementation reagents, lowering treatment expenses by 97% compared to analytical-grade chemicals [118].

In the context of crack repair in buildings, cost efficiency plays a crucial role in determining whether MICP can compete with traditional sealants like epoxies and polymer-based grouts. While epoxy-based crack fillers are widely used due to their quick application and strong adhesion, they remain costly and environmentally taxing. The ability to utilize waste-derived, low-cost bacterial growth media in MICP could make it an attractive, sustainable alternative for sealing structural cracks in concrete while significantly reducing repair expenses in large-scale infrastructure projects [100]. These cost-saving innovations bring MICP closer to large-scale feasibility, but further work is needed to integrate these cost-efficient methods into commercial applications. Reducing expenses without sacrificing effectiveness is a critical step in making MICP a practical alternative for mainstream construction projects.

5.2. Long-Term Performance and Durability Concerns

While MICP has shown great short-term success in strengthening concrete and stabilizing soil, its long-term durability remains a concern, especially under harsh environmental conditions. Natural processes like freeze–thaw cycles, wet–dry fluctuations, and prolonged exposure to water can erode calcite deposits, weakening structural integrity over time [119]. Field studies indicate that MICP-treated slopes and soil layers gradually lose their cementation effectiveness in erosion-prone environments, often requiring re-treatment or reinforcement [1,120]. In concrete applications, MICP-based biogrouting has been shown to increase compressive strength by 4.01–11.4% and reduce water absorption by 27.9–31.36%, which improves durability [121]. However, high calcium ion concentrations can inhibit urease activity, making precise formulation and timing adjustments necessary to maximize MICP's crack-healing potential [121]. Similarly, MICP-treated soils initially resist rainfall-induced erosion, but long-term performance in gravelly clay environments declines as cementation weakens, increasing the risk of slope collapse [119]. These durability challenges highlight the need for further research to improve bacterial survival rates, enhance MICP's resilience in extreme conditions, and develop more effective application techniques to extend its lifespan.

In addition, by encapsulating bacterial cells within a protective nutrient layer, this approach could enhance long-term bacterial viability and enable autonomous crack repair in concrete, addressing one of the key challenges in MICP-based crack sealing, ensuring durability and self-sufficiency over extended periods [122]. Integrating such bioengineered solutions into building repair and maintenance could significantly reduce reliance on synthetic sealants while improving structural resilience and environmental sustainability. For MICP to be widely adopted in building crack repair, it must demonstrate long-term stability comparable to conventional repair materials [37,56]. While MICP successfully seals cracks and prevents water ingress, one concern is the gradual degradation of the calcium carbonate matrix due to environmental exposure. In high-moisture environments, such as basements and exterior facades, prolonged water exposure could lead to carbonate dissolution, reducing the effectiveness of crack sealing. Future research should focus on improving the resilience of MICP-treated cracks through protective coatings or hybrid approaches that combine MICP with polymeric additives to enhance durability in harsh conditions.

5.3. Scalability and Optimization Challenges

Scaling MICP for industrial applications presents a different set of challenges, ranging from large-scale bacterial production to ensuring uniform distribution of cementation reagents. While custom-built stirred tank reactors (up to 3 m^3) have successfully scaled bacterial cultivation from 214 L to 2400 L, making large-scale MICP production technically feasible, there are still logistical hurdles to overcome [111]. One major issue is achieving uniform $CaCO_3$ precipitation in soil stabilization, as uneven distribution can create weak zones, compromising the treatment's effectiveness [123]. Field experiments suggest that staged injection techniques can reduce cementation reagent usage by 50% while improving treatment uniformity and performance [124]. When applied in crack repair for buildings, the scalability of MICP becomes a challenge in terms of application methods and efficiency. Unlike traditional crack sealants, which are pre-packaged and ready to apply, MICP requires the on-site cultivation and injection of bacterial cultures, followed by cementation solution delivery. Ensuring even bacterial distribution in deep or irregularly shaped cracks can be difficult, leading to inconsistencies in the sealing process [125].

Developing MICP-based crack repair materials in pre-mixed, easy-to-apply formulations such as sprayable biogrouts or self-contained microbial capsules could help overcome these application challenges and enhance their practicality in construction and infrastructure maintenance [80,126]. However, these findings also underscore the need for continued process refinement to balance cost efficiency, scalability, and long-term reliability. Overcoming these challenges will require interdisciplinary collaboration among microbiologists, engineers, and material scientists to optimize bacterial strains, delivery systems, and environmental adaptability. With the right advancements, MICP could transition from a promising laboratory innovation to a widely adopted solution in construction and geotechnical engineering. MICP holds immense potential for sustainable crack repair solutions in buildings, particularly as the construction industry moves towards greener, bio-based alternatives. By addressing cost, durability, and scalability challenges, MICP can provide an environmentally friendly, long-lasting solution for mitigating concrete deterioration and reducing maintenance costs in large-scale infrastructure projects. Ongoing research and technological advancements are steadily improving MICP's feasibility, bringing us closer to a future where bio-based construction materials become the industry standard.

6. MICP Integration with Existing Construction Standards

While MICP offers a promising, eco-friendly alternative to traditional construction materials, its lack of recognition in existing building codes and regulations remains a major hurdle to widespread adoption. Unlike conventional repair techniques, MICP does not yet have standardized guidelines for structural performance, durability, or environmental impact, making it difficult for engineers and contractors to confidently use it in commercial projects [118]. For MICP to become a practical and widely accepted solution for crack repair, soil stabilization, and concrete durability, it must first be aligned with established industry standards. One of the key environmental concerns surrounding MICP is the generation of NH_4^+ as a byproduct during the ureolysis process. If not properly managed, excess NH_4^+ can seep into soil and groundwater, leading to contamination [127]. Studies suggest that post-treatment rinsing with 1.8 pore volumes of rinse solution can effectively remove NH_4^+, but this process adds to the overall cost and complexity of MICP applications [127]. If MICP is to meet environmental safety standards, further research is needed to develop cost-effective and scalable NH_4^+ mitigation strategies that align with regulatory requirements.

Researchers are actively exploring alternative biomineralization methods to make MICP more environmentally friendly. Ivanov et al. [128] suggest that hydroxyapatite precipitation, calcium bicarbonate decay, and aerobic oxidation of calcium salts of organic acids could offer safer and more sustainable alternatives to urea-based MICP. Additionally, replacing live bacteria with non-living bacterial enzymes may enhance biosafety, making it easier to integrate MICP into construction regulations. These alternatives could be particularly useful in sensitive infrastructure projects, such as seepage control in dams, landfill sealing, and soil pollutant containment, where environmental compliance is strictly regulated. Beyond MICP, geopolymer concrete (GPC) is another emerging sustainable alternative to traditional concrete. Some studies highlighted that GPC made with fly ash and blast furnace slag, significantly reduces CO_2 emissions while maintaining the same strength and durability as Ordinary Portland Cement (OPC)-based concrete [29,129,130]. Since GPC has already begun to gain regulatory approval, its success provides a roadmap for MICP to follow in achieving mainstream adoption. For MICP to be widely accepted in the construction industry, it must demonstrate not only durability but also environmental benefits compared to traditional materials. Recent studies show that incorporating 30% Class C fly ash into MICP formulations significantly improves calcium carbonate deposition and self-healing capacity, allowing cracks to autonomously seal over time [131]. Additionally, MICP-based self-healing concrete has been shown to cut CO_2 emissions by 39%, aligning with global sustainability targets [18,99].

Given its ability to lower carbon footprints, improve energy efficiency, and reduce maintenance costs, MICP could help buildings earn certifications in green building standards, such as the Green Building Index, and Leadership in Energy and Environmental Design. These certification programs reward eco-friendly materials, lower embodied carbon, and long-term durability, making MICP a strong candidate for sustainable infrastructure development. However, for this to become a reality, MICP must first be formally incorporated into national (i.e., Malaysia) and international green building frameworks as a recognized, sustainable construction method. For MICP to achieve full-scale adoption, regulatory agencies must establish standardized testing protocols to validate its structural performance and environmental impact. Studies show that carbonate-based biomineralization can significantly improve soil shear strength, enhancing the load-bearing capacity of building substrates [132]. If these benefits can be consistently demonstrated, MICP has the potential to be integrated into mainstream construction codes alongside other widely accepted stabilization techniques.

Regulatory integration is essential to ensure MICP can be safely and effectively used alongside traditional materials. Without clear industry guidelines, contractors and engineers may hesitate to adopt bio-based sealing technologies, despite their sustainability advantages. Moving MICP from an experimental research concept to a standardized construction method will require collaboration between scientists, policymakers, and industry leaders to develop safety certifications and standard operating procedures. By addressing these regulatory and environmental barriers, MICP can transition from a promising lab innovation to a commercially viable construction technology, aligning with modern sustainability goals while complying with industry standards.

7. Limitations and Future Directions of MICP for Crack Repair

MICP shows remarkable potential in concrete crack repair but faces notable challenges in scalability and real-world effectiveness. Most research is confined to controlled laboratory settings, which do not accurately replicate real-world environments. Major issues include uneven microbial distribution, inconsistent bio-reagents, and varying performance across different climates and structures. Economic and environmental feasibility also present obstacles, as the cost of microbial cultivation and chemical reagents can be high. Life-cycle assessments are necessary to evaluate the sustainability benefits and minimize environmental trade-offs [133]. The long-term stability of MICP repairs under extreme conditions like saline exposure, high humidity, or fluctuating temperatures remains uncertain [134]. Additionally, the lack of standardized testing protocols hinders the comparability of results and replicability of successful implementations. Replacement of calcium and urea sources could be explored to enhance efficiency and reduce costs. Moreover, the ammonium-rich effluent produced during MICP application necessitates serious consideration for environmental management [42].

Future research should prioritize the development of cost-effective, eco-friendly microbial strains and reagents to reduce economic and environmental burdens. Advanced predictive modeling tools could optimize MICP performance by simulating diverse real-world conditions. Extensive field-scale demonstrations and pilot-scale trials are critical to bridge the gap between laboratory findings and practical applications. Exploring hybrid approaches that combine MICP with traditional repair methods could enhance repair effectiveness. Interdisciplinary collaborations between microbiologists, civil engineers, and policymakers can drive innovation and integration, maximizing MICP's benefits. Policymakers should incentivize green technologies, establish regulatory frameworks, and integrate MICP into resilience strategies to support its adoption in sustainable infrastructure development. Furthermore, continuous monitoring and adaptation of MICP technologies will ensure their durability and effectiveness in a variety of environmental conditions, including managing the ammonium effluent's environmental impact.

8. Conclusions

This study provides a comprehensive bibliometric analysis of MICP research, highlighting its potential as a sustainable solution for concrete crack repair while identifying key advancements, challenges, and future research directions.

i. This study provides a comprehensive bibliometric analysis of MICP research from 2007 to 2024, offering insights into global research trends, collaboration networks, and regulatory challenges affecting MICP adoption. The findings highlight the growing academic interest in MICP, with China, the USA, and India leading research efforts. By integrating industrial by-products like fly ash and slag, MICP contributes to sustainability and circular economy principles, reducing reliance on synthetic repair materials.

ii. MICP has demonstrated the ability to seal cracks up to 2 mm wide, enhance mechanical properties, and reduce water permeability, making it a viable alternative to conventional crack repair methods. The technology supports self-healing capabilities, reducing maintenance costs and extending the service life of concrete structures. Innovations in encapsulated bacteria and optimized nutrient formulations show promise in improving MICP's effectiveness and durability.

iii. High implementation costs remain a barrier, necessitating further research into cost-effective bacterial cultivation and cementation solutions. Scalability issues persist, as MICP's application in real-world infrastructure is limited by inconsistent performance across different environmental conditions. Regulatory barriers hinder large-scale adoption, as MICP lacks standardized testing protocols, certifications, and industry guidelines.

iv. For future research directions, researchers should develop affordable bacterial growth media using alternative nutrient sources such as agricultural and industrial by-products. There should be established clear guidelines and standards to facilitate commercial adoption and integration into construction codes. More investigations on long-term MICP performance under freeze–thaw cycles, varying humidity levels, and different pH conditions are required. Pilot projects to test MICP's feasibility in real-world construction settings should be expanded, including its integration into green building certifications like the Green Building Index.

v. MICP holds immense potential as a sustainable and innovative solution for concrete crack repair. By addressing cost, scalability, and regulatory challenges, MICP can transition from a promising research concept to a mainstream eco-friendly construction technology. Future advancements will determine MICP's role in shaping next-generation sustainable infrastructure.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15071052/s1, Figure S1 illustrates the crack formation in a Malaysian office building (A) and the repair performed using a common epoxy injection technique (B). This widely used approach effectively fills cracks and prevents further water ingress, leveraging the adhesive and mechanical strength properties of epoxy resins.; Figure S2. Network visualization of bibliographic coupling among countries based on VOSviewer analysis from the (A) Scopus and (B) WOS databases. The figures highlight China's dominant position in the research landscape, followed by India and the United States, indicating their significant influence and interconnectedness through shared references.; Figure S3. Co-authorship networks of key researchers from both Scopus and WOS databases highlight the collaborative networks of key researchers in MICP research for concrete crack repair and sealing. This figure illustrates the interconnectedness of researchers, with notable figures such as Nele De Belie, Nico Boon, and Raissa Douglas Ferron showing significant collaborations within the field.; Figure S4: Co-citation analysis of key researchers using VOSviewer software. (A) Data from Scopus. (B) Data from WOS.; Table S1: Leading terms based on textual analysis of titles and abstracts in Scopus and WOS databases.

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