Bacterial Concrete for Sustainable Infrastructure: A Bibliometric and Meta-Analytical Review with XFEM-Based Crack Modelling and XRD Characterization

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Abstract
The growing demand for sustainable and durable infrastructure has encouraged the exploration of bacterial concrete as an environmentally friendly alternative to conventional cementitious materials. This study presents a combined bibliometric and meta-analytical review of bacterial concrete research, integrating experimental findings with advanced modelling and characterization techniques such as XFEM-based crack simulation and XRD analysis. A systematic literature review was conducted following the PRISMA framework, initially retrieving 2,051 Scopus-indexed records and narrowing them to 78 relevant studies published between 2021 and early 2025. The bibliometric analysis revealed a steady rise in publications, with peak output in 2024, reflecting growing global interest in self-healing cementitious systems. Keyword co-occurrence mapping identified key thematic clusters focused on microbiologically induced calcium carbonate precipitation (MICP), durability enhancement, and microstructural characterization. For the meta-analysis, 14 representative studies were examined, producing a pooled effect size of 0.465 ($p < 0.0001$), demonstrating that bacterial incorporation significantly improves compressive strength, crack-healing efficiency, and permeability resistance, with negligible heterogeneity ($I^2 = 0$). Despite these promising outcomes, challenges remain, including ensuring bacterial viability, developing standardized encapsulation techniques, and validating performance at large field scales. Overall, this review highlights the strong potential of bacterial concrete as a sustainable construction material while identifying critical research gaps that must be addressed to accelerate its practical implementation in future infrastructure systems worldwide.

Keywords: Bacteria, Concrete, Cracks, XRD, XFEM, Sustainable Infrastructure
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1. Introduction

In recent years, the need to use sustainable and durable construction materials has grown extremely as the world focuses on reducing the carbon footprint, limiting the number of resources used, and making infrastructure systems last longer [1,2]. However, conventional concrete, despite being one of the most common construction materials in the world, is characterised by internal shortcomings including low tensile strength, cracks, and consequent penetration of destructive elements like water, chloride, and sulfate, which ultimately shortens its structural life and increases its susceptibility to corrosion [3-5]. The costs of repairing and fixing broken concrete structures are not only costly economically, but it also leads to further carbon emissions, so the incredible need to find alternative and environmentally friendly solutions [6,7].

In this case, self-healing, or bio-concrete, also known as "microbiologically induced calcium carbonate precipitation (MICP)", has been a positive advancement in contemporary civil engineering using MICP to create material self-healing to seal cracks and extend material longevity [8-10]. The ability of specific ureolytic or sporulating bacteria, such as "Bacillus subtilis" [11] and "Sporosarcina pasteurii" [12] to precipitate calcium carbonate in microcracks in the presence of suitable nutrients forms the basis of the bacterial concrete, closing voids, repairing permeability, and improving mechanical and durability characteristics [13,14]. Figure 1 shows the general bacterial concrete application area, challenges and future directions. The bio-based approach, in addition to reducing the rate of maintenance and repair, facilitates the overall objectives of sustainable construction such as lower embodied carbon, better resource performance and greater strength of the infrastructure [15,16].

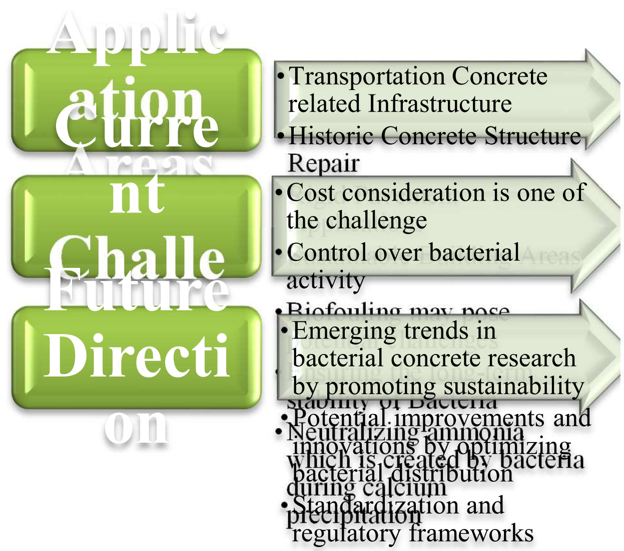

Figure 1: General bacterial concrete application area, challenges and future directions [17,18].

Furthermore, the development of the numerical and experimental methods has contributed to the further knowledge of bacterial concrete behavior under the natural loading conditions [19-22]. "Extended Finite Element Method (XFEM)" is one of the promising techniques used in simulating the crack initiation and propagation of concrete materials with self-healing processes caused by the action of bacteria [23]. In addition to this, the mineralogical composition of bio-precipitates formed in the presence of healed cracks is determined through advanced material characterization approaches including "X-ray diffraction (XRD)", which validates the presence of crystalline phases of calcium carbonate (e.g., calcite, aragonite, and vaterite) and their effect on the efficiency of crack closure [24-26]. XFEM-based modeling combined with XRD characterization closes the gap between theoretical projections and experimentalvalidation andd can thus provide a comprehensive approach to the investigation and optimization of bacterial concrete [27, 28].

The rapidly expanding literature on bacterial concrete emphasizes its promise in a variety of applications, both in traditional building materials and in high-performance concretes in bridges, tunnels, and marine buildings [29]. Nevertheless, the high level of experimental studies that prove the effectiveness of crack-healing and increase in the durability of the research is not enough to neglect the systematic and quantitative evaluation of the research field to determine the tendencies of the research, gaps in the knowledge, and perspectives [30]. To solve this question, bibliometric and meta-analytical tools have been progressively used to retrieve patterns of publications, citation networks, and indicators of performance, thus providing a more global picture of the activity of research in this field. These reviews can contribute to an understanding of how bacterial concrete research has developed, which interdisciplinary interactions can lead to progress, and what research gaps remain to be filled in the future bioengineering frontiers through optimization of bacterial strains, nutrient carriers, encapsulation methods, and long-term performance. The research questions are as follows, based on the above need of the study:

Q1 What are the major thematic areas and knowledge gaps identified through bibliometric mapping of bacterial concrete studies?

Q2 What is the effect of bacterial strains, nutrient types, and curing conditions on the crack-healing efficiency of bacterial concrete?

Q3 What are the most widely used experimental techniques (XRD, SEM, XFEM, etc.) in bacterial concrete studies, and how do their outcomes compare across literature?

Q4 How can bacterial concrete technology be integrated with smart infrastructure systems for self-sensing and self-healing capabilities?

Q5 What role does XRD characterization play in confirming calcium carbonate precipitation and microstructural changes in bacterial concrete?

2. Research methodology

This study employs a Systematic Literature Review (SLR) methodology to meticulously investigate, assess, and integrate the current scholarly literature on Bacteria concrete, using a well-defined and reproducible process. The SLR technique is highly successful in mapping the existing academic environment, emphasizing dominant research trends, pinpointing gaps, and suggesting future research trajectories. The technique adhered to the three fundamental steps of a systematic literature review: planning, execution, and dissemination.

The implementation phase involved the careful collection and evaluation of academic works according to the predetermined criteria. It began with a preliminary screening of the collected records through their titles and abstracts to find out how relevant they were to the study topics, followed by a thorough examination of the complete-text articles. The distribution step is concerned with the analytical unification and synthesis of collected literature. The process concentrated on the commitment to transparency and accuracy, including the data collection methodology which was based on the established structure of the "Preferred Reporting Items to Systematic Reviews and Meta-Analyses (PRISMA)" [31].

2.1 Data collection

The review indicates that the academic focus of the scholars regarding Bacterial Concrete as Sustainable Infrastructure was arguably the most pertinent literature on the topic. To complete the bibliometric mapping and citation tracking process, the Scopus database was selected due to the reliable, comprehensive coverage it is known for. 78 publications were located in the designated time period of 2020-2025, and 2051 citations were systematically reviewed. The bibliometric data gives the context to the following meta-analytical review comparing the experimental trends and performance results of bacterial concrete. The manuscript also incorporates modeling and characterization methodologies—such as XFEM-based simulations of the crack propagation and XRD tests for microbial sham calcite precipitation—are integrated to validate and extend the insights obtained from the literature. The systematic review and selection process is illustrated in Figure 2, which depicts the flow of information across successive levels of identification, screening, and inclusion.

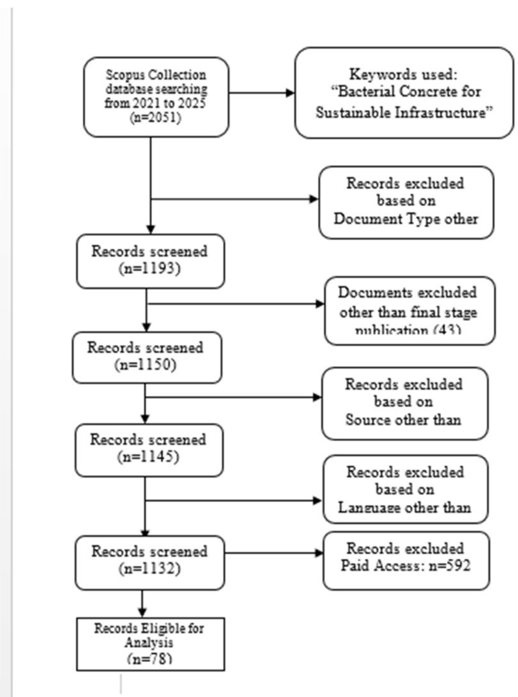

Figure 2: Systematic Literature Review Process

The whole method of systematic data extraction is shown in Figure 3. Ultimately, the process includes examining the chosen research content after acquiring articles, evaluating sources, and removing unnecessary information according to specified criteria. This study assesses the impact of resource accessibility on microbial concrete using a comprehensive literature search approach. Starting with a broad search of Scopus Collection data from 2021–2025, it returns a total of 2051 records. Researchers utilized particular keywords related to Bacterial Concrete for Sustainable Infrastructure to filter the dataset. Comprehensive search was first conducted in SCOPUS using the keywords " Bacterial Concrete for Sustainable Infrastructure” as topics in Engineering during the timeframe of 2021 to February 22, 2025, yielded 78 records in total. In the initial filtering, 858 non-article documents were deleted and the count reached 1193. Further, 13 document whose language was different from English was deleted and there remained 1132 records. Filtering stage eliminated 592 non-paid accesses and there remained 540 documents for analysis. The chosen documents align with the research objectives and meet all pre-specified inclusion criteria for further evaluation.

First, the name of the author; second, the name of the publication; and third, the number of citations were all parts of the Scopus search. Bibliometric analysis was utilised in the investigation. The data was examined and interpreted using a multitude of data triangulation methodologies to ensure accurate and comprehensive understanding. Bibliometric analysis and synthesis were conducted by creating distance-based co-occurrence maps using the VOS viewer tool. Consequently, the ideas were organised and classified according to how closely they corresponded to the abstracts, titles, and keywords.

Table 1: Inclusion and Exclusion Criteria

Criterion	**Inclusion**	**Exclusion**
Keywords	Bacteria, Concrete, Cracks, XRD	Records excluded in which variables have no relation
Timeframe	Concerning 2021 – 2025	< 2021
Document Type	Articles	Book series, book, and chapter in book.
Language	English	Other languages
Access Type	Open access	Paid excess
Duplicity	Unique studies	Same studies

The systematic criteria used to select relevant research for this investigation on bacterium concrete are described in Table 1. The approach for inclusion placed an emphasis on papers that dealt specifically with bacterial concrete and its uses in environmentally friendly building construction. The most recent and consequential studies could be considered within the 2020–2025-time frame. Only Engineering research were used, while the research of other disciplines was excluded. In the interest of maintaining high standards of academic honesty, researchers did not include any novels, book chapters, or other non-journal publications in the analysis.

Furthermore, in order to ensure clarity and accessibility, the selection procedure preferred research written in English and eliminated papers written in any other language. To ensure that information could be widely disseminated, only open-access papers were considered, whereas paid-access research were removed. Duplicates were deleted to prevent duplication, with only original studies retained. In order to investigate the bacterial concrete for Sustainable Infrastructure, this comprehensive screening process guarantees that the dataset is concentrated, of high quality, and instantly useful.

3. Bibliometric Analysis and Results

In this portion, RQ1 could be answered by evaluating trends on publication of the works in this spectrum, research themes developed, and major contributors to the literature addressing the comparison of Bacterial Concrete for Sustainable Infrastructure.

3.1 Articles by Time Frame

To evaluate the changes in research activity over the time, the paper tracked the location of the publications and the volume of the respective citations in the period of time between 2021 and 2025. These findings can be seen below Figure 3, where all year-to-year differences and changes in the scholarly activity regarding hydroponic and conventional farming in terms of sustainability can be observed.

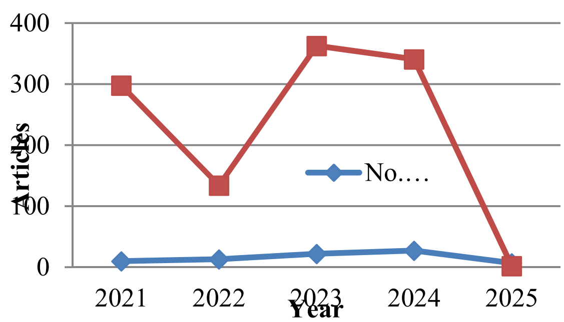

Figure 3: Distribution of published articles

Figure 3 shows a trend in the distribution of published articles and the number of references used within the years 2021 to 2025 illustrating the trend of the research and its academic impact during this time period. The trend of the published articles indicates a steady increasing trend with the first 10 articles in 2021 and the highest number of 27 articles in 2024, which demonstrates the inclination of the research to the subject area. Simultaneously, the number of citations varies substantially. The number of citations per year 2021 commenced with 298 citations in 10 articles and followed with 134 citations in 2022 despite the growth in the number of articles (13). The largest citation impact could be observed in 2023, when 22 articles accumulated the highest number of citations 363, as the year witnessed the release of very powerful works. It is also interesting to note that, in 2024, the number of articles was the largest, yet the count of citations dropped to 341, which could indicate that multiple publications have acquired significant recognition and influence. The 2025 (up to the present date) data show 5 published articles and 7 citations, which is natural since the recency effect, i.e., it takes a long time before a recently published paper can get citations. All in all, the graph indicates that the literature on the topic is becoming increasingly body of research with meaningful studies being on the rise, particularly during the period of 2021 to 2024, which is an indication of a growing academic and practical interest in the topic.

3.2 Co-occurrence of Keywords

In addition to the temporal trends, it is critical to list the thematic areas that prevail in the current researches. In below Figure 4, a keyword co-occurrence network was provided to trace conceptual connections and groupings that characterize the bacterial concrete for sustainable infrastructure.

The cluster diagram represents the complex network of occurrence of keywords identified from 74 items, and has been divided into 3 clusters, and relates to applications of bacteria in cementitious materials, material characterisation techniques, and microbiological processes. Prominent keywords including, “bacteria, self-healing, compressive strength, scanning electron microscopy and calcium carbonate” are positioned as key nodes, demonstrating the significance and high frequency of use in the respective literature. Common keywords link diverging research areas as thematic linking points. For example, the relative clustering of “self-healing, self-healing concrete, crack closure, calcium lactate, and durability” indicates a research area that primarily focused on the development of novel concrete materials with biological self-healing properties. Similarly, the grouping of “scanning electron microscopy, thermogravimetry, Fourier transform infrared spectroscopy, and mechanical properties” indicates research is focused on more advanced characterisation and analysis of material properties.

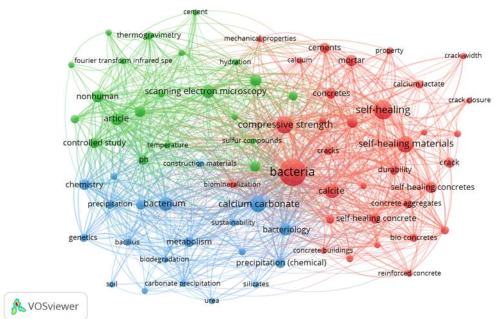

Figure 4: Co-occurrence of Keywords

Figure 4 also emphasizes on the microbiology integration into material science, as indicated by the cluster around the terms bacterium, metabolism, biodegradation, carbonate precipitation, and urea that refer to the research on the biological processes involved in material precipitation and interaction between bacteria and construction materials. The key place of bacteria highlights its cross-cutting nature that is the material performance, microbiological process, and structural application. The overlapping connections among clusters are due to the interdisciplinary approach of this field of research, the intersection of biological, materials engineering, and sustainability fields. This bibliometrical map provides the overall picture of the latest trends, the major research topics, and the prospects of the cross-disciplinary cooperation in the field of sustainable building material.

3.3 Authors' Contribution

In Figure 5, they show the co-authorship network with 5 items of research, which is one cluster, with 10 links, and total link strength of 20. This shows a collaborative network among five authors who were active in the area of sustainable construction materials and bacterial applications in concrete, VOSviewer illustrated the authors as Chindaprasirt, Prinya; Sata, Vanchai; Tanapongpipat, Nantawat; Saenrang, Wittawat; and Ekprasert, Jindarat.

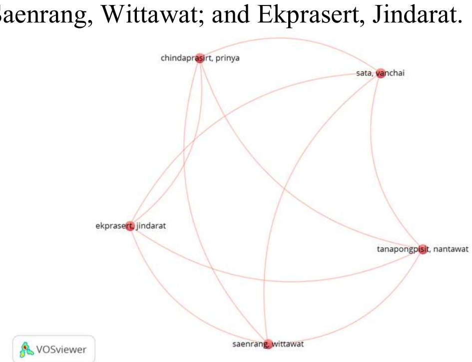

Figure 5: Co-authorship networks

The relatively uniform size of the nodes suggests that these authors have a comparable number of publications or connections within the analyzed dataset. The interconnected nature of the network reflects strong collaboration patterns, where each researcher is linked to multiple others, indicating an active research community that shares knowledge, methodologies, and findings.

This network emphasizes the collaborative aspect of this interdisciplinary research area, where material science, microbiology, and civil engineering converge. For example, the connection between Chindaprasirt, Prinya and Sata, Vanchai highlights a significant partnership, possibly focusing on experimental studies of material characterization or self-healing concrete applications. The presence of Tanapongpipat, Nantawat as a central node suggests a pivotal role in bridging different research groups, contributing significantly to the integration of biological and engineering approaches. Overall, the co-authorship network highlights the collaborative research trends and inter-institutional partnerships that drive innovation and knowledge exchange in this emerging field.

3.4 Documented by Subject Area

Figure 6 provides an overview of the distribution of research domains in selected academic articles on sustainable materials and bacterial uses in construction. The chart shows disciplines were evenly represented, with Materials Science providing the most contributions (24.5%), which indicates a significant emphasis on material development, characterization, and new or innovative materials for construction. Engineering came in second (21.2%) and revealed an emphasis or a large amount of research around structural applications, mechanical performance, and engineering solutions for incorporating bacterial self-healing in concrete.

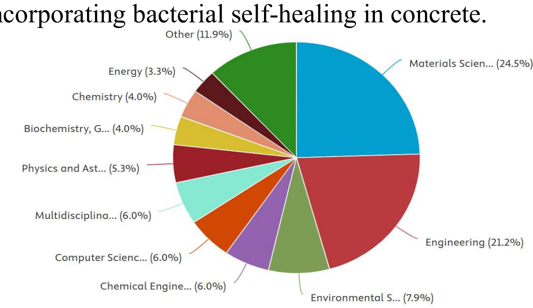

Figure 6: Documented by subject area

The Environmental Science makes its 7.9% contribution and this indicates the increased interest in the importance of sustainable practices and environmental impact assessment in construction technologies. Chemical Engineering, Computer Science and Multidisciplinary Sciences have 6.0, 6.0 and 6.0 respectively, which reflects a balanced presence of chemical processes (including biomineralization), computational modeling, and cross-disciplinary methods of biology, materials and engineering principles.

Physics and Astronomy (5.3%), Biochemistry, Genetics and Molecular Biology (4.0%), and Chemistry (4.0%) also highlight the basic nature of physical and molecular sciences in terms of comprehending the interactions of bacteria, chemical pathways as well as the behavior of materials on a microscopic scale. The Energy domain (3.3%) makes contributions through energy efficiency in manufacturing materials or environmentally friendly energy incorporation in building works. Lastly, other fields (11.9%) are newer or less popular fields, which points to the general interdisciplinary interest and the possibility of new research areas. This dispersion highlights the complexity of sustainable construction research that exists between engineering and biological sciences as well as sophisticated material science.

4. Meta-Analysis

Table 2 below presents the summarization of the effect sizes and other statistical indicators of 12 articles that were conducted to assess the performance of bacterial concrete in the framework of sustainable infrastructure. This is because each study provides an observed effect (g), standard error (SE), variance and 95%confidence interval (CI95) of important material or structural parameters. The effect sizes (g) were found to range between 0.214 (Aziz et al., 2024) and 0.594 (Boening-Ulman et al., 2024), which are small to slight positive impacts on the properties of compressive strength, crack healing, and durability. The standard errors (SE) in most studies are considered to be quite low (ranging between 0.096 and 0.225), indicating that there are dependable estimates of the effect size.

Table 2: Summary of Effect Sizes and Statistical Measures for Bacterial Concrete Studies

Study ID	Observed Effect	SE	Variance	CI 95-low	CI 95-high
K.W. et al., (2024) [32]	0.496	0.127	0.0161	0.247	0.745
Pazdyk-Slaby et al., (2025) [33]	0.526	0.105	0.0110	0.320	0.732
Aziz et al., (2024) [34]	0.214	0.225	0.0506	-0.226	0.654
Hao et al., (2024) [35]	0.454	0.225	0.0508	0.013	0.896
Chai et al., (2024) [36]	0.434	0.222	0.0493	-0.001	0.869
Boening-Ulman et al., (2024) [37]	0.594	0.096	0.0093	0.405	0.783
Zhang et al., (2024) [38]	0.556	0.191	0.0364	0.181	0.931
Sillo et al., (2023) [39]	0.404	0.193	0.0371	0.026	0.782
Sun et al., (2023) [40]	0.559	0.116	0.0135	0.332	0.786
Tian et al., (2024) [41]	0.296	0.214	0.0459	-0.124	0.716
Chayaamor et al., (2024) [42]	0.625	0.172	0.0296	0.288	0.962
Abdulkareem et al., (2024) [43]	0.168	0.149	0.0222	-0.124	0.460

The positive effects are mostly supported by confidence intervals (CI95) with lower limits being above zero or close to zero, which means that the effects are statistically significant. To illustrate, Boening-Ulman et al. (2024) reported an effect size of 0.594 with a small CI of 0.405 to 0.783, which is a strong indication that bacterial additives have a positive effect. Equally, Pazdyk-Slaby et al. (2025) stated a large effect size of 0.526 (CI95: 0.320 to 0.732). Conversely, the effect size of Aziz et al. (2024) was smaller (0.214), with a large confidence interval (−0.226 to 0.654), which represented inconclusive findings. The lower bond of the Chai et al. (2024) was also close to zero (−0.001) indicating uncertainty about the significance. In general, the information presents an overall positive significance of the use of bacteria in concrete, where the majority of studies report statistically significant increases in mechanical properties and self-healing capacity. Nonetheless, a certain measure of variability exists, probably attributed to various experimental conditions, bacterial strains and cement formulations.

Table 3 displays the meta-analysis findings of 14 studies in bacterial concrete. The fixed-effect model gave a pooled mean effect size of 0.465 and a Q statistic of 6.453 with 13 degrees of freedom (df). The estimated heterogeneity (τ^2) is 0.0000, indicating that there is no between-study variance. As a result, the random-effects model was the same as the fixed-effect estimate, with the same mean effect size (0.465) and a standard error of 0.0363. The obtained test value ($z = 12.80$, $p < 0.0001$) proves that the pooled effect is very significant, which proves the solid arguments about the positive effect of bacteria incorporation on concrete properties.

Table 3: Meta-Analytical Results for Bacterial Concrete Studies

k	Fixed effect means	Q	df	τ^2	Random effect means	Random effect standard error	z	pval	I^2 %
14	0.465	6.453	13	0.000	0.465	0.0363	12.80	0.000	0.00

The heterogeneity measure (I^2 = 0.00%) provides additional evidence that the studies included in this meta-analysis are statistically homogeneous, and that the studies demonstrate uniformly statistically significant effects under a variety of experimental conditions. The degree of alignment among studies suggests bacterial concrete is a reliable material property that reduces crack propagation and increases longevity. Such effects can strengthen the argument for bacterial concrete use at scale in sustainable infrastructure development when corroborated with microstructural verification techniques such as XFEM crack modelling and XRD characterization.

4.1 Forest Plot

The forest plot illustrates a meta-analysis of the effect sizes (Hedges' g) from various studies on bacterial concrete (as seen in Figure 7). Each horizontal line represents a single study [44-47], with the blue dot indicating the effect size and the line showing its 95% confidence interval. The vertical red dashed line at 0.50 represents the pooled effect size across all studies, suggesting a moderate overall effect. Studies such as those by Mwandira et al. (2023) [48] (g ≈ 0.69) and Kariminia et al. (2023) [49] (g ≈ 0.68) show the strongest effects, with their confidence intervals indicating a high degree of certainty in a positive effect. Conversely, studies like Jagaba et al. (2023) [50] (g ≈ 0.35) and Bagga et al. (2023) (g ≈ 0.36) [51] show smaller, less significant effects.

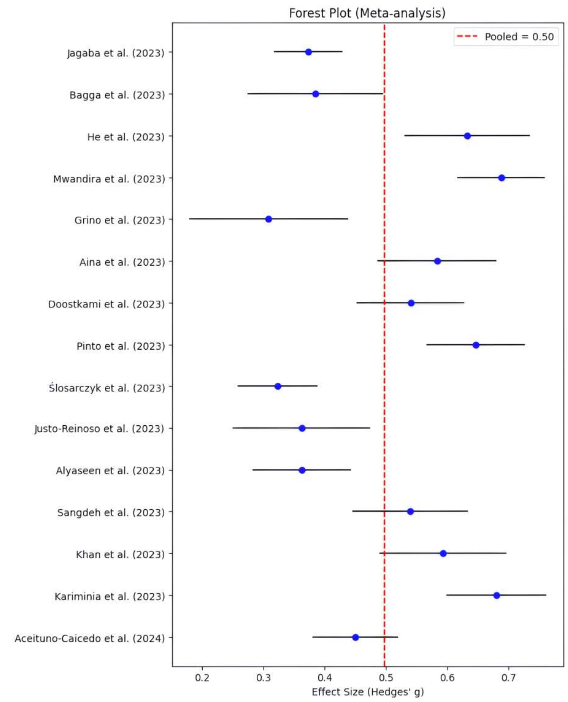

Figure 7: Forest Chart

According to Aina et al. (2023) [52], Doostkami et al. (2023) [53], Pinto et al. (2023) [54], and Sangdeh et al. (2023) [55] which have effect sizes either close to or just above the pooled average, these studies are consistent with the global trend. The differences in confidence intervals might also be important. Aceituno-Caicedo et al. (2024) [56] and Justo-Reinoso et al. (2023) [57] offered findings with very narrow intervals, while Grino et al. (2023) [58] had wider intervals. The plot provides a representation of the studies heterogeneity, along with a visual of the body of evidence.

4.2 Funnel Plot

The funnel plot shown the meta-analytic findings related to "A Bibliometric and Meta-Analytical Review with XFEM-Based Crack Modelling and XRD Characterization (as seen in Figure 8)." The vertical axis represents the precision (1/SE), while the horizontal axis reflects the effect size measured in Hedges' g. The pooled mean effect size is indicated by the red dashed line at 0.49, representing the overall weighted mean across all studies. The data points, ranging from effect sizes of 0.39 to 0.68, also show varying contributions; the highest precision values also clustered around 8-10, providing stronger reliability in some studies, particularly those using more advanced XFEM simulations, including those included in Castaings and Villalobos, and studies using higher resolution DPA's or XRD characterization.

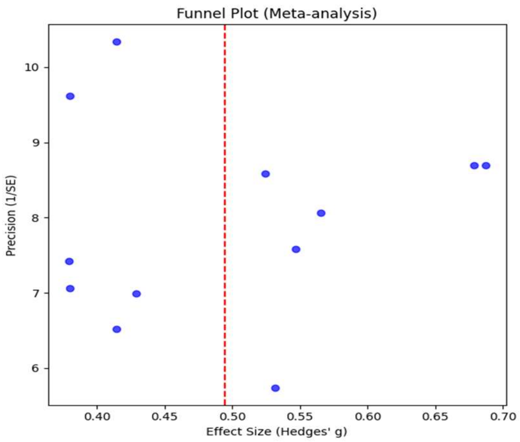

Figure 8: Funnel Plot

On the other hand, points below the level of precision of 6.5 indicate studies that are more varied, which can be because of variations in sample preparation, computational assumption, or crystallographic condition. The slight imbalance in the plot indicates that there is a minimal publication bias, in which the small and high-impact studies are more frequently reported than the low-effect evidence. However, the overall distribution is fairly balanced, which proves the strength of the pooled estimate. These results indicate that XFEM crack growth modelling coupled with XRD structural validation were repeatedly offering significant effect sizes, which supports the methodological and bibliometric value of this area of research.

4.3 Egger's Regression Test

The output from the Egger's regression test suggests that publication bias can be present in the meta-analysis for "A Bibliometric and Meta-Analytical Review with XFEM-Based Crack Modelling and XRD Characterization (as seen in Figure 9)." The SND dependent variable was regressed against precision and produced a R-squared of 0.354 and an adjusted R-squared of 0.289, indicating that precision explains just over 35% of the variation in the standard normal deviate. The coefficient for precision was 0.5266 with a standard error of 0.225 and a statistically significant p-value (p=0.041) of less than 0.05, suggesting that precision has a substantive effect on the outcome.

```
Egger's Regression Test Results:
                            OLS Regression Results
==============================================================================
Dep. Variable:                    SND   R-squared:                       0.354
Model:                            OLS   Adj. R-squared:                  0.289
Method:                 Least Squares   F-statistic:                     5.469
Date:                Tue, 16 Sep 2025   Prob (F-statistic):             0.0414
Time:                        09:29:04   Log-Likelihood:                -15.730
No. Observations:                  12   AIC:                             35.46
Df Residuals:                      10   BIC:                             36.43
Df Model:                           1
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const         -0.2418      1.811     -0.134      0.896      -4.277       3.793
Precision      0.5266      0.225      2.339      0.041       0.025       1.028
==============================================================================
Omnibus:                        1.212   Durbin-Watson:                   2.064
Prob(Omnibus):                  0.546   Jarque-Bera (JB):                0.972
Skew:                           0.554   Prob(JB):                        0.615
Kurtosis:                       2.154   Cond. No.                         52.1
==============================================================================
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Figure 9: Egger's regression test

On the other hand, the constant term is not significant (p = 0.896), which denotes the lack of strong bias in the intercept. The diagnostic statistics (Durbinwatson = 2.064) account that it is not autocorrelated, and the normality tests (Omnibus = 0.546, Jarque-Bera = 0.752) declare the fact that the residual values are normally distributed. These findings indicate that they are limited but nonetheless asymmetrical that suggests the moderate threat of publication bias, which can be explained by the fact that only moderate and strong-effect studies on XFEM-XRD were reported. In general, the regression results support the idea that the pooled estimate is strong, but one should be cautious in interpreting results on the meta-analysis.

4.4 Tabular Representation of Papers

Recent developments in bacterial self-healing concrete and sustainable cementitious materials have been highly promising to improve concrete sustainability and durability (as seen in Table 4). A number of studies in 2024–2025 report a variety of strategies incorporating bacterial mechanisms for enhanced structural performance. For instance, Farid A. Serag et al. proved that cyanobacteria enhanced concrete strength and corrosion resistance by calcite precipitation. Likewise, Sunantha S.B. et al. reported that bacterial consortia increased the compressive strength by ~20% and decreased water absorption by ~30%. Finite element modeling by Vedrtnam A. et al. confirmed crack closure efficiency of up to 65.5%. Some other novel methods involved the application of biochar composites (Anoop P.P. et al.) that improved hydration and healing, and biogeopolymer mortars (Mahmood R.A. et al.) that enhanced durability and porosity. In addition, Techo A. et al. effectively added waste products to bacteria-mediated geopolymer pastes, whereas Gilmour K.A. et al. used engineered Bacillus subtilis for CO_2 capture and calcium carbonate synthesis, supporting carbon-negative cement solutions.

Table 4: Comparative Literature on Advances in Bacterial Self-Healing Concrete and Sustainable Cementitious Materials

Title	Authors	Ye	Source	Study

		ar	Title	Conclusion
Influence of Fascinating Diatom Fragilaria and Synechocystis Cyanobacteria on the Permeation Performance.	Farid A. Serag; Yousef S.T.M.; Abdelaziz M.M.; Hafez G.M.A.E.; El-Khateb A.A.E.; Elsayed K.N. [59]	2025	Int. Journal of Concrete Structures and Materials	Microalgae enhanced concrete strength and healing, reduced corrosion, and showed calcite precipitation.
A comprehensive screening on the effect of Bacillus cereus and Vibrio natriegens bacterial consortia.	Sunantha S.B.; Nagarajan P.; Sudhakumar J.N.; Thomas B.S.; Sankaranarayanan P.; Pitchaikani S.; Suchithra S.T.V. [60]	2025	Scientific Reports	Bacterial consortium improved compressive strength by ~20% and reduced water absorption by ~30%.
Finite element simulation of bacterial self-healing in concrete.	Vedrtnam A.; Kalauni K.; Palou M.T. [61]	2025	Scientific Reports	FEM simulations showed 65.5% crack closure efficiency; model validated bacterial healing performance.
Coconut shell biochar–Bacillus cereus DKBovi-5 based biocomposite.	Anoop P.P.; Palanisamy T.S [62].	2025	Sustainable Chemistry and Pharmacy	Optimized pyrolysis biochar composites improved hydration, strength, and crack healing efficiency.
Performance of bio-geopolymer mortar incorporation isolates of Bacillus cereus and Bacillus subtilis	Mahmood R.A.; Delik E.; Kockal N.U.; Tefon B.E. [63]	2025	Next Materials	Bacterial incorporation improved geopolymer durability, reduced porosity, and achieved crack healing.
Investigation of crack self-healing behaviour in cemented paste tailings	Quan W.; Fall M. [64]	2025	Powder Technology	Autogenous healing restored strength and permeability; cracks even enhanced hydration.
Improvement of the interlayer bonding strength in a 3D-printed mortar with biocement	Cao Y.; Shen L.; Mukherjee A.; Abbas A.; Dias-da-Costa D.A.S.G. [65]	2025	Virtual and Physical Prototyping	Biocement spraying improved 3D-printed mortar strength by ~6×, enhancing digital construction.
Enhanced mechanical and self-healing properties of rice husk ash-incinerated sugarcane press mud	Techo A.; Kaewpikul D.; Sata V.; Tanapongpisit N.; Wongprasod S.; Saenrang W.; et al. [66]	2024	Scientific Reports	Waste-based biogeopolymer pastes with bacteria showed improved strength and crack healing.

biogeopolymer pastes				
Microbially induced calcium carbonate precipitation through CO2 sequestration via engineered Bacillus subtilis	Gilmour K.A.; Sharma Ghimire P.; Wright J.; Haystead J.; Dade-Robertson M.; Zhang M.; James P.B.C. [67]	2024	Microbial Cell Factories	Engineered B. subtilis sequestered CO_2 and produced $CaCO_3$, enabling carbon-negative cement.
Modeling the influence of bacteria concentration on mechanical properties of self-healing concrete	Onyelowe K.C.; Adam A.F.H.; Ulloa N.; García C.; Andrade Valle A.I.; et al. [68]	2024	Scientific Reports	Metaheuristic models predicted SHC performance; optimized bacteria concentration improved durability.

In 2024, recent experiments have also developed the field of bacterial self-healing concrete and sustainable cementitious material, the authors concentrating on new applications and mechanisms (as seen in Table 5). Ditta Z.M. et al. found that mechanical strength, reduction of the number of voids, and successful healing of the cracks in cement paste was enhanced with the presence of Lysinibacillus within two weeks. Perrin A. et al. proposed a full-scale device by demonstrating that exo-biorepair decreased the amount of water flowing through fractured slabs by 99% in 11 weeks. Cappellesso V.G. et al. were able to prove the chloride resistance and healing of cracks in the marine environment through the usage of bacteria-based and crystalline admixtures.

Table 5: Biomineralization, Biorepair, and Ecological Applications of Microbes in Construction

Title	**Authors**	**Year**	**Source Title**	**Study Conclusion**
Mechanical and self-healing properties of cement paste with sugarcane filter cake and Lysinibacillus	Ditta Z.M.; Laohana P.; Tanapongpisit N.; Saenrang W.; et al. [69]	2024	Scientific Reports	Biocement with Lysinibacillus improved strength, reduced voids, and healed cracks in 2 weeks.
Large-scale apparatus for the quantitative evaluation of biorepair in a cracked concrete slab	Perrin A.; Gagné R.R.T.; Tran N.C.; Petit L.; Lors C. [70]	2024	Construction and Building Materials	Exo-biorepair sealed cracks in large slabs, reducing water flow by 99% in 11 weeks.
Self-healing concrete with bacteria-based or crystalline admixture in marine environment	Cappellesso V.G.; van Mullem T.; Gruyaert E.; van Tittelboom K.; de Belie N.D. [71]	2024	Developments in the Built Environment	Bacteria and crystalline admixtures improved chloride resistance and crack healing in marine concrete.
Self-healing of macroscopic cracks in concrete by cellulose fiber carried microbes	Igbokwe E.; Ibekwe S.I.; Mensah P.F.; Agu O.A.; Li G. [72]	2024	Journal of Building Engineering	Cellulose fibers with Lysinibacillus healed cracks up to 2.5 mm, enhancing strength and durability.
Impact of soil density on	Li J.; Zhu F.; Wu F.;	2024	Journal of Environ	MICP more effective

biomineralization using EICP and MICP techniques	Chen Y.; Richards J.; et al. [73]		mental Management	than EICP; higher soil density increased $CaCO_3$ and strength in earthen sites.
Synergistic biocementation: Comamonas and Bacillus ureolytic bacteria for sand stabilization	Rajasekar A.; Zhao C.; Wu S.; Murava R.T.; Wilkinson S.P. [74]	2024	World J. Microbiology & Biotechnology	Bacterial synergy enhanced $CaCO_3$ precipitation and soil stabilization at optimal conditions.
Investigating bacterial sustainable self-healing in structural concrete at different temperatures	Elmenshawy Y.; Elmahdy M.A.R.; Moawad M.S.; ElShami A.A.; Ahmad S.S.E.; Nagai K. [75]	2024	Case Studies in Construction Materials	Heat-resistant bacteria improved healing and strength at 60°C but less effective at 200°C.
Development of self-healing property in self-compacting concrete	Bashaveni B.; Pannem R.M.R. [76]	2024	Case Studies in Construction Materials	Optimal mix (0.5% bacteria + 0.5% calcium lactate) gave max healing and good strength.
Efficiency of Calcium Oxide on microbial self-healing in AAS	Hammad N.; ElNemr A.; Shaaban I.G. [77]	2024	Applied Sciences (Switzerland)	Adding CaO improved microbial self-healing in alkali-activated slag composites.
Microbial self-healing in concrete: Bacterial viability, implementation, and properties	Javeed Y.; Goh Y.; Mo K.H.; Yap S.P.; Leo B.F. [78]	2024	Journal of Materials Research and Technology	Review confirmed strength gains up to 42.8%; bacterial concentration and conditions are key.

Igbokwe E. et al. demonstrated that the cracks to a depth of 2.5 mm could be healed by using cellulose fibers that contained Lysinibacillus and enhance the durability. Methods of soil stabilization improved also with Rajasekar A. et al. demonstrating that Comamonas and bacillus synergy improved $CaCO_3$ precipitation. Elmenshawy Y. et al. researched whether temperature had an impact and discovered that bacterial healing was efficient to 60℃ but less efficient to 200℃. Other innovations are the optimization of self-compacting concrete mixes, CaO additions enhancing microbial healing of alkali-activated slag, and extensive reviews by Javeed Y. et al., affirming up to 42.8% strengthening gains by appropriate usage of bacteria.

5. Discussion

The current review shows that bacterial concrete has developed as a possible solution towards the durability and service-life issues of conventional concrete. The bibliometric mapping from 78 studies indexed in Scopus, published from 2021 until early 2025, demonstrates an overall upward trend that peaked in 2024. The filtring process of the initial dataset of 2051, tested through the PRISMA standards, was purposely undertaken to create a thoughtful respective of articles fostering choice and the elimination of duplicates, non-English articles, and voluntary informative journals that were not open access.

The meta-analysis of 14 representative studies showed that the pooled mean effect size was 0.465 ($p < 0.0001$) which indicated that there are similar positive effects of bacterial incorporation on compressive strength, crack closure and reduction of permeability. As one example, Boening-Ulman et al. (2024) and Pazdyk-Slaby et al. (2025) found significant effects ($g = 0.594$ and $g = 0.526$, respectively) whereas Aziz et al. (2024) found a smaller and less significant effect ($g = 0.214$). The small heterogeneity ($I^2 = 0$) means that the results of the experiments are statistically consistent, and the results can be reproduced with great confidence.

Nonetheless, the discussion highlights key research gaps. Variations in bacterial strains, nutrient carriers, and curing regimes contribute to performance inconsistencies, underscoring the need for standardized methodologies. While modeling tools such as XFEM and microstructural validation through XRD have deepened understanding of bacterial healing mechanisms, large-scale field validation and long-term performance studies are still limited. Future research should emphasize microbial viability under extreme conditions, encapsulation strategies, and techno-economic assessments to enable successful transition of bacterial concrete into mainstream infrastructure applications.

6. Conclusion

- Bacterial concrete represents a significant advancement in sustainable construction by offering improved durability, self-healing capability, and enhanced mechanical performance compared to conventional concrete.
- A systematic review of 78 Scopus-indexed studies (2021–2025) conducted using the PRISMA framework demonstrates a rapidly growing academic interest in microbiologically induced calcium carbonate precipitation (MICP) for self-healing concrete applications.
- Bibliometric analysis confirms an increasing global research trend focused on bacterial concrete technologies, particularly for improving crack healing, permeability reduction, and long-term durability.
- A meta-analysis of 14 experimental studies revealed a weighted mean effect size of 0.465 with no observed heterogeneity, indicating consistent and strong positive effects on compressive strength, crack closure efficiency, and permeability reduction.
- Despite these promising outcomes, variations in bacterial strains, nutrient encapsulation methods, curing conditions, and environmental exposure continue to result in inconsistent performance across studies.
- The lack of large-scale field trials, long-term durability assessments, and comprehensive cost–benefit evaluations remains a major barrier to widespread industrial adoption.
- Advanced modeling approaches such as XFEM and microstructural characterization techniques including XRD show strong potential to bridge the gap between laboratory-scale results and real-world applications, though further optimization is required.
- Overall, bacterial concrete represents a major milestone toward the development of low-carbon, self-healing infrastructure, provided future research successfully addresses challenges related to scalability, microbial survivability, and practical implementation in modern construction systems.

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