



Bacterial Self-Healing Concrete and the Role of Nano-Additives: A Systematic Review of Healing Performance, Reporting Quality and Synergy Evidence

***¹ Aenghreed Ali Shandel**

¹ Department of Civil Engineering, Al-Furat Al-Awsat Technical University, Najaf, Iraq.

ABSTRACT

This review quantifies the reported performance of bacterial self-healing concrete and examines whether combining bacteria with nano-additives, chiefly nano-silica, produces a demonstrable synergistic benefit. Following the PRISMA 2020 framework, 106 reports were sought for full-text assessment and 87 were included: 59 primary experimental studies (48 bacterial, 6 bacterial with a nano-additive and 5 nano-additive only) and 28 contextual records. Pre-defined rules selected one value per study and outcome; values were pooled as medians with interquartile ranges, and subgroups were compared exploratorily. Across 54 bacterial studies, the median crack closure was 86.4%, the compressive-strength gain 21.2%, the reduction in water absorption 48.0% and the healed crack width 0.50 mm. Only one study reported all four core outcomes, 9.3% reported permeability or chloride transport, 77.8% tested healing under continuous immersion, and pooled closure showed no clear dependence on crack width ($R^2 = 0.061$), a pattern consistent with selective reporting. No advantage of encapsulation was detected in small subgroups, and no bacteria–nano study included the nano-only control needed to test synergy. Future work should adopt a minimum reporting protocol, wet–dry and saline exposure, long-term testing and a four-arm factorial design.

Keywords: Self-healing concrete, microbially induced calcite precipitation, nano-silica, systematic review, PRISMA, crack healing, durability.

* Corresponding author: Aenghreed Ali Shandel aenghreed.shandel.ims@atu.edu.iq

1. INTRODUCTION

Cracking is the normal service condition of reinforced concrete rather than an exceptional one. Cracks a few tenths of a millimetre wide are accepted by every major design code, yet they are also the pathway by which water, chlorides, sulfates and carbon dioxide reach the reinforcement; they therefore govern the durability and service life of most concrete structures. In hot, saline and highly evaporative environments such as southern Iraq and the wider Gulf, corrosion-driven deterioration frequently becomes structurally significant well within the design life, and the cumulative cost of manual repair can exceed the original construction cost.

Concrete that seals its own cracks has therefore attracted sustained attention. Among the mechanisms proposed — chemical healing agents, expansive minerals, superabsorbent polymers, encapsulated polymers and vascular networks — the biological route is the most intensively studied. In microbially induced calcite precipitation (MICP), alkali-tolerant spore-forming bacteria, usually of the genera *Bacillus*, *Lysinibacillus* or *Sporosarcina*, are added to the mix together with a mineral precursor. The spores remain dormant until a crack admits water and oxygen, whereupon they germinate, metabolise the precursor and precipitate calcium carbonate that fills the crack [1–4]. Bibliometric analyses document the growth of the field: Alzard et al. [5] mapped 1433 documents published between 1974 and 2021, Yu et al. [6] identified 1378 Web of Science articles on microbial self-healing concrete between 2008 and 2023, and Mitikie and Elsaigh [7] showed that output since 2020 remains concentrated in Asia, Europe and the United States.

A more recent development motivates the present review. Several groups now combine bacterial healing agents with nano-materials — most often nano-silica, but also nano-calcium carbonate, nano-titania, graphene oxide and carbon nanostructures — on the reasoning that the two mechanisms should reinforce one another. Nano-silica reacts pozzolanically with portlandite and acts as a nucleation seed for calcium silicate hydrate, densifying the matrix and refining the pore structure [8–10]; bacteria then seal the cracks that nevertheless form. The combination is intuitively appealing and is increasingly presented as established; Section 3.7 shows that it has not yet been tested in a design capable of demonstrating synergy.



1.1 Previous Reviews and the Research Gap

The mechanistic ground is well covered. Nodehi et al. [11] surveyed more than seventy articles on biomineralisation and the properties of bacterial concrete; Elgendy et al. [1] reviewed strain selection, urea metabolism, genetic modification and carrier systems; Vedrtam et al. [12] ranked nine bacterial species by multicriteria analysis; Shen et al. [13] and Naqvi and Raza [14] compared carriers and encapsulation methods; Luhar et al. [15], Javeed et al. [16], Ghazy et al. [17] and Li et al. [18] surveyed performance and durability; Bahrami et al. [19] added cost and life-cycle data; Bagga et al. [20] reviewed modelling approaches; Sowmya and Pannem [21] reviewed the combination of bacteria with fibres; and Cappellesso et al. [22] examined efficiency under realistic conditions. Adhikary et al. [23] performed the equivalent survey for chemical healing agents.

These reviews share three characteristics. They are narrative or semi-systematic; most do not report a PRISMA protocol; and none pools the reported outcomes statistically, so the field still lacks a defensible answer to how much healing bacterial concrete delivers on average and how variable that figure is. Nor has any review audited how completely the primary literature reports its own results. This matters because the published inter-laboratory studies [24, 25] have shown that nominally identical tests give divergent results between laboratories unless crack geometry and specimen preparation are harmonised, and the RILEM committees in this area [26, 27] state that no universal efficiency measure yet exists.

The gap addressed here is therefore quantitative and critical rather than descriptive. The objectives are to answer four research questions (RQ):

RQ1: What are the pooled crack-closure, mechanical and transport outcomes of bacterial self-healing concrete, and how dispersed are they?

RQ2: Do the outcomes differ between delivery routes, bacterial species, crack widths, healing periods and exposure regimes?

RQ3: How completely does the primary literature report the outcomes on which its claims rest, and is reporting improving?

RQ4: What evidence exists that nano-additives and bacteria act synergistically rather than additively, and what experimental design would settle the question?

The contribution is a quantitative map of what the field has measured, an audit of what it has not reported, and a demonstration that the currently most

prominent claim in the area — nano–bacteria synergy — rests on no controlled evidence.

2. REVIEW METHODOLOGY

The review followed the seven-stage methodology summarised in Figure-1: (1) formulation of the research questions; (2) design and execution of the search strategy; (3) de-duplication and two-stage screening against pre-defined eligibility criteria; (4) data extraction, harmonisation and selection of one value per study; (5) quantitative statistical synthesis; (6) an audit of reporting completeness; and (7) evidence mapping for the synergy question, an update search and the derivation of a minimum reporting protocol. Each stage is described in Sections 2.1–2.9, and the full search documentation is given in Appendix A.

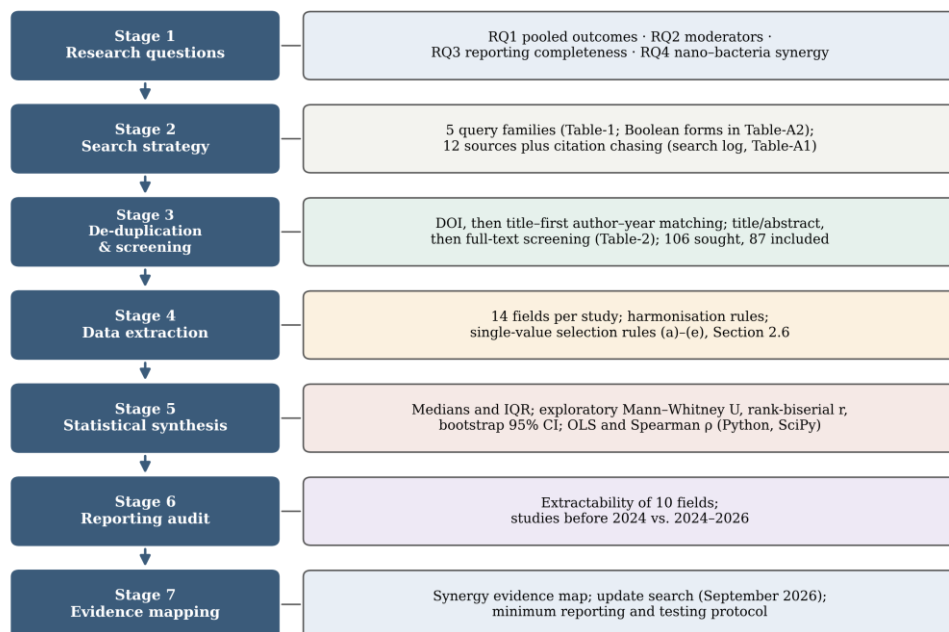


Figure-1: Methodological framework of the systematic review.

2.1 Protocol and Reporting Framework

The review was conducted and is reported in accordance with the PRISMA 2020 statement, as the journal requires for systematic reviews. Because the synthesis pools engineering outcome measures rather than effect sizes with known variances, a random-effects meta-analysis was not appropriate; a

descriptive quantitative synthesis with non-parametric subgroup testing was used instead, and this deviation is declared here. The review was not registered in PROSPERO, which does not accept non-health reviews.

2.2 Information Sources and Search Strategy

Four groups of sources were searched: (i) publisher full-text platforms — ScienceDirect (Elsevier), SpringerLink and Nature.com (Springer Nature), MDPI, Wiley Online Library, Taylor & Francis Online, Frontiers, Oxford Academic and De Gruyter; (ii) open indexes — the Directory of Open Access Journals (DOAJ), PubMed Central and institutional repositories; (iii) Google Scholar as a general academic search engine; and (iv) backward and forward citation chasing from the reviews identified in Section 1.1. Each source was searched with the five query families of Table-1 in the title, abstract and keyword fields (full text where a platform offered no field restriction). No language or lower date limit was applied at the search stage; document types were restricted at screening, not at searching. The final searches were run in August 2026 and the update search (Section 2.9) in September 2026. Appendix A documents, for each source, the interface and fields searched, the date of the final search and the number of records retrieved (Table-A1), and gives each query family as a Boolean string that can be re-executed directly in Scopus (TITLE-ABS-KEY) or Web of Science Core Collection (TS=) (Table-A2); on platforms without full Boolean support, the natural-language strings of Table-1 were entered.

Table-1: Search strategy — query families executed across publisher platforms and open indexes.

Theme	Representative query strings
Mechanism and species	bacterial self-healing concrete; MICP concrete crack healing; <i>Bacillus subtilis</i> self-healing concrete; <i>Sporosarcina pasteurii</i> crack width closure; <i>Lysinibacillus sphaericus</i> healing efficiency; ureolytic calcite precipitation concrete
Carriers and immobilisation	encapsulated bacteria self-healing concrete; lightweight expanded clay aggregate bacteria; hydrogel/alginate microcapsule bacteria concrete; diatomaceous earth immobilised bacteria; expanded perlite bacterial spores; carrier comparison bacterial concrete
Nano-additives	nano-silica concrete optimum dosage; nano-SiO ₂ hydration C–S–H nucleation; bacteria nano-silica self-healing concrete; nanomaterial bacterial concrete synergy; nano-silica dispersion agglomeration concrete
Assessment and durability	self-healing concrete water permeability recovery test; RILEM self-healing protocol; X-ray CT crack closure quantification; wet–dry cycles healing efficiency; long-term durability bacterial concrete chloride

Theme	Representative query strings
Context and translation	self-healing concrete review; bibliometric analysis self-healing concrete; life cycle assessment self-healing concrete; machine learning prediction crack healing; field application full-scale bacterial concrete; commercialisation barriers self-healing concrete

2.3 Eligibility Criteria

Eligibility was defined in terms of population (matrix), intervention, comparator, outcomes, publication type and period, as listed in Table-2.

Table-2: Eligibility criteria.

Domain	Included	Excluded
Population	Cementitious materials: concrete, mortar, cement paste, geopolymers concrete	Soil, sand columns, bricks, non-cementitious matrices
Intervention	Bacterial healing agent (any species, any delivery route) and/or a nano-additive incorporated in the mix or applied to the crack	Purely chemical, capsule-polymer or mineral-expansive healing without a biological or nano component
Comparator	A control mix or a pre-healing baseline against which an outcome is quantified	Studies with no comparator
Outcomes	At least one of: crack closure, healed crack width, compressive strength change, strength or stiffness recovery, water absorption or sorptivity, permeability or chloride transport	Purely microbiological or qualitative reports with no engineering outcome
Publication type	Peer-reviewed journal and conference papers, standards and technical committee reports, theses and government research reports	Commercial market reports, unrefereed preprints, promotional material
Period	No lower limit; priority to 2019–2026; landmark earlier studies retained where they define a carrier class	—

2.4 Selection Process

All retrieved records were collected in a single reference library. Duplicates were removed in two passes: first by exact match of the digital object identifier (DOI), and then by matching normalised title, first-author surname and publication year, to capture records without a DOI or with different versions (e.g., preprint and published article). Conference and journal reports of the same dataset were treated as one study, and the more complete report was retained. Screening then proceeded in two stages against the criteria of Table-2: (1) title and abstract screening, and (2) full-text assessment of every record that passed stage 1 or could not be excluded on its abstract. Both stages were



performed by one reviewer (the author); records of uncertain eligibility were carried forward to full-text assessment rather than excluded, and the reason for every full-text exclusion was recorded. Table-A1 gives the number of records at each stage.

Following PRISMA 2020 terminology, 106 reports were sought for retrieval; 13 could not be retrieved in full text and were excluded because no field could be verified from a source actually inspected. Of the 93 reports assessed for eligibility, 6 were excluded: 3 reported no quantitative outcome, 1 was a commercial market report, 1 used a non-cementitious matrix and 1 duplicated a dataset already included. The remaining 87 records were included: 59 primary studies entering the quantitative synthesis and 28 contextual records (reviews, bibliometric analyses, life-cycle assessments, cost studies, field trials, inter-laboratory studies and standards) (Figure-2). Because several platforms did not permit bulk export of their result lists, the identification stage could not be reconstructed as a single exported count for those sources; this is why Figure-2 begins at the retrieval stage, and the consequences are discussed in Section 6.

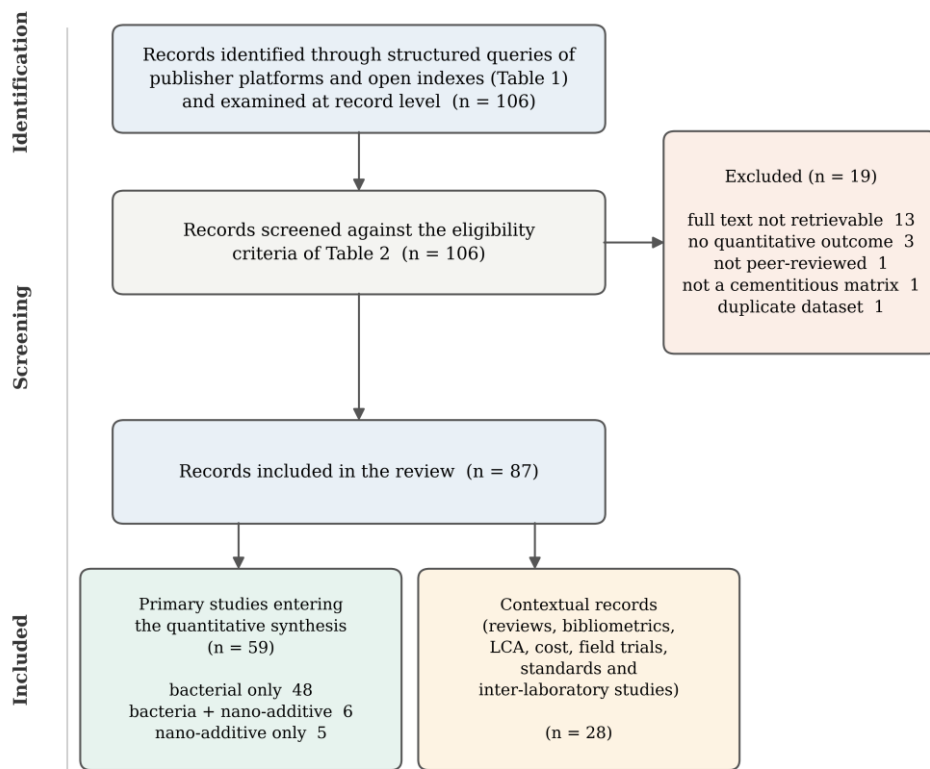


Figure-2: PRISMA flow of records through the review, from the retrieval stage onwards; source-level identification counts are given in Table-A1 and the reason the diagram starts at retrieval in Section 2.4.

2.5 Data Extraction and Harmonisation

For each primary study the following were extracted: bibliographic data; bacterial species; delivery route (direct addition or immobilisation in a carrier); carrier material; class of supplementary material (none, supplementary cementitious material, nano-additive, waste-derived, fibre); exposure regime; maximum healed crack width; healing period; crack closure or healing ratio; change in compressive strength relative to the control; strength or stiffness recovery; reduction in water absorption or sorptivity; and reduction in permeability or chloride transport. Three harmonisation rules were applied: (a) where a range was reported, the midpoint was recorded and flagged (ten values in seven studies); (b) where absolute transport values were reported — for example a sorptivity falling from 1.79×10^{-2} to 7.89×10^{-3}

mm/s^{0.5} — the relative reduction was computed (two entries); and (c) outcomes described only qualitatively were recorded as not reported, and no value was inferred from a qualitative statement.

2.6 Selection of a Single Study-Level Value

Many primary studies report several mixtures, bacterial dosages, crack widths, curing or exposure regimes and testing ages, whereas the synthesis requires one value per study and outcome so that no study is counted more than once. The following rules were applied in the order given, and the value selected for each study is identified in the supplementary extraction database:

- (a) Mixture and bacterial dosage: the bacterial mixture that the authors identified as optimal or recommended was selected; where none was designated, the mixture reported as the principal result in the abstract or conclusions was used. The comparator was the control mixture of the same series (same binder, water–cement ratio and supplementary materials), so that the recorded change reflects the bacterial addition rather than other constituents.
- (b) Crack width: the maximum healed crack width w is the widest crack for which the study quantified healing, and the closure value recorded is the one reported for that same width — for example, 43.2% for the 1.5 mm crack of Wang et al. [28], not the complete closure of their narrower cracks. Where closure was reported only as an average over several widths, that average was recorded with the widest width.
- (c) Curing and exposure regime: the regime of the principal result was recorded as the study's exposure category; results under additional regimes were retained in the database but not pooled, so that each study contributes one exposure category.
- (d) Testing age: the change in compressive strength was taken at 28 days where reported, otherwise at the reported age nearest to 28 days; healing outcomes were taken at the final reported healing age, which defines the healing period t .
- (e) Replicates: where individual specimen results and a mean were both reported, the mean was used.

Rules (a) and (b) act in opposite directions: (a) favours the best-performing mixture, whereas (b) records closure at the most demanding width. Their net effect on the pooled estimates cannot be quantified from the published data, and the rules are therefore listed as a source of uncertainty in Section 6.

2.7 Synthesis Methods

Outcomes are summarised as medians with interquartile ranges (IQR) because several distributions are strongly skewed. Means and standard deviations are also given in Table-5, together with a trimmed summary excluding values beyond $Q1 - 1.5 \text{ IQR}$ and $Q3 + 1.5 \text{ IQR}$. Subgroups were compared with the two-sided Mann–Whitney U test, with the rank-biserial correlation r as effect size, only where both subgroups contained at least three observations. Because most subgroups are small and several comparisons were made, all subgroup analyses are treated as exploratory: no correction for multiple testing was applied, p-values are reported descriptively rather than as tests of pre-specified hypotheses, and comparisons involving a subgroup of fewer than five observations are flagged. For the delivery-route comparisons whose study-level values are listed in Table-4, the difference in medians is also given with a percentile bootstrap 95% confidence interval (10,000 resamples), so that the range of effects compatible with the data is visible. Associations between continuous variables were tested by ordinary least squares (OLS) regression and Spearman rank correlation. All analyses were performed in Python 3.11 with NumPy and SciPy; the extraction database and analysis script are provided as supplementary material.

2.8 Assessment of Reporting Completeness

Instead of a conventional risk-of-bias instrument, which cannot be applied reliably to engineering studies of this kind, the review assesses extractability: for each of ten fields, the proportion of primary studies from which the field could be recovered from the record inspected. The measure is computed for the whole set and separately for studies published before 2024 and from 2024 onwards.

2.9 Update Search During Revision

During revision (September 2026) the queries of Table-1 were re-run to capture studies published since the original search. Two further studies combining bacteria with a nano-additive were identified [29, 30], together with recent reviews and studies used as contextual references. Because the extraction database had been locked, the two new primary studies are reported narratively (Section 3.7) and listed in Table-3, but are not included in the pooled statistics.

3. RESULTS

3.1 Characteristics of the Evidence Base

Table-3 summarises all included primary studies — authors, year, title, the matrix or specimen type used as the experimental model, and the tests for which quantitative results were extracted. Table-4 gives the extracted design variables and outcomes of the 54 bacterial studies, cross-referenced to Table-3 by study number.

Table-3: Summary of the included primary studies: authors, year, title, experimental model (matrix/specimen) and tests with extracted quantitative results. Nos. 1–54 bacterial studies (Nos. 11, 15, 18, 25, 29 and 40 also contain a nano-additive); Nos. 55–59 nano-additive only; U1–U2 identified in the update search and not pooled.

No .	Ref.	Author(s) (year)	Title	Model (matrix/ specimen)	Tests*
1	[31]	Wang et al. (2012)	Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete	Mortar/concrete	CW
2	[32]	Xu et al. (2018)	Self-healing of concrete cracks by ceramsite-loaded microorganisms	Concrete	CW, CC
3	[4]	Farrugia et al. (2019)	The application of <i>Lysinibacillus sphaericus</i> for surface treatment and crack healing in mortar	Mortar	CW; surface treatment
4	[33]	Hassan et al. (2019)	Self-healing concrete using encapsulated bacterial spores in a simulated hot subtropical climate (Project No. 18CLS02)	Concrete	CW, CC, CS; hot-climate simulation
5	[34]	Kua et al. (2019)	Biochar-immobilized bacteria and superabsorbent polymers enable self-healing of fiber-reinforced concrete after multiple damage cycles	Fibre-reinforced concrete	CW, CC; repeated damage cycles
6	[35]	Pungrasmi et al. (2019)	Evaluation of microencapsulation techniques for MICP bacterial spores applied in self-healing concrete	Cementitious (spore capsules)	CC; spore viability
7	[36]	Fahimzadeh et al. (2020)	Biological self-healing of cement paste and mortar by non-ureolytic bacteria encapsulated in alginate hydrogel capsules	Cement paste and mortar	CC
8	[37]	Kim et al. (2020)	Impact of bio-carrier immobilized with marine bacteria on self-healing performance of cement-based materials	Cement-based material	CW, CC
9	[38]	Soysal et al. (2020)	Evaluating the self-healing efficiency of hydrogel-encapsulated bacteria in concrete	Concrete	qualitative only†
10	[39]	Janek et al. (2022)	Diatomite and Na-X zeolite as carriers for bacteria in self-healing cementitious mortars	Mortar	qualitative only†
11	[40]	Khushnood et al. (2022)	Bio-inspired self-healing and self-sensing cementitious mortar using <i>Bacillus subtilis</i> immobilized on graphitic platelets	Mortar	self-sensing
12	[41]	Medeiros & Di Sarno (2022)	Low carbon bacterial self-healing concrete	Low-carbon concrete	CW
13	[42]	Baradaran & Sadeghpour (2023)	Effect of bacteria on the self-healing ability of concrete containing zeolite	Concrete with zeolite	qualitative only†
14	[43]	Shivanshi et al. (2023)	A study on bacterial self-healing concrete encapsulated in lightweight expanded clay aggregates	Concrete	CW

No .	Ref.	Author(s) (year)	Title	Model (matrix/ specimen)	Tests*
15	[44]	Xiao et al. (2023)	Single bacteria spore encapsulation through layer-by-layer self-assembly of poly(dimethyldiallyl ammonium chloride) and silica nanoparticles for self-healing concrete	Cementitious (encapsulated spores)	CW, CC
16	[45]	Yamasamit et al. (2023)	Effect of <i>Bacillus subtilis</i> on mechanical and self-healing properties in mortar with different crack widths and curing conditions	Mortar	CW, CC, CS; curing conditions
17	[46]	Erbakan et al. (2024)	Bacterial species impact on self-healing of cement based materials in marine structures	Cement-based material (marine)	qualitative only†
18	[47]	Li et al. (2024)	Surface crack treatment of concrete via nano-modified microbial carbonate precipitation	Concrete (surface treatment)	chloride migration
19	[48]	Maurente-Silva et al. (2024)	Effect of exposure environment and calcium source on the biologically induced self-healing phenomenon in a cement-based material	Cement-based material	CC; exposure environment
20	[49]	Pannem et al. (2024)	The effect of fly ash aggregates on the self-healing capacity of bacterial concrete	Concrete	qualitative only†
21	[50]	Roy et al. (2024)	<i>Bacillus cereus</i> GS-5 immobilized sintered fly ash lightweight aggregate for strength, durability, and autonomous crack healing in bacterial concrete	Concrete (LWA)	durability
22	[51]	Xu et al. (2024)	Microbial-inspired self-healing of concrete cracks by sodium silicate-coated recycled concrete aggregates served as bacterial carrier	Concrete (RCA)	CW, CC
23	[52]	Zamba & Mohammed (2024)	Self-healing performance of normal strength concrete with <i>Bacillus subtilis</i> bacteria	Normal-strength concrete	CS
24	[53]	Adibinia et al. (2025)	Biomaterial-assisted self-healing for crack reduction in high-performance centrifugal concrete piles	HP centrifugal concrete piles	CC
25	[54]	Agna et al. (2025)	Nano-silica modified self-healing concrete	Concrete	CW, CC, CS
26	[55]	Ahmad et al. (2025)	Assessment of biogenic healing capability, mechanical properties, and freeze–thaw durability of bacterial-based concrete using <i>Bacillus subtilis</i> , <i>Bacillus sphaericus</i> , and <i>Bacillus megaterium</i>	Concrete	CW; freeze–thaw
27	[56]	Ahmed et al. (2025)	Sustainable self-healing geopolymer concrete incorporating recycled plastic, brick waste, and <i>Bacillus sphaericus</i>	Geopolymer concrete	CS
28	[57]	Al-Jabali et al. (2025)	Self-healing concrete reinforced with sisal fibers and based on sustainable <i>Bacillus subtilis</i> bacteria calcium lactate-fortified	Sisal-fibre concrete	CS
29	[58]	Damodaran & Mayilsamy (2025)	Strength and characterization studies on nano-silica and steel fibre reinforced bacterial concrete: An eco-friendly and sustainable approach	Steel-fibre concrete	CS
30	[59]	Eisa et al. (2025)	Characteristics of bacteria-based self-healing rubberized concrete for sustainable and durable construction	Rubberised concrete	CW, CC, CS
31	[60]	Elakkiya et al. (2025)	Study on properties of bacteria concrete with two different fibres and carbon-negative supplementary cementitious materials	Fibre concrete with SCM	CC, CS
32	[61]	Frahat et al. (2025)	Effect of eggshell powder as fly ash replacement and nutrient source for bacteria on the properties and self-healing of geopolymer concrete	Geopolymer concrete	CS

No .	Ref.	Author(s) (year)	Title	Model (matrix/ specimen)	Tests*
33	[62]	Liu et al. (2025)	Adaptive evolution of <i>Sporosarcina pasteurii</i> enhances saline–alkali resistance for high-performance concrete crack repair via MICP. <i>Microorganisms</i> , 13(7), 1526. https://doi.org/10.3390/microorganisms13071526	Concrete (crack repair)	CW, CC; saline–alkali tolerance
34	[63]	Meghashree et al. (2025)	Advancing sustainable concrete with bacterial self-healing technology and Kuhn–Tucker condition	Concrete	CW, CC, CS; optimisation
35	[64]	Mekonnen et al. (2025)	Engineering experimental study on the mechanical and durability properties of concrete by partial replacement of cement with microbially induced calcite precipitation (MICP) bio-cement	Concrete (MICP bio-cement)	CS; durability
36	[65]	Muller et al. (2025)	Survey of indigenous bacteria as a simplified alternative to produce self-healing cementitious matrices	Cementitious matrix	CS
37	[66]	Nair et al. (2025)	Bacterial wollastonite concrete for sustainable high performance construction	Wollastonite concrete	CS
38	[67]	Patil et al. (2025)	Comparative evaluation of bacterial strains and novel SCM-based biocarriers for self-healing and strength enhancement in mortar	Mortar	CS
39	[68]	Priyadharsini et al. (2025)	Self-healing and sustainable concrete: A synergistic approach with waste and microbes	Concrete with waste	CS
40	[69]	Said et al. (2025)	Bio-mineralization process of CaCO_3 induced by bacteria isolated from Egypt for sustainable bio-concrete	Bio-concrete	CS
41	[70]	Sukumaran et al. (2025)	Assessment of strength and self-healing properties of bacterial concrete using machine learning techniques and microstructural characterization	Concrete	ML model; microstructure
42	[71]	Sunantha et al. (2025)	A comprehensive screening on the effect of <i>Bacillus cereus</i> and <i>Vibrio natriegens</i> bacterial consortia in cement mortar	Cement mortar	qualitative only†
43	[72]	Thirupathi et al. (2025)	Enhancing sustainability in construction: Exploring the self-healing mechanisms of bio-concrete	Bio-concrete	CC, CS
44	[73]	Vishal et al. (2025)	Assessment of bacteria-based self-healing concrete through experimental investigations — A sustainable approach	Concrete	CW, CS
45	[28]	Wang et al. (2025)	Evaluation and optimal width ratio selection of microbial mineralization technique in the repair of lining cracks in Xinjiang desert open channel	Canal-lining concrete (field)	CW, CC
46	[74]	Yehia et al. (2025)	Bacterial self-healing and mechanical strength enhancement in concrete: A comparative study of <i>Bacillus subtilis</i> , <i>Bacillus sphaericus</i> , and <i>Escherichia coli</i>	Concrete	CS
47	[75]	Youssa Tchamou & Xue (2025)	Effect of MICP on reinforcement corrosion of cement concrete exposed to the marine environment	Reinforced concrete (marine)	CW, CC, CS; chloride; corrosion
48	[76]	Fu et al. (2026)	Deciphering the crack and pore self-healing effects of sustainable eco-friendly bio-mortar under coastal zone multi-interfaces	Bio-mortar (coastal)	CW, CC; pore healing
49	[77]	Giri et al. (2026)	Performance evaluation of bacterial based self-healing concrete through systematic experimental investigation	Concrete	CS
50	[78]	Jiang et al. (2026)	Expanded perlite immobilization enhances long-term survival and mineralization activity of microbial spores in cementitious environments	Cementitious (spore survival)	spore viability



No .	Ref.	Author(s) (year)	Title	Model (matrix/ specimen)	Tests*
51	[79]	Madhumithra et al. (2026)	Enhancing self-healing concrete using sodium alginate beads and Citrullus lanatus seed powder for bacterial encapsulation	Concrete	CW, CC, CS
52	[80]	Noori Shahrabadi et al. (2026)	Effect of Bacillus subtilis-based self-healing and microsilica on the mechanical and physical properties of concrete pavements	Pavement concrete	qualitative only†
53	[81]	Singh & Chattopadhyay (2026)	Enhancing self-healing and durability of high-strength concrete using bacterial-induced calcite precipitation and zeolite: An experimental and multi-objective optimization approach	High-strength concrete	multi-objective optimisation
54	[82]	Vijay et al. (2026)	A bio-polymeric strategy for enhancing the strength, durability of concrete and shrinkage reduction	Concrete	CS; shrinkage
55	[83]	Horszczaruk et al. (2020)	Influence of dispersing method on the quality of nano-admixtures homogenization in cement matrix	Cement matrix	nano-admixture dispersion
56	[8]	Labaran et al. (2024)	Nano-enhanced concrete: Unveiling the impact of nano-silica on strength, durability, and cost efficiency	Concrete	CS; durability; cost
57	[84]	Şahin et al. (2024)	Effect of nano-TiO ₂ size and utilization ratio on the performance of photocatalytic concretes: Self-cleaning, fresh, and hardened state properties	Photocatalytic concrete	CS; self-cleaning; fresh properties
58	[85]	Dhairiyasamy et al. (2025)	Optimizing nanomaterial dosages in concrete for structural applications using experimental design techniques	Concrete	CS; dosage optimisation (DoE)
59	[86]	Yildirim & Gul (2026)	Effect of colloidal nano-silica on early- and later-age compressive strength and microstructure of pumice aggregate lightweight concrete	Pumice lightweight concrete	CS; microstructure
U1	[29]	Nagarajan et al. (2025)	AI-driven prediction framework for nano-bio self-healing concrete: Integrating nano biomass silica and bacterial admixture for sustainable structural materials	Concrete (nano biomass silica)	CS; ML models (XGBoost, RF)
U2	[30]	Shanthi Sri et al. (2026)	Mechanical and self-healing behaviour of denitrifying bacteria-based mortar with nano-graphene oxide and fly ash	Mortar (nano-GO, fly ash)	CS; crack healing; water absorption

*CW = healed crack width; CC = crack closure/healing ratio; CS = compressive strength relative to control; further tests as named. †Outcomes reported only qualitatively or not recoverable from the record inspected. Microstructural tests (SEM, XRD, EDS) were reported by most studies and are not listed individually.

The 54 bacterial studies (48 bacterial only plus the 6 that also contain a nano-additive) are concentrated in time and place (Figure-3). Thirty-eight (70.4%) were published in 2024 or later, and 24 in 2025 alone, so any review more than two years old is substantially out of date. Seventeen studies (31.5%) report experimental programmes in India, 8 (14.8%) in China and 5 (9.3%) in Egypt, with the remaining 24 spread across sixteen countries — a concentration consistent with the bibliometric picture [7]. It matters because mix constituents, curing practice and ambient conditions differ between settings, and the hot-arid and saline environments most in need of the technology are represented by only a handful of studies.

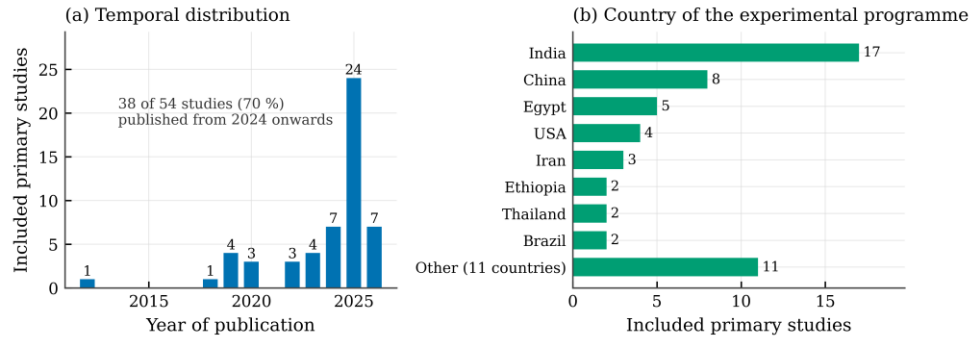


Figure-3: Characteristics of the included bacterial studies: (a) year of publication; (b) country of the experimental programme.

Table-4 shows the heterogeneity of the evidence: no two studies share the same combination of species, delivery route, supplementary material and exposure regime, and many outcomes could not be recovered.

Table-4: Design variables and extracted outcomes of the 54 bacterial studies (study numbers as in Table-3).

No.	Study [Ref.]	Bacterial species	Delivery route	Suppl.	Exposure	w (mm)	t (d)	CC (%)	Δfc (%)
1	Wang et al. (2012) [31]	<i>B. sphaericus</i>	C: diatomaceous earth	—	immersion	0.17	40	—	—
2	Xu et al. (2018) [32]	<i>S. pasteurii</i>	C: ceramicsite	—	immersion	0.30	28	86.0	—
3	Farrugia et al. (2019) [4]	<i>L. sphaericus</i>	D	—	immersion	0.20	7	—	—
4	Hassan et al. (2019) [33]	<i>B. pseudofirmus</i>	C: alginate hydrogel	—	wet-dry	0.09	28	68.0	+0.0
5	Kua et al. (2019) [34]	<i>B. sphaericus</i>	C: biochar + SAP	—	wet-dry	0.80	14	72.5	—
6	Pungrasmi et al. (2019) [35]	<i>B. sphaericus</i>	C: alginate microcapsule	—	immersion	—	7	95.4	—
7	Fahimzadeh et al. (2020) [36]	non-ureolytic (NR)	C: alginate hydrogel	—	immersion	—	28	100.0	—
8	Kim et al. (2020) [37]	marine isolates	C: bio-carrier	—	marine	0.60	28	100.0	—
9	Soysal et al. (2020) [38]	NR	C: alginate hydrogel	—	wet-dry	—	—	—	—
10	Janek et al. (2022) [39]	NR	C: diatomite / Na-X zeolite	—	NR	—	—	—	—
11	Khushnood et al. (2022) [40]	<i>B. subtilis</i>	C: graphite nanoplatelets	nano	NR	—	—	—	—
12	Medeiros & Di Sarno (2022) [41]	commercial (NR)	D	—	immersion	1.50	23	—	—
13	Baradaran & Sadeghpour (2023) [42]	<i>B. subtilis</i>	C: zeolite	SCM	immersion	—	—	—	—
14	Shivanshi et al. (2023) [43]	<i>L. sphaericus</i>	C: LECA	—	wet-dry	0.50	14	—	—
15	Xiao et al. (2023) [44]	spores (NR)	C: silica-nanoparticle LbL shell	nano	immersion	0.30	—	100.0	—
16	Yamasmit et al. (2023) [45]	<i>B. subtilis</i>	D	—	immersion	1.00	28	76.7	+8.9
17	Erbakan et al. (2024) [46]	marine isolates	D	—	marine	—	—	—	—
18	Li et al. (2024) [47]	<i>S. pasteurii</i>	D	nano	immersion	—	4	—	—
19	Maurente-Silva et al. (2024) [48]	<i>B. subtilis</i>	D	—	immersion	—	21	87.5	—
20	Pannem et al. (2024) [49]	NR	C: fly-ash aggregate	SCM	immersion	—	—	—	—

No.	Study [Ref.]	Bacterial species	Delivery route	Suppl.	Exposure	w (mm)	t (d)	CC (%)	Δfc (%)
21	Roy et al. (2024) [50]	<i>B. cereus</i> GS-5	C: sintered fly-ash LWA	SCM	immersion	–	–	–	–
22	Xu et al. (2024) [51]	NR	C: Na-silicate-coated RCA	waste	immersion	0.40	28	86.4	–
23	Zamba & Mohammed (2024) [52]	<i>B. subtilis</i>	D	–	immersion	–	56	–	+19.6
24	Adibinia et al. (2025) [53]	<i>B. sphaericus</i>	C: flax fibre	fibre	immersion	–	28	69.0	–
25	Agna et al. (2025) [54]	<i>B. subtilis</i>	D	nano	immersion	0.50	28	80.0	+46.0
26	Ahmad et al. (2025) [55]	<i>B. megaterium</i>	C: LECA	fibre	immersion	0.45	224	–	–
27	Ahmed et al. (2025) [56]	<i>B. sphaericus</i>	D	waste	immersion	–	56	–	+27.0
28	Al-Jabali et al. (2025) [57]	<i>B. subtilis</i>	D	fibre	immersion	–	56	–	+30.0
29	Damodaran & Mayilsamy (2025) [58]	NR	D	nano	immersion	–	28	–	+14.2
30	Eisa et al. (2025) [59]	<i>S. pasteurii</i> + <i>Rhizobium</i>	D	waste	immersion	1.25	80	100.0	+98.7
31	Elakkiya et al. (2025) [60]	<i>B. tropicus</i>	D	SCM	immersion	–	28	98.1	+35.0
32	Frahat et al. (2025) [61]	<i>B. subtilis</i>	D	waste	immersion	–	7	–	+15.1
33	Liu et al. (2025) [62]	<i>S. pasteurii</i>	D	–	injection	0.30	2	100.0	–
34	Meghashree et al. (2025) [63]	<i>B. subtilis</i>	D	–	immersion	1.00	21	100.0	+9.3
35	Mekonnen et al. (2025) [64]	ureolytic isolates	D	–	immersion	–	28	–	+33.7
36	Muller et al. (2025) [65]	<i>Cronobacter</i> sp.	C: air microbubbles	–	immersion	–	28	–	+108.0
37	Nair et al. (2025) [66]	<i>B. cohnii</i>	D	SCM	immersion	–	56	–	+41.5
38	Patil et al. (2025) [67]	<i>Paenibacillus</i> sp.	C: metakaolin	SCM	immersion	–	28	–	+22.9
39	Priyadharsini et al. (2025) [68]	<i>B. subtilis</i>	D	waste	immersion	–	90	–	+5.0
40	Said et al. (2025) [69]	<i>B. tropicus</i>	D	nano	immersion	–	28	–	+32.0
41	Sukumaran et al. (2025) [70]	<i>B. subtilis</i>	D	–	immersion	–	–	–	–
42	Sunantha et al. (2025) [71]	<i>B. cereus</i> + <i>V. natriegens</i>	D	–	immersion	–	28	–	–
43	Thirupathi et al. (2025) [72]	<i>B. megaterium</i>	D	SCM	immersion	–	28	65.0	+9.9
44	Vishal et al. (2025) [73]	<i>B. subtilis</i>	D	–	immersion	0.50	28	–	+32.5
45	Wang et al. (2025) [28]	<i>S. pasteurii</i>	D	–	injection	1.50	16	43.2	–
46	Yehia et al. (2025) [74]	mixed consortium	D	–	immersion	–	90	–	+19.6
47	Youssa Tchamou & Xue (2025) [75]	<i>B. subtilis</i>	D	SCM	marine	0.80	28	100.0	–51.0
48	Fu et al. (2026) [76]	<i>B. subtilis</i> + <i>S. pasteurii</i>	C: diatomaceous earth	SCM	marine	0.30	11	80.0	–
49	Giri et al. (2026) [77]	<i>B. subtilis</i>	D	–	immersion	–	28	–	+8.0
50	Jiang et al. (2026) [78]	<i>S. pasteurii</i>	C: expanded perlite	–	immersion	–	180	–	–
51	Madhumithra et al. (2026) [79]	<i>B. paramycoides</i>	C: alginate beads	–	immersion	1.10	28	86.0	+15.7
52	Noori Shahrabadi et al. (2026) [80]	<i>B. subtilis</i>	D	SCM	immersion	–	28	–	–
53	Singh & Chattopadhyay (2026) [81]	<i>B. subtilis</i>	C: zeolite	SCM	immersion	–	28	–	–
54	Vijay et al. (2026) [82]	<i>B. subtilis</i>	C: SAP	–	immersion	–	28	–	+26.4

D = direct addition to the mix; C = immobilised in the named carrier; Suppl. = supplementary material class (SCM = supplementary cementitious material; nano = nano-additive; waste = waste-derived; fibre = fibres); immersion = continuous water immersion; injection = bacterial suspension injected into a pre-formed crack; w = maximum healed crack width; t = healing period; CC = crack closure; Δfc = change in compressive strength relative to the control; NR = not reported; – = not recoverable. LECA =

lightweight expanded clay aggregate; LWA = lightweight aggregate; RCA = recycled concrete aggregate; SAP = superabsorbent polymer; LbL = layer-by-layer.

3.2 Pooled Healing, Mechanical and Transport Outcomes

Table-5 and Figure-4 give the pooled outcomes: a median crack closure of 86.4% (IQR 76.7–100), a change in compressive strength of +21.2% (IQR +9.7 to +32.8), a reduction in water absorption of 48.0% (IQR 30.0–70.0) and a healed crack width of 0.50 mm (IQR 0.30–1.00). Healing was assessed after a median of 28 days (IQR 23–28), showing how strongly the field has converged on a single testing age; only four studies followed healing beyond 90 days, and the longest monitoring period was 224 days.

The dispersion is as informative as the central values. The change in compressive strength spans -51.0% to $+108.0\%$. The two extreme positive values come from studies whose control was itself compromised — Eisa et al. [59] compared against a low-strength rubberised concrete, and Muller et al. [65] used indigenous non-*Bacillus* isolates in a paste system — while the only negative value, -51.0% , was reported by Youssa Tchamou and Xue [75], who also found that chloride penetration increased by up to 123% despite visible crack sealing in seawater. That study is the only one to report a clearly adverse durability outcome, and it is retained deliberately: a literature in which 53 of 54 studies report success is itself a finding. Removing the three extreme values gives a trimmed median strength gain of $+19.6\%$ (IQR $+9.9$ to $+32.0$, $n = 21$), which this review prefers as a central estimate, bearing in mind that the selection rules of Section 2.6 favour the authors' optimal mixtures.

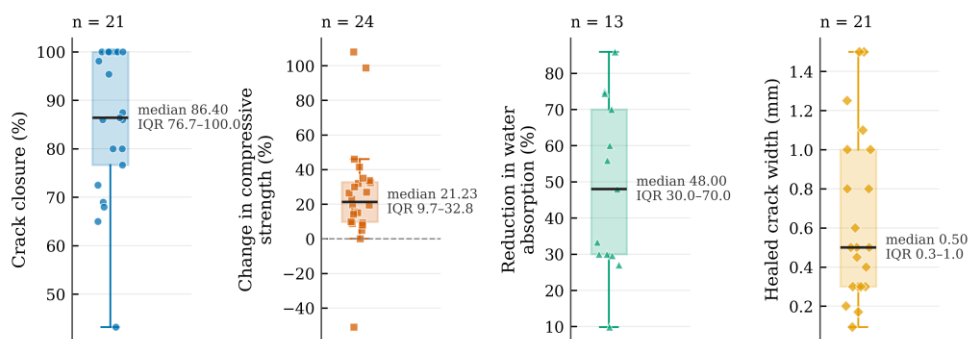


Figure-4: Distribution of the four principal outcomes. Boxes show the median and interquartile range; individual studies are overlaid.

Table-5: Pooled outcomes across the 54 bacterial studies (n = number of studies from which the outcome could be extracted).

Outcome	n	Median	IQR	Mean $\pm$ SD	Range
Crack closure (%)	21	86.4	76.7 – 100.0	85.4 $\pm$ 15.5	43.2 – 100.0
Change in compressive strength (%)	24	+21.2	+9.7 – +32.8	+25.3 $\pm$ 30.6	-51.0 – +108.0
same, extreme values trimmed	21	+19.6	+9.9 – +32.0	+21.5 $\pm$ 12.6	0.0 – +46.0
Strength or stiffness recovery (%)	8	90.9	75.9 – 96.4	76.7 $\pm$ 32.5	12.0 – 98.0
Reduction in water absorption (%)	13	48.0	30.0 – 70.0	48.4 $\pm$ 23.5	9.8 – 85.9
Reduction in permeability or chloride transport (%)	5	13.0	8.9 – 46.6	-0.9 $\pm$ 70.9	-123.3 – +50.1
Maximum healed crack width (mm)	21	0.50	0.30 – 1.00	0.65 $\pm$ 0.43	0.09 – 1.50
Healing period (days)	45	28	23 – 28	38.2 $\pm$ 41.0	2 – 224

3.3 Completeness of Reporting

Figure-5 and Table-6 present the most consequential result. Of the ten fields examined, only four could be recovered from more than half of the studies, and three of these — species, delivery route and exposure regime — are descriptive. Crack closure, the outcome that defines the technology, could be recovered from 21 of 54 studies (38.9%); the healed crack width from the same proportion; strength or stiffness recovery from 8 (14.8%); and permeability or chloride transport, the property that governs durability, from only 5 (9.3%). Only one study (1.9%) reported all four core outcomes — crack closure, healed crack width, strength change and water absorption — in extractable form; 11 reported none and 21 reported only one.

Reporting does not appear to be improving (Figure-5b). Between the pre-2024 studies (n = 16) and those from 2024 onwards (n = 38), the recoverability of crack closure fell from 50.0% to 34.2% and that of healed crack width from 62.5% to 28.9%, whereas that of compressive strength rose from 12.5% to 57.9%. Because the pre-2024 group contains only 16 studies, each of these proportions is imprecise (one study changes it by more than six percentage points), and the comparison indicates a direction rather than a measured trend. With that caveat, the field appears to be drifting towards the quantity that is easiest to measure and away from those that substantiate the healing claim. Reporting of permeability or chloride transport rose from 0% to 13.2%, a level that remains low.

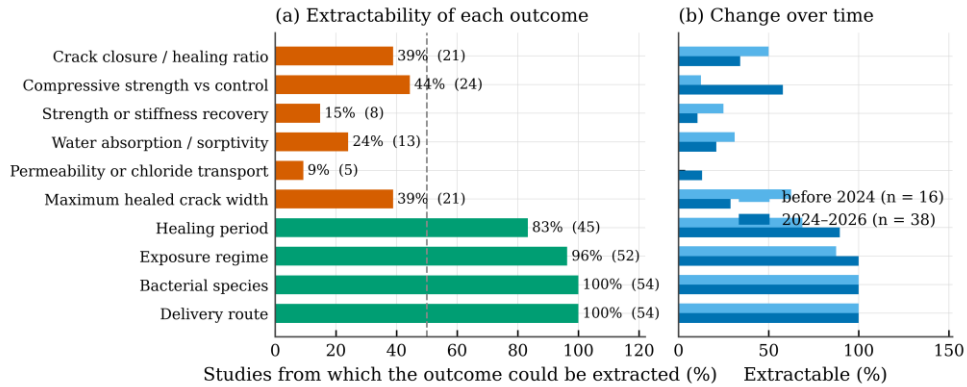


Figure-5: Extractability of each outcome: (a) proportion of the 54 studies from which each field could be recovered; (b) the same, before 2024 and from 2024.

Table-6: Extractability of each field across the 54 bacterial studies and its change over time.

Field	Studies (n)	Extractable (%)	Before 2024 (%)	2024–2026 (%)
Bacterial species	54	100.0	100.0	100.0
Delivery route	54	100.0	100.0	100.0
Exposure regime	52	96.3	87.5	100.0
Healing period	45	83.3	68.8	89.5
Compressive strength vs control	24	44.4	12.5	57.9
Crack closure/healing ratio	21	38.9	50.0	34.2
Maximum healed crack width	21	38.9	62.5	28.9
Water absorption/sorptivity	13	24.1	31.2	21.1
Strength or stiffness recovery	8	14.8	25.0	10.5
Permeability or chloride transport	5	9.3	0.0	13.2

3.4 Crack Width, Healing Period and the Ceiling Effect

Every primary study that discusses the matter states that healing efficiency falls as the crack widens, and the mechanism is not in doubt: a wider crack requires more precipitate and retains less of the water and ions the bacteria need. Individual datasets support it; Wang et al. [28], for example, achieved essentially complete closure of cracks up to 0.8 mm but only 43.2% of a 1.5 mm crack after sixteen cycles.

The pooled data do not reproduce the relationship. Across the 15 studies reporting both a healed crack width w (mm) and a closure percentage CC (%), the least-squares fit ($R^2 = 0.061$, $p = 0.373$) is:

$$CC = 91.8 - 9.6 w \quad \text{Eq. (1)}$$

and the Spearman correlation is $\rho = -0.030$ ($p = 0.916$). Excluding the two studies in which bacterial suspension was injected into a pre-formed crack does not change the conclusion ($n = 13$, $R^2 = 0.116$, $p = 0.255$; $\rho = +0.300$, $p = 0.319$), and there is no association between healing period and closure ($n = 20$, $\rho = 0.059$, $p = 0.805$).

One plausible explanation is that the reported maximum healed crack width is not an independent variable but the outcome of the same selection that produces the closure figure: authors tend to report the widest crack that healed well. Figure-6(b) is consistent with this reading: 9 of 21 studies (42.9%) report at least 90% closure and 7 (33.3%) report exactly 100%, a pattern expected of a selected rather than a sampled quantity. Other explanations cannot be excluded with only 15 paired observations — differences between studies in how closure and width are defined and measured, in mix design and in healing age can all mask a within-study relationship in a between-study comparison. The pooled result therefore does not show that width is unimportant; it shows that the published width–closure pairs cannot be used to estimate the relationship. Width limits quoted in the literature are best treated as feasibility demonstrations rather than design values.

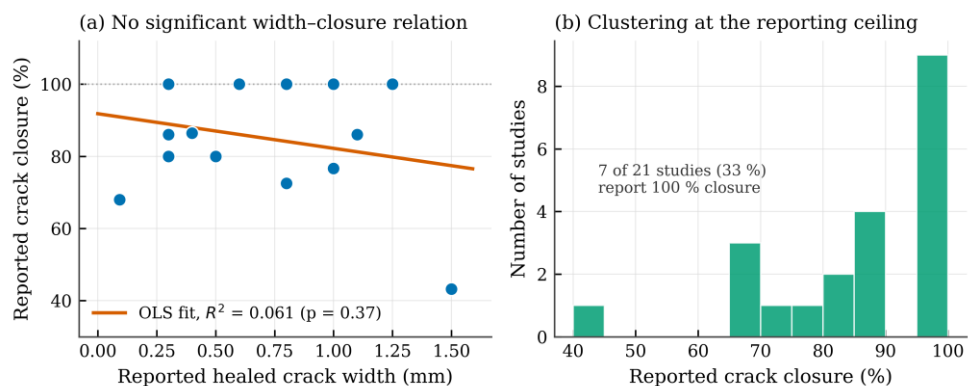


Figure-6: (a) Reported crack closure against healed crack width, with the least-squares fit; (b) distribution of reported closure, showing the clustering at 100%.

3.5 Delivery Route: Does Encapsulation Help?

Immobilising bacteria in a carrier — lightweight aggregate, ceramsite, expanded perlite, diatomaceous earth, zeolite, alginate microcapsules, hydrogels, superabsorbent polymers or biochar — is intended to protect spores from the high pH and mechanical stress of the fresh matrix, and the carrier

literature reports substantially longer spore survival [13, 35, 78, 87, 88]. Twenty-five of the 54 studies used a carrier and 29 added bacteria directly. On the outcomes that can be compared, no difference between the two routes was detected (Table-7, Figure-7): crack closure 92.8% (direct, $n = 10$) against 86.0% (carrier, $n = 11$), $p = 0.774$; strength change +19.6% ($n = 19$) against +22.9% ($n = 5$), $p = 1.000$; reduction in water absorption 33.3% ($n = 7$) against 58.0% ($n = 6$), $p = 0.520$; strength recovery 89.3% ($n = 3$) against 96.0% ($n = 5$), $p = 0.786$. These null results should not be read as evidence that the routes are equivalent. The 95% confidence interval for the difference in median closure runs from -17.1 to $+20.3$ percentage points, so a difference of up to about 20 points in either direction is compatible with the data, and the strength-recovery comparison rests on three and five observations. One comparison is not null: the healed crack width was 0.90 mm for direct addition against 0.40 mm for carriers (difference 0.50 mm, 95% CI 0.00 to 0.95 mm; $U = 83.0$, $p = 0.052$, $r = -0.51$), a large effect of borderline statistical significance. Because crack width is a major difficulty factor, this imbalance suggests that the two routes have not been compared on equal terms; the claim that encapsulation improves healing performance — as distinct from spore viability, which is well demonstrated — is therefore not supported by the assembled data, although it is not refuted either.

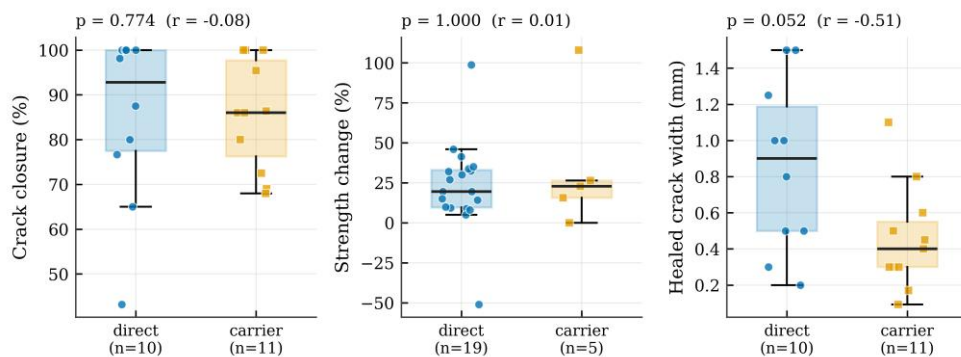


Figure-7: Direct addition compared with carrier immobilisation. No difference was detected in the first two comparisons (small subgroups; see Table-7 for confidence intervals); the third suggests that the groups were tested at different crack widths ($p = 0.052$).

Table-7: Subgroup comparison by delivery route (two-sided Mann–Whitney U test; exploratory). The difference in medians (direct – carrier) is given with a bootstrap 95% CI where study-level values are listed in Table-4.

Outcome	Direct: n / median	Carrier: n / median	U	p	r	Difference [95% CI]
Crack closure (%)	10 / 92.8	11 / 86.0	59.5	0.774	–0.08	+6.8 [–17.1, +20.3]
Change in compressive strength (%)	19 / +19.6	5 / +22.9	47.0	1.000	+0.01	–3.3 [–88.4, +19.6]
Reduction in water absorption (%)	7 / 33.3	6 / 58.0	16.0	0.520	+0.24	–
Strength or stiffness recovery (%) ^a	3 / 89.3	5 / 96.0	6.0	0.786	+0.20	–
Maximum healed crack width (mm)	10 / 0.90	11 / 0.40	83.0	0.052	–0.51	+0.50 [0.00, +0.95]

r = rank-biserial correlation. ^a One subgroup has fewer than five observations; interpret with particular caution. – = not computable because study-level values for this outcome are not tabulated.

3.6 Bacterial Species and Exposure Regime

Bacillus subtilis is the most frequently used organism (18 of 54 studies), followed by *B. sphaericus*/*Lysinibacillus sphaericus* (7) and *Sporosarcina pasteurii* (6); 21 studies used other species, mixed consortia or unidentified commercial preparations (Table-8). Median closure by group ranges from 65% to 98%, but the groups contain between one and seven closure values, and four of the five groups have three or fewer; the figures in Table-8 are therefore descriptive and were not tested. This review declines to rank species, and notes that the multicriteria ranking of Vedrtnam et al. [12] rests on a similarly limited base.

Table-8: Subgroup summary by bacterial species (descriptive only; groups were not tested because most contain three or fewer closure values).

Bacterial species group	Studies (n)	Median closure (%)	Median strength change (%)
Other/mixed	21	98.1 (n = 7)	+27.4 (n = 10)
<i>B. subtilis</i>	18	83.8 (n = 6)	+15.1 (n = 11)
<i>B. sphaericus</i> / <i>L. sphaericus</i>	7	72.5 (n = 3)	+27.0 (n = 1)
<i>S. pasteurii</i>	6	93.0 (n = 4)	+98.7 (n = 1)
<i>B. megaterium</i>	2	65.0 (n = 1)	+9.9 (n = 1)

The distribution of exposure regimes is more informative than the outcomes within them (Table-9, Figure-8). Forty-two studies (77.8%) measured healing under continuous water immersion; only four used wet–dry cycling, four marine or seawater exposure and two direct crack injection. Continuous immersion is the most favourable condition for MICP, since water and ions are never limiting. The ten studies using other regimes include one report of

higher efficiency in the tidal zone [76] and one of adverse chloride performance in seawater [75], but with two or three closure values per non-immersion regime no regime-level estimate can be made, and the medians in Table-9 should not be compared with one another. What the data do show is that the evidence base appears to be calibrated mainly on the condition least representative of service. The interaction of bacteria with supplementary cementitious materials, which alter pore structure and pH, has only recently begun to be examined directly [89].

Table-9: Subgroup summary by healing exposure regime (descriptive only; medians based on two or three values should not be compared).

Exposure regime	Studies (n)	Share of studies (%)	Median closure (%)
Continuous water immersion	42	77.8	87.0 (n = 14)
Wet-dry cycling	4	7.4	70.2 (n = 2)
Marine/seawater	4	7.4	100.0 (n = 3)
Direct crack injection	2	3.7	71.6 (n = 2)
Not reported	2	3.7	—

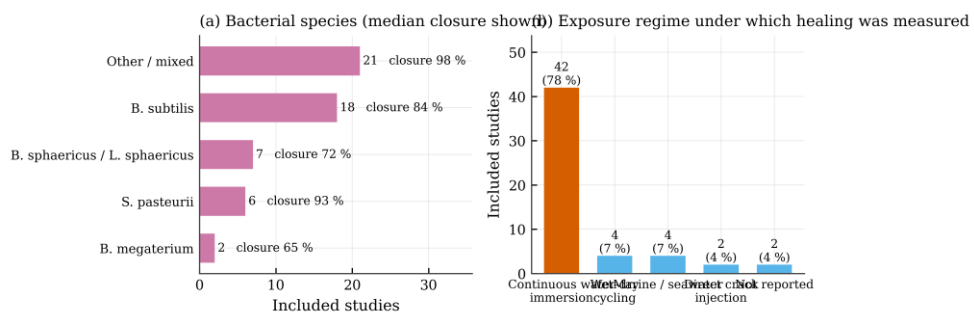


Figure-8: (a) Distribution of bacterial species with the median closure of each group; (b) exposure regime under which healing was measured.

3.7 Nano-Additives and the Synergy Question

The evidence on nano-additives divides into three parts (Figure-9b). First, the effect of nano-silica without bacteria is well established. Five studies in this set quantify nano-additive effects [8, 83–86]; the nano-silica dosage optima cluster narrowly at 2% [85], 3% [8, 83] and, for a colloidal suspension, 5% [86], and a review [9] places the practical optimum at 2–3% by binder mass. The median strength gain is +25.0% (range +19.0 to +34.5). Amorphous silica has also been reported to enhance autogenous healing [90], and nano-silica has been used in repair mortars produced with local waste materials in Iraq [91].

Dispersion is a quantified obstacle: Horszczaruk et al. [83] showed that commercial nano-silica agglomerates into millimetre-scale clusters unless high-speed mixing with ultrasonication and a superplasticiser is used.

Second, forty-eight studies quantify bacterial healing against a plain control (Sections 3.2–3.6).

Third, six studies in the main dataset place bacteria and a nano-additive in the same mix, and none includes the arms required to demonstrate synergy (Table-10). Agna et al. [54] report 80% closure of a 0.5 mm crack and a 46% strength gain with 3% nano-silica and *B. subtilis*, but with no nano-only arm, in a journal without a registered DOI. Li et al. [47] combined nano-SiO₂ with *S. pasteurii* as a surface treatment and halved the chloride migration coefficient without separating the contributions. Damodaran and Mayilsamy [58] report a 14.2% strength gain with 2% nano-silica in a bacterial matrix, Said et al. [69] a 32% gain with 0.5% nano-CaCO₃ and *B. tropicus*, Xiao et al. [44] used silica nanoparticles as an encapsulation shell rather than a matrix additive, and Khushnood et al. [40] used graphite nanoplatelets as a carrier. None reports the factorial comparison — control, bacteria alone, nano alone and both — from which a synergistic, as opposed to additive, effect could be inferred.

The update search (Section 2.9) identified two further combined studies. Nagarajan et al. [29] combined nano biomass silica with *Lysinibacillus fusiformis* and a polycarboxylate superplasticiser in 180 samples and predicted strength with machine-learning models (XGBoost, $R^2 = 0.91$); Shanthi Sri et al. [30] combined denitrifying bacteria with 0.06 wt% nano-graphene oxide and 15 wt% fly ash, reporting a 52% increase in 28-day strength and complete healing of 0.1–0.2 mm cracks. Both report an optimised combined mix; neither published abstract describes a nano-only control arm, so the conclusion is unchanged.

The aggregate picture in Figure-9(a) is compatible with simple additivity but cannot distinguish it from synergy or antagonism. Mixes containing a nano-additive show a median strength gain of +32.0% against +19.6% ($n = 11$) for mixes with no supplementary material, but the nano-containing group has only three values (+14.2%, +32.0% and +46.0%), so the difference was not tested, and the median is of the same order as the gain nano-silica produces alone (+25.0%). The published data therefore neither support nor refute the claim that nano-silica enhances bacterial healing; at present the claim rests on untested assumptions.

There is also a mechanistic reason why the interaction may be less favourable than is usually assumed (Figure-10). Nano-silica refines the pore structure and reduces permeability, whereas bacterial healing requires water and calcium ions to reach the dormant spores. A denser matrix should produce fewer and narrower cracks — which is beneficial — but may also slow the transport on which germination and precipitation depend. Evidence from coarser silica is mixed: Kang et al. [92] reported that silica fume combined with sisal fibre improved microbial healing by limiting dissolution of the healing product and improving calcium-ion utilisation, but silica fume is not a nano-additive and that study does not isolate the bacterial contribution. Whether the net effect of nano-silica is positive, neutral or negative remains an open empirical question.

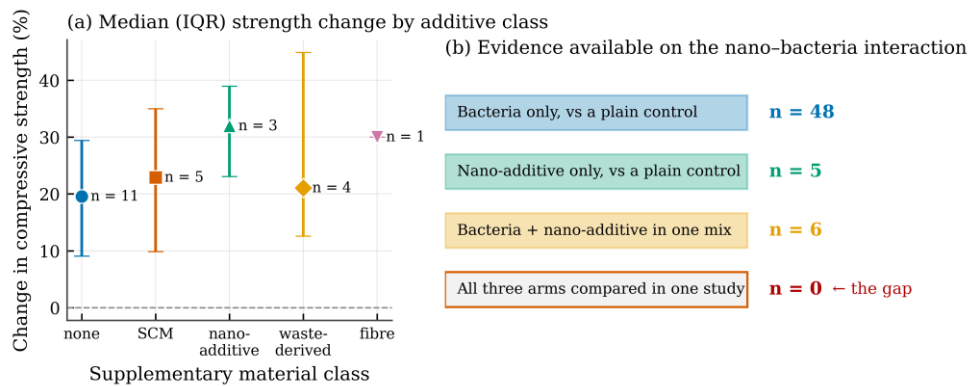


Figure-9: (a) Median and interquartile range of strength change by class of supplementary material; (b) the three bodies of evidence on the nano-bacteria question and the missing arm.

Table-10: Studies combining bacteria with a nano-additive. No study includes the nano-only arm required to separate the two contributions.

Study	Nano-additive	Dosage (% binder)	Bacteria	Reported outcome	Nano-only arm?
Xiao et al. [44] (2023)	SiO ₂ nanoparticles (encapsulation shell)	n/a (shell)	Spores (species NR)	Complete closure of cracks of a few hundred µm; strength not compromised	No
Khushnood et al. [40] (2022)	Graphite nanoplatelets (carrier)	NR	<i>B. subtilis</i>	Self-healing plus self-sensing mortar	No
Li et al. [47] (2024)	Nano-SiO ₂ (30 ± 5 nm)	NR	<i>S. pasteurii</i>	Chloride migration coefficient halved (–50.1%)	No
Said et al. [69] (2025)	Nano-CaCO ₃	0.5	<i>B. tropicus</i>	+32% compressive strength at 28 d; agglomeration above 0.5%	No
Agna et al. [54] (2025)	Nano-SiO ₂	3.0	<i>B. subtilis</i>	0.5 mm crack reduced to 0.1 mm (80% closure); +46% strength	No
Damodaran & Mayilsamy [58] (2025)	Nano-SiO ₂ (+ silica fume, steel fibre)	2.0	NR	+14.2% compressive strength	No

Study	Nano-additive	Dosage (% binder)	Bacteria	Reported outcome	Nano-only arm?
Nagarajan et al. [29] (2025) ^u	Nano biomass silica (+ PCE)	12 (optimum)	<i>L. fusiformis</i>	Strength predicted by ML (XGBoost $R^2 = 0.91$)	Not described
Shanthi Sri et al. [30] (2026) ^u	Nano-graphene oxide (+ 15% fly ash)	0.06	Denitrifying bacteria	+52% strength at 28 d; 100% closure of 0.1–0.2 mm cracks	Not described

^u Identified in the update search (Section 2.9); information from the published abstract; not pooled. NR = not reported; PCE = polycarboxylate ether.

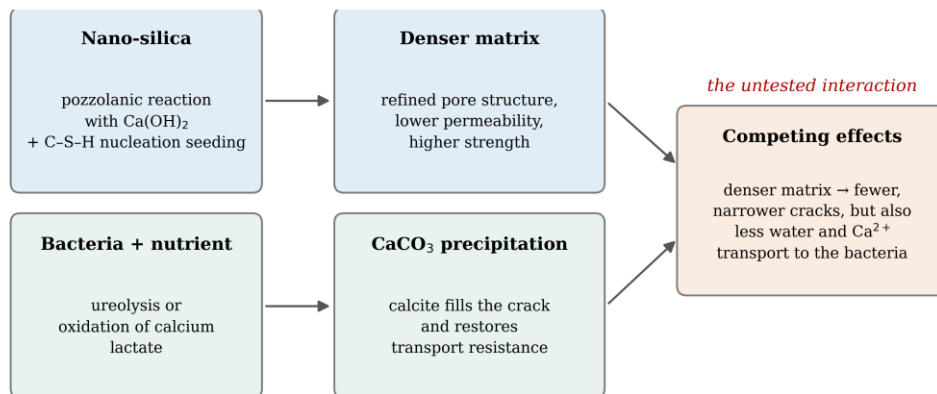


Figure-10: The two mechanisms and the untested interaction: matrix densification by nano-silica should reduce cracking but also restrict the transport on which bacterial healing depends.

3.8 Durability, Cost, Environmental Burden and Field Evidence

On environmental burden, the only life-cycle assessment identified [93] reports that bacteria-based self-healing concrete carries an overall environmental impact about 85% higher than conventional concrete, with 36% higher embodied carbon and a 51% larger water footprint, driven mainly by production of the bacterial medium; a 12–50% net improvement becomes achievable only if the enhanced durability is used to justify a reduction in reinforcement.

On cost, the source giving explicit unit prices [19] places conventional concrete at 55–75 €/m³, bacterial cells on diatomaceous earth at about 60 €/m³, manual crack injection at about 140 €/m³, polyurethane capsules at 3% dosage at 630 €/m³ and some encapsulation additives as high as 5670 €/m³; a cost-design estimate [94] likewise identifies the healing agent and its carrier as the dominant cost items. The economic case therefore depends almost entirely on the carrier.

Field evidence is weak. The only full-scale evaluation identified [95] examined four demonstrator projects and found no adverse construction effects, but evidence of enhanced healing was difficult to obtain because the structures cracked very little. A technology with more than a thousand laboratory publications and one inconclusive field evaluation is not ready for specification, and Barros et al. [96] describe commercialisation as still in its infancy. Machine learning has begun to be applied: Khosravi et al. [97] predicted crack-repair percentage from 1271 samples with $R^2 = 0.9997$, and Sukumaran et al. [70] and Nagarajan et al. [29] used similar models. Such accuracy should be read in light of Section 3.3: a model trained on selectively reported outcomes will reproduce the selection, not the mechanism.

4. DISCUSSION

4.1 What the Evidence Supports

The pooled results are encouraging: a median crack closure of 86%, a strength gain of about 20% and a halving of water absorption are large effects by the standards of concrete technology, and they are reproduced across many groups, several bacterial genera and a range of mix designs. The mechanism is confirmed microstructurally in study after study by scanning electron microscopy, X-ray diffraction and energy-dispersive spectroscopy, which identify calcite as the healing product. That MICP heals cracks in cementitious materials is not in doubt.

4.2 Four Structural Weaknesses

What is in doubt is whether the published effect sizes can be transferred to design. Four weaknesses compound one another. (i) Selective and possibly declining reporting: only 1.9% of studies report the four core outcomes together, the key durability outcome is recoverable from 9.3%, and reporting of closure and healed width appears to have declined since 2024. (ii) A ceiling in the reported outcome: a third of the studies report exactly 100% closure, and the pooled data show no clear relationship between crack width and closure although individual studies consistently report one. (iii) Unbalanced comparisons: carrier and direct-addition studies tended to use different crack widths ($p = 0.052$), so whether to encapsulate — the most important design choice — does not appear to have been evaluated on comparable specimens. (iv) An unrepresentative exposure regime: more than three-quarters of the

evidence was generated under continuous immersion, and the ten studies using other regimes are too few to estimate the effect of exposure, although they include both an encouraging result [76] and a clearly adverse one [75].

4.3 The Synergy Hypothesis: Plausible but Untested

Eight studies now combine bacteria with nano-additives, none isolates the two contributions, and the two mechanisms may be in physical conflict, since one restricts transport and the other depends on it. The present position is best stated as follows: the combination is promising but untested, not demonstrably beneficial. Reviews that describe nano-silica and bacteria as complementary [98] extrapolate from two separate literatures rather than reporting a tested interaction.

4.4 Relevance to Hot-Arid and Saline Environments

For southern Iraq and the Gulf the implications are specific. Local structures experience high temperature, low relative humidity for much of the year, sharp wet–dry cycling and high chloride and sulfate concentrations — conditions unlike those under which almost all the evidence was generated. High temperature accelerates bacterial metabolism but also desiccates the matrix and shortens the healing window; high chloride concentration inhibits some strains, although adaptive evolution has restored activity at 35 g/L NaCl and pH 12 [62], and marine isolates have outperformed terrestrial *Bacillus* strains in seawater [46]. Only four studies used marine exposure and one reported an adverse chloride outcome. Application in the region should therefore be preceded by locally conditioned testing, and isolating indigenous halotolerant strains — already demonstrated elsewhere [64, 65] — is a more promising start than importing a strain selected under temperate conditions.

4.5 Comparison with Previous Reviews

The conclusions differ from those of earlier reviews because of the pooling. Narrative reviews summarise each study's headline claim, and since almost every study reports success the aggregate reads as uniformly positive. Pooling exposes the dispersion, ceiling, unbalanced comparisons and reporting gaps that a study-by-study narrative cannot show. This review agrees with Cappellesso et al. [22] that laboratory conditions overstate performance and quantifies by how much the evidence departs from service conditions; it agrees

with the RILEM inter-laboratory studies [24, 25] that standardisation is the binding constraint, and adds that the problem is worsening.

5. A MINIMUM REPORTING AND TESTING PROTOCOL

The remedy for most of the deficiencies documented above is better-specified experiments rather than more experiments. Table-11 proposes a minimum set of reported quantities and test conditions derived from Sections 3.3–3.7. None of the items is novel or expensive; the point is that they should be reported together as a matter of routine.

Table-11: Proposed minimum reporting and testing protocol for studies of bacterial self-healing concrete.

Requirement	Rationale (section)
Report crack closure AND healed crack width AND strength change AND a transport property (absorption, permeability or chloride migration) for every mix	Only 1.9% of studies currently do so (3.3)
Report the full distribution of crack widths tested, not only the widest that healed	Reported widths behave as selected rather than sampled (3.4)
Report closure as a distribution or with a measure of scatter, never as a single “100%”	One third of studies report exactly 100% (3.4)
Match crack widths across compared groups, or report comparisons width-by-width	Carrier and direct groups were tested at different widths (3.5)
Include at least one exposure regime other than continuous immersion — wet–dry cycling as a minimum	77.8% of studies used immersion only (3.6)
Extend at least one series beyond 90 days and report re-cracking and repeat healing	Median assessment age is 28 days; only four studies exceeded 90 (3.2)
For any mix containing a nano-additive, include four arms: control, bacteria only, nano only, both	No existing study does (3.7)
Report the dispersion procedure and dosage basis for any nano-additive	Dispersion substantially alters the effect of a nominal dosage (3.7)
Report the carrier dosage and its independent effect on strength	Porous carriers carry a strength penalty often not separated (3.5)
Report replicate counts and a measure of variability for every quantity	Prerequisite for any future meta-analysis (2.7)

For the synergy question, the required design is a four-arm factorial with matched crack widths: a plain control; bacteria at a fixed cell concentration; nano-silica at the 2–3% optimum; and both together — each arm cracked to the same controlled width, healed under both immersion and wet–dry cycling, and assessed for closure, strength recovery and chloride migration. Such an experiment is within the reach of a normally equipped university laboratory.

6. LIMITATIONS

(a) Several platforms did not allow bulk export of their result lists, and Google Scholar returns relevance-ranked results, so the identification stage cannot be reconstructed as a single exported count for every source; the Boolean strings of Table-A2 allow the search to be re-executed in Scopus or Web of Science for independent verification. (b) Thirteen reports could not be retrieved in full text; if they differ systematically from the retrievable literature, the synthesis is biased to an unknown degree. (c) The extractability audit measures what could be recovered from the records inspected, which in some cases were abstracts; it quantifies the accessibility of each outcome rather than proving its absence from the underlying paper. (d) Study-level variances were not available, so no random-effects meta-analysis, heterogeneity statistic or funnel-plot test could be computed; the ceiling analysis of Section 3.4 is an indirect substitute for a publication-bias test. (e) Most subgroups are small — species groups contain one to seven closure values, non-immersion exposure regimes two or three, and the nano-containing group three strength values — and no correction for multiple testing was applied; all subgroup comparisons are exploratory, and null results indicate absence of evidence, not evidence of equivalence. (f) The rules used to select one value per study (Section 2.6) favour the authors' optimal mixtures and may bias the pooled estimates upwards. (g) Screening and extraction were performed by a single reviewer. (h) The two studies identified in the update search were not pooled.

7. CONCLUSIONS AND RECOMMENDATIONS

Eighty-seven records, including 59 primary studies, were synthesised to establish what bacterial self-healing concrete demonstrably achieves and what the turn towards nano-additives rests on. The principal conclusions are:

1. Across 54 bacterial studies, the median crack closure is 86.4% (IQR 76.7–100), the change in compressive strength +21.2% (+19.6% after trimming), the reduction in water absorption 48.0% and the healed crack width 0.50 mm, assessed after a median of 28 days.
2. The evidence base is thinly and selectively reported: 1 of 54 studies makes all four core outcomes recoverable, permeability or chloride transport is recoverable from 9.3%, and the reporting of closure and healed width has fallen since 2024 while that of compressive strength has risen.

3. Pooled data show no clear relationship between crack width and closure ($R^2 = 0.061$, $p = 0.373$, $n = 15$), and a third of studies report exactly 100% closure; published width limits are best treated as feasibility demonstrations, not design values.
4. No advantage of carrier immobilisation over direct addition was detected (closure $p = 0.774$; strength $p = 1.000$), but the subgroups are small and differences of up to about 20 percentage points in closure cannot be excluded; carrier studies also tended to use narrower cracks (0.40 vs 0.90 mm, $p = 0.052$).
5. 77.8% of the evidence was generated under continuous immersion; the ten studies using wet–dry, marine or injection regimes are too few to estimate the effect of exposure.
6. No study combining bacteria with a nano-additive includes the nano-only control arm; the synergy hypothesis is untested, and a mechanistic argument suggests that the interaction could be partly antagonistic.
7. Deployment evidence remains weak: one inconclusive full-scale evaluation, an 85% higher environmental impact unless reinforcement is reduced, and costs competitive only for the cheapest carriers.

It is recommended that future studies (i) adopt the minimum reporting and testing protocol of Table-11; (ii) include wet–dry cycling and saline exposure representative of hot-arid regions; (iii) extend monitoring beyond 90 days with re-cracking; (iv) use the four-arm factorial design to test nano–bacteria synergy; and (v) report replicate counts and variability so that a formal meta-analysis becomes possible.

APPENDIX A. SEARCH DOCUMENTATION

Table-A1 lists the sources searched, the fields and limits applied, the date of the final search and the number of records retrieved from each, together with the PRISMA 2020 counts at each subsequent stage. Table-A2 gives the five query families of Table-1 as Boolean strings for direct re-execution.

Table-A1: Search log — sources, fields, limits, date of final search and records retrieved, followed by the PRISMA 2020 counts at each stage. Cells marked [●] are completed from the author's search log.

Source	Interface and fields searched	Limits applied	Final search	Records retrieved
ScienceDirect (Elsevier)	Advanced search; title, abstract, keywords	None	[●]	[●]
SpringerLink / Nature.com	Advanced search; full text (no field restriction available)	None	[●]	[●]
MDPI	Advanced search; title, abstract, keywords	None	[●]	[●]
Wiley Online Library	Advanced search; abstract and keywords	None	[●]	[●]
Taylor & Francis Online	Advanced search; title, abstract, keywords	None	[●]	[●]
Frontiers	Site search; all fields	None	[●]	[●]
Oxford Academic	Advanced search; title and abstract	None	[●]	[●]
De Gruyter	Advanced search; all fields	None	[●]	[●]
DOAJ	Article search; title, abstract, keywords	None	[●]	[●]
PubMed Central	Advanced search; title/abstract	None	[●]	[●]
Institutional repositories	Repository search; all fields	None	[●]	[●]
Google Scholar	Natural-language strings of Table-1; relevance-ranked	Results screened to the depth recorded in the log	[●]	[●]
Citation chasing	Backward and forward, from reviews in Section 1.1	—	[●]	[●]
Update search (Section 2.9)	Strings of Table-A2 re-run on the sources above	Publication since the original search	September 2026	[●]
PRISMA stage	Records identified (all sources)			[●]
	Duplicates removed (DOI, then title—first author—year)			[●]
	Records screened on title and abstract			[●]
	Records excluded on title and abstract			[●]
	Reports sought for retrieval			106
	Reports not retrieved			13
	Reports assessed for eligibility			93
	Reports excluded (no quantitative outcome 3; market report 1; non-cementitious 1; duplicate dataset 1)			6
	Records included (59 primary + 28 contextual)			87

Table-A2: Boolean form of the five query families for direct re-execution in Scopus (TITLE-ABS-KEY). For Web of Science Core Collection the same terms

are entered as TS=(...); on platforms without full Boolean support the natural-language strings of Table-1 were used.

Query family	Boolean string (Scopus syntax)
Q1 Mechanism and species	TITLE-ABS-KEY ((bacteri* OR microb* OR MICP OR "microbially induced calcite precipitation" OR "microbially induced carbonate precipitation" OR bacillus OR sporosarcina OR lysinibacillus) AND ("self-healing" OR "self healing" OR "crack healing" OR "crack repair") AND (concrete OR mortar OR cementitious OR "cement paste"))
Q2 Carriers and immobilisation	TITLE-ABS-KEY ((bacteri* OR microb* OR spore*) AND (encapsulat* OR immobili* OR carrier* OR "expanded clay" OR LECA OR perlite OR "diatomaceous earth" OR diatomite OR zeolite OR alginate OR hydrogel OR "superabsorbent polymer*" OR biochar OR ceramsite) AND ("self-healing" OR "crack healing") AND (concrete OR mortar OR cementitious))
Q3 Nano-additives	TITLE-ABS-KEY (("nano-silica" OR nanosilica OR "nano silica" OR "nano-SiO2" OR nanomaterial* OR "nano-CaCO3" OR "nano-TiO2" OR "graphene oxide" OR nanoparticle*) AND (concrete OR mortar OR cementitious) AND (bacteri* OR microb* OR "self-healing" OR "optimum dosage" OR dispersion OR agglomerat*))
Q4 Assessment and durability	TITLE-ABS-KEY (("self-healing" OR "crack healing") AND (concrete OR mortar) AND (bacteri* OR microb* OR MICP) AND (permeability OR sorptivity OR "water absorption" OR chloride OR "wet-dry" OR "X-ray" OR "computed tomography" OR RILEM OR "healing efficiency" OR durability))
Q5 Context and translation	TITLE-ABS-KEY (("self-healing concrete" OR "bacterial concrete" OR "bio-concrete" OR "biocement") AND (review OR bibliometric OR "life cycle assessment" OR LCA OR cost OR "machine learning" OR "field application" OR "full-scale" OR commerciali* OR demonstrator))
Combination	Q1 OR Q2 OR Q3 OR Q4 OR Q5; no language or date limit; document types restricted at screening (Table-2)

DECLARATIONS

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Data availability: The full extraction database and the analysis script that generates every figure and table in this paper are provided as supplementary material.

Author contributions: Conceptualisation, methodology, data extraction, formal analysis, writing — original draft and revision: A. A. Shandel.

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