

Review

State-of-the-Art Review of Biomineralization-Based Self-Healing Concrete: Chronological Development from Bacteria to Fungi and Algae

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Abstract

Cracks pose a significant threat to the structural integrity, durability, and service life of concrete; therefore, sustainable, autonomous repair solutions are paramount. In the last 25 years, bio-based self-healing, particularly microbially induced calcium carbonate precipitation (MICP), has become an attractive technology. Self-healing by bacteria has been studied extensively, but the use of other biomineralization agents, such as fungi and algae, has unique benefits, namely, hyphal crack-bridging and photosynthetic mineralization. In this paper, a thorough state-of-the-art review is presented that compares bacteria, fungi, and algae as biomineralization agents. The comparative methodology involves a structured review of the peer-reviewed literature on these agents (2000–2025), and compares them on a set of common performance criteria: (i) biochemical precipitation mechanisms (ureolytic, non-ureolytic, photosynthetic and hyphal bridging); (ii) quantitative crack-healing efficiency (maximum width of crack closed); (iii) mechanical performance recovery (restoration of compressive and tensile strength); (iv) long-term durability enhancement. Moreover, it critically evaluates implementation challenges, including biological viability in extreme cementitious media, encapsulation methods, and the levels of technological maturity for practical engineering applications. The findings of this synthesis outline key research gaps and offer a roadmap for creating hybrid, consortium-based self-healing systems to help engineers and researchers select the best bio-based concrete for a given structure and environment.

Keywords: biomineralization; self-healing concrete; MICP; CO₂ sequestration; fungi; algae

Academic Editor: João Castro-Gomes

Received: 2 June 2026
Revised: 15 July 2026
Accepted: 30 July 2026
Published: 6 August 2026

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1. Introduction

With rapid urbanization, concrete has emerged as the core material in the construction of most civil engineering structures, including bridges, nuclear power plants, high-rise buildings, dams, and transport infrastructure, owing to its superior compressive strength, availability of raw materials, durability, and relative cost-effectiveness compared to steel or timber [1]. Concrete is the foundation of economic progress in most

countries, with an annual production exceeding 30 billion tons [2]. Nonetheless, even with these benefits, concrete has low tensile strength that generally does not go beyond 8 to 15% of its compressive strength capacity, resulting in crack initiation and propagation during the hardening stage due to plastic shrinkage, and throughout service life because of drying shrinkage (intrinsic), mechanical loading, thermal stresses, chemical attack, and environmental exposure (extrinsic) [3]. These microcracks commonly cause deterioration of the concrete matrix, affecting durability and shortening its service life. Microcracks in concrete provide an easy pathway for aggressive environmental factors, such as chloride ions, de-icing salts, soil sulfates, and atmospheric moisture [4,5]. When they reach the reinforcement, these agents break the protective oxide coating, leading to corrosion and spalling, loss of bond strength, and, ultimately, disastrous structural failures [6].

Initial research has identified that concrete has a weak intrinsic capacity to self-heal, or, more simply put, responds by forming C-S-H or other hydration products to seal cracks, a phenomenon often referred to as autogenous self-healing [7]. Nonetheless, there are limitations to these healing mechanisms, that is, they are more dependent on favorable humidity and temperature. The shortcomings of the above-mentioned healing system require the use of alternative healing agents that are more effective and sustainable [8].

Among the different healing processes studied, biomineralization, specifically, Microbially Induced Calcite Precipitation (MICP), is the most feasible and consistent approach for cementitious composites [9]. This process is predominantly influenced by bacteria, which promote self-healing in concrete. Introduction of biological agents not only heals microcracks but also seals the inner cavities of cement composites, thereby enhancing the matrix's microstructural behavior. Calcite also occupies capillary pores, depositing on these nucleation sites to densify the microstructure of the concrete matrix, that is, at the interfacial transition zones (ITZ), which are the porous, weak parts of the concrete matrix due to the contact between the cement-aggregate phase [10]. By enhancing the ITZ and decreasing total voids through MICP, the cement composites increase strength by 15–30% in compression zones [11,12].

The application of microorganisms in cementitious materials evolved from earlier studies on microbial-induced calcium carbonate precipitation (MICP). The pioneering work of Stocks-Fischer et al. (1999) first demonstrated that bacterial metabolic activity could induce calcium carbonate precipitation under controlled conditions, establishing the fundamental biomineralization mechanism [13]. Building upon this concept, Ramachandran et al. (2001) successfully demonstrated the use of microorganisms for crack remediation in concrete, providing the first evidence that microbial biomineralization could enhance the durability and service life of cementitious materials [14]. These landmark studies laid the foundation for subsequent research on bacterial self-healing concrete and later developments involving fungal and algal biomineralization.

While bacterial systems have dominated early research in this field, recent attention has shifted to fungal biomineralization, which has shown significant potential as an alternative due to its distinct physiological and structural benefits [15]. Unlike prokaryotic bacteria, fungi are eukaryotes, meaning their growth is filamentous, in the form of hyphae that combine to create a mycelial network [16]. In addition to biochemical mineralization of the mineral via metabolic pathways such as organic acid formation and respiration, fungi also play a mechanical role through hyphal bridging, in which filamentous structures are physically transferred across cracks and voids [17,18]. This twofold action not only enhances crack closure but also increases tensile strength and ductility. In addition, the vast mycelial system deeply permeates the pore structure and extends even into inaccessible areas, such as the interfacial transition zone. This will lead to denser matrices, lower porosity, and increased load transfer efficacy within the composite system.

Parallel to this, *cyanobacteria* and algae-based systems are also a new and environmentally friendly solution to biomineralization, especially in carbon sequestration-based construction materials [19]. The biochemical shift promotes the precipitation of calcium carbonate when calcium ions are available in the cement matrix. This process does not produce harmful byproducts, unlike ureolytic processes, thereby making it inherently environmentally friendly and aligned with the global sustainability agenda [18]. Moreover, the extracellular polymeric substances (EPS) released by these microorganisms can serve as efficient templates to promote nucleation and enhance crystal adhesion and distribution. Combining cementitious materials with such systems will make concrete surfaces an active carbon sink, thereby aiding the reduction of CO₂ and improving durability [20]. In addition, the slow, regulated kinetics of precipitation in the photosynthetic pathway ensure homogeneous pore fill-up and crack healing, thereby reducing permeability and improving long-term composite performance.

In recent years, several review papers have been published related to microorganism-based self-healing concrete and have improved the understanding of the topic by describing the bacterial biomineralization phenomenon, the microbial calcium carbonate precipitation (MICP) phenomenon, and the mechanical and durability performance of cementitious microorganisms' materials [21,22]. Most reviews, however, focus on bacterial systems and are limited to fungi and algae, or examine fungi and algae separately without direct comparison using the same set of engineering evaluation criteria. In addition, quantitative performance data from the literature may not be easily comparable because they do not sufficiently account for differences in the curing process, bacterial concentration, encapsulation process, crack width, exposure environment, and testing methods.

To address these limitations, the present review critically evaluates bacteria-, fungi-, and algae-based self-healing systems, as shown in Figure 1, using a comparative approach within a common framework comprising biomineralization mechanisms, crack-healing capability, mechanical performance, durability enhancement, encapsulation strategies, and technology readiness. The reported results are not interpreted as percentage improvements in themselves, but rather within the experimental context in which they have been obtained. Furthermore, recent pilot-scale demonstrations, developments, and new technologies for encapsulation are discussed to evaluate the practical application of each biological system. This review combines a mechanistic understanding approach with a critical performance evaluation and implementation approach, and offers an updated assessment of the self-healing concrete with microorganisms.

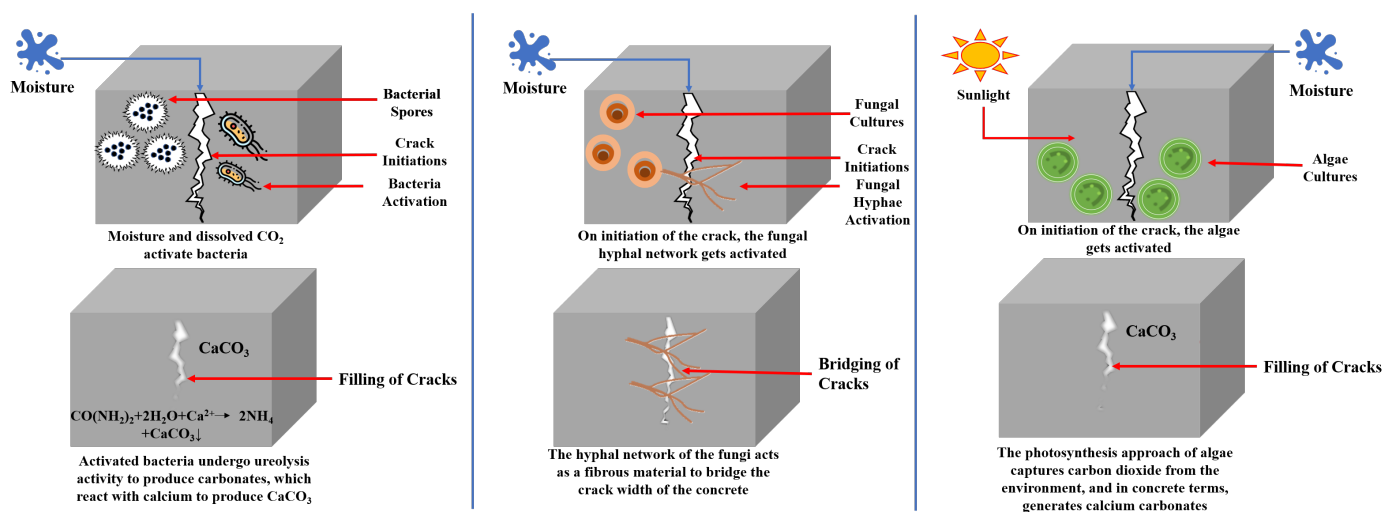


Figure 1. Biomineralization in cement composites using bacteria, fungi, and algae.

2. Review Methodology and Framework

2.1. Review Methodology

A structured literature review was conducted to evaluate the current state of micro-organism-based self-healing concrete, focusing on the mechanisms, performance, advantages, limitations, and practical applicability of bacterial-, fungal-, and algal-mediated systems. A total of 194 relevant studies published between 2000 and 2025 were systematically reviewed, with literature retrieved from Scopus, Web of Science, MDPI, ASCE Library, and other major scientific databases. The review included highly cited peer-reviewed journal articles, along with selected conference proceedings.

Searches used keywords such as self-healing concrete, microbial-induced calcium carbonate precipitation (MICP), bio-concrete, bacteria, fungi, algae, encapsulation, crack healing, and durability, supplemented by backward and forward citation tracking. Studies were included if they investigated microorganisms as self-healing agents in cementitious materials and reported crack healing, mechanical performance, durability, or biomineralization outcomes.

Duplicate, irrelevant, and technically insufficient studies were excluded. Field demonstrations, pilot projects, and commercial implementations were also assessed to evaluate technology readiness and practical feasibility, enabling identification of current research trends, knowledge gaps, and future research directions.

2.2. Review Framework

This review begins with an introduction to the basic self-healing processes in cement-based materials, such as autogenous and autonomous healing, to provide the conceptual context for biologically induced healing. This is followed by an explanation of bacterial self-healing systems, including the different types of microbes, the metabolic pathway that facilitates the precipitation of calcium carbonate, and different incorporation methods, including direct addition, encapsulation, and advanced incorporation. The mechanical properties and durability performance of bacterial healing are critically analyzed. In addition, recent developments in bacterial self-healing, such as sustainable nutrient sources and hybrid healing systems, are presented to highlight the growing trends in research.

The review then examines fungi-based self-healing solutions, specifically within the groups of filamentous fungi, biomineralization mechanisms, and fungal adaptation to harsh cementitious conditions, and their effects on crack healing, mechanical properties, and durability of concrete. The major issues associated with biological viability, scalability, and biosafety are also discussed, and the latest breakthroughs aimed at enhancing fungal healing are described.

It is then followed by a discussion of algae-based self-healing systems, focusing on their photosynthetic biomineralization processes and carbon-capture capabilities. A critical evaluation of algal performance in terms of crack sealing, environmental compatibility, and sustainability benefits is conducted. The constraints on their applicability to dark and strongly alkaline concrete conditions are identified, and efforts to address them are also discussed in the present research.

Lastly, the relative benefits, constraints, and levels of technological readiness of bacterial, fungal, and algal healing systems are proposed through comparative analysis. The review concludes by summarizing the major gaps in the research, future perspectives, and how integrating biological healing with innovative materials can support the next generation of self-healing cementitious composites. The review framework is depicted in Figure 2.

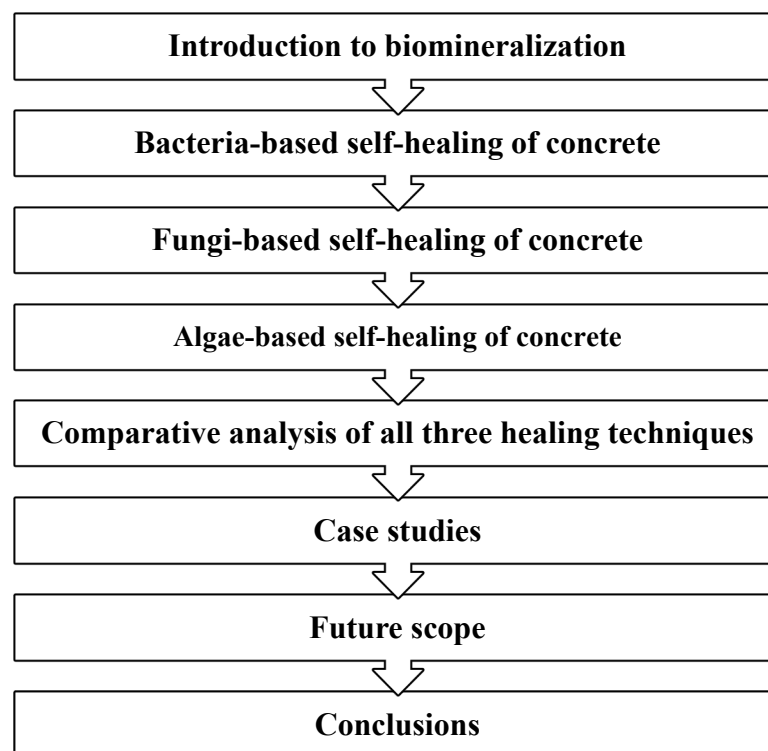


Figure 2. Review framework as per the chronological evaluation of the self-healing mechanism of concrete via biomineralization.

3. Bacteria-Based Self-Healing Concrete

Carolyn M. Dry originated the concept of self-healing concrete, and it has since become one of the main research directions in civil engineering. Early research focused on the process of autogenous healing, and scientists such as Havard Edvardsen and Steffen Jacobsen demonstrated the effectiveness of continued hydration and calcite deposition in closing cracks. This was inspired by polymer-based self-healing systems, especially the microcapsule system first proposed by Scott R. White. Later, encapsulated healing agents and strain-controlled materials developed by researchers such as Victor C. Li and Hirozo Mihashi were incorporated into cementitious systems, leading to a shift toward intelligent concrete [1,23]. Of these developments, the most widely researched has been bacteria-based self-healing, which uses Microbially Induced Calcite Precipitation (MICP) to precipitate calcium carbonate to seal cracks and restore structural integrity, having progressed from experimental laboratory testing to field implementation [24,25].

One key aspect of this approach is the strategic selection of bacterial species that can survive in a harsh concrete environment, including high alkalinity, limited moisture, and restricted nutrient availability [26]. Spore-forming bacteria are particularly suitable because they can remain in a dormant state for extended periods and activate to metabolize when moisture and oxygen are present. These species operate through a variety of metabolic processes, including ureolytic and non-ureolytic processes, resulting in the precipitation of calcium carbonate (CaCO_3) [27,28].

The resultant precipitates not only seal cracks but also enhance the mechanical and durability properties of cement composites [29,30]. Researchers consistently report recovery of the compressive and flexural strength in bacteria-based samples, even after cracking. To increase the longevity of bacteria in concrete environments, studies have explored immobilization using materials such as hydrogels, polyurethane, lightweight aggregates, and fibers, thereby enhancing concrete's inherent properties and improving sealing efficiency [31,32]. This section critically analyzes the types of bacteria used over the past two

and a half decades, their efficiency in crack healing, the different healing mechanisms they use, and their effects on the mechanical and durability properties of cement composites and new-age bacterial concrete.

Although much is said about the crack-healing property of Microbially Induced-Calcium Carbonate Precipitation (MICP), there is a critical difference between the biological precipitation of calcium carbonate in localized areas and the carbonation of the matrix. The uncontrolled deposition of some CaCO_3 polymorphs may lead to localized expansive stresses and a corresponding decrease in matrix alkalinity that can start steel rebar corrosion. To overcome this, the right selection of alkaliphilic bacterial strains (e.g., certain strains of the genus *Bacillus*) and the right protective carrier mediums (e.g., hydrogels or microcapsules) must be used, as highlighted in recent advanced materials literature (ISBN: 978-1-83962-480-3) [33]. These functional systems are advanced and ensure that crystal deposition is only in structural voids, allowing the concrete to be sealed against moisture intrusion while maintaining the high pH required to inhibit corrosion of the concrete's internal reinforcement.

3.1. Principles and Types of Bacterial Selection

The microbial-induced calcium carbonate precipitation (MICP) bacteria are often classified in groups based on their environmental preferences (acidophilic, neutrophilic, alkaliphilic, halophilic) and oxygen requirements (aerobic, facultative/anaerobic), and the biochemical pathway through which they get their carbonate (ureolytic vs. non-ureolytic), as demonstrated in Figure 3. This three-axis system (pH, oxygen, metabolism) is not only taxonomic; it defines survival in the cement pore solution, kinetics and morphology of precipitated CaCO_3 , and environmental trade-offs (e.g., ammonia production in ureolytic systems) [34]. Modern reviews and experimental studies suggest that the strain should be chosen for characteristics that resemble the desired field environment and curative needs.

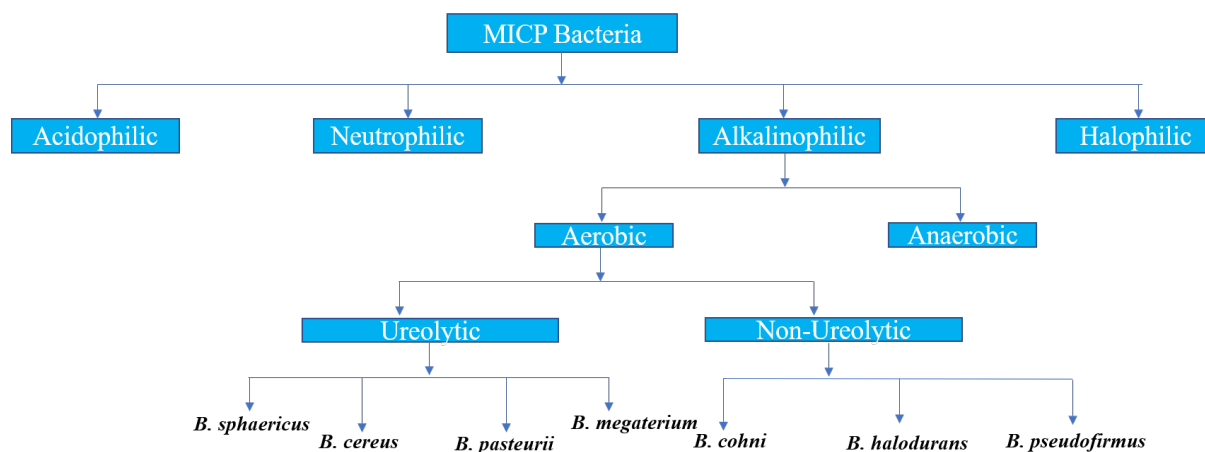


Figure 3. Hierarchical classification of MICP-producing bacteria according to pH tolerance, oxygen requirements, and biomineralization pathways (ureolytic and non-ureolytic) (proposed/compiled by the authors based on literature criteria) [35–37].

Alkaliphilic, Gram-positive, and spore-forming bacteria of the genera *Bacillus* and *Sporosarcina* are among the most used in MICP-based self-healing. They are also highly endosporic, which makes them highly resistant to harsh environments such as desiccation, high pH, and chemical stress; hence, they are suitable for cementitious conditions [34]. Among these, *Sporosarcina pasteurii* (also known as *Bacillus pasteurii*) has been widely used for its high efficacy in calcite precipitation and as a model organism in early MICP

research and scale-up experiments [38,39]. However, recent investigations have begun to broaden the scope to include other alkaliphilic *Bacillus* species (non-ureolytic), such as *Bacillus pseudofirmus*, *Bacillus halodurans*, and *Bacillus cohnii*, due to limitations in ureolytic metabolic pathways (as discussed in subsequent Section 3.2.2). These strains are gaining popularity because they can produce a stable, dense CaCO_3 with better environmental suitability [40].

The second determinant axis of strain choice is oxygen tolerance (aerobic vs. facultative/anaerobic), since oxygen diffusion into cracks is depth- and geometry-sensitive. Surface and hairline cracks are open to the air, supporting strictly aerobic and fast-acting ureolytic strains in the generation of fast surface sealing [41]. On the contrary, deep interior microcracks, internal crevices, or areas distant from oxygen uptake require facultative anaerobes or strains capable of altering their metabolism to low-oxygen conditions to proceed with biomineralization [42,43]. The literature has reported several facultative *Bacillus* strains and other denitrifying organisms that can sustain calcifying activity in low-oxygen microenvironments, thereby extending the effective healing depth compared with aerobic-based systems.

The practical strain selection thus involves the trade-off between four competing goals, which are long-term survival in a high-pH matrix, adequate production of minerals to seal or densify the target defects, acceptable environmental footprint (e.g., minimum ammonia), and economic and processing limitations (i.e., easy cultivation, nutrient cost, and encapsulation capability) [40]. A typical pragmatic approach, well documented in the literature, is to combine a strong spore-forming *Bacillus* or *Sporosarcina* strain with an encapsulation/carrier system and to choose the metabolic route based on site constraints [40].

3.2. Biochemical Mechanisms of Precipitation

MICP in cementitious materials occurs through two main biochemical pathways, as shown in Figure 3: ureolytic and non-ureolytic, which are regulated by the different metabolic abilities of the bacterial species present [35]. The choice of metabolic pathway is not only highly mechanistic but also influences the kinetics of calcite formation, the morphology of the crystals formed, and the environmental compatibility of the overall system. Figure 4 illustrates the evolution of bacterial self-healing concrete from conventional ureolytic systems to environmentally friendly non-ureolytic approaches.

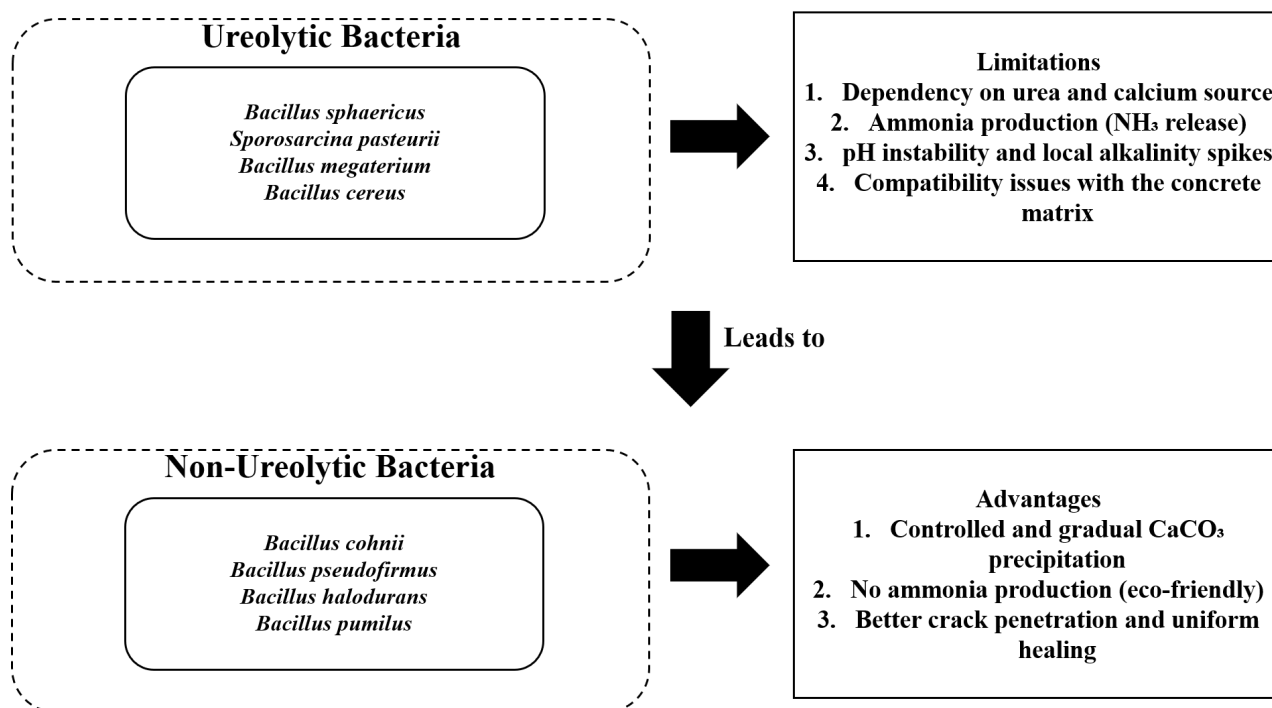
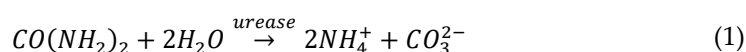


Figure 4. Evolution of bacteria-based self-healing concrete from ureolytic to non-ureolytic biomineralization pathways, highlighting the limitations of ureolytic systems and the advantages of non-ureolytic bacterial approaches.

3.2.1. Ureolytic Pathway

MICP research has historically focused on the ureolytic mechanism, with most studies between 2000 and 2025 utilizing urease-producing bacteria, including *Sporosarcina pasteurii* (formerly *Bacillus pasteurii*) and *Bacillus sphaericus* [1,44]. These organisms harbor one of the most efficient naturally occurring ureases, enabling them to rapidly break down urea into ammonium ions and carbonate species, as depicted in Figure 5a. This hydrolysis process is the key to the ureolytic pathway and occurs in accordance with the reaction as explained in Equation (1):



There are two profound effects of ureolysis on calcite precipitation. To begin with, the ammonium release raises the local pH, and in many cases, it raises the bacterial cell microenvironment by one to two units. This pH increase is significant in cementitious systems, where the elevated pH promotes carbonate stability. Second, the free carbonate ions liberated readily react with the free calcium ions present in the pore solution, the major source of which is the dissolution of portlandite, and the formation of calcium carbonate crystals in the form of the following equation:



The urease activity and naturally high calcium level of cement paste led to extremely rapid precipitation kinetics [40]. Most experimental studies have shown that ureolytic bacteria can trigger visible mineral deposition within several hours and cracking and bridging within several days. They are much more effective in short-term sealing efficiency than most non-ureolytic systems. As is frequently observed in microstructural studies, rhombohedral calcite grows on the surfaces of bacterial cells and subsequently fills cracks or capillary voids [45]. Such rapid nucleation and growth are why ureolytic strains are best suited for use when quick crack closure is needed, as with shrinkage cracks repaired at early ages and with buildings that are occasionally wetted. It is observed that the

production of ammonium may lead to nitrogen and, likely, odor, as well as long-term ecological impacts, particularly in water-sensitive environments or closed structural systems [40,46]. The sustainability of ureolytic systems in the field has led some researchers to question their viability, thereby encouraging a switch to other biochemical pathways that do not produce ammonium.

3.2.2. Non-Ureolytic Pathway

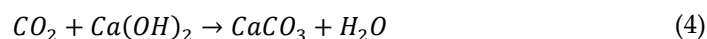
Since the eco-friendly shift toward ureolytic pathways, recent scientific publications (since 2015) have focused more on non-ureolytic bacterial systems capable of causing calcite precipitation by metabolically transforming organic carbon sources [47]. Several alkaliphilic *Bacillus* species, such as *Bacillus cereus*, *Bacillus pseudofirmus*, and *Bacillus halodurans*, have attracted interest because they can use calcium-based organic nutrients, most likely calcium lactate, without producing ammonium as a metabolic by-product, and because they contribute to localized alkalinity [43,46,48].

Unlike the direct precipitation process, the non-ureolytic process is a coupled, consecutive transformation that occurs in a sequence of steps, as schematically represented in Figure 5b. Firstly, bacterial metabolism oxidizes organic sources of calcium, producing carbon dioxide and intermediate metabolites. This is followed by a secondary transformation phase in which the generated carbon dioxide is used in subsequent reactions within the system, leading to the formation of calcium carbonate. Therefore, the general process can be viewed as a cyclic, indirect precipitation pathway rather than a one-step process. The conceptual reaction of the overall precipitation route is as follows:

- Bacterial Oxidation:



- Chemical Conversion:



Pathways for Bacterial Healing of Concrete

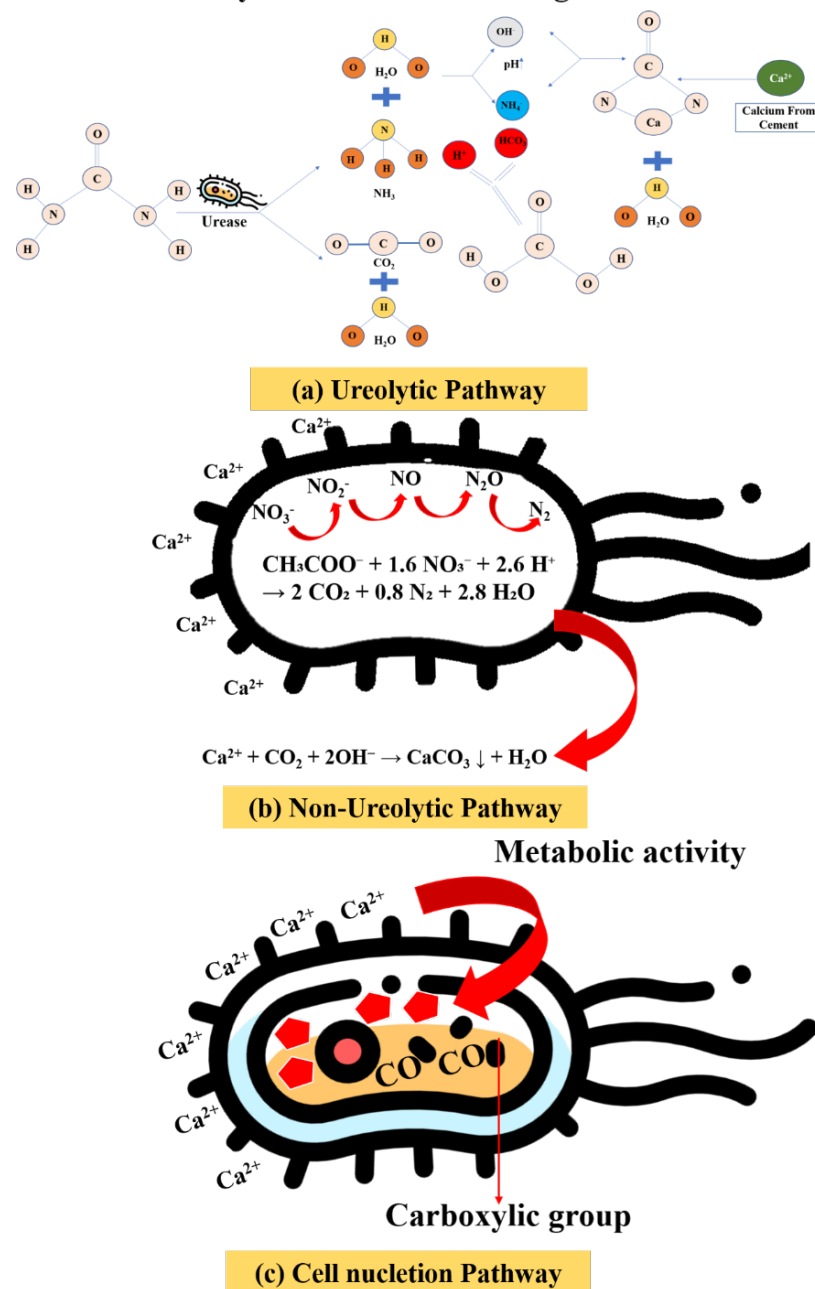


Figure 5. Schematic illustration of (a) ureolytic, (b) non-ureolytic, and (c) cell nucleation processes of healing in bacteria. (bacterial icons created by Magnific—Flaticon, “a free tool” https://www.flaticon.com/free-icon/bacteria_1432420 (accessed on 18 July 2026)).

This circuit is commonly associated with relatively slower precipitation kinetics, but has been reported to yield a smaller, better-integrated calcite microstructure [40]. Microstructural observations, especially those obtained by SEM, often reveal larger intergrown crystals that bond strongly with other phases, helping refine pores and increase long-term strength, as summarized in Tables 1 and 2. These properties make non-ureolytic systems especially useful in durability-related applications such as chloride-exposed ones and heritage conservation, where crack closure by densification is sought after rather than rapid densification [49]. Although these benefits exist, some constraints remain intact. The precipitation process is naturally slower and typically requires higher bacterial concentrations and nutrient control to achieve effective performance [50,51]. Also, the mix design is

complicated using organic substrates. However, with the development of encapsulation techniques, such as lightweight aggregates, hydrogels, and silica-based carriers, the practicality of such systems has improved significantly, as explained in Section 3.3.2.

3.2.3. Cell-Surface Nucleation Mechanism

Besides the ureolytic and non-ureolytic metabolic pathways, cell-surface nucleation is a universal physicochemical process present in most microorganisms that form calcite. As depicted in Figure 5c, the electrostatically directed movement of this process is supported by the presence of negatively charged functional groups (carboxyl, phosphate, and hydroxyl moieties) that are very abundant in the Gram-positive bacterial cell wall (peptidoglycan matrix) [52]. These are negatively charged sites with a high affinity for Ca^{2+} ions in the alkaline pore solution of concrete. The localized accumulation of Ca^{2+} on the bacterial surface creates a region of supersaturation, effectively converting the cell into a natural nucleation scaffold [53].

Due to the generation of carbonate or bicarbonate ions by bacterial metabolism, these ions precipitate immediately within the calcium-enriched layer, forming CaCO_3 crystals directly on the bacteria's surface. This mechanism is demonstrated in Figure 5, in which a bacterial cell is depicted adsorbing Ca^{2+} ions via negatively charged groups, which then form crystals upon contact with CO_3^{2-} ions produced by metabolic reactions [54]. Notably, this mechanism can transpire even when bacterial metabolism is disrupted or shut down by extreme pH or inadequate nutrient concentration, which is another resilience complementary to both ureolytic and non-ureolytic activities [55]. Cell precipitation via cell-surface nucleation generally yields finer crystals than those formed by this solution-based method, more uniform dispersion, and better integration into the cement matrix. SEM observations commonly show bacteria as homogeneous calcite shells, thus acting as both active and passive templates for nucleation. This kind of microstructure refinement enhances mechanical interlocking and sealing of microcracks and capillary voids [54,56]. The cell-surface nucleation is therefore a stabilizing reaction for mineralization and ensures the stability of the precipitation even in the presence of changes in environmental conditions, thereby promoting the further survival and consolidation of the cured regions [57].

In practice, this decision is primarily determined by the performance characteristics and environmental constraints of either the ureolytic or non-ureolytic route. Ureolytic systems are more suitable for cases where crack sealing is required quickly, such as in the early stages of shrinkage cracks, surface repair, and coating, and in structures subjected to frequent wetting–drying cycles. Compared to them, non-ureolytic pathways are preferred in all the sustainability-related uses, including marine structures, groundwater-sensitive environments, and heritage conservation, where slower yet denser calcite growth and environmental friendliness are of concern. In addition, cell-surface nucleation is another complementary process that enhances the homogeneous deposition of the mineral, namely, microcrack sealing and long-term matrix densification. As a result, the route will be application-specific and tailored to the requirements of kinetics, durability, and sustainability.

3.3. Incorporation of Bacteria into the Cement Matrix

The successful integration of bacteria in the cement matrix is a crucial aspect that determines the performance of self-healing concrete. Several techniques have been devised to keep bacteria viable and functional, which are described in this section.

3.3.1. Direct Addition of Bacteria

Earlier studies on bio-based crack healing were primarily based on the direct incorporation of vegetative bacterial cells into the fresh concrete mix. Such cells had been very

effective in controlled laboratory broths where nutrient supply and pH were both favorable, but their survival in cementitious systems had been extremely poor. The hydration of portland cement creates a highly alkaline environment (pH 12–13), in which $\text{Ca}(\text{OH})_2$ predominates and rapidly disrupts cell membrane integrity, denatures metabolic enzymes, and causes complete loss of viability [58]. Rapid viability loss of more than 95% of vegetative cells within the first 24–48 h, before they can engage in any biomineralization process, has been demonstrated in studies by Ramachandran et al. (2001) [14] and subsequently by De Muynck et al. (2008) [59]. Consequently, preliminary experiments showed insignificant crack healing, low CaCO_3 precipitation, and low enhancement of mechanical and durability characteristics. As summarized in Table 1, the performance of vegetative-cell systems generally remained lower than that achieved using bacterial spores, primarily because of their poor survival in the highly alkaline cement matrix. Although the success rate was low, this stage offered invaluable information: the severe chemical conditions in concrete required a more resilient biological agent that could endure extended periods of dormancy and act only when cracks form [58,60].

Another significant change was the introduction of bacterial spores, especially those of the genus *Bacillus*, which marked the second phase of development in MICP-based self-healing. Spores are extremely robust, metabolically dormant, dipicolinic acid-enriched, peptidoglycan-layered, proteinaceous coats that provide better resistance to desiccation, thermal, and alkalinity conditions [61]. As illustrated in Figure 6, the transformation from vegetative cells to mature endospores involves a sequential process of sporulation, including initiation, forespore engulfment, cortex formation, and eventual release of mature spores. Jonkers, Schlangen, and co-authors (2008–2010) revealed that *Bacillus* spores, particularly those of *Bacillus pasteurii* (renamed *Sporosarcina pasteurii*), *Bacillus sphaericus*, and *Bacillus megaterium*, can remain viable up to a few decades in the cementitious matrices [62]. Until a crack is formed, these spores remain dormant. When spores are hydrated, they germinate to form vegetative cells, which trigger ureolysis or denitrification-mediated CaCO_3 precipitation. Consequently, spore-based systems consistently demonstrated greater crack-healing capacity, along with improved mechanical and durability performance, compared with direct incorporation of vegetative cells. This innovation not only confirms the long-term viability of the bacteria but also makes spores the most significant feature of bio-concrete systems, allowing highly effective, autonomous healing with quantifiable changes in mechanical properties, lowered permeability, and increased service life of concrete structures.

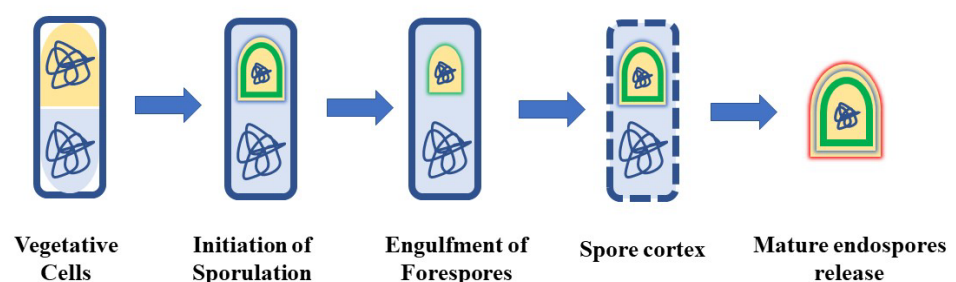


Figure 6. Spore-forming method of a bacterium.

The results summarized in Table 1 further demonstrate that the reported performance of bacterial systems should not be interpreted as an intrinsic characteristic of an individual strain alone. Healing efficiency depends on the interaction between bacterial physiology and experimental conditions, including bacterial concentration, nutrient source, crack width, curing regime, exposure environment, specimen geometry, and

concrete mix composition. Consequently, direct comparison of reported healing widths, strength improvements, or durability enhancement across different studies should be made with caution, since variations in testing methodology frequently contribute as much to the observed performance as the bacterial species itself.

Among the investigated microorganisms, *Sporosarcina pasteurii* remains the most extensively studied because of its highly efficient ureolytic metabolism, which promotes rapid CaCO_3 precipitation under favorable curing conditions. Nevertheless, its reported healing performance varies considerably depending on specimen type, healing duration, and crack geometry [63]. Studies conducted on mortar specimens with extended moist curing generally reported progressive strength recovery over periods ranging from 28 to 120 days, whereas investigations performed under hot and humid environmental conditions demonstrated successful healing of cracks up to 0.75 mm [64–66]. Similarly, the performance of *Bacillus sphaericus* is strongly influenced by the surrounding exposure environment. While conventional water curing produces satisfactory crack closure, recent studies have shown substantially greater durability recovery under seawater exposure [67], where changes in mineralogy from predominantly calcite to calcite-aragonite mixtures produce denser healing products and improved water tightness [68]. These findings indicate that environmental conditions influence not only bacterial survival but also the composition and compactness of the precipitated calcium carbonate.

The remaining *Bacillus* species exhibit comparable trends, where bacterial concentration and curing conditions largely determine the reported improvements. For example, *Bacillus subtilis* consistently performs well at optimized bacterial concentrations (approximately 10^6 cells/mL) and under favorable moist curing, whereas lower bacterial populations or less favorable curing conditions considerably reduce healing efficiency [69,70].

Likewise, *Bacillus megaterium* has demonstrated some of the highest reported strength recoveries when appropriate nutrient availability and bacterial dosage are maintained; however, excessive bacterial concentrations may adversely affect the concrete microstructure and reduce the overall benefit [71]. In contrast, *Bacillus cohnii* generally exhibits more moderate improvements and appears more sensitive to curing conditions and matrix composition [72]. Similar dosage-dependent behavior has also been reported for *Bacillus licheniformis*, while comparatively fewer studies are available for *Escherichia coli*, *Bacillus alcalophilus*, *Bacillus pumilus*, and *Bacillus mucilaginosus*. For these less extensively investigated microorganisms, the available evidence remains insufficient to establish generalized performance rankings because experimental conditions differ substantially among studies.

Table 1. Performance of bacterial strains incorporated as vegetative cells and spores in self-healing concrete.

Bacterial Strain	Mode of Incorporation	Crack Width Healed (mm)	Compressive Strength Increase in Bacterial Concrete vs. Control Concrete	Effect on Durability Properties in Bacterial Concrete vs. Control Concrete	References
<i>Sporosarcina pasteurii</i>	Vegetative cells	0.40–0.70	19–37.23% ↑	Water permeability ↓ 83%; Water absorption ↓ 11.57%	[63–66]
<i>Escherichia coli</i>	Vegetative cells	-	22.6% ↑	-	[73]
<i>Bacillus sphaericus</i>	Vegetative cells	0.50–0.80	14.5–41.5% ↑	Water absorption ↓ 65%; Carbonation ↓ 25%; Chloride permeability ↓ 40%; Gas permeability ↓ 70%; Porosity ↓ 25%	[51,68,74–77]
	Spores	1.0	14.5% ↑	-	[78–80]

<i>Bacillus subtilis</i>	Vegetative cells	0.40–0.55	14.37–33% ↑	Water absorption ↓ 23–30%; Porosity ↓ 25%; Gas permeability ↓ 70% [51,69,70,77,79,81]
<i>Bacillus cohnii</i>	Vegetative cells	-	41.5% ↑	Frost salt scaling ↓ 90%; Chloride penetration ↓ 46% [72]
	Spores	0.40–0.65	33% ↑	- [82]
<i>Bacillus megaterium</i>	Vegetative cells	0.40–0.55	39.9–92% ↑	- [83]
	Spores	-	38% ↑	- [84]
<i>Bacillus alcalophilus</i>	Spores	0.45–0.50	38% ↑ (Flexural strength)	Water absorption ↓ 50% [73]
<i>Bacillus pumilus</i>	Spores	0.80	35% ↑	- [51,68,74–77]
<i>Bacillus mucilaginosus</i>	Vegetative cells	-	30% ↑	- [78–80]

Here, ↑ indicates an increase, ↓ indicates a decrease, and “-” indicates that the corresponding data were not reported in the original study.

Overall, Table 1 demonstrates that bacterial spores consistently outperform vegetative cells due to their superior long-term survival in the cementitious environment. However, the comparison also highlights that no bacterial strain can currently be regarded as universally superior, as the observed variations largely reflect differences in curing conditions, bacterial dosage, nutrient availability, crack characteristics, and testing methodologies rather than differences in bacterial species alone. More importantly, although spores significantly improved bacterial survival compared with vegetative cells, they remained vulnerable to mechanical damage during concrete mixing, prolonged exposure to highly alkaline pore solutions, and gradual nutrient depletion before crack formation. Consequently, spore incorporation alone could not consistently ensure long-term bacterial viability and reliable self-healing performance in practical concrete applications. These limitations prompted researchers to develop protective carrier systems that physically isolate bacterial spores from the cementitious matrix while simultaneously providing controlled nutrient storage and release. This marked the transition from direct spore incorporation to encapsulation-based strategies, which represent the next major stage in the evolution of bacteria-based self-healing concrete.

3.3.2. The Idea of Encapsulation

Following the initial decade of bio-concrete development, where the conceptual principles of the spores were established as viable but it became evident that spores face serious losses of their viability as a result of mixing shear, high alkalinity, and nutrient loss, the research emphasis shifted in the direction of encapsulation technologies that protect spores physically and chemically and release nutrients when and where required, as depicted in Figure 7 [81].

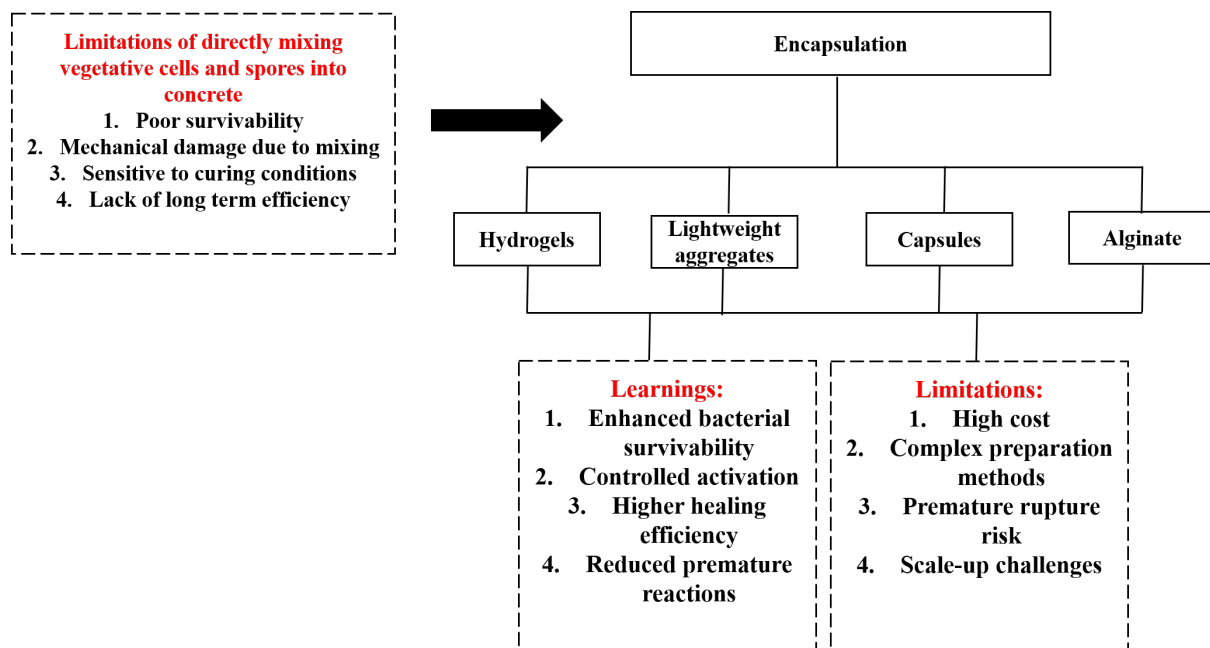


Figure 7. Limitations and learning from spores to encapsulation.

Encapsulation is the entrapment of free bacterial cells in a secure medium, creating a discrete microenvironment that isolates the cells from the harsh cementitious matrix while retaining their activity, as shown in Figure 8. This technique is motivated by four overlapping conditions, i.e., guarding the spores against mechanical shear in mixing and placement, buffering the spores against the caustic pore solution (pH 12–13) of hydrating cement, transporting a stable nutrient reservoir that can be released on wetting, and distributing the biological agents in the matrix without significantly undermining fresh and hardened concrete qualities [85].

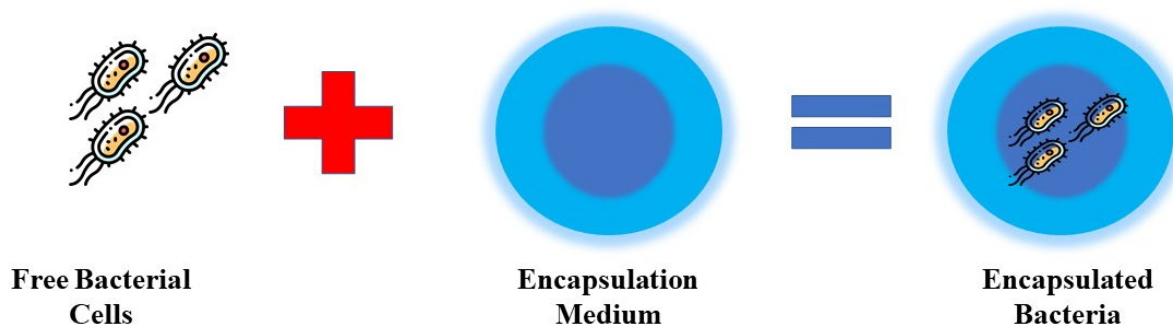


Figure 8. Encapsulation technique of bacteria. (bacterial icons created by Magnific—Flaticon, “a free tool” https://www.flaticon.com/free-icon/bacteria_1432420 (accessed on 18 July 2026)).

The common types of encapsulation strategies are porous carrier impregnation (lightweight aggregates, expanded clay, pumice), micro-/macro-capsules with polymeric or inorganic shell (sol–gel silica, urea–formaldehyde, polyurethane), hydrogel matrices (alginate, polyacrylamide, gelatin), and ceramic/inorganic immobilization (sintered fly ash, diatomite, bio-glass), as shown in Table 2. Both strategies ensure protection and release through various mechanisms [81,85–87]. The lightweight aggregates are commonly used in porous form (usually pre-wetted by a vacuum or pressure suspension) and are impregnated with a suspension of spores and nutrients. Several high-impact studies have indicated that vacuum-impregnated expanded clay or LWAs are much better at

improving healing efficiency and compressive strength recovery than direct addition, and that they offer good workability at an optimized dosage [88].

Microcapsules and microencapsulation methods were developed to offer more controlled rupture and release properties. Polymer or inorganic silica-shelled microcapsules synthesized by interfacial polymerization, emulsion templating, or sol–gel synthesis can remain intact during mixing, yet fracture under local strain or moisture gradients within the capsule, releasing spores/nutrients at a specific location along the crack. Later experiments maximized the capsule size, shell thickness, and chemistry to trade off survivability against release threshold. Capsules made with sol–gel silica and TEOS (Tetra Ethyl Ortho Silicate) have the benefit of being chemically inert when mixed in alkaline pore solutions; they serve as a secondary protective layer of spores [89]. However, the effectiveness of microcapsules depends strongly on capsule geometry, shell properties, and rupture behavior [90]. Premature rupture during mixing reduces bacterial survival, whereas excessively robust shells may delay or prevent bacterial release after cracking. Consequently, recent research has focused on optimizing capsule design to achieve reliable crack-triggered activation while maintaining mechanical integrity during concrete production.

Another route that became prominent in this decade was hydrogel encapsulation, since hydrogels have a high capacity to hold large amounts of water and nutrients and can provide a physically soft microenvironment to spores [85]. Spores of calcium lactate or other carbon sources were embedded in calcium-alginate beads, polyacrylamide gels, and composite hydrogels. Upon crack activation and wetting, the hydrogels swell, releasing nutrients and providing a moist microenvironment that supports spore germination and microbial activity [11,86]. Hydrogel carriers have also been shown to have high healing efficiencies in laboratory-scale experiments, especially in non-ureolytic systems where nutrient solubility and controlled release are significant factors. However, hydrogels can reduce early compressive strength at large volumes, and the mix design must be balanced [90]. Nevertheless, their performance depends on hydrogel composition, swelling behavior, dosage, and curing environment. Excessive hydrogel incorporation may increase matrix porosity and reduce early-age compressive strength, indicating that the encapsulation dosage must be optimized to balance healing efficiency with structural performance.

In addition to hydrogels, ceramic and sintered carriers (e.g., sintered fly ash, diatomaceous earth, or silica matrices) offer high mechanical resistance and excellent chemical stability, and can be loaded with bacteria and nutrients, then covered with a thin polymeric or silica coating to prevent premature leakage [91,92]. The inorganic carriers are appealing for use in field deployment over long periods since they are not attacked by alkali and can be abraded by mechanical forces; they have greater density and may influence the concrete rheology; thus, they must be evaluated thoroughly [93]. More recently, single-spore encapsulation in layers, where spores are encased in nano- to microscale shells, has been reported and should enable wide distribution and minimal impact on mix properties; the precision of nano- to microscale shells is still moving from laboratory demonstrations of concept to scalable production [94,95].

The volume fraction of capsules, size distribution, and mechanical properties have a major impact on fresh-state rheology, air content, and initial compressive strength. According to studies, small decreases in 28-day strength have been observed with high doses of encapsulants, suggesting a trade-off between healing ability and structural performance [96]. Widespread adoption was also restricted by economic factors, scale-up, capsule production costs, nutrient price, and the need to reproduce production [97,98]. In addition, the long-term stability of certain polymeric shells under alkaline conditions was becoming problematic, leading to a transition to inorganic and hybrid shells (silica-polymer composites, alkali-stable ceramics) [92]. End-of-2010s and early-2020s comparative reviews thus suggested hybrid designs (e.g., LWA + hydrogel or silica-coated LWAs) that

trade mechanical protection for controlled nutrient release and suitably concrete performance.

Similarly, natural fiber-based immobilization using jute and coir fibers has emerged as a sustainable alternative because the fibers serve as both bacterial carriers and crack-bridging reinforcement [99]. Rubber particles have also been investigated as environmentally sustainable carrier materials by utilizing waste resources while providing additional bacterial protection [78]. Although these alternative carriers have demonstrated encouraging healing performance in laboratory investigations, their effectiveness remains dependent on factors such as carrier porosity, bacterial loading capacity, fiber durability, and compatibility with the surrounding cementitious matrix, requiring further validation under long-term field conditions.

Table 2. Strain-wise comparison of encapsulation and immobilization strategies used in bacteria-based self-healing concrete.

Bacterial Strain	Encapsulation/Immobilization Strategy	Crack Width Healed (mm)	Mechanical Strength Improvement vs. Control	Durability Improvement vs. Control	References
<i>Sporosarcina pasteurii</i>	Polyurethane tube	-	60% ↑ (post-healing)	-	[100]
	Calcium sulphoaluminate cement	0.417	2.3% ↑ (Compressive strength)	-	[101]
	Rubber particles	0.86	17% ↑ (Compressive strength)	-	[78]
	Recycled aggregates	0.50	80% ↑ (Compressive strength)	Water tightness ↑ 77.8%	[102]
	Injection method	0.10	19.2% ↑ (Flexural strength)	Water absorption ↓ 11.54%	[66]
<i>Bacillus sphaericus</i>	Silica gel	10	-	Water absorption ↓ 20%	[103]
	Diatomaceous earth	-	-	Water absorption ↓ 50%	[104]
	Melamine microcapsules	1.0	-	Water absorption ↓ 48%	[103]
	Hydrogel	0.50	-	-	[105]
	Sodium alginate beads	0.24	36% ↓ (Compressive strength)	Water permeability ↓ 70–82%	[106]
<i>Bacillus cohnii</i>	Fiber immobilization	1.5–2.5	65% ↑ (Compressive strength), 70% ↑ (tensile strength)	Water absorption ↓ 67%	[99]
	Expanded perlite	0.51	-	-	[107]
	Hydrogel	0.46	-	-	[108]
<i>Bacillus subtilis</i>	Jute & coir fibres	0.65	33% ↑ (Compressive strength)	-	[109]
	Jute & coir fibres	0.60	32% ↑ (Compressive strength)	-	[109]
<i>Bacillus pseudofirmus</i>	Expanded perlite	0.159	-	-	[110]
	Hydrogel	0.49	-	-	[108]
	Acid-etched alumina hollow spheres	0.40	14.74% ↑ (7 d) (Compressive strength)	Thermal conductivity ↓ 14.8% (−20 °C); ↓ 11.9% (25 °C)	[111]
<i>Bacillus halodurans</i>	Hydrogel	0.45	-	-	[108]
<i>Bacillus cereus</i>	Biocapsules	-	5% ↑ (Compressive strength)	Water permeability ↓ 11%	[112]
<i>Bacillus licheniformis</i>	Iron oxide nanoparticles	-	50% ↑ (Compressive strength)	-	[113]
<i>Bacillus megaterium</i>	Carbon fiber-coated bacterial balls	-	20% lower strength loss after fire exposure	-	[114]

Here, ↑ indicates an increase, ↓ indicates a decrease, and “-” indicates that the corresponding data were not reported in the original study.

The effectiveness of these encapsulations can be seen in the strain-wise comparison shown in Table 2 and is influenced by the bacterial species, nutrient availability, curing

conditions, crack width, and environmental exposure. *Sporosarcina pasteurii*, for instance, has been successfully seeded in polyurethane tubes, recycled aggregates, rubber particles, and calcium sulphoaluminate cement, while *Bacillus cohnii*, *Bacillus pseudofirmus*, and *Bacillus halodurans* have demonstrated good healing properties when encapsulated in expanded perlite and hydrogel systems. In practice, direct comparison between individual studies is still difficult due to variation in experimental methods, crack geometries, and evaluation criteria across studies.

The various major encapsulation technologies have been compared to each other in Table 3, regarding a range of other performance metrics such as bacterial protection, healing efficiency, mechanical compatibility, durability, scalability, technology readiness, advantages, and limitations, to give a wider engineering perspective than the individual experimental studies. This comparison gives an idea of the pros and cons of the various forms of encapsulation and helps to choose the appropriate one, depending on the structure for which it is to be used.

Table 3. Comparative assessment of encapsulation strategies used in bacteria-based self-healing concrete (compiled and synthesized by the authors based on Refs. [81,85–114]).

Encapsulation Strategy	Bacterial Protection	Healing Efficiency	Mechanical Compatibility	Major Advantages	Major Limitations
Lightweight aggregate (LWA)	High	High	High	Mature technology; compatible with conventional concrete	Requires pre-treatment; may reduce workability
Expanded perlite	High	High	Moderate to High	Lightweight; good bacterial protection	Lower nutrient storage
Hydrogel	Very High	High	Moderate	Excellent moisture retention; repeated healing	High dosage may reduce early strength
Polymeric microcapsules	High	High	High	Controlled crack-triggered release	Complex fabrication; shell degradation
Sol-gel silica	High	High	Moderate	Chemically stable in alkaline concrete	Higher production cost
Ceramic/inorganic carriers	High	Moderate to High	High	Excellent durability and chemical stability	Higher density affects workability
Natural fibres	Moderate	High	High	Sustainable; improves crack bridging	Variable durability
Rubber particles	Moderate	Moderate	Moderate	Sustainable waste utilization	Limited experimental evidence
Sodium alginate beads	High	High	Moderate	Good nutrient retention	Scale-up required
Nanomaterial-assisted carriers	Very High	High	Very High	Multifunctional protection	High cost; laboratory stage

Here, High, Moderate, and Low represent the relative performance of each encapsulation strategy based on the collective evidence reported in the reviewed literature, considering bacterial survival, crack-healing capability, influence on concrete properties, durability, ease of implementation, and level of technological maturity. These ratings are qualitative and intended for comparative purposes only.

Overall, no single encapsulation strategy can currently be regarded as universally superior. As summarized in Table 2, lightweight aggregates, expanded perlite, and hydrogel systems represent the most mature technologies because they consistently provide high bacterial survival, effective crack healing, and compatibility with conventional concrete production. Polymeric microcapsules offer excellent crack-triggered release but involve relatively complex fabrication and may experience long-term degradation under highly alkaline conditions. Ceramic and inorganic carriers provide superior chemical stability and durability but may affect fresh concrete workability because of their higher density. More recent multifunctional systems incorporating natural fibres, rubber particles,

sodium alginate beads, nanomaterial-assisted carriers, and hybrid encapsulation approaches have demonstrated promising improvements in both healing efficiency and mechanical performance. However, these technologies remain largely at the laboratory scale and require further validation under realistic conditions before widespread structural implementation.

3.3.3. Vascular Systems, 3D Printing, and Multi-Cycle Healing Technologies

Although encapsulated systems are a very promising source of reliability, they are essentially single-use, and most healing agents are consumed during the first major cracking event. In a bid to address this drawback, studies since 2020 have increasingly focused on vascular self-healing systems, which are based on the hierarchical vascularity of biological organisms, in which hollow channels built into the concrete facilitate the repeated transfer of bacterial suspensions and nutrients [115]. Such vascular networks are built with sacrificial formers (e.g., sugar rods, 3D-printed PVA filaments) or by direct 3D printing of pathways that create voids within structural members. When installed, they serve as a reusable transport system, and fresh bacterial cultures, nutrients, or curative solutions can be injected into the structure if it remains in service [116].

Several studies have shown that vascular systems enable multiple healing cycles that effectively repair both microcracks and deep macrocracks (>1 mm), whereas traditional encapsulated spores cannot heal them. When cracks penetrate the vascular channels, healing fluids containing *Bacillus* spores or non-ureolytic bacterial consortia ooze out, and rapid CaCO_3 biomineralization commences. The treatment can be repeated, making it applicable to large infrastructure components that are often vulnerable to cracking, such as bridge decks, tunnel linings, and offshore structures [116].

Another disruptive technology in this step is the integration of 3D printing (also referred to as additive manufacturing). Digital construction processes enable accurate positioning of bacteria, capsules, and vascular conduits, resulting in ideal distribution and reduced waste. Bacterial spores or healing units can be deposited strategically in extrusion-based 3D concrete printing (3DCP), along pre-programmed paths, according to areas of high tensile stress expectation [66]. A few studies have also examined printing bacteria-laden hydrogels into concrete layers to preserve the bacteria and maintain a moist environment during printing. This permits tailor-made healing arches, including lattice-based vascular patterns, multi-material extrusion, or different distributions of bacterial agents in complicated geometries [99].

Autonomous sensing and healing integration in the vascular bio-concrete systems is also supported. With a mixture of 3D-printed channels and fiber-optic sensors or microfluidic sensors, the system can detect crack formation and will automatically inject bacterial solutions where necessary [66]. This is indicative of a tendency toward an intelligent bio-concrete, in which biological healing will be built into a cyber-physical network to monitor in real time, enable predictive maintenance, and automate repair cycles.

3.4. Impact on Mechanical Properties (Strength Enhancement)

The mechanical behavior of bacterial concrete is not only determined by the presence of microbial agents but also by the basic microarchitectural changes induced by biomineralization. Several investigations over the past two decades have shown that bacterial metabolic activity, specifically that of *Bacillus* species, leads to the controlled precipitation of CaCO_3 in the cementitious matrix. It influences porosity, pore-size distribution, crack morphology, and the integrity of the interfacial transition zone (ITZ), all of which affect compressive and tensile strength, as discussed in the literature listed in Table 1. The integration of bacterial agents, therefore, represents a shift from reactive crack repair to proactive microstructural engineering.

3.4.1. Microstructural Densification

Biogenic precipitation of calcium carbonate is among the most frequently reported outcomes of bacterial incorporation, leading to microstructural densification. The physicochemical characteristics of bacterial cell surfaces underlie the existing mechanism. Most bacterial species have negatively charged functional groups on their cell walls, as discussed in Section 3.2.3. When the bacteria initiate ureolytic or non-ureolytic metabolic activity, local supersaturation of carbonate species results in the formation of CaCO_3 crystals, which are fixed directly to the bacterial surface [56,117].

The importance of this process has been widely reported, with numerous microstructural studies using SEM. Repeated observations by researchers show that bacterial cells become mineralized, thereby forming biologically catalyzed calcite clusters (biodeposits) that later develop into pore-bridging networks [76]. Research consistently documents a decrease in capillary porosity of biomineralization, a tightening of the pore structure between capillary and gel pores, and an impediment to the development of interconnective permeable pathways, as observed in Tables 1 and 2. These mechanical changes are directly affected by these microstructural changes. It has been shown in the literature that strength gains of 15–30% have been observed in bacterial concrete compared with control mixes without bacteria, especially when ureolytic bacteria are used [118,119]. This is further promoted by long curing, as well as wetting and drying cycles. Biogenic calcite will continue to deposit in dormant pores and microcracks over time, whereas normal concrete undergoes slow deterioration through microcracking caused by shrinkage [117]. The long-term durability and strength results indicate that the microstructural weaknesses in compressive strength at young ages are offset by bacterial mineralization, which supports the growth of compressive strength after 6 or 12 months of exposure [120]. Depending on the biochemical pathway, biogenic crystals typically assume rhombohedral, prismatic, and needle-like shapes, and their high adhesion to the C-S-H gel matrix also significantly enhances overall load-bearing capacity [119].

Several researchers have reported improvements in tensile strength (10–20%) and flexural strength (12–25%), with crack-bridging calcite deposition and microstructural compactness as key contributors [26,121]. In this way, microstructural densification in bacterial concrete is a chemical and mechanical improvement mechanism that provides long-term strengthening of the concrete and is not limited to the initial curing period. Although densification of the cement matrix generally improves bulk mechanical performance, the interfacial transition zone (ITZ) is particularly sensitive to bacterial mineralization, where localized enhancements are a determining factor in crack resistance and load transfer.

3.4.2. Strengthening of the Interfacial Transition Zone (ITZ)

It is well known that the interfacial transition zone (ITZ) is the weakest part of concrete because it is highly porous, has coarse crystallization (especially portlandite), and is prone to microcracks [122]. Bacteria and calcite deposits preferentially colonize the ITZ due to its pore structure and relative permeability. Experiments on microbial movement have revealed that bacterial spores may move or be triggered into action in the ITZ when moisture is present, forming localized mineralization that strengthens the bond between aggregate and paste [60,123].

The presence of biogenic calcite deposition in the ITZ enhances the contact rigidity between the aggregates and the surrounding cement paste. SEM-EDS studies indicate that the microvoids surrounding coarse aggregates are slowly filled with bacterial precipitates, thereby refining the ITZ. The calcite crystals thicken the porous zone and impart a denser, more crystalline microstructure, which limits the propagation of microcracks under load. Also, the formation of calcite depletes Ca^{2+} ions and lowers the concentration of weak

portlandite in the ITZ, thereby reacting with it effectively in favor of the stronger mineral phases [124].

Mechanical tests support these microstructural findings. It has been reported that there are extremely high increases in the aggregate-paste bond strength, increases in splitting tensile strength (which is much more related to the behavior of an ITZ), and a decrease in the rate of crack propagation [106]. The slow formation of microcracks, coupled with enhanced interfacial cohesion, increases the modulus of elasticity and improves load distribution throughout the composite [125]. These enhancements are essential in structural components exposed to dynamic or cyclic loads, and ITZ performance will dictate long-term performance and crack resistance.

3.5. Impact on Durability (Permeability and Corrosion Resistance)

Transport properties, permeability, diffusivity, and capillary suction are mostly involved in controlling durability. The beneficial effects of bacterial self-healing include reducing pathway connectivity between pores, sealing cracks, and altering the environment to prevent the influx of harmful agents, such as chloride ions, sulfates, and carbon dioxide.

3.5.1. Permeability Reduction

The effect of MICP-based healing systems, which have been most frequently reported to be effective, is their significant reduction in water permeability in cracked cementitious matrices, as discussed in Tables 1 and 2. As concrete develops, the smallest microcracks form, and its permeability may increase manyfold due to the formation of continuous pathways that allow the penetration of water, chlorides, sulfates, and other aggressive ions. Nonetheless, the addition of bacterial spores and nutrient precursors enables the autonomous precipitation of calcium carbonate (CaCO_3) in micro- and macro-cracks, forming thick biogenic plugs that practically impede fluid transmission. Several studies have indicated that 90–100% of the initial impermeability loss in bacterial concrete can be restored, even when cracks are 0.3–0.5 mm wide [30]. Thermodynamically stable in high-alkalinity cementitious environments despite cyclic wetting and drying, biogenic CaCO_3 does not shrink, degrade, or become ineffective, unlike polymeric sealants or crystalline chemical admixtures [26]. This stability also provides long-term resistance to fluid penetration, even under aggressive exposure conditions. Also, bacterial healing significantly reduces freeze–thaw wear by preventing water infiltration into microcracks, as ice crystallization and hydraulic pressure cycles depend on the presence of water in the pore network [126]. Long-term durability results show that MICP-treated samples exhibit 30–60% lower mass loss and fewer microcracks than negative controls when subjected to repetitive freeze–thaw cycles. Altogether, the independent formation of chemically stable, crack-sealing CaCO_3 not only provides impermeability following damage but also prepares for long-term resistance to deterioration induced by moisture [121].

3.5.2. Corrosion Inhibition

The corrosion of steel in reinforced concrete is chiefly initiated when chloride ions diffuse through the pore network and accumulate at the steel surface to a critical level (usually 0.4–1.0% by cement mass), which destabilizes the passive film of ferric oxide [127]. In normal concrete, microcracks serve as preferred pathways for chloride transport, increasing chloride movement and maintaining an oxygen-rich environment at the reinforcement. The conducted long-term immersion and fast-chloride-permeability experiments have indicated that biogenic calcite deposition can reclog cracks as small as 10–50 μm aperture and penetrate a few hundred microns through the walls of the cracks, forming a dense interlocked layer of CaCO_3 with rhombohedral and globular morphologies that are more similar to those of geogenic calcite [128]. Such a crystalline barrier

significantly reduces mass movement; chloride diffusivity has been reduced by 40–70%, and the effective diffusion coefficient has decreased by at least 1 order of magnitude in bacterial concrete [129]. Also, mercury intrusion porosimetry and X-ray microtomography results prove the idea that MICP does not simply bridge the crack mouth but also substantially refines the inner pore structure around the crack, reducing capillary connectivity and enhancing the tortuosity of ion routes [130]. This densification of chloride ions decreases the rate of chloride ions, retards depassivation, and prolongs the time to corrosion initiation.

In addition to physical sealing, there is a second biochemical oxygen-regulation mechanism that provides a biological defence. When the cracked area becomes moist, the inert bacterial spores germinate and begin aerobic metabolism, in which dissolved oxygen serves as the electron acceptor. This localized oxygenation loss, caused by bacteria that can lower O_2 levels by 30–60% in closed pore systems, establishes microaerobic or near-anoxic conditions, which are essentially incompatible with the metabolic reactions that occur on the cathode portion of the steel corrosion process [130–132]. Measures of electrochemical impedance spectroscopy (EIS) and linear polarization resistance consistently report lower corrosion current densities, differing by 20–50% among bacterial-treated samples, demonstrating that the absence of oxygen inhibits corrosion kinetics even in the presence of small amounts of chloride ions. In other experiments, the passive potentials of steel lasted months longer than in control specimens, and it was established that the biological oxygen consumption slows the decomposition of the passive layer. Moreover, the CO_2 generated during the metabolic activities of non-ureolytic bacteria engaging in reactions with $Ca(OH)_2$ will add to more calcite formation, which restricts the protective layer in a process of feedback-reinforcement [133].

A combination of the above effects, including calcite-based crack sealing, pore refinement, chloride mobility inhibition, and biologically induced oxygen depletion, has a synergistic corrosion-protective effect that is many times longer than that obtainable with individual chemical healing agents [134]. Bacterial systems also respond to the electrochemical environment at the steel surface, whereas polymeric or capsule-based systems can only provide physical sealing. Consequently, buildings located in areas with aggressive marine splash zones, tidal cycles, or freeze–thaw de-icing exhibit record-long corrosion initiation times, lower long-term corrosion, and a lower likelihood of rebar section loss [135,136]. Bacterial self-healing is therefore not just a self-repair process but also a powerful bio-electrochemical corrosion-mitigation approach that offers the best durability benefit reported in the self-healing concrete literature.

3.6. Critical Analysis and Limitations of Bacteria-Based Systems

Despite these remarkable crack-healing efficiencies (0.1–3.15 mm) and compressive-strength improvements (14–92% across strains; Table 1), several limitations remain, preventing large-scale early adoption of bacterial MICP. Firstly, the ureolytic strains (which are dominant in >80% of the literature) produce large amounts of ammonia as a by-product, raising valid concerns about nitrogen pollution, odor, and long-term ecological effects in water-sensitive or closed systems. Non-ureolytic routes alleviate this problem; however, they exhibit significantly slower kinetics and stricter nutrient regulation, which can lead to lower sealing performance in the short term.

Second, the wide range of reported strength recovery (e.g., *Bacillus megaterium* 38–92% vs. *Bacillus cohnii* 33–41.5%) underscores the poor reproducibility due to differences in encapsulation techniques, curing conditions, and crack structures. Numerous studies continue to use ideal laboratory conditions (constrained to 20 to 25 °C, >90% RH), whereas field exposure to freeze–thaw cycles, UV radiation, and persistent loading severely affects spore viability and healing effectiveness. Encapsulation strategies (Table 2) enhance survival but

often impair fresh-state workability and early-age strength, a trade-off whose quantification in life-cycle cost analysis remains inadequately investigated.

Lastly, many bacterial systems are single-cycle, meaning that once the encapsulated nutrients are depleted, there is no opportunity to replenish them, unless vascular networks are added. These limitations demonstrate that, although bacteria are the most technologically advanced agent, no further optimization of non-ureolytic consortia, hybrid encapsulation, or validation at the scale of large structures is possible before it can be stated that they are ready for use in structural applications.

4. Fungi-Based Self-Healing Concrete: The Era of Dual-Action Healing

Over the past ten years, fungi have emerged as an attractive alternative to bacteria for self-healing concrete, as bacterial systems have certain drawbacks, including high spore production, poor crack-bridging capacity, and reliance on nutrient-rich environments. Fungi offer an entirely new approach to healing; it works through a two-stage process of chemical biomineralization, enhanced by physical fortification. Fungi are eukaryotic organisms that grow as long filaments, called hyphae, which combine to create a network in space, resulting in a three-dimensional structure [17,137]. This filamentous architecture helps fungi harness microcracks, anchor along their walls, and bridge gaps, unlike unicellular bacteria, which act as discrete nucleation points and therefore serve as biological micro reinforcement that stabilizes the crack face before mineral precipitation initiates [138].

The biochemical excellence of fungi also increases the use of the system in concrete. Their walls are composed of chitin, glucans, melanin, and complex polysaccharides, which harbor high levels of negatively charged functional groups (COOH, OH, NH₂) and exhibit high affinity for the divalent calcium ions present in the cement pore solution [17]. This ionic natural pull-down turns the fungal hyphae into highly efficient nucleation scaffolds, thereby creating localized supersaturation conditions that enable CaCO₃ precipitation. Some fungi, such as *Trichoderma reesei*, *Aspergillus niger*, and *Penicillium chrysogenum*, also release extracellular metabolites and enzymes such as urease and carbonic anhydrase to make carbonate more accessible and enhance the rate of mineralization [139]. Therefore, fungi can develop very thick, compact layers of calcite on their hyphal surfaces, and these layers will be stable and continuous in mineral deposition across the crack.

The benefit of fungi-based healing, in addition to its mechanical and mineralizing properties, is that it is highly resistant to environmental conditions, as shown in Figure 9. Oligotrophs are among the fungal species used in self-healing research and grow in nutrient-free, highly alkaline environments that are not colonized by common bacteria [140]. They are well-suited for long-term in situ recovery of concrete infrastructure because of their ability to withstand desiccation, nutrient scarcity, and fluctuating moisture conditions. Moreover, fungal mineralization often induces polymorphic transformations in CaCO₃, resulting in a microstructure that is more firmly bonded to the sides of cracks and extending the sealing service life. The unique hybrid characteristics of hyphal bridging, effective nucleation, biomineralization mediated by enzymes, and high survivability make fungi the best next-generation material to autonomously heal cracks, especially in areas that require long-term performance, bigger cracks to be repaired, or microstructural integrity.

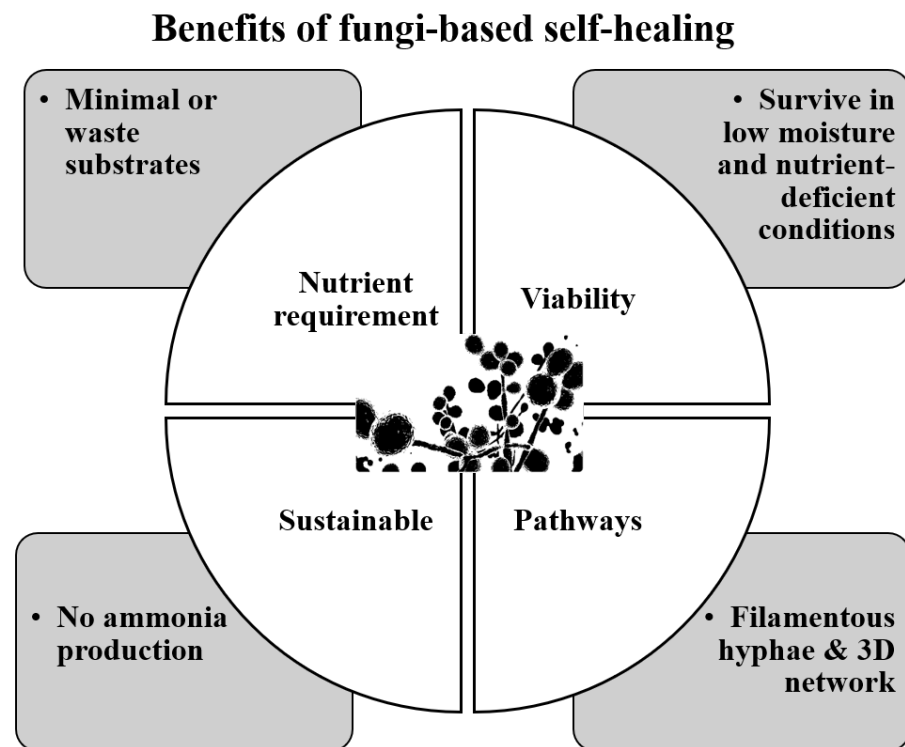
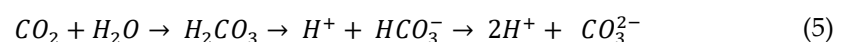


Figure 9. Benefits of using fungi-based self-healing.

4.1. Mechanisms of Fungal-Based Self-Healing Concrete

4.1.1. Chemical Healing Mechanism: Fungi-Based Biomineralization

Fungal-based systems mainly depend on biomineralization, which occurs through respiration, ionic interactions, and hyphal-surface nucleation. When dormant fungal spores in the concrete are exposed to moisture and oxygen through cracks, they begin to germinate and switch to aerobic metabolism. The emission of carbon dioxide (CO_2) as a natural by-product of respiration takes place in this process. This CO_2 is then dissolved in the pore solution to form carbonic acid (H_2CO_3), which dissociates over time to bicarbonate (HCO_3^-) and carbonate ions (CO_3^{2-}). The reaction mechanism is the classical equilibrium mechanism, depicted as Equation (5):



Since the concrete pore solution has a high content of calcium ions (Ca^{2+}), which is released by portlandite [$\text{Ca}(\text{OH})_2$], these carbonate ions quickly react with calcium ions (Ca^{2+}) to produce solid calcium carbonate (CaCO_3), which is deposited on the crack as illustrated in Figure 10a.

Fungal cell walls have chitin, melanin, and other polysaccharides that have functional groups (carboxyl, phosphate, and hydroxyl) attached to them [141]. The groups have a high affinity for Ca^{2+} , lowering the crystallization energy barrier and allowing rapid, dense deposition of CaCO_3 . SEM observations documented in the literature depict that the fungal mineralization process normally results in the formation of dense calcite-vaterite composites that are tightly bound to the hyphal filaments, resulting in the formation of long mineral bridges and not individual clusters of crystals [142,143]. Furthermore, genomic research conducted between 2020 and 2025 in model fungi (*Neurospora crassa* and *Aspergillus niger*) has identified nucleation-linked proteins, especially hydrophobins and surface adhesins, that substantially increase the rates of mineral precipitation [144]. This has provided a pathway to the development of hypercalcifying fungal strains for next-generation self-healing concrete. In general, fungal systems exhibit efficient crack filling,

pore densification, and high recovery compressive strength through chemical biomineralization and are competitive, and in some cases better, than bacterial systems.

4.1.2. Physical Healing Mechanism: Hyphal Bridging and Bio-Fiber Reinforcement

Besides chemical precipitation, fungi also provide a second, uniquely distinct, physical mechanism, hyphal bridging, which essentially distinguishes them from bacterial systems. Upon germination, the fungal spore produces long and filamentous hyphae, which grow actively in their search for moisture-rich areas such as newly opened cracks, as can be seen in Figure 10b [145]. The hyphae of fungi can extend over a millimeter-long fissure, unlike bacteria, which remain microscopic and non-directional, and can connect the crack faces by forming a continuous mycelial meshwork. This bridging effect forms a natural bio-derived reinforcement system that functions similarly to synthetic microfibers in engineered cementitious composites [15,145].

Having these chitin-containing hyphae over the crack helps significantly improve the structural integrity of the damaged area. Chitin gives the hyphae a high tensile strength and flexibility [146], so that a fraction of the tensile force is transferred on the fracture plane [16]. This significantly reduces the crack-opening displacement, delays crack propagation, and increases post-cracking toughness. Empirical studies published since 2019 indicate that fungal systems exhibit superior split-tensile strength recovery compared to bacterial systems, attributed to a mechanical bridging effect. Although bacterial CaCO_3 usually forms brittle, granular formations that may be removed under stress, the mineralized fungal hyphae are an effective, continuous reinforcement. The chemical reaction results in the mineral precipitates covering the surface of the hyphae to create hybrid structures of biological fibers, wrapped in CaCO_3 [147]. These bio-mineral micro-fibers can provide mechanical continuity and chemical sealing, yielding an overall synergistic healing response characterized by tensile reinforcement and a thick crack filling.

Fungal hyphae also have the advantage of being able to persist even after partial mineralization, unlike bacteria, which predominantly have their healing capacity in the form of surviving spores and, therefore, provide more than one opportunity to conduct repeated cycles of crack healing, even in the course of extended service life. Due to their long-term operation and dual-action healing, the fungus-based systems are especially promising for use when both sealing and mechanical property restoration are essential.

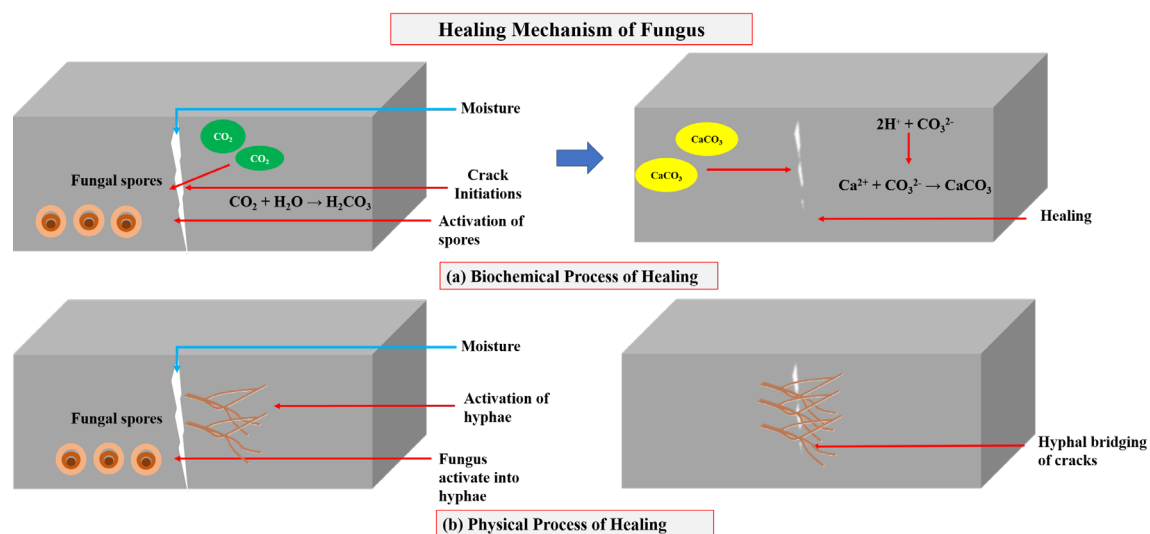


Figure 10. (a) Biochemical healing, and (b) physical healing process of fungus [145,148].

4.2. Chronological Evolution of Fungi in Self-Healing Concrete

4.2.1. Surface Protection by Fungi Bridging (Direct Addition)

The initial stage of fungal research in cementitious materials was developed to address biodeterioration and bioprotection of concrete rather than deliberate self-healing. The main topic of study during this time was the use of fungi as a surface-applied material to reduce porosity and prevent moisture ingress in hardened concrete. Some species used, including *Trichoderma reesei*, *Aspergillus niger*, and strains of *Penicillium*, were sprayed onto or grown on partially carbonated concrete surfaces, with the surface pH decreasing over time to more moderate values [149]. The studies mentioned in Table 4 showed that fungi can withstand, colonize, and remain metabolically active on concrete surfaces by adapting to alkaline stress and consuming limited nutrients. Fungi promoted localized calcium carbonate precipitation, leading to partial pore blockage and surface densification via respiratory activity and the release of extracellular polymeric substances [150]. However, efforts to propagate fungal activity outside the surface were not that successful. The compactness of the pore structure of the uncarbonated concrete, the extreme restriction of oxygen, and the maintenance of the alkalinity did not allow the hyphae to penetrate and grow in the long run. This step, therefore, made it clear that although the fungi have latent mineralization potential and can withstand alkaline conditions, the existing concrete matrices were not necessarily compatible with internal fungal healing, indicating that a change in the material system itself was required.

Table 4. Overview of crack healing ability, mechanical, and durability of fungi-based self-healing concrete.

Fungi Species	Delivery Method	Crack Width Healed (mm)	Mechanical Properties of Fungi-based Samples vs. Control Samples	Durability Studies of Fungi-Based Samples vs. Control Samples	Reference
<i>Aspergillus niger</i>	Direct Mixing	0.35	—	0.1 μm $\downarrow$ pore size	[139]
<i>Trichoderma reesei</i>	Direct addition	0.48	20–45% $\uparrow$ compressive strength, 23% $\uparrow$ split tensile strength	—	[145,146,151]
<i>Fusarium oxysporum</i>	Direct mixing	0.15	—	—	[15]
<i>Rhizopus oryzae</i>	Encapsulation by recycled aggregates	1.3	8% $\uparrow$ compressive strength	—	[145]
<i>Aspergillus fumigates</i>	Direct mixing	—	4.3% $\uparrow$ in flexural strength	—	[152]

Here, $\uparrow$ indicates an increase, $\downarrow$ indicates a decrease, “—” indicates that the corresponding data were not reported in the original study. “_”: Not Reported.

4.2.2. Encapsulation and Bulk Incorporation

The second phase is based on findings from surface-based research, which aimed to enhance the viability of fungi in the bulk concrete matrix by altering the microenvironment in which the biological agent could remain viable. Following progress in bacterial self-healing, scientists began modifying encapsulation principles for fungal systems, as the direct addition of fungal spores would cause rapid inactivation [153]. Fungi are mainly aerobic and cannot sustain hyphal growth and metabolism without a constant supply of oxygen. This physiological need was a defining challenge and directly influenced the encapsulation schemes used at the time [154]. Lightweight aggregates, porous expanded clay aggregates, and engineered void-forming inclusions became the preferred carriers, providing internal air reservoirs while sheltering fungal spores from extreme alkalinity and mechanical damage during mixing [155]. Crack-sealing capacities of up to approximately 1.3 mm were consistently reported, placing fungal systems on par with bacterial MICP in crack-width closure [156]. Notably, nutrient requirements in fungal systems were significantly lower due to the oligotrophic nature, resulting in lower material costs and greater scalability. This step made fungal healing a key enabling technology and transformed it into a practical internal self-healing process rather than a superficial one.

4.3. Effect of Fungi-Based Biomineralization on Concrete Mechanical and Durability Properties of Concrete

Fungi-based self-healing systems enhance the mechanical performance of concrete through a combined mechanism of mineral precipitation and physical crack stabilization, yielding distinct mechanical and durability outcomes compared to bacterial systems [139]. However, unlike bacterial systems, in which rapid calcite filling predominates to strengthen the system, fungal biomass induces a softer, yet distributed, phase within the cement matrix. As a result, compressive strength recovery of fungal concrete is generally moderate, with a range of 5 to 45% reported in Table 3, and fungal species, nutrient availability, and crack geometry heavily influence it [140]. On the other hand, the hyphal network is filamentous, serving as a biological fiber system that forms bridges across crack faces and transmits stress through the concrete matrix [148]. This hyphal bridging slows crack widening and enhances the load-carrying capacity of the structures. The hyphae also improve post-cracking ductility and resistance to cracking under cyclic or dynamic loading environments.

Regarding durability, fungal biomineralization provides significant enhancement of resistance to fluid ingress by sealing a network of interconnected pores and micro-cracks [156]. CaCO_3 deposition, in combination with hyphal occupation, decreases water uptake, sorptivity, and chloride ion uptake. Fungal growth is more widespread in the crack network, unlike bacterial precipitation, which tends to be localized near the crack mouths, resulting in a more uniform internal sealing and enhanced long-term impermeability [146]. Also, the thick bio-mineralized layer that forms along hyphae provides resistance to carbonation and sulfate ingress by inhibiting diffusion pathways. Research also reveals superior freeze–thaw stability, in which crack stabilization inhibits crack recurrence and reduces moisture concentration within the matrix [149].

4.4. Critical Analysis and Limitations of Fungi-Based Self-Healing

Fungi present an interesting dual-action mechanism, that is, chemical biomineralization and physical hyphal bridging, which, in theory, is superior to unicellular bacteria in tensile and flexural recovery. Compressive strength increases are reported with substantial variability (8–45%), and tensile/flexural values are very sparse, so they cannot be directly compared with those of bacterial systems. The advantage of having oligotrophic species like *Trichoderma reesei* and *Aspergillus niger* in nutrient-poor environments, given their strict aerobic nature, is that internal viability is limited unless complex air-reservoir encapsulation (e.g., LECA) is employed.

An important gap concerns long-term stability: although hyphal networks can provide micro-reinforcement, the chitinous biomass may be weakened over prolonged alkaline exposure or during repeated wetting–drying cycles, potentially forming new weak interfaces. Another issue not well addressed is biosafety; certain types of filamentous fungi are allergenic or mycotoxic, and thus due diligence in selecting and containing strains is required during field applications. Therefore, despite the evident promise of fungi for larger crack widths (>0.5 mm) and cyclic loading conditions, the technology remains in its infancy as a proof of concept.

5. Algae-Based Self-Healing Concrete: The Sustainable Frontier

The growing need to decarbonize the construction industry has shifted research focus. The process of conventional concrete production itself accounts for almost 8% of the world's anthropogenic CO_2 emissions, making the development of next-generation materials that go beyond mere durability essential to facilitate environmental (eco)-solar sustainability [157]. Within this context, self-healing concrete, originally proposed as a

technique to both increase service life and reduce maintenance, has become a broader framework for approximating biological, chemical, and environmental features. Algae-based self-healing concrete is one of the newest and most progressive frontiers of the bio-based approach, offering a much-needed perspective on the future.

In contrast to bacterial and fungal self-healing systems, which primarily follow heterotrophic metabolic pathways and release CO_2 as a by-product of respiration, algae and *cyanobacteria* introduce autotrophic metabolism to cementitious composites [158]. These photosynthetic microorganisms use atmospheric carbon dioxide as a nutrient source, converting it into biomass while also encouraging mineral precipitation, as illustrated in Figure 11. Consequently, the algae-based technologies are the only property to balance two historically incompatible goals of concrete technology, building durability, and carbon capture. This twofold purpose makes algal concrete a possible source of carbon-neutral (or perhaps even carbon-negative) infrastructure [159].

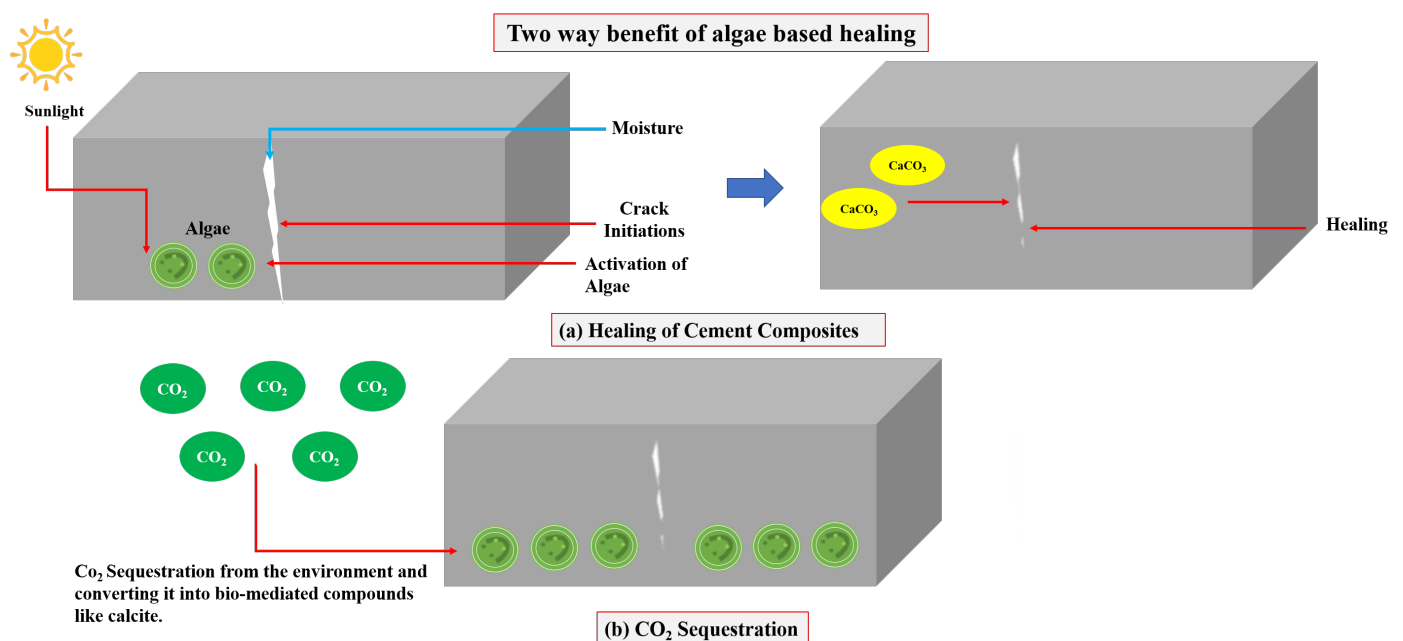


Figure 11. Benefits of using an algae-based self-healing mechanism.

Conceptually, algae-based self-healing is a shift in bio-concrete toward repair in ecosystem-mimicking construction materials. Instead of passively operating as integrated healing factors in response to cracking, algae can actively respond to environmental conditions, including light availability, moisture intrusion, and CO_2 concentration [159]. This means it is highly responsive to repeated and adaptive healing, especially on concrete surfaces or in semi-porous concrete buildings such as facades, footways, and marine constructions. Moreover, oxygen evolution during photosynthesis provides a secondary source of durability, with potential advantages such as possible remediation of anaerobic corrosion by microbes and biofilms [160].

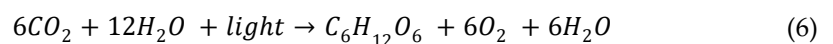
The above studies extensively situate algae-based concrete within the broader discourse on nature-based solutions and circular construction, which align with principles of global sustainability and net-zero policies [161]. Technical issues also persist, such as microbes' ability to survive in extreme alkaline conditions and to allow adequate light into the cementitious products, but the quickening pace of development in encapsulation methods, translucent cementitious matrices, and biomorphic biosystems indicates high scalability in the future [162]. As a result, self-healing concrete made from algae is no longer considered a hypothetical idea but a revolutionary approach to construction that changes the way we think about self-healing methods, carbon emissions, and environmental

impact in a single construction material. Its creation represents a major paradigm shift in bio-concrete research, in which the task is no longer focused on increasing service life but rather on redefining the role of concrete infrastructure per se in ecology.

5.1. Healing Mechanism: Photosynthesis-Driven Biomineralization and Carbon Sequestration

Photosynthetic microorganisms, such as microalgae and cyanobacteria, use autotrophic pathways, unlike bacterial and fungal systems, which use heterotrophic metabolism and release CO₂ during respiration. These organisms actively absorb atmospheric or dissolved CO₂, as shown in Figure 11, thereby transforming cementitious materials into biologically active carbon sinks. Such a property makes algal concrete consistent with world-scale decarbonization. It broadens the range of the self-healing material to the non-functional repair of the structure to climate-aware infrastructure [18,163].

Photosynthesis, which mediates the precipitation of carbonates, is the fundamental healing process in algal concrete, in which dissolved inorganic carbon is converted biologically into solid calcium carbonate [164]. In the presence of light, algal cells undertake oxygenic photosynthesis as per the generalized reaction given below:



In the process, as CO₂ is consumed, the concentration of carbonic acid in the pore solution decreases, and the carbonate equilibrium shifts toward the alkaline side. With depletion of CO₂, bicarbonate (HCO₃[−]) and carbonate (CO₃^{2−}) ions gain prominence, leading to a local increase in pH around the algal cell surface. This pH increase in the calcium-rich setup of cementitious matrices causes supersaturation relative to calcium carbonate.

The precipitated calcium carbonate selectively attaches to the algal cell wall and related extracellular polymeric substances, resulting in dense interlocking layers of calcite that gradually fill cracks and interpenetrating pore space [159,165]. This mechanism does not require the presence of urea or nitrogen-containing substrates, unlike ureolytic bacterial pathways. It thus does not produce ammonium or ammonia by-products. The resulting calcite is chemically inert in an alkaline environment. It has a high adhesion to the cement matrix, which helps achieve effective crack sealing and long-term suppression of water permeability [18].

Another unique benefit of algae-based systems is that the molecular oxygen (O₂) is produced as a by-product of photosynthesis. Localized anaerobic environments that are otherwise favorable to microbiologically influenced corrosion can be alleviated by diffusion of oxygen into crack zones and pore networks [166]. This oxygen supply can sustain the passivation of steel in reinforced concrete by inhibiting the growth of anaerobic microorganisms that favor corrosion [167]. Though this effect does not replace traditional corrosion protection measures, it offers an additional mechanism for durability enhancement that is not present in bacterial- or fungal-based self-healing systems.

In general, self-healing concrete made from algae can exhibit a rapid healing cycle that consumes carbon, can be repeatedly activated, and can interact with the environment. In combination with crack sealing, permeability minimization, oxygen production, and carbon capture, the photosynthetic self-healing systems reverse the functional role of concrete, from a passive structural material to an active constituent of climate-adaptive, sustainable infrastructure [22,168]. This makes algal concrete a potential future in the following generation of bio-engineered cementitious compositions.

5.2. Chronological Evolution and Challenges of Algae-Based Self-Healing Concrete

5.2.1. Surface-Oriented Applications

The earliest investigations into algae-concrete interactions did not target autonomous crack healing within the bulk matrix but instead focused on surface-level applications

aimed at environmental and aesthetic enhancement. From approximately 2018 to 2025, researchers explored the concept of green facades, or bio-curtains, in which photosynthetic microorganisms were deliberately cultivated on the exposed surfaces of cementitious materials [169]. *Cyanobacteria* such as *Synechococcus*, *Chroococcidiopsis*, and *Nostoc* species were found to colonize carbonated concrete surfaces effectively [170], owing to their inherent tolerance to alkaline environments and desiccation. These organisms demonstrated the ability to induce calcium carbonate precipitation through photosynthetic activity, leading to partial sealing of surface pores and microcracks [171].

Although these early systems did not qualify as self-healing concrete in a structural sense, since the microorganisms were not embedded within the concrete matrix, they played a crucial foundational role. They provided the first experimental evidence that photosynthetic microorganisms can survive on cementitious substrates, promote biomineralization, and form adherent calcite layers under natural light. Furthermore, these studies highlighted the dual environmental benefit of such systems, combining surface protection with atmospheric CO₂ uptake [172]. A comprehensive overview of the crack-healing capacity, mechanical properties, durability, and CO₂ sequestration efficiency of different algae-based systems is summarized in Table 5. However, the healing action remained superficial and highly dependent on external environmental conditions, particularly light intensity, moisture availability, and the depth of surface carbonation. As a result, the applicability of this approach was largely restricted to architectural envelopes and non-load-bearing components.

Table 5. Overview of crack healing ability, mechanical, durability, and CO₂ sequestration of algae-based self-healing concrete.

Algae Species	Crack Width Healed (mm)	Effect on Compressive Strength of Algae-Healed Concrete vs. Control Samples	Durability Properties of Algae-Healed Concrete vs. Control Samples	CO ₂ Sequestration (%)	Source
<i>Spirulina platensis</i>	0.7	72% ↑	-	30% CO ₂ ▲	[173]
<i>Synechococcus elongatus</i>	0.7	36% ↑	-	30% CO ₂ ▲	[173]
<i>Cyanobacteria</i>	0.6–1.1	15% ↑	80% ↓ water permeability 75% ↓ water absorption was seen.	40% CO ₂ ▲	[158,174]

Here, ↑ indicates increase, ↓ indicates decrease, ▲ indicates sequestration or capturing, and “-” indicates that the corresponding data were not reported in the original study.

5.2.2. Transition to Internal Healing and the Challenge of Light Availability

Based on the success of the surface systems, the research shifted to the development of internal self-healing using algae-based systems. This shift represented a highly significant conceptual forward step because incorporating photosynthetic microorganisms into concrete presented a fundamental limitation that was not present in bacterial and fungal systems: the need for light. Light penetration is the limiting factor of internal healing, unlike in heterotrophic microorganisms, in which light penetration is not a major variable, as algae cannot stay metabolically active in total darkness [162].

The bio-skin concept, in which algal healing was deliberately confined to the top 5–10 mm of the concrete cover, was one of the major strategies developed to solve this challenge. This area is commonly known to be the most critical for durability, controlling processes like chloride ingress, carbonation, and moisture transport [18]. By exposing only this near-surface layer, researchers were able to ensure adequate light, yet the durability

improvement was significant. As shown by experimental studies, algae entrenched in this zone could quickly precipitate calcium carbonate when cracks formed, commonly sealing cracks on the surface within 24 h in natural sunlight because of rapid photosynthetic rates [173]. This quick response made algal systems different to bacterial counterparts, as they normally need wet-dry cycles and take more time to activate.

Simultaneously, more technologically sophisticated solutions were developed to overcome light constraints in deeper areas of the concrete matrix. The introduction of optical fibers or light-conducting components into concrete is one of them. They are light-transmitting or translucent concrete systems meant to direct outside light into the interior, thus keeping photosynthetic processes alive at deeper levels [175]. Even though it is an experimental phase, initial tests show that these systems have the potential to sustain internal algal viability and localized carbonate precipitation, enabling repeated healing cycles beyond the surface layer. Nevertheless, the current obstacles to large-scale use are associated with cost, constructability, and mechanical compatibility.

Although these advances have been made, light dependence remains the primary limitation of algae-based self-healing concrete. The healing efficiency can be affected by variations in solar exposure, shading, biofouling, and seasonality. However, the remarkably rapid crack sealing observed at exposed surfaces, along with the inherent carbon sequestration capacity of photosynthetic systems, has made algal concrete a very appealing solution for facade elements, pavements, bridge decks, and other infrastructure elements where light is naturally present.

5.3. Critical Analysis and Limitations of Algae-Based Self-Healing

Because algae-based systems combine crack sealing with photosynthetic CO₂ sequestration, they offer a unique carbon-negative route aligned with global decarbonization goals. However, light dependence limits their practical applicability. Internal curing is practically limited to the outermost 5–10 mm bio-skin zone; further inclusion of the matrix cannot be achieved without expensive optical fibers or transparent aggregates, which compromise structural integrity and increase material costs.

Although surface crack closure during 24 h of sunlight is impressive, gains in compressive strength (15–72%) and decreases in permeability have been observed under ideal laboratory conditions that rarely reflect on shaded structural components or seasonal changes. Prolonged survival under high alkalinity (pH > 12) and desiccation is poorly reported, and there are other biosafety and regulatory challenges posed by the threat of toxin-producing cyanobacterial strains.

When it comes to sustainability, CO₂ capture rates of 30–40% are mentioned, but there is no full-life-cycle analysis that considers encapsulation materials and light-transmitting additives. As a result, algae-based self-healing is now more appropriately considered a surface or facade technology than a general-purpose bulk repair technology. This method will need significant improvements in low-light-adapted strains or biomorphic light-guiding matrices before it can compete with bacterial or fungal systems in structural concrete.

6. Comparative Analysis: Bacteria vs. Fungi vs. Algae

One area of considerable research interest in cementitious materials is biological self-healing to enhance durability and sustainability. When comparing bacterial, algae-based, and fungal healing systems, significant differences are observed in healing efficacy, kinetics, mechanical improvements, biological maturity, and technological maturity.

As shown in Table 6, the curing potency of the bacterial self-healing systems shows medium efficiency in sealing cracks 0.1 to 1 mm wide. These systems are especially useful in curing drying-shrinkage cracks, internal microcracks, and load-induced microcracks

[70,174,176]. Fungal systems have a higher healing ability than algae systems, which can heal both external and internal microcracks [153,156]. Compared with algae-based healing systems, conventional systems are more efficient and can repair surface cracks [174]. The healing kinetics further differentiate these biological approaches. Fungal systems can initiate the healing process within 1–7 h of crack formation, whereas bacterial systems do not achieve this until 10 to 40 days, depending on environmental factors [17]. The healing process in algae is relatively slow, often taking more than 28 days, which limits their use for structural repair in urgent situations.

There is a great disparity in the improvement of mechanical properties across the biological systems. Bacterial self-healing has been reported to achieve significant improvements, including 20–60% increases in compressive strength, 15–20% increases in tensile strength, and 10–15% increases in flexural strength [26,27]. Fungi-based systems have moderate compressive strength recovery of between 10–40%, though tensile and flexural strength recovery data are limited [140,146]. Conversely, the mechanical performance data of the algae-based healing systems are still not adequate, which means that they still require additional experimental confirmation [174,177]. Likewise, gains in durability properties, such as decreased permeability, have been well investigated in the context of bacterial self-healing, with reported reductions of 20–50%. Nonetheless, there is a lack of durability data on fungi- and algae-based systems, indicating a significant gap in research on long-term performance measurement.

Biological viability is of paramount concern for the efficacy of bio-mediated healing. The alkaliphilic, spore-forming bacteria commonly used in bacterial systems include *Bacillus* and *Sporosarcina*, which can withstand the very alkaline concrete environment through sporulation. The fungi-based systems, especially those with filamentous species like *Trichoderma* and *Fusarium*, have a high level of tolerance to extreme pH conditions, mineral deficiency, and low moisture content. Their hyphal network structure increases the contact of cracks; thus, mineral deposition becomes easier. Algae-based systems, conversely, are usually associated with non-spore-forming, photosynthetic microbes like *Cyanobacteria* or *Dunaliella*, which are less resistant to high alkalinity and a dark, claustrophobic atmosphere within concrete matrices and, therefore, are highly unfavorable to viability.

Bacterial self-healing can also lead to lower maintenance needs and longer structural service life, and, in terms of environmental sustainability, the effects differ depending on nutrient sources, especially in urea-based systems. Sustainability can be improved by integrating waste materials like rubber, natural fibers, and eggshells. Fungal-based systems can also convert industrial and agricultural by-products into a nutrient source, though such systems have not been studied in their entirety. There is an interest in algae-based systems because they have potential for carbon capture via photosynthetic CO₂ fixation, but these systems have not been studied in much detail regarding durability, performance, or structural-scale life-cycle modeling.

The use of biological curing agents should also be considered regarding health care and biosafety. Most bacterial isolates used in self-healing processes are non-pathogenic, though ammonia production in urea-based systems needs to be addressed. Some fungal species can cause allergic or pathogenic effects, and a specific strain selection and containment may be required. Similarly, certain species of algae can be toxic or cause ecological imbalance, and environmental management must be controlled.

Techno-economically, bacterial self-healing is the most developed to date and is most likely to be implemented, with extensive optimization research and reduced prices for growing and encapsulating microbes. The systems based on fungi are still early in their development, and uncertainties about cost and scalability persist. Algae-based systems are mostly in concept or early demonstration stages, with viability limitations and

environmental constraints on light and CO₂ availability restricting their large-scale structural applicability.

In general, the level of technological maturity and performance reliability of bacterial self-healing systems is the highest, with strong evidence of crack healing, mechanical recovery, and durability improvements. Fungal-based strategies exhibit high potential for healing and eco-friendliness, though additional research is needed to define their structural performance. Algae-based systems have an appealing sustainability potential. However, there is insufficient experimental evidence to justify broad-scale structural use.

Table 6. Master comparison matrix of biological self-healing agents.

Parameters	Bacterial Self-Healing	Fungi-Based Self-Healing	Algae-Based Self-Healing	Citations
	Healing efficiency			
Crack width 0.1–1 mm	High efficiency	High efficiency	Low efficiency	
Crack type healed	Drying-shrinkage cracks, internal microcracks, and load-induced microcracks	Surface and internal microcracks	Limited to Surface cracks	[46,140,148,174]
Healing speed	10 to 40 days (initiation of healing to complete healing)	7 to 12 h (initiation of healing products)	≥28 days (initiation of healing to complete healing)	
Mechanical properties enhancement	20 to 60% of compressive strength 15 to 20% tensile strength 10 to 15% flexural strength	10 to 80% compressive strength	15 to 70% compressive strength	[140,146,178]
Durability properties	20 to 90% reduction in permeability	0.1 µm of pore size reduction	75% water absorption reduction	[121,140,166,177]
Environmental & sustainability aspects	Extends service life and reduces repair needs	Extends service life and reduces repair needs	Strong interest due to carbon capture potential	[148,173,174]
Health & biosafety	Generally non-pathogenic; ureolytic systems may produce ammonia, requiring appropriate nutrient management	Most strains are non-pathogenic, but some species (e.g., <i>Fusarium</i>) may present allergenic or pathogenic concerns, requiring careful strain selection	Generally, environmentally benign; however, certain cyanobacterial species may produce toxins or blooms if unsuitable strains are used	[15,179,180]
Cost & technology readiness	Most advanced and closest to practice; costs driven by culture, nutrient, and encapsulation methods	Early-stage technology; higher uncertainty in cost and scale-up; encapsulation and biosafety may raise costs	Concept/early demonstration stage; viability and process constraints (light, CO ₂) make large-scale structural adoption uncertain so far	[156,176,181]
Biological features and viability	Mostly alkalophilic, spore-forming	Mostly filamentous and halotolerant	Photosynthetic species	[161,177]

7. Case Studies of Bio-Based Materials in Construction

The study of microbial self-healing concrete has been gradually shifted from laboratory studies to engineering applications. But this advancement has not been consistent among all microorganisms. Compared with bacterial, fungal, and algal systems, bacterial systems are the only ones that have been fully explored at the pilot scale and commercialized, while fungal and algal systems are still at the laboratory and pilot stages. By examining these case studies, it is possible to evaluate the extent of practical application of each biological method.

The first practical application was introduced by Professor Henk Jonkers and his research team at Delft University of Technology through the development of BioConcrete, which consists of bacterial spores of *Bacillus subtilis* and other alkaliphilic bacteria, together with nutrients encapsulated in lightweight granules made from limestone [182]. This research eventually led to the commercialization of Basilisk Self-Healing Concrete,

one of the first successful applications of microbial self-healing concrete from the lab to engineering practice [183].

Since then, the technology has been tested on several pilot-scale structures. BioConcrete was applied in the Netherlands in underground parking facilities and water-retaining concrete elements, where cracking is often a problem due to restrained shrinkage and environmental exposure [178]. Structural performance over nearly five years was satisfactory and indicated that the maintenance requirements were less than those for conventional concrete. Coinciding with this, during the monitoring period, only limited cracking occurred, making it difficult to directly quantify the healing efficiency under real service conditions [183,184]. The same type of demonstrations in Belgium, the United Kingdom, and prototype bridge elements have also demonstrated the successful implementation of bacteria-based self-healing concrete at larger scales. The studies also highlight, however, that longer monitoring periods are still required, as the occurrence of crack formation in service structures is very variable [185].

Recent studies have also broadened the scope of microorganisms that can be used for self-healing concrete. Ujjwala Rani and Gupta (2024) [186] isolated alkaliphilic bacterial strains from Sambhar Salt Lake, Rajasthan, such as *Halomonas*, *Halobacillus*, and *Oceanobacillus* species. The study showed that these extremophilic bacteria enhanced compressive and split tensile strengths and decreased water absorption through biomineralization. Furthermore, bacterial consortia outperformed single strains, which indicates that combined microbial systems may be more effective in healing in highly alkaline conditions.

Fungal self-healing concrete, on the other hand, is still in the lab and pilot phase, with the results so far promising. Van Wylick et al. demonstrated that filamentous fungi, such as *Fusarium oxysporum* and *Trichoderma longibrachiatum*, can survive the very alkaline environment of cement and form mycelial networks that act as nucleation points for the precipitation of calcium carbonate [187]. Based on this idea, Ghent University researchers added immobilized fungal spores to recycled aggregate concrete and claimed that cracks up to about 0.5 mm were healed after extended exposure to moisture [148]. Fungi are interesting for long-term applications due to their ability to store nutrients and continue metabolizing when nutrient levels are low. More recent research has therefore concentrated on protecting fungal spores by co-encapsulation with lightweight expanded clay aggregates (LECA), polyethylene glycol (PEG), and other carrier materials, which enhance the survival of the spores in concrete [188]. Even with these advances, fungal systems have not been tested on a large scale in field structures.

Microalgae are at the very beginning of development, among the three biological approaches. Most of the published work has focused on the capacity of photosynthetic microorganisms to precipitate calcium carbonate while removing carbon dioxide from the atmosphere. For example, *Chlorella vulgaris* was cultivated on living concrete, which consists of porous concrete panels, developed for architectural use [189]. These panels do not repair structural cracks but rather act as a biologically active surface that facilitates the local alkaline environment, leading to the precipitation of calcium carbonate and surface densification. The concept has been proven successful in lab and greenhouse settings, but has yet to be demonstrated in structural applications [185].

Another interesting avenue is Artificial Biological Reefs (ABRs). The materials are bioactive, allowing the growth of natural microorganisms, such as *Cyanobacteria*, *Proteobacteria*, and other microorganisms that produce carbonates in marine environments. These biofilms develop over time and encourage the formation of carbonate on the surface of the concrete [190]. Although the technology has been developed to restore the environment, it can be used for the autonomous mineral formation of cementitious materials in an aggressive environment for a long time.

In addition to adding microorganisms to fresh concrete, researchers have also explored microbial repair systems for existing structures. Li et al. formulated a microbial slurry with *Sporosarcina pasteurii*, sodium alginate, and nano-silica and applied the slurry to the pre-cracked concrete under negative pressure, followed by the addition of a calcium source [191]. The results after 28 days of curing showed that calcium carbonate precipitation was quite effective in bridging cracks, decreasing permeability, and enhancing resistance to carbonation. These surface treatments are useful when microorganisms are not added to the cast concrete.

Overall, these case studies illustrate that the bacterial system is better developed and closer to use than the fungal and algal systems. The technical feasibility of pilot-scale applications and commercialization of Basilisk Self-Healing Concrete has been demonstrated, but there is limited long-term quantitative data from field applications. Typically, demonstrations do not provide much data on actual percentages of crack closure over time, permeability reduction under actual service conditions, maintenance cost savings, or overall life-cycle cost-effectiveness.

Fungal and algal systems have shown encouraging results in laboratory and small-scale pilots, but have not yet been validated for use in full-scale structural applications. Thus, a further research focus should be placed on long-term field monitoring (longer than 5 years), standardized testing measurement methods, large-scale demonstration, and detailed economic analysis to fully evaluate the true cost-effectiveness and durability benefits of these biological self-healing technologies to achieve a broad scale of adoption in the future.

8. Challenges and Future Perspectives

Despite more than twenty-five years of intensive research and a rapidly expanding body of literature, bio-based self-healing concrete has yet to achieve widespread commercial implementation. While laboratory-scale investigations have conclusively demonstrated the technical feasibility of microbial healing, several critical challenges continue to impede translation from academic research to real-world infrastructure. Based on a comprehensive synthesis of published studies, this review identifies three fundamental bottlenecks that must be addressed to unlock the full potential of bio-concrete: scalability and survival under realistic exposure conditions, the absence of standardized performance metrics, and limited integration with modern monitoring and control technologies.

8.1. Lab-to-Site Gap: Survival, Robustness, and Scalability

A significant weakness of existing bio-concrete research is the gap between laboratory study conditions and field realities. Most reported studies compare healing performance under controlled conditions, usually at 20–25 °C with relative humidity above 90%. On the contrary, real concrete structures are subjected to cyclic freeze–thaw action, ultra-violet radiation, drying–wetting, continuous mechanical loading, and chemical attack. This may severely affect microbial viability, nutrient conditions, and healing performance. As a result, good laboratory performance does not always translate into the final field performance.

Another difficulty is scalability. Most experimental programs are based on small mortar and paste specifications prepared through laboratory mixing. Large-scale concrete production involves high-shear mixing, long transportation times, and fluctuating curing periods, which may adversely affect microorganisms. The solution to this gap requires extensive field testing with an industrial batching plant and realistic curing conditions. Moreover, the latest developments in microbial genetics provide an encouraging path to overcome survival constraints. The production of gene-edited or naturally occurring extremophiles that can withstand cement hydration temperatures, pH levels near 13, and

protracted desiccation without costly encapsulation systems is an essential area of focus for future studies.

8.2. Standardization, Testing Protocols, and Quality Control

The second significant barrier to commercial implementation is the absence of standardized testing procedures to measure self-healing performance. Currently, only a limited number of ASTM, ISO, or EN standards specify the meaning of self-healing efficiency in cementitious materials. The researchers use several testing methods, including visual crack width, water-permeability-based recovery, sorptivity reduction, ultrasonic pulse velocity, and mechanical-strength regain. Although all these metrics are useful, the lack of standardization makes it challenging to compare studies and diminishes the trustworthiness of industry participants. It is therefore critical that a standardized, multi-parameter testing protocol be established. Mechanical recovery, transport properties, durability of the surrounding environment, and long-term stability of the healing product should be incorporated into such a framework. Standardization would also help incorporate bio-concrete into design specifications and building codes, so engineers can specify biological healing systems with greater predictability of performance. Without this, bio-concrete would likely be limited to laboratory showcases rather than a construction material.

8.3. Smart Monitoring and Digital Construction Technologies Integration

In the future, the most radical development in bio-concrete should come through its collaboration with Industry 4.0-related digital technologies. The future vision extends beyond the passive self-healing of intelligent, responsive materials. The damage can be detected in real time by embedding Internet of Things (IoT)-based sensors that measure moisture, pH, strain, and crack formation in concrete structures. In combination with bio-based healing systems, these sensors may be used to trigger specific activation syndromes, including the controlled release of water or nutrients into internal vascular systems to wake up inactive microorganisms where and when healing is needed.

This merger of biology, sensing, and automation can lead to the creation of a live infrastructure with the ability to self-diagnose, self-repair, and adaptively respond to environmental stimuli. Still in its early years, initial proof-of-concept results show that these hybrid bio-digital systems have the potential to offer a long life cycle, minimize maintenance, and redefine durability design philosophies in civil engineering.

9. Conclusions

This review demonstrates that microorganism-based self-healing concrete has evolved into a promising approach for improving the durability and service life of cementitious materials. Although bacteria, fungi, and algae all promote calcium carbonate precipitation through distinct biological mechanisms, their technological maturity levels differ considerably. Among these systems, bacteria-based self-healing has emerged as the most advanced and reliable approach because of its ability to rapidly seal internal cracks, restore mechanical performance, and remain viable in the highly alkaline cementitious environment. Its successful progression from laboratory investigations to pilot-scale studies and limited field applications makes it the only biological self-healing technology currently ready for near-term engineering implementation. Nevertheless, challenges associated with ammonia generation in ureolytic pathways, long-term microbial viability, environmental exposure, and repeated healing cycles require further optimization before widespread commercial adoption.

Fungal systems provide a promising alternative by combining biomineralization with hyphal crack bridging, thereby improving overall mechanical behavior and resistance to crack propagation under cyclic loading. Algae-based systems offer an

additional sustainability advantage by coupling calcium carbonate precipitation with atmospheric CO₂ sequestration, making them attractive for environmentally responsive construction materials. However, both approaches remain considerably less mature than bacterial systems. Fungal self-healing is still constrained by biosafety concerns, encapsulation strategies, long-term durability, and the lack of standardized evaluation methods, while algae-based systems are limited by their dependence on light, which restricts their application primarily to exposed or near-surface concrete. Consequently, both fungal and algae-based technologies remain at the laboratory or early demonstration stage and require substantial validation before practical structural implementation.

No single biological system can be considered universally optimal, and the selection of a self-healing strategy should be guided by the intended application rather than the search for a superior microorganism. Bacteria-based systems are currently the preferred choice for structural concrete requiring rapid healing of internal cracks, particularly those below approximately 1 mm, owing to their proven performance and higher technology readiness. Fungal systems may be more suitable where crack bridging and improved tensile performance are desired, whereas algae-based systems are better suited for non-structural surface elements and bioactive concrete designed to promote carbon sequestration and environmental sustainability. To facilitate practical implementation, a decision framework for selecting the appropriate microorganism-based self-healing system based on these engineering considerations is presented in Figure 12.

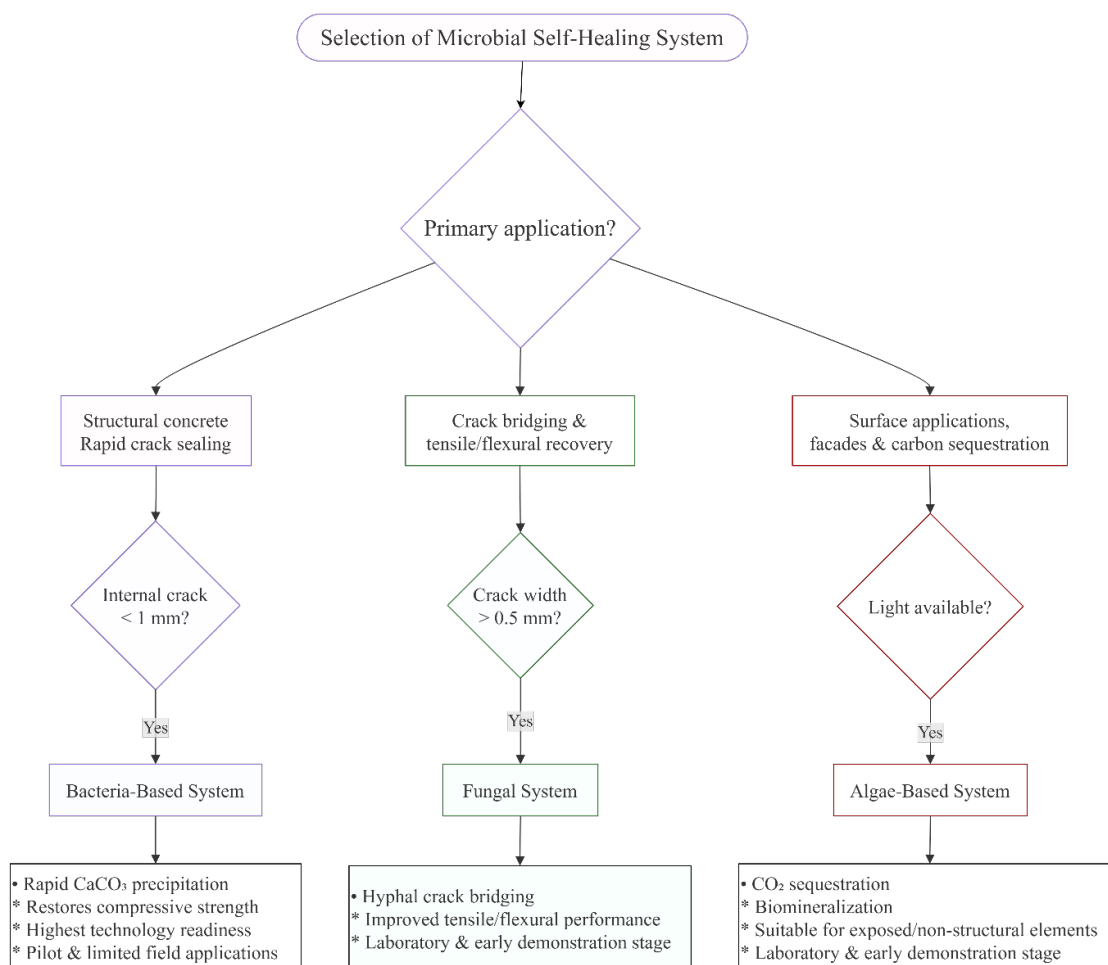


Figure 12. Flowchart for selecting the most suitable microorganism-based self-healing concrete system according to crack width, structural application, environmental exposure, and sustainability objectives.

Despite significant advances, several challenges continue to limit large-scale implementation, including long-term performance under field conditions, microbial survival in aggressive environments, encapsulation efficiency, economic feasibility, and the lack of universally accepted testing protocols. Future research should therefore focus on long-term field validation, development of robust multi-cycle healing systems, improved carrier and encapsulation technologies, and standardized testing procedures that enable meaningful comparison across different biological approaches. Addressing these challenges will be essential for translating bio-based self-healing concrete from promising laboratory research into a reliable, durable, and widely adopted construction technology.

Funding: This research was supported and funded by the Mahindra University–Virginia Tech Interdisciplinary Advanced Research Center for Transformative Technologies under Project No. MU-VTIARCT2/TA-SCC/2025/02.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no competing interests.

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