

Biological concrete in modern civil construction: Advances, applications, and challenges — A narrative review

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Abstract

Concrete and mortar are among the most widely used construction materials worldwide; however, their susceptibility to crack formation significantly compromises structural durability and increases maintenance costs. Although crack formation cannot be entirely prevented, several remediation techniques have been developed. Conventional repair methods, including chemical sealants and polymer-based materials such as epoxy resins, often present environmental concerns, potential health risks, and limited long-term effectiveness. Consequently, sustainable and durable alternatives have gained increasing attention in recent years. Among these alternatives, microbial self-healing concrete has emerged as a promising technology due to its ability to autonomously repair cracks through biologically induced calcium carbonate (CaCO_3) precipitation. This process is primarily mediated by aerobic and anaerobic bacteria capable of surviving within the concrete matrix and producing mineral deposits that seal cracks, restore structural integrity, and enhance durability. Compared with traditional repair techniques, microbial self-healing systems offer advantages such as prolonged effectiveness, reduced maintenance requirements, and lower environmental impact. This narrative review examines the mechanisms involved in microbial CaCO_3 production and discusses the application of bioconcrete in civil construction. The review covers the characteristics of conventional concrete, the main pathological manifestations affecting concrete structures, current remediation strategies, and recent advances in the development of high-performance bioconcrete. Furthermore, the potential of biological concrete as a sustainable, cost-effective, and environmentally friendly technology for modern civil construction is critically evaluated. The findings highlight the significant role of microbial-based self-healing materials in improving infrastructure longevity while supporting more sustainable construction practices.

Keywords: bioconcrete, sustainable infrastructure, biomineralization, eco-friendly materials, concrete repair, civil engineering.

Concreto biológico na construção civil moderna: avanços, aplicações e desafios — Uma revisão narrativa

Resumo

O concreto e a argamassa estão entre os materiais de construção mais utilizados em todo o mundo; entretanto, sua suscetibilidade à formação de fissuras compromete significativamente a durabilidade estrutural e aumenta os custos de manutenção. Embora a formação de fissuras não possa ser totalmente evitada, diversas técnicas de remediação têm sido desenvolvidas. Métodos convencionais de reparo, incluindo selantes químicos e materiais à base de polímeros, como resinas epóxi, frequentemente apresentam preocupações ambientais, potenciais riscos à saúde e eficácia limitada a longo prazo. Consequentemente, alternativas sustentáveis e duráveis têm recebido crescente atenção nos últimos anos. Entre essas alternativas, o concreto autorregenerativo microbiano tem se destacado como uma tecnologia promissora devido à sua capacidade de reparar fissuras de forma autônoma por meio da precipitação biologicamente induzida de carbonato de cálcio (CaCO_3). Esse processo é mediado principalmente por bactérias aeróbias e anaeróbias capazes de sobreviver na matriz do concreto e produzir depósitos minerais que selam fissuras, restauram a integridade estrutural e aumentam a durabilidade do material.

Em comparação com as técnicas tradicionais de reparo, os sistemas microbianos de autorregeneração oferecem vantagens como maior durabilidade dos reparos, redução das necessidades de manutenção e menor impacto ambiental. Esta revisão narrativa examina os mecanismos envolvidos na produção microbiana de CaCO_3 e discute as aplicações do bioconcreto na construção civil. A revisão aborda as características do concreto convencional, as principais manifestações patológicas que afetam as estruturas de concreto, as estratégias atuais de remediação e os avanços recentes no desenvolvimento de bioconcretos de alto desempenho. Além disso, o potencial do concreto biológico como uma tecnologia sustentável, economicamente viável e ambientalmente amigável para a construção civil moderna é avaliado de forma crítica. Os resultados destacam o papel significativo dos materiais autorregenerativos baseados em microrganismos na ampliação da vida útil das infraestruturas, ao mesmo tempo em que promovem práticas construtivas mais sustentáveis.

Palavras-chave: bioconcreto, infraestrutura sustentável, biomineralização, materiais ecológicos, reparo de concreto, engenharia civil.

1. Introduction

Concrete is the second most consumed material worldwide after water, playing a central role in modern infrastructure such as roads, bridges, tunnels, marine structures, parking facilities, and hydroelectric and nuclear plants (Bashir et al., 2016). Global consumption has already exceeded 4.08 billion tons, reflecting its strategic importance in civil construction (Nagrockiene; Girskas, 2016). Due to its versatility, concrete is widely applied in different environmental conditions, including terrestrial, freshwater, and marine systems, as well as in high-performance and architectural applications (Bauer, 1979; Arroyo et al., 2016).

Despite its extensive use, conventional concrete presents inherent limitations related to its brittle nature and susceptibility to cracking. Even under controlled production and reinforcement, concrete structures inevitably develop microcracks and fissures due to mechanical loading, thermal variation, shrinkage, and chemical degradation processes (Zhengyao et al., 2021). These defects significantly compromise structural integrity by increasing permeability and facilitating the ingress of aggressive agents such as chlorides, sulfates, and carbon dioxide, which accelerate reinforcement corrosion and reduce service life (Ahmad et al., 2021).

The deleterious effects of cracking on durability have been widely documented, indicating a direct relationship between crack propagation, increased permeability, and structural degradation (Akhtar et al., 2020; Aldea et al., 1999; Torrijos et al., 2010; Zaitsev; Wittmann, 1981). Consequently, maintenance and repair strategies are essential to ensure structural safety and longevity. However, conventional repair techniques, including periodic inspections and epoxy-based sealing systems, are often costly and environmentally unfavorable. Epoxy resins, despite their efficiency, may release toxic compounds that pose risks to both human health and the environment (Rahman; Islam, 2022). These limitations highlight the need for more sustainable and durable repair solutions.

In this context, self-healing concrete technologies have emerged as a promising alternative. Self-healing mechanisms are generally classified into autogenous and autonomous systems. Autogenous healing occurs naturally through continued hydration and carbonation reactions, allowing partial sealing of microcracks under favorable moisture conditions, typically for crack widths up to approximately 100 μm (Souza; Sanchez, 2023). However, this mechanism is limited in efficiency and long-term effectiveness.

Autonomous self-healing strategies, on the other hand, rely on external healing agents such as polymers, chemical encapsulants, and silicate-based systems. Although effective, many of these materials still present environmental and economic drawbacks. As a result, biological approaches based on microbial activity have gained increasing attention as sustainable alternatives for crack remediation in cementitious systems.

Microbially induced calcium carbonate precipitation (MICCP) has been extensively investigated as a self-healing mechanism in concrete systems. In this process, specific bacterial strains—such as species of *Bacillus* and *Escherichia*—induce the precipitation of calcium carbonate, which acts as a natural sealing material within cracks and pores. This biomineralization process enhances material densification and improves mechanical performance while reducing permeability (Mohanadoss et al., 2015; Soundharya et al., 2014).

Bioconcrete systems have demonstrated the ability to extend service life, reduce maintenance requirements, and decrease cement consumption, thereby contributing to energy savings and reduced carbon emissions (Rahmani; Bazrgar, 2015). Additionally, microbial healing processes are often compatible with the highly alkaline environment of cementitious matrices, allowing long-term viability of selected bacterial strains under harsh conditions.

The healing mechanism is primarily associated with calcium carbonate formation, resulting from biochemical

reactions involving microbial metabolism, dissolved CO₂, and calcium ions present in the cement matrix. This leads to progressive crack closure, reduced permeability, and partial restoration of mechanical continuity within the structure (Fukuda et al., 2013; Sahmaran et al., 2014; Umesh et al., 2018).

In addition to microbial systems, alternative sustainable materials such as geopolymer binders, magnesium phosphate cements, and natural reinforcements have also been explored to enhance the performance and sustainability of cement-based composites (Ahmad et al., 2021; Al-Sabaei et al., 2022; Caldas et al., 2020).

Given the growing interest in sustainable construction technologies, it is essential to critically evaluate the most effective biological and biomineralization-based approaches for crack mitigation in cementitious materials. Such understanding can guide technological advancements and promote the development of more durable, environmentally friendly, and cost-effective construction systems.

Therefore, this study aims to conduct a narrative review of recent advances in bioconcrete and microbial self-healing technologies, focusing on biomineralization-based strategies for the repair and durability enhancement of cement-based structures, with emphasis on their potential contribution to sustainable civil engineering.

2. Materials and Methods

2.1 Study design

A narrative review design was selected because the available literature comprises heterogeneous experimental designs, different bacterial species, distinct encapsulation techniques, and diverse evaluation methods, which preclude a systematic quantitative synthesis. This narrative review was conducted through a structured literature search to identify and analyze scientific publications addressing biological concrete and its applications in modern civil engineering.

2.2 Literature search strategy

Literature searches were performed between March and April 2026. The literature search was conducted using the databases Google Scholar, Web of Science, Scopus, ScienceDirect (Elsevier), Brazilian Digital Library of Theses and Dissertations (BDTD), Redalyc, Ulrichsweb, and Scientific Electronic Library Online (SciELO).

Only full-text publications written in English, Portuguese, or Spanish were considered.

The search strategy employed combinations of the following keywords and related terms:

"bioconcrete" OR "biological concrete";
"self-healing concrete" OR "MICP";
"microbial-induced calcium carbonate precipitation (MICP)";
"concrete durability";
"concrete repair";
"construction materials";
"civil engineering" OR "construction materials".

Boolean operators (AND and OR) were applied to refine the searches according to the characteristics of each database.

2.3 Eligibility criteria

The inclusion criteria comprised:

- peer-reviewed original research articles;
- review articles;
- conference proceedings;

- master's dissertations and doctoral theses;
- publications published between 2016 and 2026;
- full-text documents available in English, Portuguese, or Spanish;
- studies addressing biological concrete (bioconcrete), microbial self-healing concrete, microbial-induced calcium carbonate precipitation (MICP), biomineralization processes, concrete durability, crack remediation, or sustainable applications in civil engineering,
- studies directly related to the objectives of this narrative review, with emphasis on microbial mechanisms involved in calcium carbonate precipitation, self-healing technologies, concrete durability, and sustainable construction materials.

The exclusion criteria comprised publications focused exclusively on conventional concrete without discussing biological or self-healing approaches, except when such studies were included to provide comparative background information.

2.4 Study selection

Publications retrieved from the databases were initially screened based on their titles and abstracts to assess their relevance to the objectives of this review. Subsequently, the full texts of potentially eligible studies were evaluated according to the predefined inclusion and exclusion criteria.

Studies were selected based on their scientific relevance, methodological contribution, and consistency with the objectives of this review. Particular emphasis was given to publications addressing microbial mechanisms involved in calcium carbonate precipitation, self-healing technologies, concrete durability, crack remediation, and sustainable construction applications. A total of 318 records were initially identified through database searches. After screening and eligibility assessment, studies that met the predefined inclusion criteria constituted the core evidence base of this narrative review. Additional references, including books, technical documents, standards, and historical publications, were incorporated whenever necessary to provide conceptual background and contextual support.

2.5 Data extraction and qualitative synthesis

For each selected publication, relevant information was extracted regarding bacterial species, biomineralization mechanisms, self-healing efficiency, crack-sealing performance, mechanical properties, durability improvements, environmental sustainability, and technological limitations.

The retrieved studies were comparatively analyzed and organized into thematic categories, including:

- characteristics of conventional concrete;
- degradation mechanisms and structural pathologies;
- microbial self-healing mechanisms;
- microbial-induced calcium carbonate precipitation (MICP);
- performance and durability of bioconcrete;
- sustainability aspects,
- recent technological advances and future perspectives.

The qualitative synthesis of the available evidence provided a comprehensive overview of the current state of knowledge regarding biological concrete, highlighting the principal advances, existing limitations, technological challenges, and future research opportunities for sustainable civil construction.

As a narrative review, this study was designed to provide a comprehensive qualitative synthesis of the available evidence rather than a systematic quantitative assessment. Therefore, although a structured literature search and predefined eligibility criteria were adopted, the selection and interpretation of the literature may be subject to selection bias and should be interpreted within the inherent limitations of the narrative review methodology.

3. Biological concrete

3.1 Concrete as a material in civil construction

Concrete is one of the most widely used construction materials worldwide due to its versatility, mechanical strength, durability, and relatively low production cost. Its composition typically consists of cement, water, fine aggregates, and coarse aggregates, which interact through hydration reactions that begin immediately after mixing and continue during the curing process, resulting in the development of mechanical strength and structural stability (Seifan et al., 2016; Araújo et al., 2019; Castro-Alonso et al., 2019).

The extensive use of concrete in civil engineering is associated with its ability to be molded into different shapes and its excellent performance under compressive loads. Globally, concrete remains the most consumed manufactured material, supporting the development of buildings, bridges, highways, dams, and other infrastructure systems essential to modern society (Durga et al., 2020; Jakubovskis et al., 2020). Recent studies have further emphasized that concrete is indispensable for urban development and remains the backbone of modern infrastructure due to its availability, adaptability, and long service life (Amran et al., 2022; Griffiths et al., 2023).

Despite its numerous advantages, concrete exhibits an inherent tendency to crack due to shrinkage, thermal stresses, mechanical loading, environmental exposure, and corrosion of reinforcement. These cracks can facilitate the ingress of water, chlorides, sulfates, and other aggressive agents, accelerating deterioration processes and reducing the service life of structures (Jakubovskis et al., 2020; Amran et al., 2022).

Advances in concrete technology have enabled the development of high-performance, lightweight, and sustainable concretes capable of meeting increasingly demanding engineering requirements. However, the durability of concrete structures remains a major challenge, particularly regarding crack control and maintenance costs. Consequently, innovative approaches such as self-healing concrete and bioconcrete have gained considerable scientific and industrial interest due to their potential to repair cracks and improve long-term structural performance autonomously (Wong et al., 2024; Adhikary et al., 2024).

In recent years, research on microbial self-healing concrete has expanded significantly because of its ability to induce calcium carbonate precipitation within cracks, restoring impermeability and enhancing durability. These technologies are increasingly viewed as promising solutions for sustainable civil construction, contributing to reduced maintenance interventions, extended infrastructure lifespan, and lower environmental impacts associated with repair and reconstruction activities (Deeba; Ammasi, 2024; Wong et al., 2024).

3.2 Degradation mechanisms and durability limitations of conventional reinforced concrete

The durability of reinforced concrete structures depends largely on the ability of concrete to protect embedded steel reinforcement from aggressive environmental conditions (Figure 1). Freshly hardened concrete presents a highly alkaline pore solution, typically with a pH ranging from 12.5 to 13.5, resulting from the presence of calcium hydroxide ($\text{Ca}(\text{OH})_2$) and alkali hydroxides generated during cement hydration reactions. This highly alkaline environment promotes the formation of a thin, stable, and adherent passive oxide film on the steel surface, effectively protecting reinforcement against corrosion processes (Araújo et al., 2019; Bertolini et al., 2021).

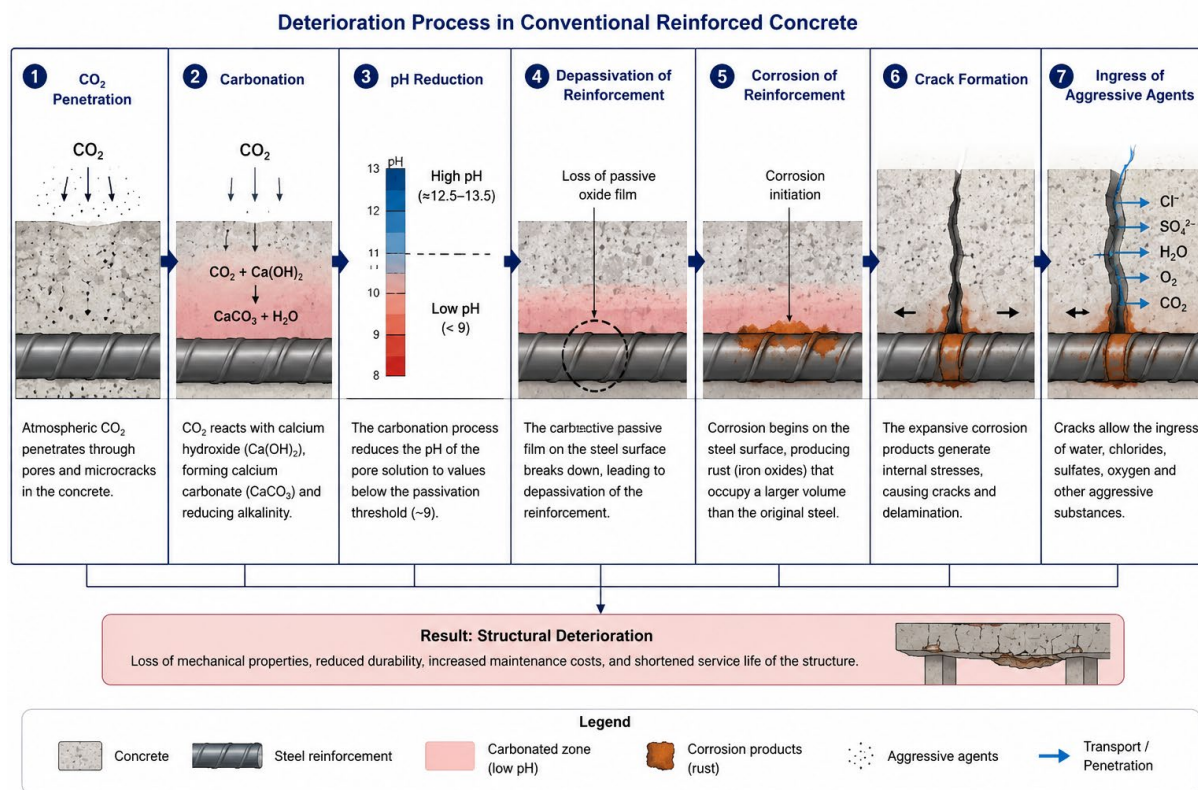


Figure 1. Deterioration mechanisms in conventional reinforced concrete, highlighting the need for self-healing and bioconcrete technologies. Source: Authors, 2026.

In addition to its chemical protective function, concrete acts as a physical barrier that limits the ingress of aggressive substances such as chloride ions, carbon dioxide, sulfates, and moisture. The effectiveness of this protection is directly associated with the pore structure, permeability, and cracking condition of the concrete matrix. When the concrete remains chemically stable and relatively impermeable, the passive layer surrounding the reinforcement is preserved, ensuring long-term structural durability (Bertolini et al., 2021).

However, reinforced concrete structures are continuously exposed to environmental factors capable of initiating deterioration mechanisms. Among these, carbonation and chloride-induced corrosion are considered the most significant causes of reinforcement degradation worldwide. Carbonation occurs when atmospheric carbon dioxide (CO₂) penetrates the concrete pores and reacts with calcium hydroxide, forming calcium carbonate (CaCO₃) and reducing the alkalinity of the pore solution. As the carbonation front advances and reaches the steel reinforcement, the pH may decrease below the threshold required for passivation, leading to depassivation and increased susceptibility to corrosion (Figure 2) (Araújo et al., 2019; Shi et al., 2022).

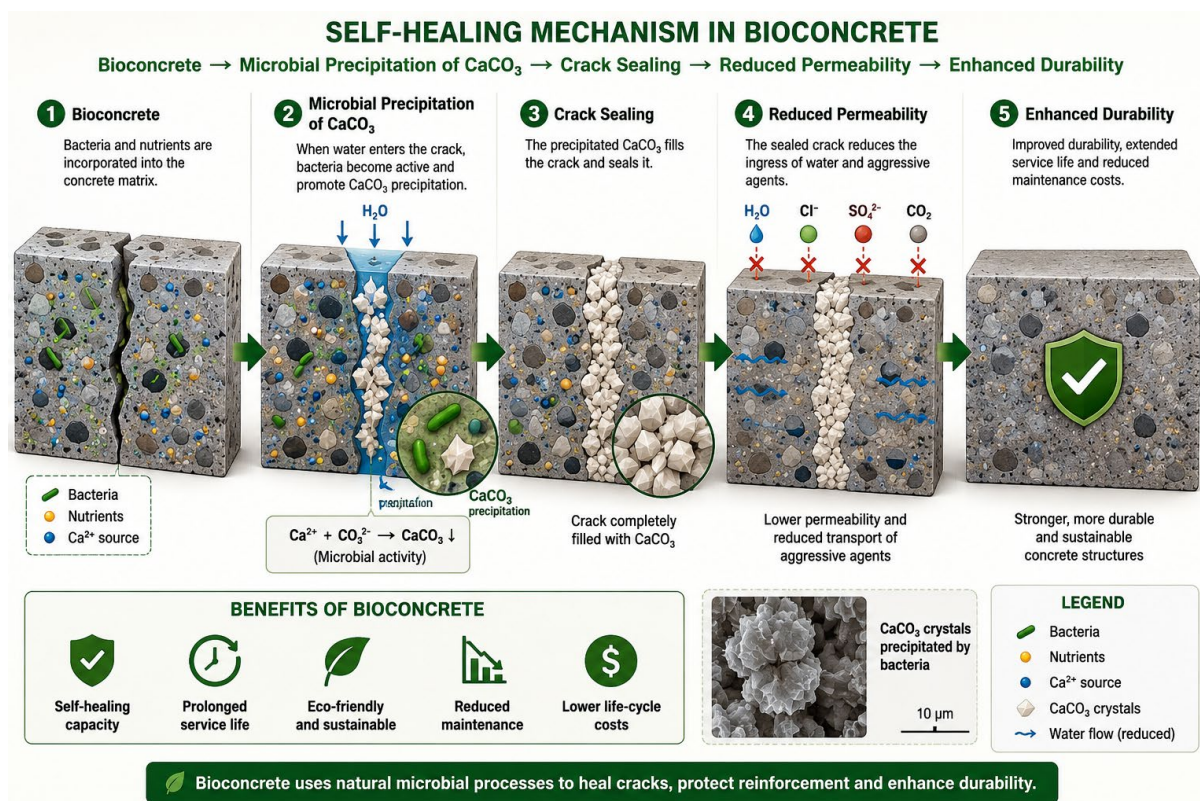


Figure 2. Schematic representation of the microbial self-healing mechanism in bioconcrete through calcium carbonate (CaCO_3) precipitation. Source: Authors, 2026.

Similarly, chloride ions originating from marine environments, deicing salts, or contaminated materials can diffuse through the concrete matrix and accumulate at the steel surface. Once a critical chloride concentration is reached, the passive oxide film is disrupted, initiating localized corrosion processes. Corrosion products occupy a larger volume than the original steel, generating expansive stresses that promote cracking, delamination, and spalling of the concrete cover, thereby accelerating structural deterioration (Angst et al., 2024; Bertolini et al., 2021).

The transport of aggressive agents into concrete occurs through several mechanisms, including capillary absorption, permeability, diffusion, and ionic migration. These processes are strongly influenced by moisture content, pore connectivity, temperature fluctuations, and the presence of microcracks. Water plays a central role in deterioration phenomena because it serves as the primary transport medium for dissolved ions and gases. Furthermore, water vapor movement within the pore network facilitates the penetration of atmospheric pollutants, particularly carbon dioxide, which contributes to carbonation and long-term degradation processes (Araújo et al., 2019; Xu et al., 2022).

Microcracking significantly exacerbates these deterioration mechanisms by creating preferential pathways for the ingress of aggressive agents. Consequently, the development of innovative materials capable of autonomously sealing cracks and restoring impermeability, such as microbial self-healing concrete, has emerged as a promising strategy to enhance durability, reduce maintenance costs, and extend the service life of reinforced concrete structures (Amran et al., 2022; Wong et al., 2024).

3.3 Crack formation and propagation in conventional concrete structures

Crack formation (Figure 3) is one of the most common pathological manifestations affecting concrete structures and is considered a critical factor influencing durability and service life. Although concrete exhibits excellent compressive strength, its relatively low tensile strength makes it highly susceptible to cracking when subjected to mechanical loading, thermal stresses, shrinkage, chemical reactions, and environmental exposure (Freitas et al.,

2021; Safiuddin et al., 2018).

The occurrence of cracks can significantly compromise structural performance by facilitating the ingress of water, oxygen, carbon dioxide, chlorides, sulfates, and other aggressive agents. Once these substances penetrate the concrete matrix, deterioration mechanisms such as reinforcement corrosion, carbonation, sulfate attack, and freeze–thaw damage may be accelerated, ultimately reducing the durability and safety of the structure (Araújo et al., 2019; Bertolini et al., 2021).

Cracks may develop during both the fresh and hardened stages of concrete. In fresh concrete, plastic shrinkage and plastic settlement are among the primary causes of cracking. In hardened concrete, thermal contraction, drying shrinkage, overload conditions, differential settlement, creep, and expansive chemical reactions such as alkali–silica reaction (ASR) are frequently associated with crack initiation and propagation (Neville, 2011; Xu et al., 2022).

According to Oliveira (2012) and Safiuddin et al. (2018), discontinuities in concrete may be classified according to crack width. Openings smaller than 0.5 mm are generally classified as fissures, while larger openings may be categorized as cracks, cleavages, slits, or gaps depending on their dimensions and severity. The characterization of crack geometry, orientation, location, and propagation pattern provides valuable information for diagnosing deterioration mechanisms and selecting appropriate repair strategies.

Temperature variations represent one of the most important environmental factors contributing to crack development. Thermal expansion and contraction cycles generate internal stresses within the concrete matrix, particularly in structures lacking adequate expansion joints. When these stresses exceed the tensile capacity of concrete, cracking occurs. Repeated thermal cycling may further promote crack propagation and increase permeability (Araújo et al., 2019; Amran et al., 2022).

Environmental conditions can further aggravate cracking phenomena. In humid climates, moisture fluctuations contribute to drying shrinkage and creep-related deformation. In colder regions, freeze–thaw cycles induce volumetric expansion of water within the pore structure, generating internal stresses capable of producing microcracks and progressive material degradation. Likewise, sudden temperature changes may produce thermal shock, resulting in localized cracking and reduced structural integrity (Xu et al., 2022; Wong et al., 2024).

The presence of microcracks and macrocracks is particularly relevant because they create preferential pathways for aggressive agents, increasing concrete permeability and accelerating deterioration processes. Consequently, considerable research efforts have focused on the development of self-healing materials capable of autonomously sealing cracks and restoring durability. Among these technologies, microbial self-healing concrete has emerged as a promising solution due to its ability to precipitate calcium carbonate within cracks, reducing permeability and extending the service life of concrete structures (Amran et al., 2022; Wong et al., 2024).

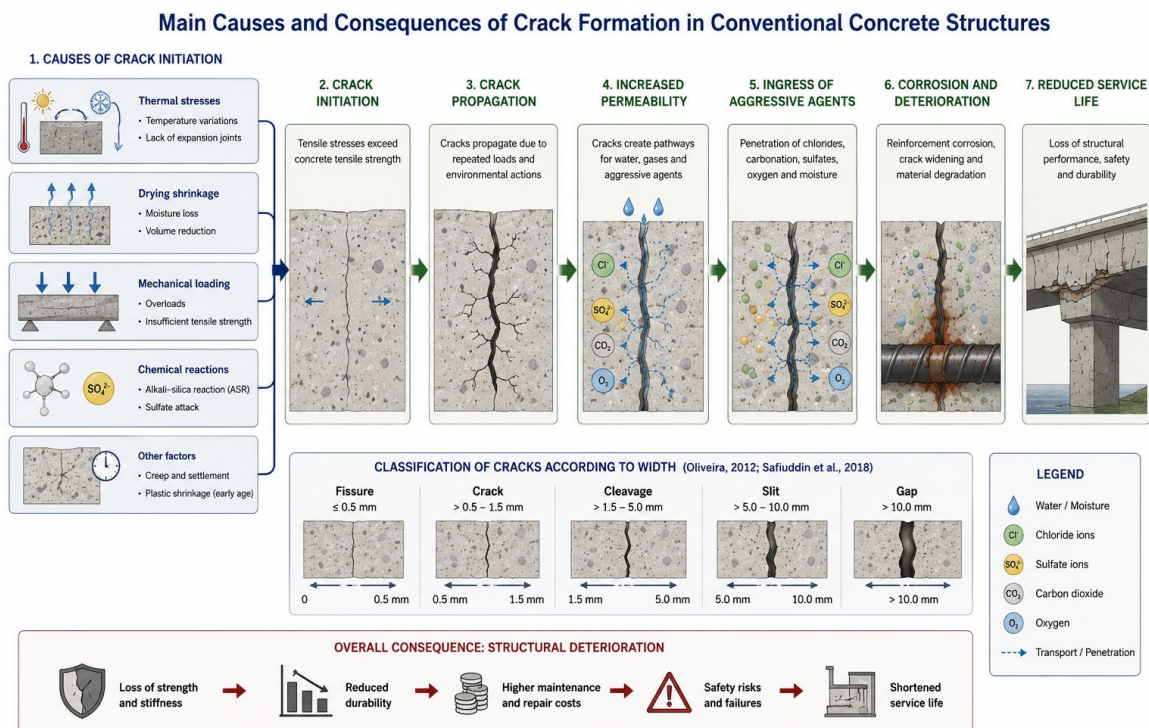


Figure 3. Main causes and consequences of crack formation in conventional concrete structures. Source: Authors, 2026.

3.4 Bioconcrete: Principles, components, and self-healing mechanisms

Bioconcrete, also known as microbial self-healing concrete, represents one of the most promising innovations in sustainable construction materials. The concept originated from the pioneering work of Adolphe et al. (1990), who investigated the use of microbial-induced mineral deposition for the restoration of ornamental stone surfaces, a process initially referred to as “biocalcification” or “biodeposition.” Since then, advances in biotechnology and materials science have led to the development of bioconcrete as an autonomous self-healing material capable of improving the durability and service life of concrete structures.

Bioconcrete can be defined as a cement-based composite material incorporating microorganisms capable of inducing microbial-induced calcium carbonate precipitation (MICP). This biological process promotes the formation of calcium carbonate (CaCO_3) crystals within cracks and pores, thereby reducing permeability and restoring the integrity of the concrete matrix (Jonkers, 2011; Achal et al., 2015; Castro-Alonso et al., 2019). Owing to its self-healing capacity, bioconcrete has attracted considerable scientific and industrial attention as a sustainable alternative to conventional repair techniques (Amran et al., 2022; Wong et al., 2024).

Similar to conventional concrete, bioconcrete is produced using cement, aggregates, and water. However, additional components such as bacterial spores, nutrients, and calcium-based precursors are incorporated into the mixture. These biological agents remain dormant within the concrete matrix and become metabolically active only when cracks develop and water penetrates the structure (Rao et al., 2013; Bashir et al., 2016). Under favorable environmental conditions, including sufficient moisture, oxygen availability, and suitable pH, bacterial spores germinate and initiate metabolic pathways leading to calcium carbonate precipitation.

The self-healing mechanism is generally based on the metabolic activity of bacteria belonging to genera such as *Bacillus*, *Sporosarcina*, *Lysinibacillus*, and related endospore-forming microorganisms. These bacteria are particularly suitable because of their ability to withstand the highly alkaline environment of concrete and remain viable for extended periods (Jonkers, 2011; Achal et al., 2015; Wang et al., 2023). Once activated, bacterial metabolism converts nutrient sources, commonly calcium lactate, urea, or other organic compounds, into carbonate ions. These ions subsequently react with calcium ions present in the concrete matrix or supplied through nutrient formulations, resulting in the precipitation of calcium carbonate crystals that fill and seal cracks

(Ramachandran et al., 2001; Masoud et al., 2023).

The biomineralization process contributes not only to crack sealing but also to the refinement of the pore structure and reduction of concrete permeability. As a consequence, the ingress of aggressive agents such as water, chlorides, sulfates, carbon dioxide, and oxygen is significantly reduced. This effect helps mitigate reinforcement corrosion and enhances the long-term durability of concrete structures (Castro-Alonso et al., 2019; Amran et al., 2022).

Recent studies have demonstrated that microbial self-healing systems can effectively repair cracks ranging from a few hundred micrometers to several millimeters in width, depending on the bacterial species, nutrient availability, and environmental conditions. Furthermore, the precipitated calcium carbonate exhibits mineralogical characteristics similar to naturally occurring calcite, ensuring strong compatibility with the cementitious matrix and contributing to mechanical performance recovery (Wong et al., 2024; Sankaran; Kumar, 2024).

Beyond technical advantages, bioconcrete offers important environmental benefits. By extending service life and reducing maintenance interventions, the technology decreases the consumption of repair materials and lowers the environmental footprint associated with infrastructure rehabilitation. In addition, bioconcrete may contribute to reducing greenhouse gas emissions throughout the life cycle of concrete structures, supporting the transition toward more sustainable construction practices (Griffiths et al., 2023; Wong et al., 2024).

The fundamental constituents of bioconcrete include: (i) microorganisms capable of inducing MICP; (ii) nutrient sources that sustain microbial metabolism; and (iii) calcium sources required for mineral precipitation. The interaction among these components enables the formation of a biologically active self-healing system capable of autonomously restoring microcracks and improving the overall durability of concrete structures (Achal et al., 2015; Castro-Alonso et al., 2019). Consequently, bioconcrete is increasingly recognized as a next-generation construction material that integrates biological processes with engineering solutions to address durability challenges in modern infrastructure.

Several bacterial genera have been identified as efficient biomineralizing agents, particularly members of the genera *Bacillus*, *Sporosarcina*, *Arthrobacter*, and *Rhodococcus*. These microorganisms exhibit high tolerance to alkaline conditions and possess metabolic pathways capable of promoting calcium carbonate precipitation within the concrete matrix. Their ability to survive under harsh environmental conditions and induce mineral formation makes them attractive candidates for self-healing concrete applications. Table 1 summarizes the principal bacterial genera and species investigated for bioconcrete production and microbial self-healing systems (Jonkers, 2011; Castro-Alonso et al., 2019; Wong et al., 2024).

Table 1. Bacteria insertion into concrete.

Bacteria	Mechanism	Material	References
<i>Acinetobacter johnsonii</i>	Calcite formation	concrete	Banerjee & Joshi (2014)
<i>Arthrobacter crystallopoietes</i>	Carbonate precipitation	biocementation	Montaño-Salazar et al. (2018)
<i>Bacillus alkalinitrilicus</i>	Alkaliphilic	Self-regeneration	Roque et al. (2023)
<i>Bacillus cereus</i>	Urea or uric acid degradation	concrete	Mondalet al. (2017)
<i>Bacillus holodurans</i>	Metabolic conversion of an organic compound	concrete	Kunal et al. (2014)
<i>Bacillus megaterium</i>	Metabolic conversion of an organic compound	concrete	Andalib et al. (2016)
<i>Bacillus pseudofirmus</i>	Metabolic conversion of an organic compound	concrete	Sharma et al. (2017)
<i>Bacillus pasteurii</i>	Urea or uric acid degradation	concrete	Qian et al. (2010)
<i>Bacillus sphaericus</i>	Ureolysis	increase in mechanical strength	Nasser et al. (2022)

<i>Bacillus subtilis</i>	Urea or uric acid degradation	concrete	Feng et al. (2021) and Mondalet al. (2017)
<i>Bacillus mucilaginous</i>	Mineral solubilization	concrete	Qian et al. (2021)
<i>Lysinibacillus fusiformis</i>	MICP	concrete	Choi et al. (2025)
<i>Myxococcus xanthus</i>	Extracellular biomineralization	concrete	Piñar et al. (2010)
<i>Pseudomonas aeruginosa</i>	Production of biofilms and biominerals	concrete	Beatty et al. (2022)
<i>Rhodococcus erythropolis</i>	Surface restoration	biocementation	Elias et al. (2025)
<i>Shewanella oneidensis</i>	Metabolic reduction of metals	experimental applications	Yahya et al. (2026)
<i>Sapovarcina pasteurii</i>	Urea or uric acid degradation	concrete	Abo-El-Enein et al. (2013)

Source: Authors, 2026.

3.5 Biocementation and microbial-induced calcium carbonate precipitation (MICP)

Biocementation is a biomineralization process in which microorganisms induce the precipitation of calcium carbonate (CaCO_3), promoting the binding of granular materials and improving the mechanical properties of cementitious systems. This process is primarily associated with microbial-induced calcium carbonate precipitation (MICP), a mechanism that has attracted considerable attention in civil engineering due to its potential applications in soil stabilization, crack remediation, concrete repair, and the development of self-healing construction materials (Hong; Qian, 2012; Achalet al., 2015; Castro-Alonso et al., 2019).

The most widely studied biocementation pathway is ureolysis, in which urease-producing bacteria hydrolyze urea into ammonium and carbonate ions. In the presence of calcium ions, carbonate reacts to form calcium carbonate crystals, which precipitate within pores, cracks, and intergranular spaces. These mineral deposits act as natural cementing agents, enhancing particle cohesion and reducing permeability. Consequently, the precipitated calcite contributes to the formation of dense and durable cementitious matrices capable of improving structural performance (Achalet al., 2015; Wang et al., 2023).

The efficiency of biocementation depends on several factors, including bacterial strain selection, urease activity, nutrient availability, calcium concentration, pH, temperature, and environmental conditions. Alkaliphilic and endospore-forming bacteria such as *S. pasteurii*, *B. subtilis*, *B. sphaericus* (*L. sphaericus*), and *B. megaterium* are among the most frequently employed microorganisms due to their ability to survive the highly alkaline conditions characteristic of concrete and cement-based materials (Achal et al., 2015; Castro-Alonso et al., 2019; Wang et al., 2023).

Microorganisms play a fundamental role in creating localized alkaline microenvironments that favor carbonate precipitation. Through their metabolic activities, bacteria modify the chemical composition of their surroundings, increasing carbonate ion concentrations and promoting crystal nucleation on cell surfaces and within the cement matrix. The resulting calcite crystals effectively fill pores and microcracks, thereby enhancing material density, reducing water penetration, and improving resistance to aggressive environmental agents (Ariyanti et al., 2011; Wong et al., 2024).

Biocementation has been successfully applied in various engineering contexts. In geotechnical engineering, MICP has been used to stabilize soils, reduce erosion, and produce bio-sandstones through the binding of sand grains. In construction materials, the technology has demonstrated significant potential for improving the compressive strength, durability, and impermeability of mortars and concretes (Rong et al., 2012; DeJong et al., 2013).

Experimental studies conducted by Achal et al. (2009, 2011) demonstrated the effectiveness of incorporating bacterial cultures into cementitious materials. Mortars and concrete specimens containing bacterial suspensions exhibited compressive strength increases ranging from 17% to 36% compared with control samples. Furthermore, water permeability was significantly reduced, indicating improved durability and resistance to environmental degradation. These improvements were attributed to the precipitation of calcite within the pore structure and at

the interface between cement hydration products and aggregates (Achal et al., 2011).

Recent investigations have confirmed that MICP-based biocementation can substantially improve the long-term performance of concrete structures. Besides increasing compressive strength, the process reduces porosity, limits chloride ingress, delays carbonation, and mitigates reinforcement corrosion. Such benefits are particularly relevant for infrastructure exposed to aggressive environments, where maintenance and repair costs represent a significant economic burden (Amran et al., 2022; Wang et al., 2023; Wong et al., 2024).

The growing interest in biocementation is also associated with sustainability considerations. By extending service life and reducing the need for conventional repair materials, microbial technologies contribute to lower resource consumption and decreased environmental impacts. Consequently, biocementation is increasingly recognized as a promising, eco-friendly strategy capable of enhancing the durability and resilience of future concrete infrastructures while supporting sustainable construction practices.

3.6 Performance and durability of bioconcrete: Mechanical strength, permeability, and self-healing efficiency

The performance of bioconcrete is primarily evaluated based on its mechanical properties, durability-related parameters, and self-healing efficiency. Conventional concrete is typically characterized by its compressive strength; however, long-term durability, particularly resistance to fluid ingress, is increasingly recognized as a critical factor governing service life. In this context, microbial-induced biomineralization has emerged as an effective strategy to enhance durability by reducing permeability, water absorption, and diffusivity within the cementitious matrix (Pacheco-Torgal; Labrincha, 2013; Amran et al., 2022).

Several studies have reported that the incorporation of microbial agents can significantly influence the transport properties of concrete. For instance, *B. sphaericus* has been shown to reduce permeability and water absorption, although its influence on early-age compressive strength may be limited under certain conditions (Wang et al., 2014; Achal et al., 2011). The observed improvement in durability is primarily attributed to the precipitation of calcium carbonate (CaCO_3), which progressively blocks capillary pores and microcracks, thereby restricting fluid transport within the concrete matrix.

Similarly, *Sporosarcina pasteurii* has demonstrated positive effects on compressive strength development in mortar specimens, particularly at early curing ages such as 7 days. However, the durability performance of this strain has been less extensively evaluated in terms of long-term permeability and water absorption behavior (Seifan et al., 2016). Other strains such as *Bacillus cohnii*, *Bacillus pseudofirmus*, and *Diaphorobacter nitroreducens* have also been investigated, showing variable performance depending on curing time, environmental conditions, and immobilization techniques (Jonkers et al., 2010; Sierra-Beltrán et al., 2014; Erşan et al., 2015).

The effectiveness of microbial treatments is strongly influenced by the method of bacterial incorporation. Immobilized cell systems have shown superior performance compared to free bacterial cells due to improved survival rates and sustained metabolic activity within the concrete matrix. For example, Wang et al. (2012) reported that immobilized *B. sphaericus* combined with polyurethane carriers reduced permeability by up to six times compared to control specimens without bacteria. In another study, immobilization on diatomaceous earth resulted in approximately 50% reduction in water absorption, highlighting the importance of carrier materials in enhancing microbial efficiency.

Further evidence provided by Achal et al. (2011) demonstrated that *B. sphaericus* significantly improved impermeability, reducing water absorption coefficients by up to six-fold over a 168-hour testing period. These improvements were directly associated with in situ CaCO_3 precipitation, which densifies the pore structure and enhances resistance to fluid penetration. Overall, these findings confirm that microbial biomineralization contributes substantially to improving the durability of cement-based materials by sealing internal voids and reducing connectivity between pores.

However, the influence of microbial agents on compressive strength remains controversial. Some studies have reported reductions in compressive strength, particularly when bacteria are incorporated in high concentrations or without proper encapsulation techniques (Wang et al., 2014). In contrast, other investigations have demonstrated significant increases in compressive strength under optimized conditions. For example, Achal et al. (2013) observed strength improvements in mortar specimens containing *B. sphaericus* over curing periods of 7 to 28 days. Similarly, Bang et al. (2010) reported up to a 24% increase in compressive strength when *S. pasteurii* was immobilized in porous glass beads, with performance positively correlated with increasing bacterial cell concentration.

These contradictory findings suggest that the mechanical performance of bioconcrete is highly dependent on multiple factors, including bacterial strain selection, immobilization technique, nutrient availability, curing conditions, and bacterial concentration. While compressive strength may vary, there is a general consensus in the literature that durability-related properties, particularly permeability resistance and crack sealing ability, are consistently improved by microbial activity.

Therefore, bioconcrete should be primarily considered a durability-enhancing and self-healing material rather than solely a strength-enhancing material. Its main advantage lies in its ability to autonomously reduce permeability, extend service life, and mitigate deterioration processes in reinforced concrete structures, contributing to more sustainable and resilient infrastructure systems.

3.7 Sustainability implications of microbially induced calcium carbonate precipitation (MICP) in cement-based materials

The construction industry continues to expand at an estimated rate of 0.8–1.2% per year, with global concrete consumption projected to reach 3.7–4.4 billion tonnes by 2050 (Handore et al., 2021). Conventional cement, the primary binder in concrete, is responsible for approximately 10% of global anthropogenic CO₂ emissions, making it one of the largest industrial contributors to greenhouse gases worldwide. Cement production ranks among the leading sources of CO₂ emissions, surpassed only by the energy and transport sectors. Although concrete remains indispensable for modern infrastructure, its production and use generate significant environmental and health impacts across its entire life cycle.

In this context, microbially induced calcium carbonate precipitation (MICP) emerges as a promising sustainable alternative for the development of biocement and bioconcrete systems. Microbially Induced Calcium Carbonate Precipitation (MICP) offers an eco-friendly approach by promoting calcium carbonate formation through biological pathways, reducing reliance on conventional cementitious materials, and lowering associated carbon emissions. Studies indicate that MICP-based materials can function both as partial replacements and as repair or rehabilitation agents in existing concrete structures, contributing to improved durability and reduced maintenance demand (Achalet al., 2015; Ahmad et al., 2021; Huseien et al., 2022).

From a sustainability perspective, MICP-based systems demonstrate advantages such as reduced energy demand, potential use of waste-derived substrates, and improved material longevity. These characteristics make the technology particularly relevant for enhancing the performance of commonly used construction materials, including limestone, sand, mortar, and conventional concrete. Benefits such as increased compressive strength, reduced permeability, and lower material consumption further support its potential contribution to sustainable construction practices.

The environmental performance of bioconcrete is commonly assessed using Life Cycle Assessment (LCA), standardized under ISO 14040 Life Cycle Assessment (LCA). LCA is a key methodological tool for quantifying environmental impacts across all stages of a product's life cycle and is widely recognized as a primary indicator of sustainability performance in construction materials. Previous studies have applied LCA to cement and concrete systems, identifying significant environmental burdens associated with conventional technologies (Gursel et al., 2014; Huntzinger; Eatmon, 2009; Knoeri et al., 2013; Van den Heede; De Belie, 2012).

Despite its potential, the application of LCA to MICP-based materials remains limited. Key challenges include unclear system boundaries, insufficient life cycle inventory data, and limited understanding of long-term performance and service life. As highlighted by DeJong et al. (2013), further research is required to accurately quantify inputs such as urea and calcium chloride production chains and their associated energy demands. Therefore, continued experimental and methodological advancements are essential to better evaluate the true environmental benefits and scalability of MICP technologies.

Overall, the integration of MICP into construction materials presents a promising pathway toward reducing the environmental footprint of the cement industry, although its large-scale implementation still requires further technical validation and comprehensive sustainability assessment.

3.8 Chemical and microstructural contradictions in the mechanical response of bioconcrete

Although the literature widely supports MICP as a promising strategy for self-healing cracks, the efficiency of this process is not linear. It is strongly conditioned by critical operational factors, such as initial bacterial concentration and the physicochemical nature of the encapsulation method. A frequent gap in scientific

discussions is the lack of detailed chemical and microstructural justifications underlying the phenomenon in which certain bacterial strains or inadequate dosages lead to a reduction in concrete compressive strength, rather than the expected mechanical improvement.

From a purely chemical standpoint, the direct introduction of live bacterial cultures or spores (non-encapsulated) significantly alters the cement Portland hydration kinetics. The culture medium and nutrients essential for microbial metabolism (such as urea and external calcium sources, e.g., calcium lactate) directly compete with the free water required for calcium silicate dissolution and precipitation reactions. Jonkers et al. (2010) pioneeringly demonstrated that the direct addition of bioactive agents without proper protection reduces the mechanical strength of the matrix by up to 10% at 28 days. This occurs because metabolic by-products and organic compounds act as setting retarders, interfering with the primary formation of the Calcium Silicate Hydrate (C-S-H) gel, which is the phase responsible for stiffness gain and load-bearing capacity of the material.

From a microstructural perspective, the negative impact is correlated with the formation of structural voids and physical degradation of the matrix caused either by the spores themselves or by the carrier material. When bacterial concentration exceeds optimal thresholds, the accumulated cellular biomass acts as a physical discontinuity. In the absence of sufficient nutrients or oxygen in deeper layers of the concrete, bacteria die, and decomposing organic residues generate microcavities. Additionally, when immobilization and encapsulation techniques using porous lightweight aggregates (e.g., expanded clay) or hydrogels are employed to ensure long-term bacterial survival, the carrier aggregate often exhibits mechanical properties significantly inferior to natural aggregates (gravel and sand). As noted by Wang et al. (2014a), volumetric replacement of rigid aggregates with porous capsules creates “weak points” of stress concentration within the cementitious matrix, temporarily outweighing the benefits of subsequent CaCO_3 precipitation and resulting in a decrease in the early-age mechanical strength of the composite.

4. Conclusions

The application of microorganisms in self-healing concrete presents a highly promising alternative to conventional repair and maintenance strategies. This technology is based on biomineralization processes capable of inducing the precipitation of calcium carbonate, which effectively seals cracks and microcracks within cementitious matrices. As a result, both superficial and deeper structural defects can be progressively filled, limiting crack propagation and improving overall material integrity.

In addition to enhancing mechanical performance, microbial self-healing systems contribute to increased durability and service life of concrete structures. This directly translates into reduced inspection frequency and lower long-term maintenance requirements, improving economic efficiency in civil infrastructure management. From an environmental perspective, the reduced need for repair and reconstruction leads to lower cement consumption, thereby contributing to a decrease in associated carbon dioxide emissions.

Further advantages include improved matrix densification, reduced porosity, and enhanced compatibility between precipitated minerals and the cementitious environment, which collectively strengthen the material and improve its resistance to environmental degradation. These mechanisms also contribute to more stable internal microstructural behavior over time, supporting better long-term performance.

Overall, microbial self-healing concrete represents a sustainable and innovative approach for extending the lifespan of infrastructure while reducing environmental impact. Its integration into cement-based materials offers a viable pathway toward more resilient, cost-effective, and environmentally responsible construction systems.

5. Authors' Contributions

Ihan Fortunato Martins: contributed to manuscript drafting and preparation of the text. *Abner Santos Baroni Salea*: acted as advisor and supervisor of the study, providing conceptual guidance, critical review, and final approval of the manuscript.

6. Conflicts of Interest

No conflicts of interest.

7. Ethics Approval

Not applicable.

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