Microbially Induced Calcium Carbonate Precipitation as Bio-Mimetics Material in Applications of Slashing Carbon Emission and Carbon Sequestration: A Review

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Received: 10 Jan 2024 **Revised: 31 Jan 2024** **Published: 31 Jan 2024**

Abstract— *Concrete production contributes radically to global carbon dioxide emissions. Microbially induced calcium carbonate precipitation (MICP) is an evolving technology that allows calcium carbonate to be precipitated on concrete through microbial metabolic activity. This review paper aims to present an overview of contemporary findings on the solicitation of MICP for advancing the properties of concrete, reducing carbon emissions from cement production, and elevating carbon sequestration. The results of previous studies have expounded that MICP treatment can enhance the compressive strength, stiffness, and durability of concrete. More importantly, MICP technology propounds the potential to moderately supersede cement content in concrete, thereby lowering carbon emissions from cement production. The microbial precipitated calcium carbonate may also accelerate the sequestration of carbon dioxide. While more research is still needed, MICP shows capacity as a sustainable technique for developing low-carbon concrete materials.*

Keywords— *Microbially induced calcium carbonate precipitation; concrete; carbon emission; carbon sequestration*

Abstrak— Produksi beton berkontribusi secara radikal terhadap emisi karbon dioksida global. Microbially induced calcium carbonate precipitation (MICP) adalah teknologi yang berkembang yang memungkinkan kalsium karbonat diendapkan pada beton melalui aktivitas metabolisme mikroba. Studi literatur ini bertujuan untuk menyajikan ikhtisar temuan kontemporer tentang kekuatan MICP untuk memajukan sifat-sifat beton, mengurangi emisi karbon dari produksi semen, dan meningkatkan penyerapan karbon. Hasil penelitian sebelumnya telah menguraikan bahwa perlakuan MICP dapat meningkatkan kekuatan tekan, kekakuan, dan daya tahan beton. Lebih penting lagi, teknologi MICP mengemukakan potensi untuk secara moderat menggantikan kandungan semen dalam beton, sehingga menurunkan emisi karbon dari produksi semen. Mikroba kalsium karbonat yang diendapkan juga dapat mempercepat penyerapan karbon dioksida. Sementara penelitian lebih lanjut masih diperlukan, MICP menunjukkan kapasitas sebagai teknik berkelanjutan untuk mengembangkan bahan beton rendah karbon.

Kata kunci— Presipitasi kalsium karbonat yang diinduksi secara mikroba; beton; emisi karbon; Penyerapan karbon

I. INTRODUCTION

Concrete is the supreme broadly luxuriated construction material, with twelve-monthly production prodigious 10 billion tons universally [1]. Conversely, the fabrication of cement, an integral and vital constituent in concrete, is highly energy-intensive and accounts for 5-8% of global carbon dioxide emissions [2]. There is an imperative and domineering constraint need to redecorate and modernize alternative binders and methods to convalesce the sustainability of concrete. MICP is an innovative bio-based modus operandi that has freshly transpired as a guaranteeing elucidation.

MICP insinuates to the progression manner by which microorganisms precipitate calcium carbonate minerals owing to their metabolic activities [3]. By nurturing bacteria adept of MICP in a calcium-rich medium, uniform calcium carbonate coatings can be materialized on the surface of concrete specimens [4]. The precipitated calcium carbonate crystals can hypothetically augment and boost the assets of concrete, over and above relegate cement usage. Explorations have reconnoitered the consequences of MICP behavior on several characteristics of concrete, embracing compressive strength [5], stiffness [6], and durability against chloride penetration [7]. Inclusively, MICP-treated, and remedied concrete expounded amended mechanical and transport properties compared to untreated concrete.

More prominently, MICP technology concedes concrete with low cement content to succeed analogous execution to conventional high-cement concrete [8]. The cement content in concrete assortments can be partially and moderately superseded by the microbial precipitated calcium carbonate. This presents diagnoses and projections to demote carbon emissions linked to concomitant cement fabrication. Appraisals publicized that superseding 20% of cement with MICP medication pathway could lessen carbon emissions by approximately 20% [9]. Into the bargain, the microbially precipitated calcium carbonate crystals may expediate the confiscation of carbon dioxide through mineral carbonation [10].

Even though MICP flourishers advantageous and expedient promise and capability for advancing sustainable construction materials, there are still confronts to overcome before extensive all-encompassing application. These comprise conserving harmonious treatment impressions, lessening treatment costs and duration, and affirming the calcium carbonate precipitates are durable over the lifetime of concrete [11]. Nevertheless, with supplementary exploration and field testing, MICP could become an operative and efficacious stratagem to relegate the carbon footprint of concrete in the future.

II. MATERIALS AND METHODS

This literature review collects findings from previous original research and review articles on MICP behavior of concrete and construction materials published in research and peer-reviewed journals. The articles were identified through searches on Google Scholar, MDPI, Springer and Scopus databases using a combination of relevant keywords such as “MICP” "microbe-induced calcium carbonate precipitation", "biomineralization", "self-healing concrete", "microbial concrete", and "microstructure".

Search results are filtered based on the relevance of the topics covered. Priority is given to research published in the last 10 years in reputable journals related to construction materials, microbiology, and environmental engineering. However, previous important writings are also included to provide background information. Abstracts and full texts are reviewed to select articles that report experimental data on relevant parameters such as compressive strength, stiffness, and transport properties of MICP-treated concrete specimens and also their metabolic activities.

Quintessential information extracted from the articles included the bacterial strain used for the MICP treatment, treatment methodology/mechanism involved, parameters employed, and influence on concrete properties. Quantitative and qualitative results are compiled and analyzed to evaluate improved concrete performance through MICP treatment as testified in various studies. The findings are contextualized through comparisons with conventional concrete and discussions of implied reductions potential capacity in carbon emissions. The gaps and challenges of the observed research were also highlighted.

The current study also conducted a bibliometric analysis to gain insightful perspectives on scholarly collaborations and trends within the research domain of MICP. The data were acquired from the Scopus database using a dedicated search query and filtering criteria to retrieve the top 100 most cited publications between 2014 and 2024. Co-authorship network analysis mapping authors, organizations, and countries as the units was employed to depict collaborative linkages utilizing VOSviewer software. Concomitantly, a co-occurrence network of keywords depicted the conceptual structure and burgeoning topics within MICP research. This dual mapping of collaborative associations through co-authorship alongside conceptual relations via co-occurrence networks delivered a comprehensive outlook on understandings documented in high-impact publications. Network visualizations and bibliometric indicators from VOSviewer shed strategic intelligence on previous trends and futuristic directions within this flourishing interdisciplinary field.

The data compiled from this literature review form the basis for assessing the current state of knowledge about MICP treatment applications to amend concrete sustainability. The results provide insight into the potential of MICP as a promising bio-based technique for developing low-carbon bacterial-concrete materials.

III. RESULTS AND DISCUSSION

1. Microbially Induced Calcium Carbonate Precipitation (MICP)

Biomineralization is a biological progression in which subsisting organisms form minerals [12]. Minerals formed through biomineralization embrace carbonates, phosphates, silicates, sulfates, sulfides, oxides, or hydroxides along with diverse cations such as Ca^{2+}, Fe, Mg^{2+}, and MnO_2 [13]. The biomineralization manner also encompasses organic macromolecules such as proteins, glycoproteins, polysaccharides, and proteoglycans, which occupation as a skeletal framework [14].

It is evident from available scientific literature that microorganisms are capable of precipitating calcium carbonate ($CaCO_3$) through diverse mechanisms. A prominent pathway involves the production of the enzyme urease, which catalyzes the hydrolysis of urea and results in the formation of ammonia and carbon dioxide. The ensuing rise in pH owing to ammonia release facilitates the crystallization of calcium carbonate particles. Another mechanism hinges on the enzymatic activity of carbonic anhydrase, which accelerates the conversion of carbon dioxide and water into bicarbonate ions. The latter subsequently react with calcium ions to yield calcium carbonate [15]. Additionally, microbes may secrete extracellular polymeric substances that serve as nucleation sites for calcium carbonate deposition [16].

Several types of microorganisms have demonstrated applicability for calcium carbonate precipitation competent bacteria. Notable examples include the bacteria *Sporosarcina pasteurii*, *Bacillus* spp. and *Pseudomonas* spp., which harbor the requisite urease and/or carbonic anhydrase for calcium carbonate precipitation [17]. Cyanobacteria like *Synechococcus* spp. and *Anabaena* spp. have also found use owing to their photosynthetic capacity and accompanying calcium carbonate coproduction [18].

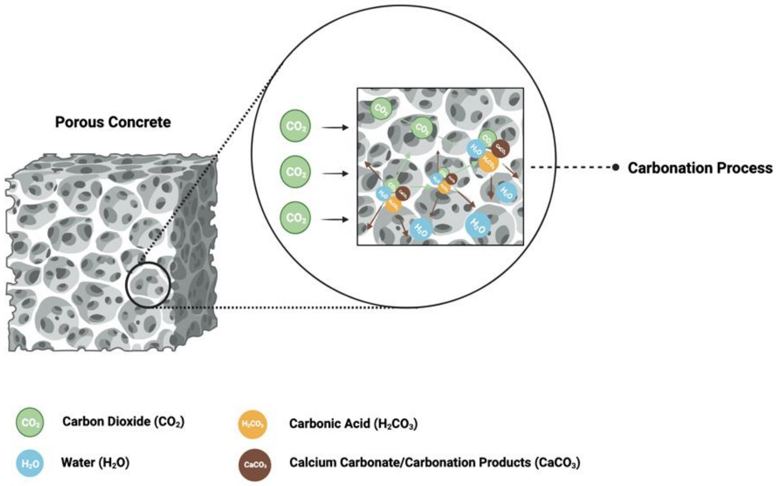


Figure 1. General schematic pathway of calcium carbonate production process (carbonation process)

MICP is mediated by microorganisms that hydrolyze urea to produce carbonate ions, which then react with calcium ions to form solid $CaCO_3$ precipitates. The normal process of $CaCO_3$ fabrication as shown in **Figure. 1** through we called as carbonation process. Common ureolytic bacteria utilized include *Sporosarcina pasteurii, Bacillus sphaericus, Bacillus megaterium,* and *B. subtilis* as shown in **Table 1**. Key parameters influencing $CaCO_3$ production rates include urea and calcium concentrations, pH, temperature, dissolved oxygen, and bacterial cell concentration. Strategies such as encapsulation in polymers or bio-augmentation have been employed to enhance ureolytic activity.

Several studies have reconnoitered using bacteria to induce calcite precipitation in cementitious materials and concrete through a process called microbiologically induced calcite precipitation (MICP) as shown in **Table 1**. The key contrivance is that bacteria like *Bacillus* and *Escherichia coli* metabolize urea to produce ammonia and carbonate. The ammonia increases pH and enables carbonate to precipitate with calcium to form calcium carbonate (calcite).

Different strains have been studied including *Bacillus subtilis, Bacillus pasteurii, Bacillus cohnii, and Escherichia coli*. Precipitated calcite can improve compressive strength, tensile strength, flexural strength, toughness, crack healing, and sulfate resistance. The improvements are attributed to the calcite crystals increasing density and binding ability in the cementitious matrix.

Some studies explored encapsulating the bacteria in clay pellets to control distribution. Others examined the effects of varying the ratio of bacterial culture to cement. Several tested both living and dead cells. In all cases, the urease activity of the bacteria was the key driver of calcite precipitation.

Parameters studied include compressive strength, tensile/flexural strength, toughness, ultrasonic pulse velocity, water absorption, sorptivity, percentage of calcite formed, crack healing width, and microstructure. Test methods included standard compression, tension, and flexure tests, SEM imaging, measurement of healed crack widths, and quantification of precipitated calcite. The effects were generally positive, with 10-50% increases in mechanical properties, decreased permeability, and evidence of crack closure from precipitated calcite crystals.

Holistically, a range of *Bacillus* and related strains have been shown to improve cementitious properties through microbiologically induced calcite precipitation. The improvements are attributed to the bacteria's urease activity which enables calcite formation in the cement matrix, increasing density and binding ability. A variety of mechanical properties and transport characteristics are beneficially impacted.

A variety of parameters can impact calcium carbonate generation by microbes. These encompass environmental pH, temperature, calcium and carbon dioxide concentrations, nutrient sufficiency, and the presence of inhibitory or stimulatory substances [16], [37]. The pH dictates enzymatic reactions underpinning MICP, with bacteria exhibiting distinctive optimal ranges. Temperature affects microbial proliferation and metabolism, and thus calcium carbonate synthesis. Higher calcium and carbon dioxide levels tend to augment precipitation. Nutritional availability of nitrogen and phosphorus facilitates growth and activity conducive to MICP. Inhibitors like heavy metals and activators such as organic acids may also modulate the process [16], [18], [37]–[40].

Moreover, the microbiologically induced calcite precipitation process shows promise for developing low-emission construction materials. By metabolizing urea, the bacteria promote calcite formation which improves strength and durability properties while also serving as a carbon sink. Approximately half of the weight of precipitated calcite originates from atmospheric CO_2 absorbed during calcium carbonate synthesis. Widespread use of MICP in cementitious materials could provide a route for large-scale carbon sequestration. The ability of the precipitated calcite to stably store captured carbon dioxide while enhancing the properties of concrete, mortar, and other construction materials makes MICP an attractive and potentially impactful technology for sustainable development and climate change mitigation through production of low-emission infrastructure. The breadth of positive mechanical improvements evidenced in these studies highlights the versatility and capacity of MICP to produce durable and reliable low-carbon construction materials.

2. MICP as Bio-Mimetics Potential: Microbial Concrete

The phenomenon of microbially induced calcium carbonate precipitation has of late garnered considerable scholarly attention as a novel technique of bio cementation that shows potential for enhancing the attributes of cementitious composites. In this biomineralization process, taxonomically classified bacterial varieties capable of catalyzing the abiotic formation of calcium carbonate minerals through their innate metabolic pathways are implemented.

Table 1. Typical bacterial used in MICP System

Ref	Bacterial used	Mechanism/Pathway	Parameters
[19]	*Bacillus subtilis* JC3	Biomineralization or Microbiologically Induced Calcite Crystal Precipitation	-
[20]	*Bacillus* sp. CT-5	Microbiologically induced calcite precipitation (MICP)	Compressive strength and water permeability of cement mortar
[21]	Urease producing bacteria	Microbiologically induced calcite precipitation (MICP)	2 different ratios of water to culture (75:25; 50:50) and compared them to the conventional system (100:0). The study used 1 prefixed culture density (OD_{600} 0.5 ± 0.1)
[22]	Group of alkali resistant spore forming bacteria related to the genus *Bacillus*	Microbiologically induced mineral precipitation	-
[23]	*Bacillus Sphaericus* and *Bacillus Pasteurii*	Microbiologically induced calcite precipitation (MICP)	-
[24]	Ureolytic bacteria from the genus *Bacillus*	Microbial cementation with calcite	Microbial cementation to optimize the mechanical behavior of cement-based materials
[25]	*Bacillus subtilis*	Selected types of bacteria genus Bacillus, a calcium-based nutrient (calcium lactate), nitrogen, and phosphorus are added to the concrete and are encased in clay pellets in the ratio 1:19 of bacteria to calcium source	Toughness
[26]	*Bacillus subtilis* JC3	Microbiologically induced calcite precipitation (MICP) on the surface of the concrete layer	Foaming agent
[27]	*S. pasteurii, Bacillus pseudofirmus, Bacillus cohnii, Arthrobacter crystopoietes, Bacillus subtilis,* and *Bacillus sphaericus*	Microbiologically induced calcite precipitation (MICP)	Tensile strength values
[28]	*Escherichia coli (E. coli)*	Microbiologically induced calcite (caco3) precipitation (MICP)	Compressive strength, water absorption capacity, ultrasonic pulse velocity (UPV), SEM analysis
[29]	*Bacillus cohnii*	Addition of different concentrations of live and dead cells of *Bacillus cohnii* in cement mortars	Flexural strength, compressive strength
[30]	*Bacillus pasteurii*	Microbiologically induced calcite precipitation (MICP)	Compressive strength, flexural strength, sulfate resistance, percentage of calcium carbonate precipitations, area repair rate
[31]	*Bacillus megaterium*	Microbiologically induced calcite precipitation (MICP)	Compressive strength of cement concrete cubes, water absorption of cement concrete cubes, water permeability of cement concrete cubes
[32]	*Bacillus pasteurii*	Microbiologically induced calcite precipitation (MICP)	Healed crack width, precipitation formed at cracks (calcium carbonate)
[33]	*Bacillus subtilis*	Microbiologically induced calcite precipitation (MICP)	Compressive strength
[34]	*Bacillus cohnii*	Microbiologically induced calcite precipitation (MICP)	Crack healing, regained compressive strength after pre cracking, sorptivity, water absorption, concrete microstructures
[35]	*Bacillus subtilis*	Bio calcification and microbiologically induced calcite precipitation (MICP)	Compressive strength of concrete, tensile strength of concrete, ultrasonic pulse velocity (UPV) of concrete
[36]	*Lysinibacillus sphaericus* strain SKC/VA	Bacterial oxidation of organic carbon to precipitate calcite that may fill the voids and cracks on cement-based materials	Compressive strength, indirect tensile strength, self-healing occurrence

Remarkable usages of this microbially mediated carbonate precipitation include fortifying mechanical performance parameters, conferring heightened material durability, and potentially enabling an intrinsic ability of self-repair [18].

Previous experimental inexertsions have elucidated the capability of microbially induced carbonate precipitation to exert a beneficial influence upon critical mechanical characteristics of cementitious materials. The bio mediated deposition of calcium carbonate minerals serves to occupy microdefects such as micro fissures within the composite matrix, thereby bolstering compressive resistance, flexural tenacity, and fracture toughness [18]. By bridging cracks and buttressing the microstructure in such a manner, bacterial biomineralization is postulated to increase resistance against crack propagation and augment overall mechanical resilience.

Research has additionally demonstrated the prospect of microbially mediated carbonate precipitation to boost the durability of cementitious materials by reducing material permeability. The bioprecipitation of calcium carbonate functions to occlude pores and capillaries, limiting ingress of deleterious species like water, chlorides, and sulfates [37]. This mitigates degradation pathways including corrosion, freeze-thaw deterioration, and others, potentially prolonging service life.

Potentially the most promising attribute of MICP-amended cementitious materials is its latent crack remediation capability. The precipitation of calcium carbonate serves as an in-situ healing agent, sealing, and repairing micro fissures as they develop over time. Reactivated dormant bacteria catalyze mineralization to restore integrity when infiltrated by water and nutrients. This self-healing functionality could lengthen material lifespan and lessen maintenance needs [31], [32], [36], [41]–[43].

A variety of approaches have been optimized for introducing MICP into cementitious composites. Bacteria competent in carbonate biogenesis may be directly incorporated during mixture as an admixture or through bio-based components [15], [18], [37]. An alternative technique applies bacterial solutions externally to cementitious surfaces. Choice depends on the envisioned application, material formulation, and project-specific considerations. Broadly, MICP has demonstrated promise across an array of cementitious material contexts, though further investigations are still warranted [15].

Incorporating MICP in concrete has shown considerable improvements in compressive strength and stiffness while reducing permeability and enhancing resilience to freezing thawing and acid exposure. MICP enables passive self-healing of cracks via $CaCO_3$ precipitation induced by penetrated microbes and nutrients. Successful implementation techniques include surface treatments, direct addition of microbes, and encapsulation. The ability of MICP to fill cracks and voids while binding aggregates can significantly enhance concrete durability.

Table 2. Several applications used in concrete by using MICP system

Ref	Bacterial used	Applications
[41]	Aerobic mixotroph bacterial strains CPB 1, CPB 3, and CPB 5	Self-healing concrete
[44]	*Bacillus sphaericus* (LMG 22257)	Concrete crack repair and permeability reduction enhancement
[45]	*Micrococcus yunnanensis*	Durability improvement of concrete
[46]	*Sporosarcina pasteurii* (ATCC 11859)	Non-woven geotextiles application
[47]	*Bacillus subtilis* HU58	Water sealing performance of concrete surface
[48]	*P. psycrodurans* M414 *Escherichia coli* ATCC 47076 *Arthrobacter crystallopoietes* strain KNUC403	Bio cementation
[49]	*Bacillus Acetophenoni* and *Bacillus Odyssevi*	Enhance the concrete compressive strength properties

As shown in **Table 2** outlines various bacteria that have been studied and implemented for diverse applications in the domain of construction materials and structures. At the outset, the three Aerobic mixotrophic bacterial strains CPB1, CPB3 and CPB5 isolated from concrete specimens have been examined for their potential in self-healing concrete [41]. These heterogeneous bacterial strains were found to precipitate calcium carbonate in mortar and concrete samples upon nutrient supply, thereby autonomously repairing artificially induced cracks.

In another study, *Bacillus sphaericus* (LMG 22257) was implemented as a bio-grout for concrete crack repair and reducing concrete permeability [44]. Through calcium carbonate precipitation induced by this bacterium, concrete cracks could be effectively sealed and the ingress of chlorides or water into concrete was significantly diminished. The table further notes that *Micrococcus yunnanensis* was explored to improve the durability of cementitious materials through metabolic processes [45].

Regarding geotechnical applications, *Sporosarcina pasteurii* (ATCC 11859) was utilized to develop bio-enhanced non-woven geotextiles that exhibited enhanced water sealing performance [46]. *Bacillus subtilis* HU58 likewise mediated calcium carbonate precipitation for improving water barrier functions of cementitious composites [47].

An assemblage of ureolytic bacteria including *P. psycrodurans* M414, *Escherichia coli* ATCC 47076 and *Arthrobacter crystallopoietes* strain KNUC403 was investigated for biocementation applications such as crack remediation and structural reinforcement [48]. Finally, two *Bacillus* species namely *Bacillus Acetophenoni* and *Bacillus Odyssevi* were demonstrated to elevate the compressive strength of cementitious blends through their cementation abilities [49].

In abridgment as shown in **Table 2**, this table provides a succinct overview of diverse bacterial strains that have been explored through bio-mediated approaches for achieving multifarious performance enhancements in construction materials and edifices. The references thoroughly portray the microbial-induced ameliorations in properties such as self-healing, permeability reduction, durability, watertightness, reinforcement, and mechanical strength.

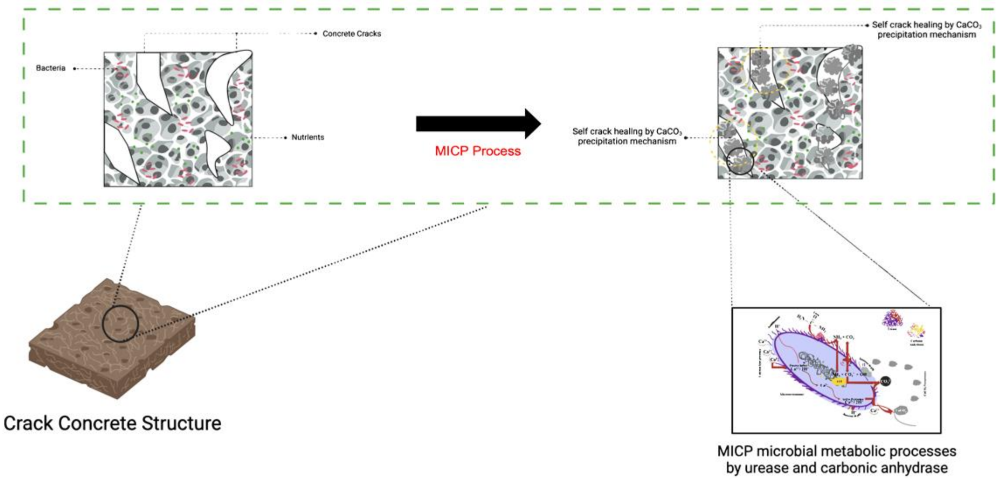


Figure 2. Self-healing process on microbial concrete (The microbial metabolic process was taken from [3])

Ultimately, the phenomenon of microbially induced calcium carbonate precipitation has received notable scholarly attention as a promising bio cementation strategy for bettering the properties of cementitious composites via metabolic biomineralization within the matrix. Notable applications involving mechanical parameter enhancement, durability improvement, and autogenous self-healing functionality have been demonstrated as shown in **Figure 2**. Further optimization of implementation techniques and investigations across diverse material formulations also carbon sequestration potential may support more widespread adoption.

Table 3 presents a comprehensive summation of diverse ureolytic bacteria examined in antecedent works for their viability within cementitious materials across delineated durations. As the perseverance of bacteria encapsulated within construction materials is crucial for crack remediation via MICP, evaluating microbial survival rates furnishes empirically derived choice guidance. A diversity of urease-producers is catalogued, ranging from the coupling of *Lysinibacillus boronitolerans* and *Bacillus* to sole *Bacillus* types to blended bacterial consortia. Observation periods extend from instant assessments to 56 days thereafter [50-53].

Notably, the *Lysinibacillus-Bacillus* paired culture exhibited the longest retention at 24.6% following the sole day of assessment, significantly outmatching the 1% viability of solitary Bacillus cohnii [50,51]. Furthermore, the *Lysinibacillus-Bacillus* combined culture maintained 3.1% viability at 3 days compared to the isolated 1 % of *Bacillus megaterium* [50,51]. Regarding singular *Bacillus* types, *Bacillus megaterium* displayed the briefest survival of merely 1 day prior to declining beneath quantifiable limits of 0.1% [53]. Comparatively, *Bacillus pseudofirmus* preserved 3.24% viability until 7 days while achieving 32% durability until 28 days, the longest period reported amongst singular bacterial strains [52].

Table 3. Viability rate of calcium carbonate precipitation competent bacteria in concrete by using MICP systems

Bacterial used	MICP Bacterial Viability in Concrete (days)							Ref
	0 (%)	1 (%)	3 (%)	7 (%)	9 (%)	28 (%)	56 (%)	
L. boronitolerans YS11 and *Bacillus* sp. AK131	100	24.6	3.1	0.9	-	2.26	n/r	[50]
Bacillus cohnii	100	-	-	-	1	-	n/r	[51]
	100	12.36 ± 0.69	-	-	-	-	2.90 ± 0.07	[52]
Bacillus megaterium	100	-	1	-	-	0.1	n/r	[53]
B. pseudofirmus	100	-	-	3.24 ± 0.23	-	32 ± 0.74	n/r	[52]
B. halodurans	100	-	-	-	-	31 ± 1.40	n/r	[52]

*n/r not reported
[1]as BPM (Bacterial pellet mortar)

Mixed bacterial consortia presented additional survival advantages, as 31% of *Bacillus halodurans* persisted through 28 days [52]. Overall, the table quantitatively exemplifies the enhanced ruggedness furnished by congregational and multi-species assemblages relative to axenic cultures. Such empirical results offer choice direction for bacteria optimized for crack repair in construction materials and enhancement on cementitious materials physical properties.

Essential factors influencing viability included bacterial species and strains, growth conditions, nutrient availability, and interaction effects [50]. Co-cultured strains supported one another metabolically. Environmental stresses were mitigated in mixed cultures versus axenic cultures. Notably, physiochemical tolerances impart strain-specific viability profiles under cementitious conditions. Survival durations illuminated selection of bacteria optimized for crack repair applications in construction materials [51].

Physiological adaptations such as endospore formation conferring desiccation resistance and an enlarged cell size hampering diffusion in *Bacillus megaterium* likely account for its marginal survival at day 9. Variations in stress response mechanisms and intrinsic tolerances to pH and nutrient limitation across phyla rationalize the wide variability in persistence under analogous conditions. This empirical data supplies valuable insight into the dynamics of microbial activity in cementitious materials. Optimizing bacterial selection and encapsulation techniques to circumvent environmental pressures could potentiate prolonged MICP and is worthy of further research. The effects of supplemental nutrients, buffering agents or genetic engineering of stress response systems may also merit exploration [50]–[53].

3. Progress on Carbon Emission Reduction through Carbon Sequestration Mechanism

The mechanism by which microbially induced carbonate precipitation (MICP) sequesters carbon dioxide from the atmosphere involves ureolytic bacteria metabolizing urea in concrete. Urease enzymes produced by bacteria like *Sporosarcina pasteurii* or *Bacillus cereus* hydrolyze urea into ammonium and carbonate ions [54]. The carbonate ions react with calcium ions from cement hydration to form calcium carbonate precipitates in the calcite or aragonite crystalline form as shown in **Figure 1**. Through this carbonation process, one mole of calcium carbonate can permanently sequester one mole of carbon from the atmosphere [55], [56].

The hydrolysis reaction follows this process:

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$

Through this reaction, the urease enzymes effectively convert urea into ammonium and carbonate ions. When these bacteria are inoculated into concrete mixes, they can metabolize any additional urea supplied and continuously produce carbonate ions directly within the cementitious material [57], [58].

The carbonate ions then react with calcium ions (Ca^{2+}) that are naturally present due to the hydration of calcium-rich cement components like tricalcium silicate and dicalcium silicate [57], [58]. This reaction forms solid calcium carbonate precipitates according to the reaction:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad (2)$$

The result is that through the biological urea hydrolysis carried out by MICP, aqueous carbon dioxide from the atmosphere is continually converted into immobile calcium carbonate minerals within the concrete itself. This permanently sequesters the carbon from the atmosphere by incorporating it into the stable carbonate form within the concrete matrix. It is this carbonation mechanism that makes MICP a promising approach for mitigating CO_2 emissions associated with cement and concrete production [54], [56].

Estimates indicate that MICP treatment of concrete has the potential to uptake significant amounts of CO_2. Based on typical concrete mixes, MICP calcite precipitation could sequester between 0.22 to 0.59 kg of CO_2 per kilogram of cement. On a global scale, with annual cement production of over 4 billion tons, MICP implementation could mitigate 180 to 470 million tons of CO_2 emissions annually. However, these estimations assume saturated calcium carbonate precipitation throughout the concrete matrix, which is difficult to achieve with current application methods at commercial scales [17], [39], [54], [59], [60].

Respective defies still must be overcome for widespread adoption of MICP for concrete's carbon footprint. Issues relate to ensuring sufficient and even bacterial urease enzyme distribution, controlling bacterial metabolism rates, and longevity of the calcite for perpetual carbon storage. Further research is also needed to optimize economical and large-scale production and application techniques. Improving the efficiency and reliability of MICP-driven CO_2 sequestration would facilitate its implementation as a carbon mitigation strategy in the ubiquitous building material of concrete [37], [61], [62].

4. Concise Bibliometric Analysis towards MICP Comprehensions: Co-authorship and Co-occurrence Analysis

The current bibliometric analysis employs co-authorship and co-occurrence techniques to gain insightful perspectives regarding scholarly collaborations and trends within the research domain of MICP. The data were extracted from the Scopus database using the search query “microbially AND induced AND calcium AND carbonate AND precipitation” and filtered to include only articles published between 2014 to 2024 comprising the top 100 most cited publications. VOS viewer software was utilized to conduct bibliometric analysis, with the co-authorship network mapping authors, organizations, and countries as the units of analysis. Fractional counting was applied to quantify collaborations amongst these actors. Concurrently, a co-occurrence network of keywords depicted the conceptual structure and emerging topics within MICP research, taking all keyword occurrences as the unit of analysis and also adopting fractional counting. This dual approach of mapping collaborative connections alongside conceptual relations through co-authorship and co-occurrence networks respectively offered a comprehensive outlook on MICP comprehensions as documented in high-impact publications indexed on Scopus. Insights gleaned from the network visualizations and quantitative bibliometric indicators provided by VOS viewer delivered strategic intelligence regarding past trends and future directions within this prospering interdisciplinary domain.

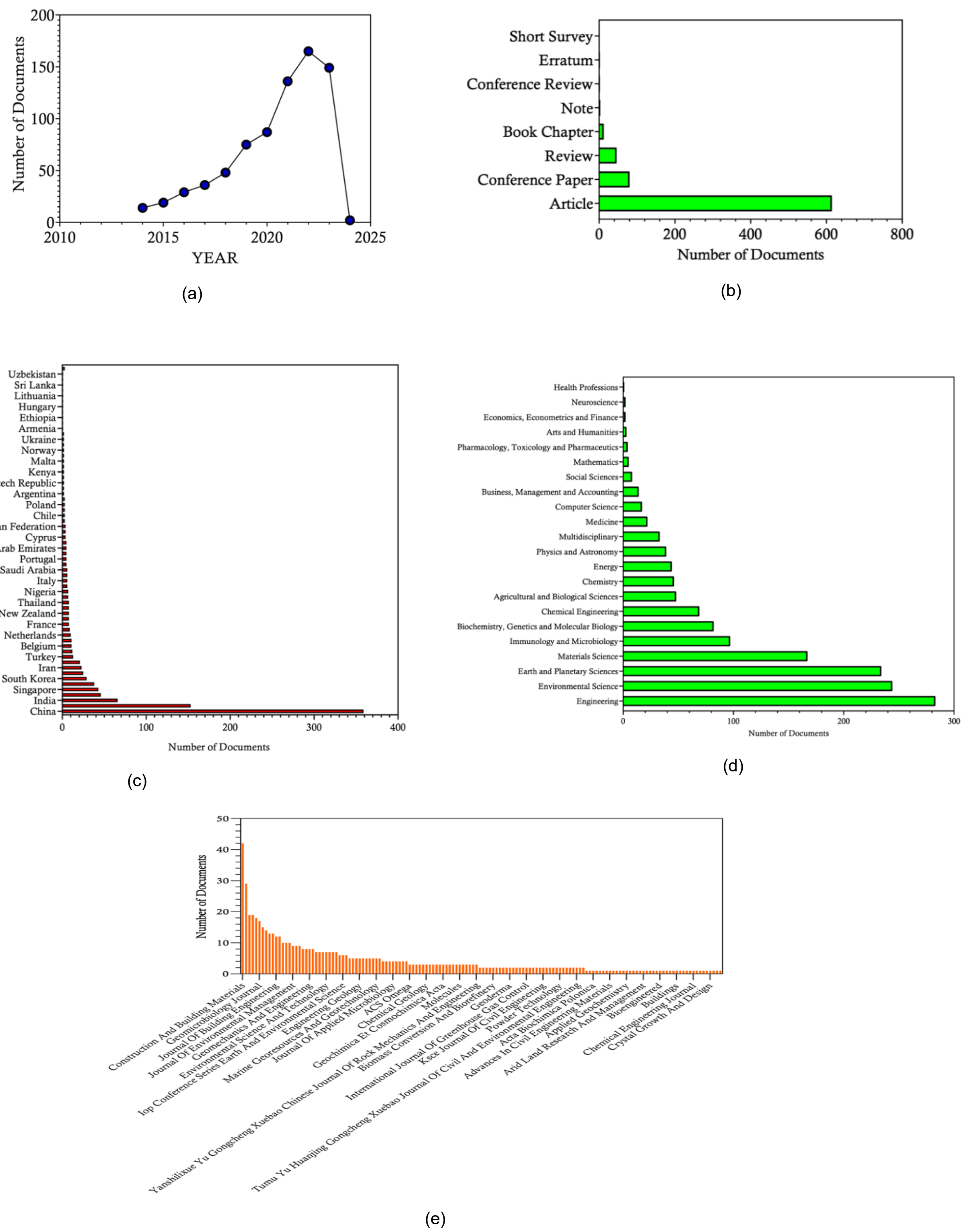


Figure 3. Document analysis of document production on basis of (a) year, (b) type of document, (c) country, (d) scope/subject, and (e) journal (data adopted and modified from Scopus).

The co-authorship network mapping focused on the collaborative ties between authors, organizations, and countries involved in MICP research. Nodes represented individual actors while the links signified their co-authoring relationships on published articles. Applying fractional counting, the strengths of these connections were quantitatively measured. Key indicators such as the total links, average number of co-authors per paper, and betweenness centrality of the most influential nodes were obtained. This revealed prolific collaborators across national and institutional boundaries. Countries and institutes contributing substantially to this field through international collaborations were also identified. The network contours showcased the research stratification and provided insight into strategic partnership opportunities going forward.

The co-authorship analysis using VOS viewer as shown in **Figure 4, 5** and **6** aimed to identify prominent authors, organizations, and countries that have collaborated on MICP research. Fractional counting was employed to quantify collaborative links between actors. The results revealed that China, United States and Australia have been the most productive countries in co-authored publications. Strong collaborations were also observed between China and United States. Over time, there has been a rise in international collaborations, indicating increased global partnerships in MICP research. The network visualization uncovered predominant clustering of authors/organizations from China, suggesting focused regional collaborations.

A co-word network of all keyword occurrences in the literature sample depicted the conceptual structure and evolution of research topics under the MICP spectrum. Nodes represented distinct keywords and the linking lines between them indicated their co-presence within article metadata. Fractional counting was implemented to indicate the intensity of connections. Network metrics allowed identification of keystone concepts and emerging areas of interest. Clustering by VOS viewer provided a visual segregation of specialty fields. Analyzing total keyword links, density and central nodes supplied a quantitative dimension to the qualitative mapping. This two-pronged technique captured research dynamics to better comprehend progression and potential future directions in MICP.

The co-occurrence analysis of keywords detected conceptual structures and emerging topics in the MICP literature. All keyword occurrences in the 100 publications were used as the unit of analysis with fractional counting. The network mapping revealed major research themes centered around calcium carbonate, calcite, and carbonate precipitation. Additionally, keywords like calcium carbonate have grown in occurrence over time, pointing to promising new research avenues. The density of linking lines between calcium carbonate indicates converging research interests on related sub-topics. This co-word analysis offers novel insights into the evolutionary trajectory of knowledge development within the MICP domain.

IV. CONLUSION

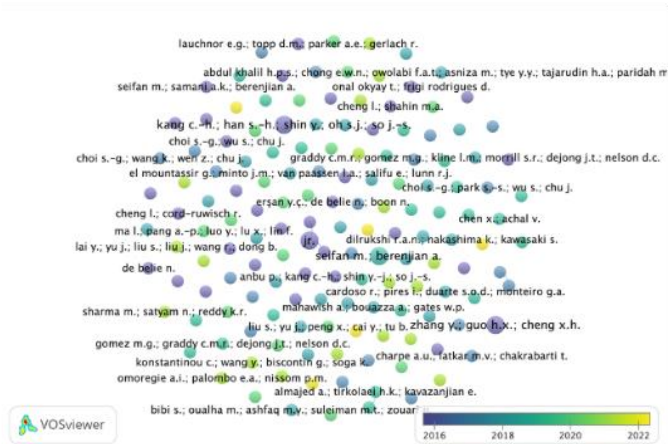
The literature assessment corroborates that MICP spectacles prodigious promise and capacity as a sustainable modus operandi to cultivate and expound farther ecologically friendly and affable concrete as construction materials. Subsequent investigations have validated that MICP treatment amends mechanical properties, self-healing ability, and durability of concrete while also conceding partial surrogate of carbon-intensive cement. This dual competency connotes MICP's insinuate as a carbon capture and utilization tactic, with estimates flaunting it could demote global cement industry emissions through sequestering carbon dioxide as stable calcium carbonate minerals within the concrete matrix. Whereas auxiliary assessments is still necessitated to boost microbial manner and enactment methods for commercial scale-up, MICP may ultimately dispense on amplifying carbon-negative 'microbial based concrete' through perpetual encroachment, gratifying its ambition to hasten sustainability within the construction industriousness.

ACKNOWLEDGMENT

The authors would like to appreciate to King Mongkut’s University of Technology Thonburi for database resources and journal access subscriptions. R also thanks to KMUTT for his grant (KMUTT International Scholarship Program/KISP) along Bachelor Degree study in Environmental Engineering. Special thanks is also given to Assistant Professor Dr. Pichet

Chaiwiwatworakul as Ramadhani's Academic supervisor.

(a)



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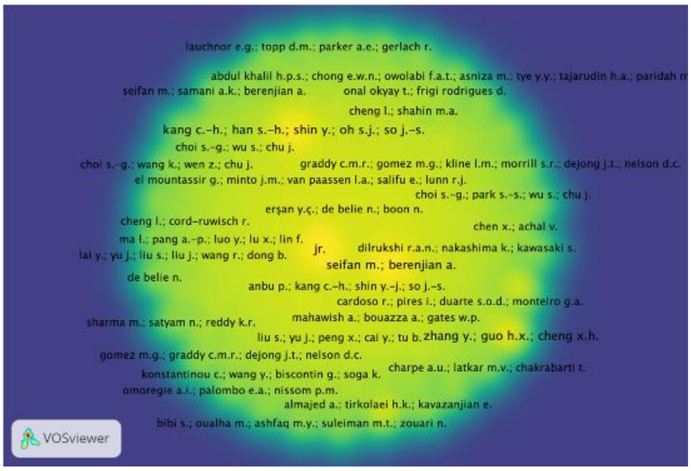
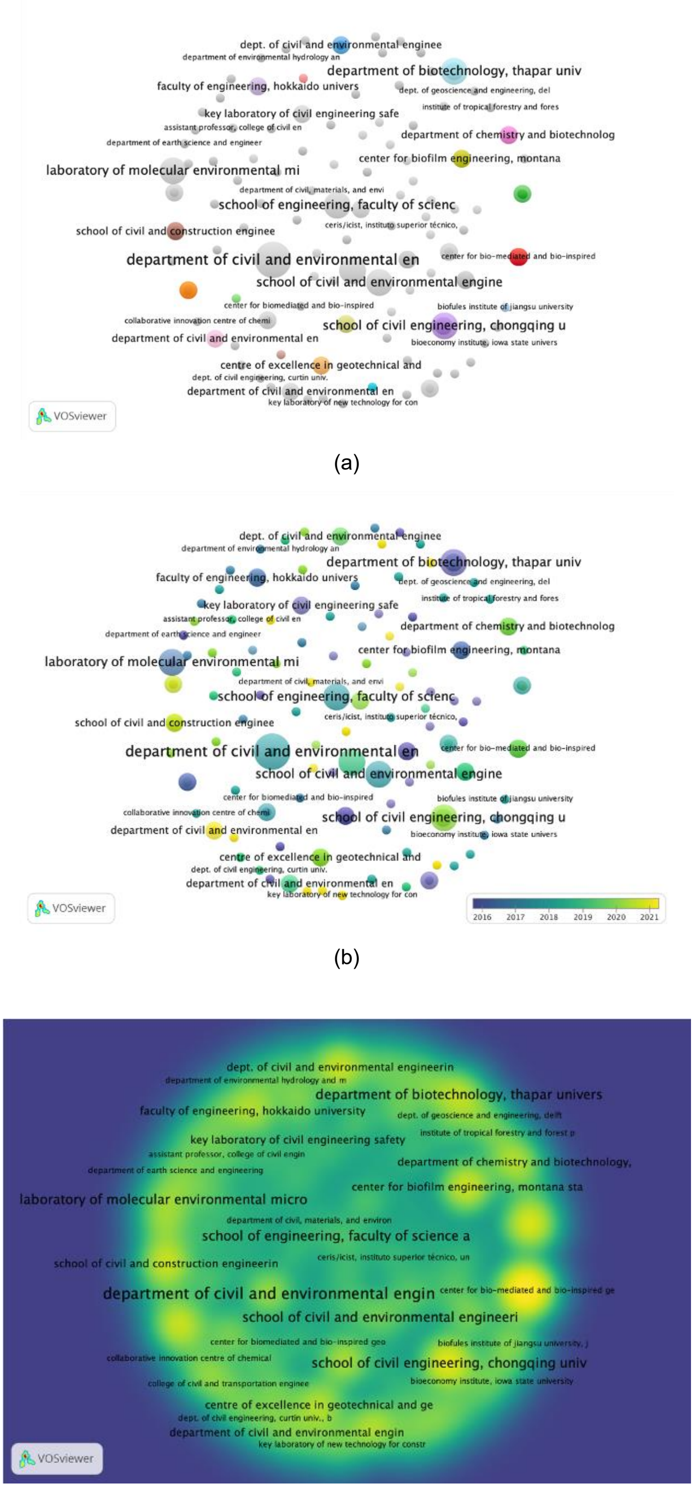


(c)

Figure 4. Co-authorship analysis by unit analysis of "Authors": (a) networks, (b) overlay, and (c) density visualizations



(a)

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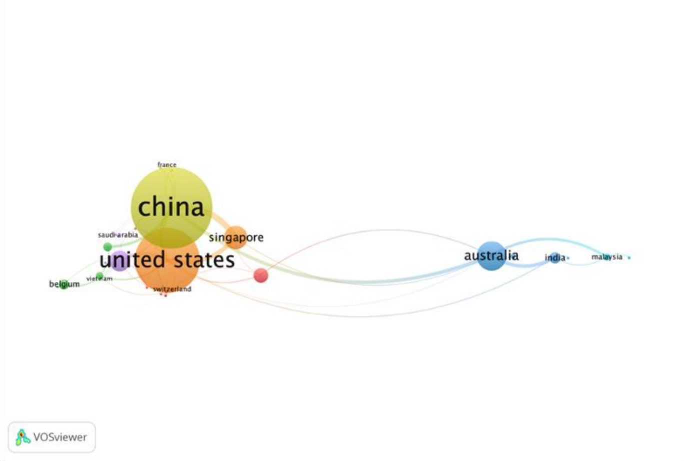
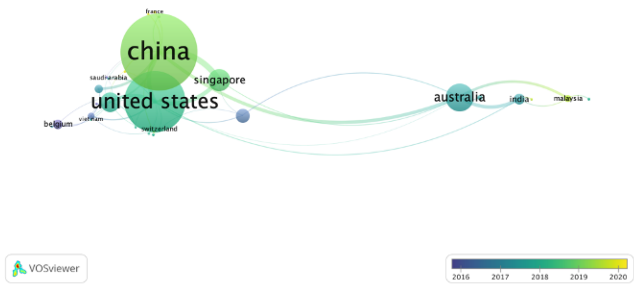
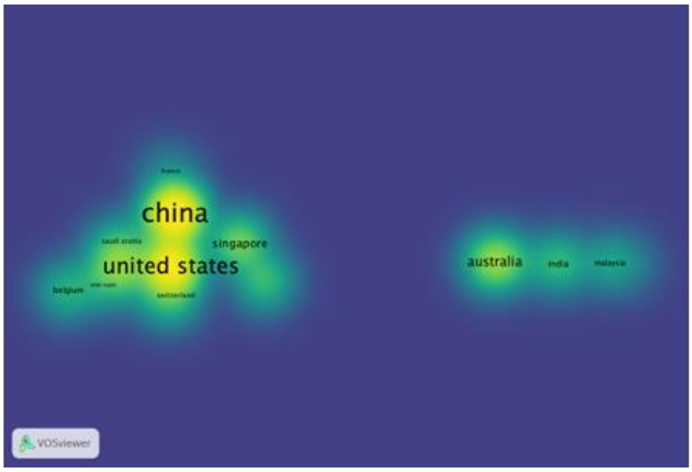
Figure 5. Co-authorship analysis by unit analysis of “Organizations”: (a) Networks, (b) Overlay, and (c) Density Visualizations



(a)

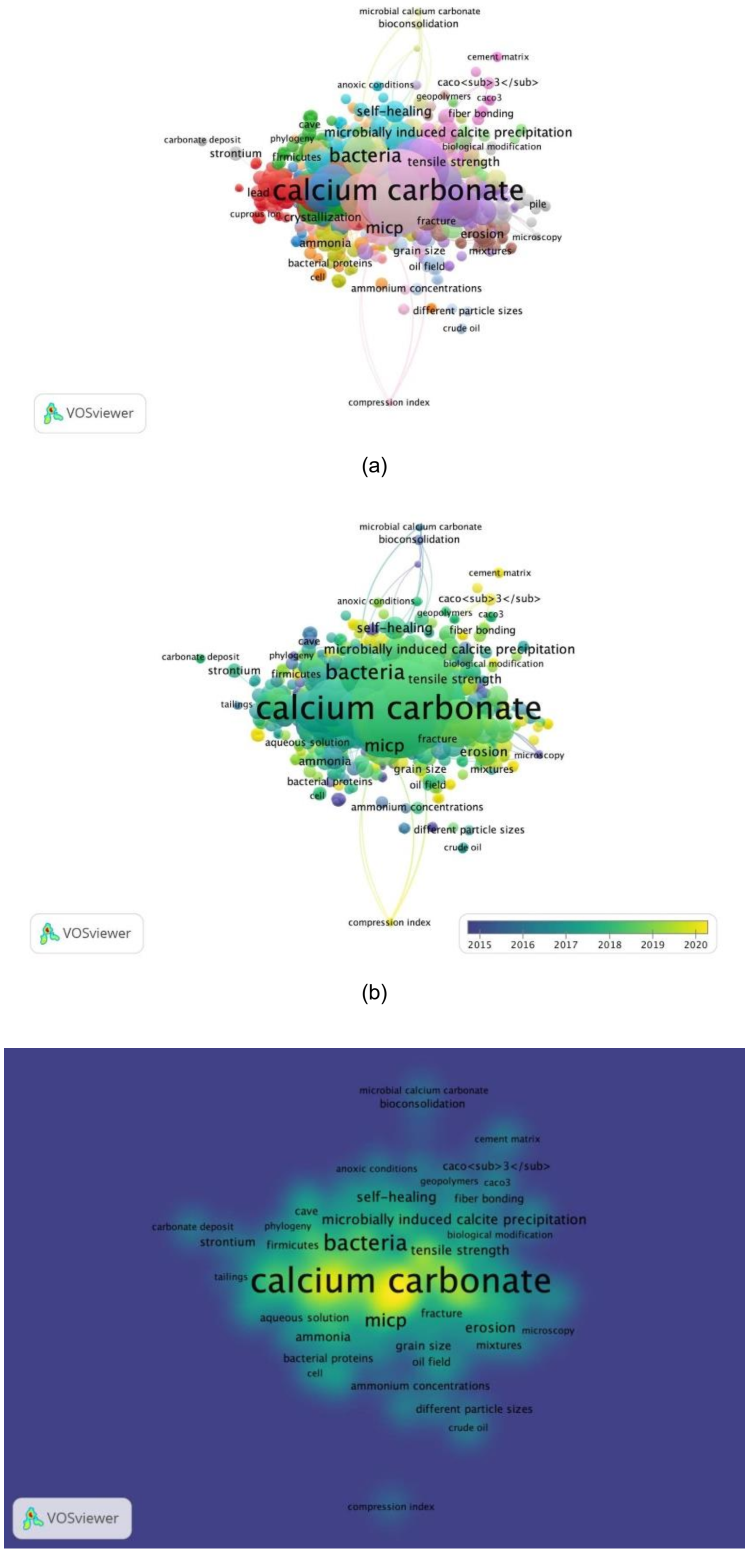


(b)



(c)

Figure 6. Co-authorship analysis by unit analysis of “Countries”: (a) networks, (b) overlay, and (c) density visualizations



(a)

(b)

(c)

Figure 7. Co-occurrence analysis by unit analysis of “All keyword”: (a) networks, (b) overlay, and (c) density visualizations

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