BioScientific Review (BSR)
Volume 7 Issue 4, 2025
ISSN$_{(P)}$: 2663-4198, ISSN$_{(E)}$: 2663-4201
Homepage: https://journals.umt.edu.pk/index.php/bsr

Title: **Building Climate-resilient Infrastructure through Microorganisms: A Mini Review**

Author (s): Muhammad Naqeeb Ur Rehman Qureshi[1], Muhammad Jahanzaib Javaid[2], Maria Kanwal[3], Atta Rasool[4], and Muhammad Anees Ur Rehman Qureshi[5]

Affiliation (s):
[1]Pir Mehr Ali Shah ARID Agriculture University, Rawalpindi, Pakistan
[2]Al-Wedad General Medical Group, Alwesam, Al Taif, Makkah Region, Saudi Arabia
[3]Capital University of Science and Technology, Islamabad, Pakistan
[4]University of the Punjab, Lahore, Pakistan
[5]Allama Iqbal Open University, Islamabad, Pakistan

DOI: https://doi.org/10.32350/bsr.74.05

History: Received: August 07, 2025, Revised: October 03, 2025, Accepted: November 20, 2025, Published: December 03, 2025

Citation: Qureshi MNUR, Javaid MJ, Kanwal M, Rasool A, Qureshi MAUR. Building climate-resilient infrastructure through microorganisms: a mini review. *BioSci Rev.* 2025;7(4):49-68. https://doi.org/10.32350/bsr.74.05

Conflict of Interest: Author(s) declared no conflict of interest

A publication of
The Department of Life Sciences, School of Science
University of Management and Technology, Lahore, Pakistan

Building Climate-resilient Infrastructure through Microorganisms: A Mini Review

Muhammad Naqeeb Ur Rehman Qureshi[1], Muhammad Jahanzaib Javaid[2], Maria Kanwal[3], Atta Rasool[*4], Muhammad Anees Ur Rehman Qureshi[5†]

[1]Department of Zoology and Biology, Faculty of Sciences, Pir Mehr Ali Shah ARID Agriculture University Rawalpindi, Pakistan
[2]Al-Wedad General Medical Group, Alwesam, Al Taif, Makkah Region, Saudi Arabia
[3]Department of Bioinformatics and Biosciences, Capital University of Science and Technology (CUST), Islamabad, Pakistan
[4]School of Chemistry, University of the Punjab, Lahore, Pakistan
[5]Department of Chemistry, Allama Iqbal Open University, Islamabad, Pakistan

ABSTRACT

Microorganisms were considered as the disease-causing agents a long time ago. However, this fear transformed into their acceptance due to their biological, physiological, and ecological understanding which resulted in the modification of Germ Theory. Currently, mutualistic and parasitic role of microbes is well-understood which paved the path for their biotechnological use. Additionally, microbial bio-coatings are outstanding bio-sensors for environmental monitoring, food analysis, heavy metal detection, and bioelectronics. The use of bacteria in self-healing concrete repair is advantageous due to their potential for low-cost binding, providing strength, stiffness, durability, and reduction in steel reinforcements. The surface membrane of bacteria is negatively charged which binds with metallic ions in basic medium that is a key factor in carbonate precipitation on their surfaces to repair cracks. On the other hand, calcite precipitation also influences the life span and stability of concrete. Recently, microorganisms assisted remediation, geo-polymerizations, and carbon capture. Furthermore, heavy metal detections were reported which may revolutionize microbial utilization in building climate resilient infrastructure. The current review spotlighted the applications of microorganisms in concretes, soil engineering, bio-coatings, bio-remediation, carbon capturing, and monitoring soil properties. In the end, recent developments and future directions were meticulously-vetted. The study concluded that the application of microbes in building climate-resilient infrastructure is reliable to decrease carbon emissions, enhancing self-repair concrete systems and developing sustainable green systems. Exploitation of natural phenomenon occurring in microorganisms not only aids in more climate resilient systems but also contributes positively for a green environment.

Keywords: bio-concretes, bioremediation, climate resilience, microbial construction, microorganisms

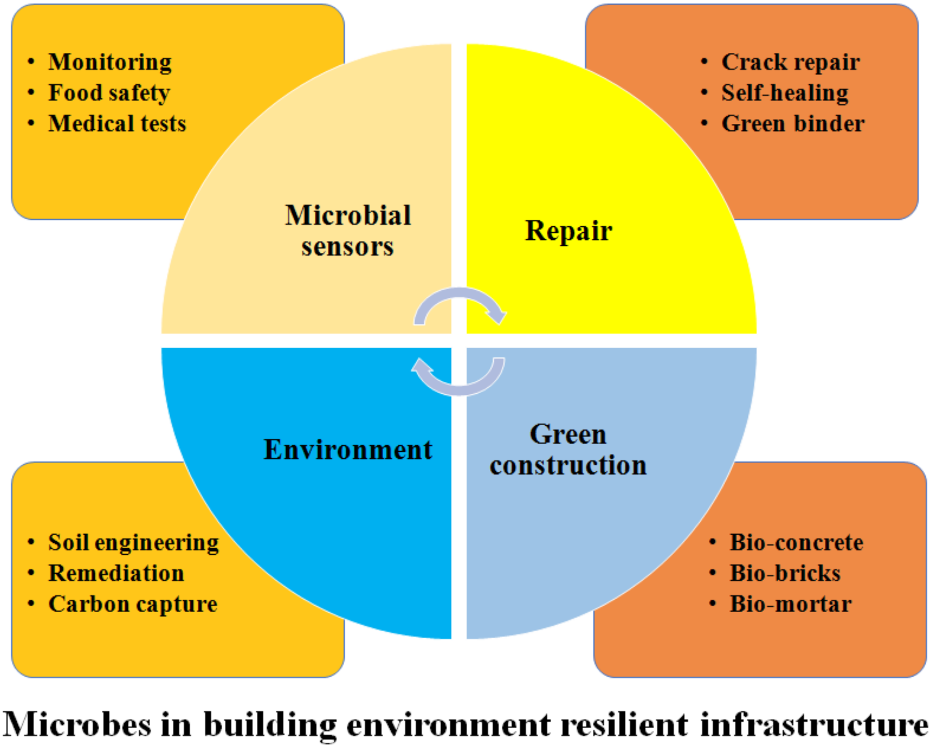
Highlights

- Microbe-based infrastructures impart durability, sustainability, and strength under climatic stress.

[*]Corresponding Author 1: attarasul.92@gmail.com
[†] Corresponding Author 2: aneesqureshi287@gmail.com

- Microbe-assisted building materials offer self-healing in concretes and repair cracks in oil wells by carbonate precipitation.
- Microbes aid in carbon capture, green construction materials, and mitigate corrosion/erosion.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Long ago, it was believed that microorganisms are the only disease and infection-causing agents. This belief led towards significant advancements in the development of aseptic, hygienic techniques, and infection control protocols [1-3]. Resultantly, Germ Theory was proposed in 1860s which influenced food sector, shaped public policies, and improved the basic health practices. However, taxonomical, ecological, physiological, and genetic understanding of microorganisms has refined the strict idea about microbes ascribed in Germ Theory. In 1900s, the successful development of microbial cultures reflected the commensal associations of microbes without harming the host [4]. Further studies on protozoans, vibrio, and squid reflected that microorganisms may also develop mutualistic relationship with other organisms [5-7]. There are numerous research reports which emphasized the essential and beneficial existence of microbe-host relationships. For instance, in urban population, the lack of microbial associations resulted in the higher level of inflammatory and respiratory disorders, such as asthma and allergies [8].

Consequently, the only idea of pathogenicity belonging to the microorganisms was redefined and amended by replacing all microbes as "disease causative agents" to the "pathogenic microorganisms" only. The idea of beneficial microbes gave rise to the Old Friends Hypothesis due to the development of stronger immune systems in childhood and symbiotic associations among communities 9. This ideological change regarding microbes brought a revolution in healthcare to develop vaccines and drugs in order to strengthen the immune system by the use of stable and functional microbes. In health sector, microbes were exploited in the prevention and treatment, specifically in the probiotics and microbial transplants not only to stabilize gut micro-biota but also for immune regulation against resistant and recurrent infections [10-12].

Microorganisms are found everywhere in the environment, habitat, buildings, soils, roads, vehicles, water, space stations, and even in ultra clean rooms which eventually develops overall environmental biome [13,14]. Numerous studies reflected the usefulness of microbes in biomedical sector. However, the role of microbes in building environment-resilient infrastructure is rarely reported to the best of our knowledge. Therefore, the current study overviewed the exploration of microbes in bio-based construction materials, microbial concretes, bio-coatings, bio-mediated soil stabilization, carbon capture, bioremediation, biosensors, and microbial geo-polymerization.

2. BUILDING CLIMATE-RESILIENT INFRASTRUCTURE THROUGH MICROORGANISMS

From fear to recognition, microbial world took almost a century. Microbial applications in building climate-resilient materials are briefly stated in this section.

2.1. Microbiological Concrete Repair System

The word "concrete" is derived from Latin word "concretus" which refers to the heterogeneously-compounded material comprised of cement, water, coarse, and fine aggregates. It is used by Romans in building roofs and walls. Ordinary concrete is made up of afore-mentioned constituents, while the steel reinforcement to the mixture of cement, coarse, fine aggregates in water is termed as 'reinforced concrete' [15]. It is a cheaper, durable, and recyclable material but it suffers from cracks due to chemical attacks, design defects, poor quality materials, corrosion, and extreme loads. The strength of concrete is largely compromised by the corrosion of steel due to aggressive chemical attacks which decreases the bond between concrete materials and steel. Billions of dollars are spent every year in order to maintain and repair bridges and buildings in the world. For instance, the United Kingdom (UK) spends half of construction budget of worth 80 billion pounds for rehabilitation and repair of buildings and bridges [16]. In Table 1, applications of microbes in building climate-resilient construction materials are briefly vetted.

Table 1. Most Common Microbes Exploited in Climate-resilient Infrastructures

Microbes	Advantages	Applications	Reference
Bacillus cereus	Highly-adaptive in extreme conditions	Crack healing	[17]

Microbes	Advantages	Applications	Reference
Sporosarcina pasteurii	Higher growth rates at extreme temperature and pH.	Stronger concretes	[18]
Bacillus subtilis	Works well even at pH 9.	Continuous CaCO3 precipitation	[19]
Bacillus acetophenoni	Resistant to weather conditions	Improve compressive strengths of mortar and cement	[20]
P. aeruginosa	Increases compressive strength and CaCO3 precipitation	Repair cracks up to 500 µm	[21]
B. sphaericus	Reduces water absorption	Fills cracks in 120 days	[22]

2.1.1. Microbe-based Self-healing Concrete. Several synthetic materials, such as epoxies are utilized for the recovery of concrete cracks. However, these materials display disadvantages related to their toxic nature and difference in thermal expansion. Consequently, bacteria-based self-healing is induced in the concretes as environmentally-friendlier substitute. In fact, calcium carbonate precipitation imparted by the bacteria seals the cracks and also reduces the repair cost. Additionally, microorganisms are also applied in concrete mixtures to improve self-healing efficacy [23]. Fig. 1 reflected the useful role of microorganisms in self-healing concretes.

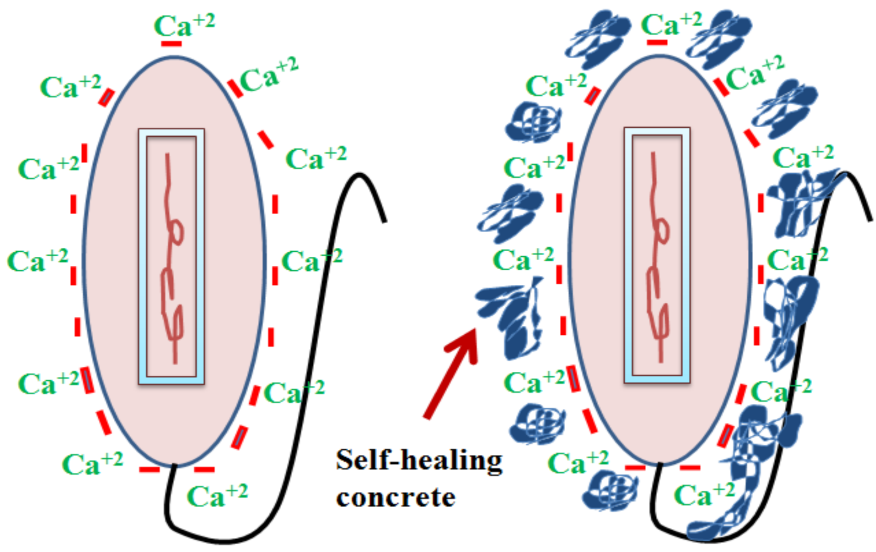


Figure 1. Graphical Illustration of Self-healing Concrete by the Use of Bacteria (Self-constructed)

2.1.2. Advantages vs. Disadvantages of Bio-concrete. The exploration of bacteria in concrete has many advantages. First of all, these can be exploited to fill the cracks and offer the incorporation of appropriate sand in order to enhance strength and stiffness. Secondly, bacteria act as biological binder and also impart durability and strength. Thirdly, their use also leads towards the reduction in steel reinforcement along with the production of compatible materials which provide strength and stability. In contrast, the first drawback of bacterial or microbial use in concrete is that it costs almost double relative to the ordinary concretes. However, this cost is compensated later on due to lower maintenance and repair [24]. Secondly, insertion of bacterial capsules decreases the compression strength inside concrete. Third disadvantage is the nutrient management of bacteria depending upon their requirements and atmosphere. Lastly, there is no standard protocol in bacterial mixing in the concrete which additionally necessitates microbial protection at higher pH.

2.1.3. Bacterial Viability in Concrete. The surface of bacteria plays a critical role in calcium precipitation owing to the existence of anionic groups at their surfaces. Hence, cationic metal ions could be attracted at bacterial membrane [25]. Resultantly, carbonate precipitates on their exterior surfaces due to continuous stratification which also enables their use in remedy of stones and cracks [26].

2.2. Applications of Bacteria in Construction

In last two decades, the bacterial capability of producing CaCO3 has been exploited in a variety of commercial, construction, and engineering applications, such as in oil recovery units, soil-upgradation, stone-protection, bio-cements, and restoration of building materials. Brief overview of such kind of applications is discussed in this section.

2.2.1. Oil Wells. Crude oil is the fundamental energy source which influences modern economy of the world. Biotechnology is employed in oil extraction from oil wells, plugging fractures, and to prevent water production during oil recovery. Through using traditional recovery methods, only 25-25% of the oil is extracted, while 65% of the oil is left in reservoir [27]. Therefore, attempts were made to improve the efficiency of oil extraction by employing thermal or chemical flooding methods. Both methods are costly, toxic, and produce unwanted residual products which are difficult to remove from the oil. Biotechnology provides relatively cheaper and environmentally-compatible solutions to the aforesaid problem by decreasing the interfacial tensions between oil-rock and oil-water [28]. For instance, *Bacilus pasteurii* were used to plug very high permeability area, lessening water flooding and enhancement in oil yield from oil wells [23]. Another research group led by Zhong et al. also reported microbial mineralization for repair of fractures in the oil wells [29].

2.2.2. Soil Improvements. Friction, stiffness, permeability, and cohesion are significant mechanical properties of the soil in engineering constructions of materials for roads, slopes, dams, and railways. In this regard, soil stability is quite vital which can be improved by chemical grouting technique. Nevertheless, it is rather costly. Consequently, bio-grouting and bio-cementation are favored which are cost-effective and eco-friendly approaches. For the first time, the CaCO3 precipitation was reported by Boquet et al. in 1973 [30]. Likewise, Achal and co-workers investigated the CaCO3 formed in sand samples plugged by *Bacilus pasteurii,* and mutant *Bacilus pasteurii* were 24% and 33%, respectively [31]. Microbe-based CaCO3 precipitation and bio-mineralization substantially improved the strength (up to 6.1 MPa), stiffness, volumetric response, shear strength, and permeability of the sandy soils [32].

2.2.3. Stone Protection. Weather is the primary factor which causes damage to the buildings, monumental, and ornamental stones due to the carbonate loss. First of all, microbial biotechnology was applied in 1993 on Thouars Saint Medard Church tower at the area of 50 m2 in order to provide protection against weather. After one year, the outcomes reflected the presence of significant quantity of organic carbonates over the surface of the tower that protected the surface from deterioration. It was also stated that microbial/biological treatment for carbonate deposition did not affect the aesthetic appearance of the stones used in building Santa Maria Church, Italy [33].

2.2.4. Biological Mortar. Microorganisms are important in the development of biological mortar which, in turn, is used to fill cracks in stones and concretes. Biological mortar is composed of three ingredients, that is, bacteria/microorganism, calcium salt, and limestone powder. These ingredients are optimized to acquire biological mortar and its optimum dosage that can resist surface tension in micro-cracks. Referring to the literature, the best and optimum concentration of the bio-based mortar is bacterial paste, nutrition media, limestone powder (size 40-60 μm) with 25%, 25%, and 50% proportion. This mortar was applied on Amiens Cathedral sculptures and Church Portal of Argenton-Château in France as test case. After two years, the results were encouraging in the specified treated area [34].

2.2.5. Concrete. Besides the application of microbes in the petrochemical, geotechnical engineering, and building materials, microorganisms have also been used as potential binder-based materials in self-healing bio-concretes. This not only improves strength but also recovers cracks in the concrete and building materials. Fig. 2 describes the primary components of bio-concrete.

2.3. Bio-sensor and Monitoring

Techniques involving the sensors and sensing tools have become an essential part of our daily routine. The most appealing area is the use of microbes as sensing equipment [35]. Microbial biosensors are tools to analyze and monitor the environment and climate changes mainly by using microbes, such as bacteria, fungi, and algae [36].

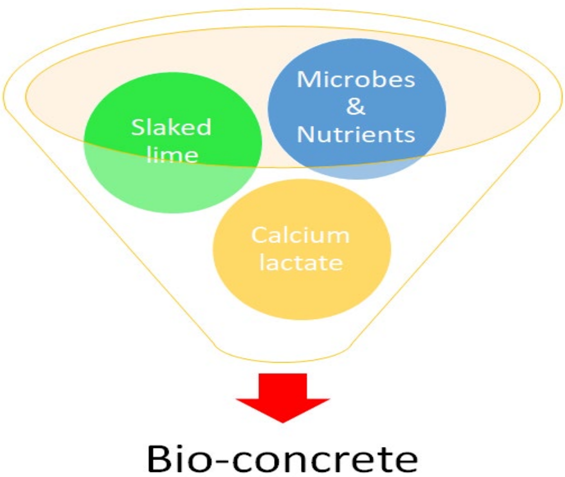


Figure 2. Primary Ingredients in a Bacterial Concrete (Self-constructed)

Currently, the ability of biosensors is substantially enhanced by using genetically-modified organisms for their remarkable role. These biosensors are low in price, reliable, and eco-friendly which makes them accessible [37]. In Fig. 3, the benefits and limitations of the microbial bio-sensors are represented.

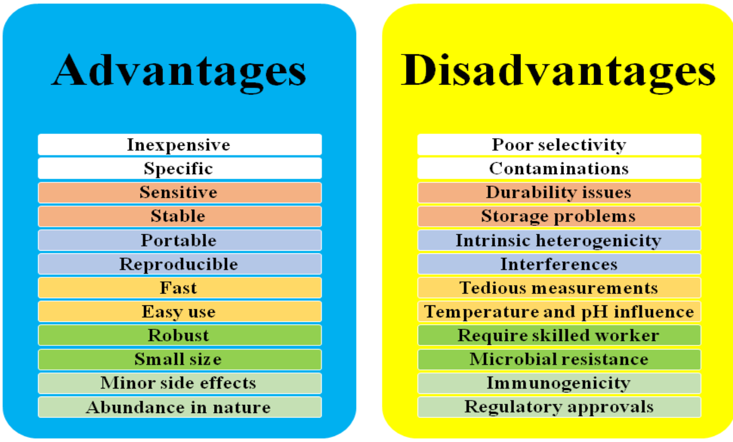


Figure 3. Advantages and Limitations of Microbe-based Biosensors (Self-constructed)

2.3.1. Types of Microbial bio-sensors. Cell free biosensors, non-specific whole cell biosensors, and specific whole cell biosensors detect pollutants from environment and work on sensing, transduction, and signaling principle. The cell free biosensors utilize the DNA, protein, and aptamer (a synthetic single stranded DNA or protein) as sensing prerequisites [38]. Aptamer increases the selectivity of target chemicals for definite pollutants' recognition based on selective bonding, such as in nano-materials. On the other hand, non-specific whole cell biosensors are built mainly by stress reactive genetic regulation, such as heat shock and DNA damage responses. The specific whole cell biosensors depend upon the metabolism and detoxification genes in microbes [39].

2.3.2. Microorganism-based Environmental Bio-sensors. Huang et al. worked on the Sustainable Development Goals (SDGs) initiated by United Nations (UN) associated with biosensors to monitor the environment. Their study revealed that the cell free biosensors are rapid and definite in terms of acting against environmental pollutants specifically for heavy metals. While the non-specific whole cell biosensor delivers bioavailability and toxicity which cannot be scrutinized by cell free biosensors and informed about the consequences regarding the impact of environmental pollutants on climate [40]. The specific whole cell biosensor grants fine information on target pollutants. Another study conducted by Md. Mafiqul Islam illustrated the identification of water pollutants by using microorganisms. They concluded that *Clostridium perfringes* act as a biosensor to identify the water pollutants [41]. In addition, the Algae, *E-coli* and fungi can also be explored for bio-sensing applications. The major shortcomings in microbial bio-sensors were stability, convenience, and renewability of biosensors. To overcome these hurdles, researchers and scientists are working on the nano-material electrode in cell free biosensors and whole cell biosensors [42].

2.4. Microbial Enhanced Geo-polymerization

Geo-polymers are defined by their durability, heat endurance, and chemical inertness. In the same stream, the introduction of microbes increases the above-mentioned attributes and takes part in building climate-resilient infrastructure. Geo-polymers are group of inorganic substances in the shape of geo-polymeric paste, geo-polymer concrete, and mortar for the development of industrial infrastructure. This phenomenon is referred to as 'geo-polymerization'. Microbial geo-polymerization includes bio-mineralization, bio-cementation, and microbial activity.

Likewise, the study reported by Griño et al. [43] examined the auto-healing in geo-polymer mortar treated at normal temperature utilizing poly(propylene) fiber and bacterial co-cultures of *Bacillus subtilius* and *Bacillus megaterium.* A well-established design was used which resulted in eight run complete factorial design with four levels in the initial part with variable propylene content from 0-0.75%. The second stage experiments were conducted with and without bacterial concentration. The materials used by Grino et al. were fly ash with low calcium content, an alkaline activator, such as sodium silica solution, flakes of sodium and potassium, and sodium silicate solution to increase geo-polymerization along with bacterial culture and poly(propylene) fibers [43].

The geo-polymeric sample and bacterial culture were applied as ultra-pulse velocity tests. The microstructure of geo-polymeric paste was observed by X-ray fluorescence test. After 28 days, *B. subtilis* showed growth at pH 8, while no growth was observed in *B. megaterium.* This indicated that the bacterial strains undergo log growth phase within geo-polymer but tolerate high pH and temperature conditions. Grino et al. [43] concluded that a geo-polymer mortar comprises poly(propylene) and bacteria can be used as repair mortar. The bacteria increase the strength-regain value of the geo-polymeric mortar. Poly(propylene) along with bacteria reduces the damage degree and increases the healing percentage of geo-polymeric mortar. Moreover, the combination of geo-polymer and poly(propylene) fiber depicted the ability to work as a structural repair material in aggressive environment. The concern of how diverse bacteria influence natural fibers as reinforcements under a range of healing conditions in the cementitious medium is also a study of significance.

2.5. Microbe-assisted Bio-coatings

Bio-coating is referred to as a permeable polymeric film which sticks to the microorganisms and retains them on the surface for their bio-catalytic action in different sensors and bioreactors [44-46]. For instance, *E. coli* is used with different kinds of nanoparticles, polymeric colloids, and carbohydrates to fabricate cohesive film. The confocal laser scanning microscope and scanning electron microscopes were used to observe the bacterial presence in the prepared bio-coatings. The fabricated microbe-assisted bio-coating was independent of freeze-drying arrangements of halloysite, latex polymers, and bacteria [47].

2.6. Bio-mediated Soil Improvement

A bio-mediated soil improvement system is a network of chemical reactions within soil that are regulated and controlled by biological activity, and whose by-products change the soils engineering characteristics [48].

2.6.1. Underlying Web of Chemical Reactions. A network of chemical reactions takes place in the soil for improvement in the texture, stiffness, and mechanical characteristics of the soil which are the backbone of these systems [49]. Incorporation of microbes and their produced by-products are categorized into three kinds, namely gas generation, organic precipitation, and inorganic precipitation by-products which upgrade soil properties. In addition, these microbial reactions produce instant and larger amounts of the by-products in order to improve soil properties rapidly [48].

2.6.2. Monitoring the Processes. The monitoring and detection of different geotechnical, chemical, and biological compounds in real soil samples without altering soil properties is imperative. Therefore, the assessment of microbial by-products' imparted changes in soil can be examined by the use of microorganisms. For this purpose, shear wave velocity, resistivity, and compression wave velocity evaluations were carried out to ascertain the microbial monitoring without affecting the soil processes and soil characteristics [50].

2.6.3. Engineering Soil Properties. The engineering and examination of soil properties may differ significantly amongst various bio-mediated treatment techniques. Permeability, stiffness, compressibility, shear strength, and volumetric behaviors are the main characteristics that could alter by at least ten times. Variations in their properties offer multiple applications. In every instance, analytical analysis and/or review of previously studied non-biomediated treatment methods can be used to reasonably estimate the potential extent to which a particular bio-mediated treatment method may enhance the soil properties. For instance, studies looking at the use of gypsum, cement, CIPS (Calcite In-Situ Precipitation), and epoxy to improve soils may find a comparable increase in the shear strength of sands from bio-mediated calcite precipitation [51].

2.7. Microbial Carbon Capture

Anthropogenic activities, such as burning fossil fuels and industrial production release carbon dioxide (CO2) into the atmosphere. Fears of catastrophic climate change and global warming have therefore increased. Conventional CO2 capture technologies are generally hazardous, ineffectual, and contribute to secondary pollution in the environment [52]. Conversely, biological systems offer a promising avenue for CO2 conversion due to their considerable versatility and application selectivity. Furthermore, a variety of microorganisms may convert CO2 into high-value compounds by using it as their only supply of carbon as shown in Fig. 4. Certain microbes, such as cyanobacteria and algae can photosynthesize, capturing CO2 and converting it into biomass [53]. Other microbes, such as methanotrophs, can also consume methane which is another potent greenhouse gas [54].

The recent progress in genetic modifications in bacteria for more CO2 capture led to the development of modified *Escherichia coli,* cyanobacteria, and *Ralstonia eutropha*. These bacteria have been engineered to more efficiently absorb CO2 and convert it into valuable products, such as biofuels, bio-plastics, and chemicals. Advances in synthetic biology and metabolic engineering have allowed for precise control over bacterial metabolic pathways, significantly improving their CO2 sequestration capabilities [55]. This section highlights specific strategies, including the introduction of new CO2-fixation pathways and optimization of native ones. It also addresses challenges, such as the complexity of bacterial metabolism, scalability, economic feasibility, and suggests future research directions to further develop robust and efficient bacterial systems for industrial applications [56].

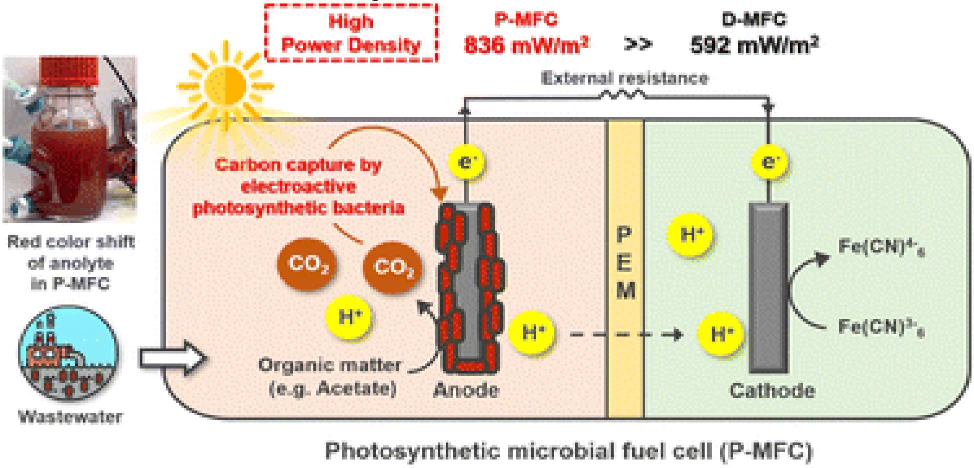


Figure 4. Schematics of a Microbial Cell Capturing Carbon [57]. Open Access Article licensed under a Creative Commons Attribution-Non-Commercial 3.0 Unported License).

Some bacteria can induce the formation of minerals. This process is called ‘bio-mineralization’. For instance, *Bacillus pasteurii* can convert calcium ions and CO2 into calcium carbonate which is a stable mineral that can be used in construction materials, such as concrete. The biomass produced by carbon-capturing microbes can be processed into bio-based materials that can replace traditional carbon-intensive building materials. This reduces the carbon footprint of construction.

Microbial activity can improve soil structure and stability, making landscapes more resilient to extreme weather events. Enhanced soil carbon storage also contributes to the long-term carbon sequestration. Integrating microbial carbon capture systems into green roofs and walls may enhance urban infrastructure’s resilience. These systems not only sequester carbon but also provide insulation, reduce urban heat island effects, and manage storm water. Microbial carbon capture can be combined with renewable energy sources. For instance, algae farms can be co-located with solar or wind farms using the excess CO2 from renewable energy production to enhance biomass growth. Utilizing captured carbon in new products creates a circular economy. For instance, captured CO2 can be converted into bio-plastics or biofuels, reducing reliance on fossil fuels.

2.8. Microbe-assisted Bioremediation

Bioremediation is broadly defined as any process in which a living or dead biological system (typically bacteria, microalgae, fungi in myco-remediation and plants in phytoremediation) is used to remove environmental pollutants from air, water, soil, flue gasses, industrial effluents, and other sources in natural or artificial settings. The natural ability of organisms to absorb, collect, and degrade prevalent and new contaminants has led to the use of biological resources in the treatment of contaminated environments. Fig. 5 shows the schematics of bacterial-assisted bioremediation. In comparison to the traditional physicochemical treatment approaches, bioremediation may have advantages. This is because it is sustainable, environmentally-benign, inexpensive, and scalable. It involves using microorganisms, plants or enzymes to clean up the contaminated soil, groundwater, and air, improving infrastructure durability and environmental sustainability [58]. Bioremediation can break down harmful chemicals, heavy metals, and petroleum products that may damage infrastructure. In addition, bio-remediation also enhances soil stability, strength, and water-holding capacity, reducing erosion and landslide risks. Bioremediation can be used to detect potential infrastructure failures and monitor environmental conditions. Bioremediation can restore ecosystem balance, improve air and water quality, and support biodiversity. In general, in-situ and ex-situ bioremediation techniques are widely reported in the literature.

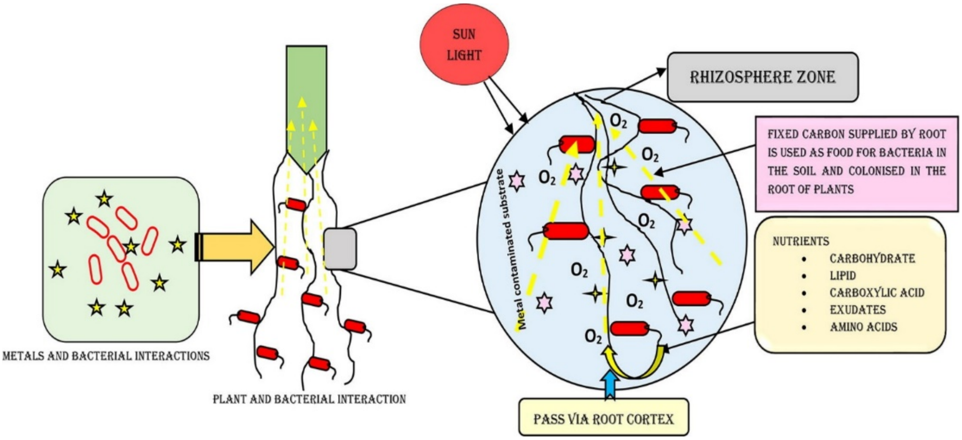


Figure 5. Bioremediation Assisted by Bacterial Interactions with Plants. Adopted with permission from Sharma [59]. Copyrights 2021, Elsevier.

2.8.1. In-situ Bioremediation Techniques.

2.8.1.1. Bio-sparging and bio-slurping. Bio-sparging is an in-situ remediation technology used to treat contaminated groundwater and soil by injecting air or oxygen into the sub-surface. This process enhances the natural biodegradation of organic contaminants by stimulating aerobic microbial activity. The injected air increases the oxygen concentration in the groundwater and soil, thereby promoting the growth of aerobic bacteria that may degrade pollutants, such as hydrocarbons (e.g., petroleum products), solvents, and other organic compounds. On the other hand, bio-slurping is a remediation technique used to clean up sites contaminated with hydrocarbons, such as oil and petroleum products. It combines elements of bioventing and vacuum-enhanced free-product recovery to simultaneously remove liquid-phase hydrocarbons (free product) and enhance the biodegradation of hydrocarbons in the unsaturated zone of the soil.

2.8.1.2. Bio-attenuation and Bio-stimulation. Bio-attenuation is also known as natural attenuation or intrinsic bioremediation. It is the process by which natural microbial communities degrade and reduce the concentration and toxicity of environmental contaminants without human intervention. This method relies on naturally-occurring physical, chemical, and biological processes to break down pollutants in soil and groundwater over time. Similarly, stimulating indigenous microorganisms to perform bio-remediation is known as bio-stimulation. Building climate-resilient infrastructure through bio-stimulators involves natural substances to stimulate the growth and activity of indigenous microorganisms. This enhances the natural degradation process of pollutants and improves infrastructure durability. By integrating bioremediation into infrastructure development, more sustainable, resilient, and environmentally-friendly infrastructure can be created that may withstand the impacts of climate change.

2.8.2. Ex-situ Bio-remediation.

2.8.2.1. Bio-piles and Windrows. Bio-piles is also known as bio-cells or bio-heaps. It is an ex-situ remediation technology used to treat contaminated soils. This method involves excavating the contaminated soil and piling it into engineered heaps, where microbial activity is enhanced to break down pollutants, primarily organic contaminants, such as petroleum hydrocarbons. Whereas, windrows are the elongated piles of organic wastes arranged for composting purposes. This method is widely used for the aerobic decomposition of organic matter, such as agricultural waste, yard clippings, food scraps, and manure. The windrow composting technique facilitates the breakdown of organic materials into nutrient-rich compost that can be used to improve soil quality.

2.8.2.2. Land Farming and Bio-augmentation. Land farming is a soil remediation technique that involves the controlled application and incorporation of contaminated soil or sludge into the upper soil layers of a designated land treatment area. This method relies on natural biological processes to degrade organic contaminants, primarily hydrocarbons, through microbial activity. It is often used to treat petroleum-contaminated soils, refinery waste, and organic waste materials. Adding microorganisms is a good strategy to boost bio-remediation. Bio-augmentation is a bioremediation technique that involves adding microorganisms to the environment in order to increase the natural degradation process of pollutants. Building climate-resilient infrastructure through bio-augmentation involves using microorganisms to improve the durability and sustainability of infrastructure, making it more resistant to climate-related stresses [60].

2.9. Recent Developments

Microorganism-assisted architecture is an evolving research area which provides sustainable solutions regarding building materials, environment management, and energy systems. This section explains some of the recent developments. An example includes the syntheses of bio-concretes using new bacterial strains that not only healed the cracks but also survived under extreme environments [61]. Recently, microbial fuel cells are reported to produce electricity from waste by using bacteria. There are numerous studies to help optimize the efficiency of microbial fuel cells for waste treatment plants in order to produce energy [62]. Progress in genetic engineering enables the researchers to generate new microbes having the ability to degrade complex toxins, hydrocarbons, and complex pollutants [63]. Bio-cements and bio-bricks are prepared which are more resistant and quicker to make [64]. Moreover, agriculture waste is used to create bio-bricks [65]. NASA proposed the use of microbial Lithificaton technique to replace the cement in Martian soil that is critical in building infrastructure where resources are limited, for instance on Mars [66]. Research is being conducted to produce protective layers on metal surfaces in order to protect their surfaces from corrosion by deposition of biofilms [67].

3. CONCLUSION

Despite several advantageous of microorganisms in bio-concretes, there is still a need to optimize the standard protocol and decrease its cost in order to explore it at massive scale. Another drawback of the algal, bacterial, and fungal-based biosensors is their poor stability which should be overcome by the introduction of some nano-materials. Leveraging microorganisms for CO2 utilization and bioremediation offers promising avenues for building climate-resilient infrastructure. By engineering bacteria to capture and convert CO2 into valuable products, such as bio-fuels and bio-plastics, greenhouse gas emissions can be reduced while creating sustainable materials for construction. Additionally, using microorganisms for bioremediation may help manage heavy metals and other contaminants in the environment, ensuring that our infrastructure remains safe and environmentally-friendly. Continued research and development in these areas is essential to realize the full potential of microorganisms in building resilient and sustainable infrastructure for the future.

3.1. Challenges and Future Directions

Although use of microbes in building materials and concrete systems is beneficial, climatic vulnerability, higher initial price, policies/regulation problems, public acceptance, biological safety fears, long-term durability, environmental influence, and large scale practicality are some challenges in mass utilization of microbes in building climate-resilient materials [68].

The development of stress tolerant, durable, and high-performance microbes for self-healing bio-concretes and bio-mineralization could be a promising future research. In the same way, the integration of microbes with sensors to design smart biosensors for real monitoring of erosion, cracks, degradation, and corrosion studies are imperative by devising predictive models [69, 70]. Bacterial calcite precipitation at commercial scale for synthesis of bio-cement, soil engineering, bio-films, and bio-bricks is another way to bring microbial infrastructure to further elevation. However, it requires setting global standards, safety protocols, and field trials to gauge long-term performance, stability, and durability of microbe-based climate resistant materials. For this purpose, academia, industry, public, and government partnership is very important.

Author Contribution

Muhammad Naqeeb Ur Rehman Qureshi: writing-original draft, investigation. **Muhammad Jahanzaib Javaid:** resources, software, formal analysis. **Maria Kanwal:** writing-original draft, validation, formal analysis. **Atta Rasool:** conceptualization, visualization, supervision. **Muhammad Anees Ur Rehman Qureshi:** software, resources, writing-review & editing.

Conflict of Interest

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

In the current review, neither new data was generated nor laboratory experiments were performed. The data was acquired form already published articles which are provided in the reference list.

Funding Details

No funding has been received for this research.

Generative AI Disclosure Statement

The authors did not used any type of generative artificial intelligence software for this research.

REFERENCES

1. Rizwan M, Selvanathan V, Rasool A, et al. Metal–Organic framework-based composites for the detection and monitoring of pharmaceutical compounds in biological and environmental matrices. *Water Air Soil Pollut*. 2022;233:e493. https://doi.org/10.1007/s11270-022-05904-2
2. Qureshi MAUR, Arshad N, Rasool A, Rizwan M, Fawy KF, Rasheed T. pH-responsive chitosan dendrimer hydrogels enabling controlled cefixime release. *European Polymer Journal*. 2024;219:e113377. https://doi.org/10.1016/j.eurpolymj.2024.113377
3. Rasool A, Qureshi MNUR, Kanwal M, Anwar MA, Butt MS, Firdous N. Chemical modifications of alginates for biomedical applications-a review. *Sci Inq Rev.* 2025;9(2):1-48. https://doi.org/10.32350/sir.92.03
4. Chapman R, Gause G. The struggle for existence. *Ecology*. 1935;16(4):656-657.
5. Hungate R. Further experiments on cellulose digestion by the protozoa in the rumen of cattle. *Biol Bull*. 1943;84(2):157-163. https://doi.org/10.2307/1538178
6. McFall-Ngai MJ, Ruby EG. Symbiont recognition and subsequent morphogenesis as early events in an animal-bacterial mutualism. *Science*. 1991;254(5037):1491-1494.
7. Dunlap PV, Mcfall-Ngai MJ. Initiation and control of the bioluminescent symbiosis between Photobacterium leiognathi and leiognathid fish. *Ann New York Acad Sci*. 1987;503(1):269-283. https://doi.org/10.1111/j.1749-6632.1987.tb40614.x
8. Liu AH. Revisiting the hygiene hypothesis for allergy and asthma. *J All Clin Immunol*. 2015;136(4):860-865. https://doi.org/10.1016/j.jaci.2015.08.012
9. Rook G, Brunet L. Microbes, immunoregulation, and the gut. *Gut*. 2005;54(3):317-320. https://doi.org/10.1136/gut.2004.053785
10. Lau CS, Chamberlain RS. Probiotics are effective at preventing Clostridium difficile-associated diarrhea: a systematic review and meta-analysis. *Int J Gen Med*. 2016:27-37. https://doi.org/10.2147/IJGM.S98280
11. Manzoor H, Arshad N, Qureshi MAR, Javed A. Hydroxyapatite-reinforced pectin hydrogel films PEC/PVA/APTES/HAp: doxycycline loading for sustained drug release and wound healing applications. *RSC Adv*. 2025;15(37):30026-30045. https://doi.org/10.1039/D5RA01989C
12. Arshad N, Chaudhary AA, Saleem S, Akram M, Qureshi MAUR. Surface modification of surgical suture by chitosan-based biocompatible hybrid coatings: In-vitro anti-corrosion, antibacterial, and in-vivo wound healing studies. *Int J Biol Macromol*. 2024;281:e136571. https://doi.org/10.1016/j.ijbiomac.2024.136571

13. Qureshi MAUR, Arshad N, Rasool A, et al. Kappa-carrageenan and sodium alginate-based pH-responsive hydrogels for controlled release of methotrexate. *Royal Soc Open Sci*. 2024;11(4):e231952. https://doi.org/10.1098/rsos.231952

14. Cockell CS. Are microorganisms everywhere they can be? *Environ Microbiol*. 2021;23(11):6355-6363. https://doi.org/10.1111/1462-2920.15825

15. Hassoun MN, Al-Manaseer A. *Structural Concrete: Theory and Design*. John Wiley & Sons; 2020.

16. Jefferson A, Joseph C, Lark R, Isaacs B, Dunn S, Weager B. A new system for crack closure of cementitious materials using shrinkable polymers. *Cement Concr Res*. 2010;40(5):795-801. https://doi.org/10.1016/j.cemconres.2010.01.004

17. Wu M, Hu X, Zhang Q, Xue D, Zhao Y. Growth environment optimization for inducing bacterial mineralization and its application in concrete healing. *Construct Build Mater*. 2019;209:631-643. https://doi.org/10.1016/j.conbuildmat.2019.03.181

18. Omoregie AI, Ngu LH, Ong DEL, Nissom PM. Low-cost cultivation of Sporosarcina pasteurii strain in food-grade yeast extract medium for microbially induced carbonate precipitation (MICP) application. *Biocat Agricul Biotech*. 2019;17:247-255. https://doi.org/10.1016/j.bcab.2018.11.030

19. Schwantes-Cezario N, Porto MF, Sandoval G, Nogueira G, Couto A, Toralles BM. Effects of Bacillus subtilis biocementation on the mechanical properties of mortars. *Revista IBRACON de Estruturas e Materiais*. 2019;12(01):31-38.

20. Rao PP, Asadi S, Krishna MR, Babu AS, Alla S. An experimental investigation of bacteria impact on compressive strength of cement mortar and concrete. *Materials Today: Proceedings*. 2021;43:1949-1955. https://doi.org/10.1016/j.matpr.2020.11.213

21. Cagatay Ersan Y, Erşan Y. *Microbial Nitrate Reduction Induced Autonomous Self-Healing in Concrete* [dissertation]. Ghent: Ghent University; 2016.

22. Wang J, Soens H, Verstraete W, De Belie N. Self-healing concrete by use of microencapsulated bacterial spores. *Cement Concr Res*. 2014;56:139-152. https://doi.org/10.1016/j.cemconres.2013.11.009

23. Alazhari MS. *The effect of microbiological agents on the efficiency of bio-based repair systems for concrete*. University of Bath; 2017.

24. Gutierrez-Padilla MGD. *Activity of Sulfur Oxidizing Microorganisms and Impacts on Concrete Pipe Corrosion* [dissertation]. Boulder: University of Colorado at Boulder; 2007.

25. Kantzas A, Stehmeier L, Marentette D, Ferris F, Jha K, Maurits F. A novel method of sand consolidation through bacteriogenic mineral plugging. Paper presented at: The Annual Technical Meeting; June 6–9, 1992; Calgary, Alberta. https://doi.org/10.2118/92-46

26. Rivadeneyra M, Delgado G, Ramos-Cormenzana A, Delgado R. Biomineralization of carbonates by Halomonas eurihalina in solid and liquid media with different salinities:

crystal formation sequence. *Res Microbiol*. 1998;149(4):277-287. https://doi.org/10.1016/S0923-2508(98)80303-3

27. Suthar H, Hingurao K, Desai A, Nerurkar A. Selective plugging strategy based microbial enhanced oil recovery using Bacillus licheniformis TT33. *J Microbiol Biotechnol*. 2009;19(10):1230-1237.

28. Sen R. Biotechnology in petroleum recovery: the microbial EOR. *Prog Energy Combust Sci*. 2008;34(6):714-724. https://doi.org/10.1016/j.pecs.2008.05.001

29. Zhong L, Islam M. A new microbial plugging process and its impact on fracture remediation. Paper presented at: SPE Annual Technical Conference and Exhibition; October 22–25, 1995; Dallas, Texas.

30. Boquet E, Boronat A, Ramos-Cormenzana A. Production of calcite (calcium carbonate) crystals by soil bacteria is a general phenomenon. *Nature*. 1973;246(5434):527-529. https://doi.org/10.1038/246527a0

31. Achal V, Mukherjee A, Basu P, Reddy MS. Lactose mother liquor as an alternative nutrient source for microbial concrete production by Sporosarcina pasteurii. *J Indust Microbiol Biotechnol*. 2009;36(3):433-438. https://doi.org/10.1007/s10295-008-0514-7

32. Martinez B, DeJong J, Ginn T, et al. Experimental optimization of microbial-induced carbonate precipitation for soil improvement. *J Geotech Geoenviron Eng*. 2013;139(4):587-598. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000787

33. Zhu T, Dittrich M. Carbonate precipitation through microbial activities in natural environment, and their potential in biotechnology: a review. *Front Bioeng Biotechnol*. 2016;4:e4. https://doi.org/10.3389/fbioe.2016.00004

34. Le Metayer-Levrel G, Castanier S, Orial G, Loubière J-F, Perthuisot J-P. Applications of bacterial carbonatogenesis to the protection and regeneration of limestones in buildings and historic patrimony. *Sedim Geol*. 1999;126(1-4):25-34. https://doi.org/10.1016/S0037-0738(99)00029-9

35. Rasool A, Islam A, Fayyaz S. Hydrogels and their emerging applications. In: Kumar A, Gupta R, eds. *Hydrogels*. CRC Press; 2023:24.

36. D'souza S. Microbial biosensors. *Biosens Bioelectron*. 2001;16(6):337-353.

37. Su L, Jia W, Hou C, Lei Y. Microbial biosensors: a review. *Biosens Bioelectron*. 2011;26(5):1788-1799. https://doi.org/10.1016/j.bios.2010.09.005

38. Rasheed T, Bilal M. Thermo-responsive functionalized polymeric nanocomposites. In: Ali N, Bilal M, Gupta RK, eds. *Smart Polymer Nanocomposites: Design, Synthesis, Functionalization, Properties, and Applications*. Elsevier; 2022:219-240.

39. Bracaglia S, Ranallo S, Ricci F. Electrochemical cell-free biosensors for antibody detection. *Angew Chem*. 2023;135(8):e202216512. https://doi.org/10.1002/ange.202216512

40. Huang C-W, Lin C, Nguyen MK, Hussain A, Bui X-T, Ngo HH. A review of biosensor for environmental

monitoring: principle, application, and corresponding achievement of sustainable development goals. *Bioengineered*. 2023;14(1):58-80. https://doi.org/10.1080/21655979.2022.2095089

41. Islam M, Rana MS. Contaminant identification in water by microbial biosensors: a review. *J Knowled Learn Sci Technol*. 2023;1(1):25-33. https://doi.org/10.60087/jgrkv103
42. Xu X, Ying Y. Microbial biosensors for environmental monitoring and food analysis. *Food Rev Int*. 2011;27(3):300-329. https://doi.org/10.1080/87559129.2011.563393
43. Griño Jr AA, Soriano HSP, Promentilla MAB, Ongpeng JMC. Exploring the potential of polypropylene fibers and bacterial co-culture in repairing and strengthening geopolymer-based construction materials. *Buildings*. 2023;13(10):e2668. https://doi.org/10.3390/buildings13102668
44. Hingley-Wilson S, Keddie J. *Biocoatings: Painting Bacteria onto Surfaces for Sustainable Processes*. University of Surrey; 2019.
45. Rasool A, Hafeez S, Islam A, et al. Polymer nanocomposite films and coatings for biomedical applications. In: Pandey M, Deshmukh K, Hussain CM, eds. *Polymer nanocomposite films and coatings*. Elsevier; 2024:729-758.
46. Flickinger MC, Bernal OI, Schulte MJ, et al. Biocoatings: challenges to expanding the functionality of waterborne latex coatings by incorporating concentrated living microorganisms. *J Coat Technol Res*. 2017;14:791-808. https://doi.org/10.1007/s11998-017-9933-6
47. Krings S, Chen Y, Hingley-Wilson S, Keddie, J. Biocoatings: painting bacteria on surfaces. *Access Microbiol Soc*. 2020;2(74). https://doi.org/10.1099/acmi.ac2020.po0333
48. DeJong JT, Mortensen BM, Martinez BC, Nelson DC. Bio-mediated soil improvement. *Ecoog Eng*. 2010:197-210. https://doi.org/10.1016/j.ecoleng.2008.12.029
49. Azeem MK, Islam A, Khan RU, et al. Guar gum/polyethylene glycol/graphene oxide environmentally friendly hybrid hydrogels for controlled release of boron micronutrient. *Royal Soc Open Sci*. 2023;10(12):e231157. https://doi.org/10.1098/rsos.231157
50. Hart MM, Cross AT, D'Agui HM, et al. Examining assumptions of soil microbial ecology in the monitoring of ecological restoration. *Ecol Solut Evid.* 2020;1:e12031. https://doi.org/10.1002/2688-8319.12031
51. El Mountassir G, Minto JM, van Paassen LA, Salifu E, Lunn RJ. Applications of microbial processes in geotechnical engineering. *Adv Appl Microbiol*. 2018;104:39-91. https://doi.org/10.1016/bs.aambs.2018.05.001
52. Shahroz M, Arshad N, Qureshi MAR. Investigating synergistic effects of biomass-derived carbon coatings on TiO_2 for anode candidacy in electrochemical OER and supercapacitor performance enhancement. *Int J Hydro Energy*. 2025;137:214-224. https://doi.org/10.1016/j.ijhydene.2025.05.117

53. Liang X, Duan Y, Su Y, et al. Carbon capture by biological methods. *Cambridge Prism: Carb Technol*. 2025;1:e4. https://doi.org/10.1017/cat.2025.10005

54. Chen FY-H, Jung H-W, Tsuei C-Y, Liao JC. Converting Escherichia coli to a synthetic methylotroph growing solely on methanol. *Cell*. 2020;182(4):933-946. https://doi.org/10.1016/j.cell.2020.07.010

55. Cheng J, Zhu Y, Zhang Z, Yang W. Modification and improvement of microalgae strains for strengthening CO2 fixation from coal-fired flue gas in power plants. *Biores Technol*. 2019;291:e121850. https://doi.org/10.1016/j.biortech.2019.121850

56. Fixen KR, Zheng Y, Harris DF, et al. Light-driven carbon dioxide reduction to methane by nitrogenase in a photosynthetic bacterium. *Proc Nat Acad Sc*. 2016;113(36):10163-10167. https://doi.org/10.1073/pnas.1611043113

57. Park WG, Kim M, Li S, et al. A light-driven photosynthetic microbial fuel cell for carbon-negative bioelectricity production. *Sustain Energ Fuel*. 2024;8(11):2476-2484. https://doi.org/10.1039/D3SE01487H

58. Yuvraj. Microalgal bioremediation: a clean and sustainable approach for controlling environmental pollution. In: Arora S, Kumar A, Ogita S, Yau Y-Y, eds. *Innovations in Environmental Biotechnology*. Springer; 2022:305-318.

59. Sharma P. Efficiency of bacteria and bacterial assisted phytoremediation of heavy metals: an update. *Bioresour Technol*. 2021;328:e124835. https://doi.org/10.1016/j.biortech.2021.124835

60. Vidali M. Bioremediation. an overview. *Pure Appl Chem*. 2001;73(7):1163-1172.

61. Omoregie AI, Wong CS, Rajasekar A, et al. Bio-based solutions for concrete infrastructure: a review of microbial-induced carbonate precipitation in crack healing. *Buildings*. 2025;15(7):e1052. https://doi.org/10.3390/buildings15071052

62. Rusanowska P, Dębowski M, Zieliński M. Microalgae-Assisted microbial fuel cell for treatment of difficult waste streams. *Energies*. 2025;18(4):e963. https://doi.org/10.3390/en18040963

63. Ali M, Khan M, Naveed M, Tanvir M. Microbe-assisted rhizodegradation of hydrocarbons and growth enhancement of wheat plants in hydrocarbons contaminated soil. *Int J Environ Sci Technol*. 2024;21(3):3169-3184. https://doi.org/10.1007/s13762-023-05174-3

64. Sharma K, Dhiman S, Mukherjee G. Embracing microbial systems in built environments. In: Dhiman S, Mukherjee G, eds. *Waste to Wealth: Emerging Technologies for Sustainable Development*. CRC Press; 2025:1-32.

65. Jaramillo HY, Vasco-Echeverri O, López-Barrios R, García-León RA. Optimization of bio-brick composition using agricultural waste: mechanical properties and sustainable applications. *Sustainability*. 2025;17(5):e1914. https://doi.org/10.3390/su17051914

66. Lima-Zaloumis J, Cady S, Blank J, et al. Laminae as structural biosignatures

in NASA's Life detection knowledge base. *Astrobiology*. Preprint posted online April 1, 2025.

67. Zhao H, Gu Y, Zhang X, et al. Synergistic addition of Cu and Ce enhanced sulfate reducing bacteria-assisted corrosion cracking resistance of 2205 duplex stainless steel. *J Mater Sci Technol*. 2024;196:1-11. https://doi.org/10.1016/j.jmst.2024.02.023

Zhai S, Zhang D, Liu W, et al. Microbial electrochemical technologies assisted nitrogen recovery from different wastewater sources: performance, life cycle assessment, and challenges. *Resour Conserv Recycl*. 2023;194:e107000. https://doi.org/10.1016/j.resconrec.2023.107000

69. Das A, Das N, Pandey P, Pandey P. Microbial enhanced oil recovery: process perspectives, challenges, and advanced technologies for its efficient applications and feasibility. *Arch Microbiol*. 2025;207(5):e106. https://doi.org/10.1007/s00203-025-04307-1

70. Qureshi MAUR, Arshad N, Rasool A, Qureshi MN, Kanwal M. Applications of carbon nanotubes for fabrication of photovoltaic devices. In: Singh M, Singh AK, eds. *Advanced Nanomaterials for Solution-Processed Flexible Optoelectronic Devices*. CRC Press. 2025:1-29.