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REVIEW ARTICLE

Review on Bacteria Associated with Metal Rusting

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ABSTRACT

Metal rusting, also known as corrosion, is the deterioration of a material's characteristics, particularly metals, caused by chemical or electrochemical reactions in the surrounding environment. It consists of the interaction of iron or steel with atmospheric oxygen and moisture, resulting in the creation of iron oxide (rust). Bacteria have an important impact on the development and advancement of metal corrosion. microbiologically influenced corrosion (MIC), is becoming increasingly problematic as it affects multiple materials and industries in society. MIC demonstrates the possible negative effect that microorganisms may cause to a substance. Different categories of bacteria, such as sulfate reducing, sulfate oxidizing, slime forming, and iron oxidizing, are active bacteria involved in bio-corrosion. The bacteria have evolved different ways to survive in the metal-polluted surroundings, including an efflux system pump, complexation/stabilization, enzymatic transformation/detoxification, and plasmid mediation. Effective management of microbial corrosion in different industrial and environmental settings requires the integration of microbiology, materials science, and corrosion engineering. This paper highlights the crucial role of microbiologically driven corrosion, which leads to the deterioration of different materials and consequential economic losses. Furthermore, it highlights future studies that aim to gain a thorough understanding of the mechanisms behind bacterial-induced corrosion and develop strategies to prevent and control rusting.

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INTRODUCTION

The process by which metals break down into more stable forms, like oxides or sulfides, is known as corrosion, and it presents serious environmental and economic problems. This natural occurrence can result in expensive repairs, inefficient operations, and safety risks in a number of industries, such as infrastructure, transportation, and the oil and gas sector. Microbially Induced Corrosion (MIC) is a particularly dangerous kind of corrosion among the several forms. Materials like metals, concrete, and plastics are affected by MIC, which speeds up corrosion due to the actions of microorganisms like bacteria, fungi, and algae (Abbas and Shafiee, 2020).

Microbially Induced Corrosion (MIC) occurs when microorganisms, such as bacteria, fungi, archaea, and microalgae, are present on material surfaces, leading to accelerated corrosion (Machuca, 2019). Metals, concrete, polymers, industrial settings, marine environments, the oil and gas industry, and water treatment facilities are just a few examples of the materials and environments that MIC impacts. The degree of corrosion varies depending on the kinds of microorganisms present, the material's properties, and environmental factors. Iron and steel, used in infrastructure like pipelines, marine structures, and oil and gas equipment, are especially susceptible to MIC (Machuca, 2019). This phenomenon can be either direct or indirect, based on the interactions between the microorganisms, the material, and the surrounding electrolyte. Over the past quarter-century, more than 2000 research articles have been published on MIC, focusing on real-world failures and experiments conducted in both lab and field settings under diverse conditions (Kip and Van Veen, 2015).

MIC is the result of the confluence of microorganisms, media (chemical composition and physical parameters, e.g., temperature and flow), and metals (metallurgy). Defining the specific contribution of MIC to corrosion is further complicated because MIC and abiotic corrosion often occur simultaneously (Yazdi *et al.,* 2022). All non-sterile corrosion experiments conducted in aqueous environments at temperatures below 100°C are carried out

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in the presence of microorganisms. Thus, biofilm formation and its influence on corrosion processes can be assumed but are typically ignored (Little *et al.,* 2020).

MIC is a problem in numerous industries where biofilms form on metal surfaces. Systems with high microbial populations and ineffective control, and those experiencing periods of stagnation or low flow conditions and temperatures are permitting microbial life and are more susceptible to MIC, e.g., power plants, refineries, petrochemical facilities, steel mills, pulp and paper mills, and maritime infrastructure (Salgar-Chaparro *et al.,* 2020). Despite the large number of publications dealing with MIC, a remarkable gap remains between the body of information and effective approaches to recognizing and solving the practical problems caused by MIC (Little *et al.,* 2020).

Corrosion, the natural process that converts refined metals into more chemically stable forms such as oxides, hydroxides, or sulfides, has significant economic and environmental effects. Understanding these effects is crucial for industries and governments alike as they seek to mitigate the impacts of corrosion through technology, policy, and practice (Bender *et al.,* 2022). Corrosion can lead to the deterioration of infrastructure, machinery, and equipment, necessitating costly repairs, replacements, and maintenance (Abbas and Shafiee, 2020). This includes everything from pipelines and bridges to vehicles and electronic devices (Abbas and Shafiee, 2020). The global cost of corrosion is substantial, amounting to billions of dollars annually. Corrosion can compromise the safety and reliability of structures and systems. This may result in accidents, outages, or failures that not only have financial repercussions but can also cause injury or loss of life. For example, corrosion-related failures in the oil and gas industry or transportation sector can have catastrophic consequences (Prasad *et al.,* 2020).

In industries such as oil and gas, water treatment, and chemical processing, corrosion can lead to the leakage of valuable products, resulting in direct material losses and environmental pollution (Alamri, 2020). Corroded machinery and equipment are often less efficient, requiring more energy to achieve the same output. This leads to increased operational costs and a higher carbon footprint. Corrosion can also lead to the release of hazardous substances into the environment. For example, rusting storage tanks or pipelines can leak chemicals into soil and water bodies, posing risks to wildlife and human health (Yan *et al.,* 2020). The need to replace corroded materials consumes additional resources, including metals, energy, and water. The extraction, processing, and transportation of these materials further contribute to environmental degradation. The process of repairing or replacing corroded parts generates waste materials that may require special handling and disposal. This includes hazardous waste from the corrosion process itself and the manufacturing of new parts (Alamri, 2020).

The purpose of the manuscript is to close the significant gap that exists between the large corpus of research on MIC and the useful, workable strategies for detecting and resolving MIC-related issues. Despite the fact that MIC has been the subject of in-depth research, not enough practical solutions have been developed to utilize this information in real-world situations (Salgar-Chaparro *et al.,* 2020).

The specific objectives of the current review are to gather and reveal the current knowledge, the mechanisms of metal corrosion, and environmental impact and to identify the knowledge gaps in MIC.

BACTERIA THAT INFLUENCE CORROSION

Sulfate-Reducing Bacteria (SRB)

SRB Represents a group of anaerobic microorganisms that play a significant role in bio-corrosion, particularly affecting infrastructure in the oil and gas industry and marine settings (Machuca, 2019). Among these bacteria, species such as *Desulfovibrio* are notable for their ability to convert sulfate ions into sulfide as part of their metabolic activities. This biochemical process is crucial because the sulfide produced can be highly corrosive to metals (Kushkevych *et al.,* 2020).

When SRBs are present in environments like oil and gas pipelines or marine installations, they thrive in the absence of oxygen, utilizing sulfate available in water or soil as an electron acceptor for respiration (Kushkevych *et al.,* 2020). The metabolic end-product, hydrogen sulfide (H_2S), is a gas known for its corrosive properties, especially towards iron and steel. This leads to a specific type of damage known as pitting corrosion, characterized by the formation of small, localized pits on the metal surface. These pits can penetrate deeply into the material, significantly compromising its structural integrity and leading to failures that are costly to repair and pose substantial safety risks (Qian *et al.,* 2019).

The prevalence of SRB in such environments and their impact on metallic structures underline the importance of understanding their biological and chemical mechanisms. Effective strategies to combat MIC caused by SRB include controlling their growth and activity through the use of biocides, altering environmental conditions to make them less hospitable for these bacteria, and employing materials and coatings that are resistant to sulfide-induced corrosion (Jia *et al.,* 2019).

Iron-Oxidizing Bacteria (IOB)

Aerobic iron-oxidizing bacteria, such as *Gallionella* and *Mariprofundus*, are key players in the process of bio-corrosion, especially in environments where iron and steel are prevalent. These microorganisms catalyze the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), a reaction that leads to the formation of rust and, consequently, corrosion. This type of corrosion is particularly problematic in both freshwater and marine settings, impacting water distribution systems, bridges, ships, and offshore platforms (Černoušek *et al.,* 2021).

In addition to *Gallionella* and *Mariprofundus*, there are several other species of iron-oxidizing bacteria that contribute to bio-corrosion, including.

Zetaproteobacteria: A class of bacteria found in marine environments, particularly known for their role in the corrosion of offshore and marine infrastructure (Procópio, 2019).

Leptothrix: These bacteria are commonly found in freshwater and are known for producing sheaths that encapsulate and protect the bacterial colonies, enabling them to thrive and induce corrosion in various water systems (Singh *et al.,* 2020).

Sideroxydans: Like *Gallionella*, *Sideroxydans* bacteria oxidize ferrous to ferric iron, contributing to corrosion in natural and engineered water systems (Lee *et al.,* 2020).

These bacteria thrive in oxygen-rich environments where ferrous iron is available, making them particularly suited to environments with steel structures or iron-containing materials exposed to water or moisture. Their metabolic process not only leads to the direct conversion of ferrous to ferric iron, contributing to the rusting process, but it can also create acidic conditions that further accelerate corrosion (Emerson, 2018).

Iron-Reducing Bacteria (IRB)

Species such as *Shewianella* and *Geobacter* play a critical role in the corrosion process of iron and steel structures. These microorganisms are capable of reducing ferric iron (Fe^{3+}), the oxidized form of iron, back to ferrous iron (Fe^{2+}), its more soluble and reactive reduced form. This biochemical reduction is significant because it can directly contribute to the corrosion process, particularly in environments where iron and steel are exposed to water or moist conditions (Kappler *et al.,* 2015). IRBs are versatile in their environmental requirements, with the ability to function under both aerobic (oxygen-present) and anaerobic (oxygen-absent) conditions. This adaptability allows them to inhabit a wide range of environments, from deep-sea sediments to soil and freshwater systems, making them a pervasive factor in the corrosion of metal structures across diverse settings (Ebrahiminezhad *et al.,* 2017). The mechanism of corrosion facilitated by IRBs involves a couple of key steps. IRBs use ferric iron as an electron acceptor in their metabolic processes, reducing it to ferrous iron. This reaction is energetically favorable for the bacteria and results in the mobilization of iron from its solid form, leading to the weakening and degradation of iron and steel structures. The activity of IRBs can create localized environments that promote further corrosion. For example, the accumulation of ferrous iron can lead to the formation of iron sulfides when combined with sulfide-producing bacteria, further exacerbating corrosion (Ahmed and Lin, 2017).

Additional species of IRB that contribute to the corrosion process include *Ferribacterium*. This genus is known for its role in the iron cycle, capable of reducing ferric to ferrous iron under anaerobic conditions. *Acidiphilium*, Often found in acidic environments, these bacteria can also participate in the reduction of ferric iron, contributing to acid mine drainage and the associated corrosion of metal structures (Zhu *et al.,* 2014).

Sulfur-Oxidizing Bacteria (SOB)

SOB such as those from the *Thiobacillus* genus, are aerobic microorganisms that play a significant role in the corrosion of infrastructure, especially in environments associated with sewer systems and wastewater treatment facilities. These bacteria are known for their ability to oxidize sulfur compounds, including hydrogen sulfide (H_2S), thiosulfate, and elemental sulfur, converting them into sulfuric acid (H_2SO_4). The production of sulfuric acid is a key factor in the acid corrosion of various materials, most notably concrete (Wu *et al.,* 2020). Concrete sewer pipes and wastewater systems are particularly vulnerable to SOB because these environments often contain high levels of sulfur compounds, which serve as a food source for the bacteria (Wu *et al.,* 2020). The sulfuric acid produced by SOB attacks the concrete, dissolving the calcium carbonate that helps bind the concrete together. This results in the weakening of the structural integrity of concrete infrastructure, leading to cracks, leaks, and, ultimately, the failure of sewer pipes and wastewater treatment systems. This type of corrosion is not only a concern due to the direct damage it causes but also because it can lead to significant environmental contamination and costly repairs (Song *et al.,* 2019).

Other species of SOB that contribute to this process include, *Acidithiobacillus*, known for its strong acidophilic nature, this genus includes species that are highly efficient in oxidizing sulfur compounds and producing sulfuric acid, exacerbating the corrosion of concrete and metal surfaces in acidic environments (Chaudhary *et al.,* 2019). *Beggiatoa* genus is found in both freshwater and marine environments and can oxidize hydrogen sulfide to sulfuric acid, contributing to the corrosion of submerged structures (Murthy *et al.,* 2023).

TOLERANCE MECHANISMS

Bacteria involved in bio-corrosion have developed various tolerance mechanisms that enable them to survive and thrive in harsh environments, such as,

Biofilm Formation

Many corrosion-causing bacteria produce biofilms, which are protective layers that adhere to metal surfaces. Biofilms provide a microenvironment that facilitates corrosive processes and protects the bacteria from environmental stresses and antimicrobial agents (Paln and Lavanya, 2022).

Extracellular Polymeric Substances (EPS) Production

EPS are complex organic molecules produced by bacteria within biofilms. EPS contributes to the structural integrity of biofilms and can sequester metal ions, promoting corrosion. Metabolic Flexibility: Many corrosion-related bacteria can switch between metabolic pathways depending on environmental conditions, allowing them to survive in both aerobic and anaerobic environments (Jasu *et al.,* 2021).

Chemical Resistance

Some bacteria have developed resistance to corrosion inhibitors and biocides used in industrial settings, making them difficult to control. Bacteria can undergo spontaneous genetic mutations that alter their physiology or metabolic pathways, enabling them to survive in the presence of chemical agents designed to inhibit their growth or kill them (Chugh *et al.,* 2020). Bacteria can acquire genes from other microorganisms that confer resistance to specific biocides or inhibitors. This transfer of genetic material can occur even between different species or genera, facilitating the spread of resistance traits within microbial communities (Machuca *et al.,* 2019).

TYPES OF CORROSION AND THEIR IMPACTS

Pitting Corrosion

This is caused by localized attacks (often by SRB and IOB), leading to small, deep pits on the metal surface. Pitting is dangerous because it can lead to rapid penetration of metal with minimal overall material loss, potentially causing structural failure. Uniform Corrosion: This involves the even, overall surface degradation of metal and is less severe than pitting but can lead to significant material loss over time (Akpanyung and Loto, 2019).

Crevice Corrosion

Crevice corrosion is a type of localized corrosion that occurs in locations where the metallic surface is exposed to a confined, stagnant electrolyte in a "crevice" while the rest of the metallic surface is in contact with the bulk electrolyte. Crevice corrosion of passive metals occurs above critical potentials and temperatures in the presence of a depassivating agent (mostly chloride), while in the case of non-passive metals, crevice/under-deposit corrosion occurs in non-specific environments as they are actively corroding (Jafarzadeh *et al.,* 2022).

Table 1: Some examples of systems affected by microbial-influenced corrosion (Singh and Singh, 2020)

System/application	Problem components/area	Microorganisms
Maritime transport	Ship hulls, pipes immersed in seawater	Mussels and barnacles responsible for macrofouling, disulfovibrio, and iron-reducing microorganisms Aerobic microorganisms such as Pseudomonas sp.
Cooling system	Heat exchanger, cooling towers, storage tank	Aerobic (iron/manganese-oxidizing bacteria) and anaerobic bacteria (sulfate-reducing bacteria and sulfur-oxidizing bacteria)
Pipelines	Stagnant part of interior and external part of buried pipelines, specially in wet environments	Aerobic (metal-oxidizing bacteria) and anaerobic (sulfate-reducing bacteria), slime forming bacteria, algae
Nuclear power generation plants	Condensers and heat exchangers, water pipes, and tubes	Aerobic (metal-oxidizing bacteria) and anaerobic (sulfate-reducing bacteria)
Fire sprinkler system	Stagnant areas	Anaerobic (sulfate-reducing bacteria) and aerobic (metal-oxidizing bacteria)
Vehicle fuel tanks	Stagnant area	Fungi
Oil and gas industries	Pipeline network and associated infrastructures	Sulfate-reducing bacteria

Galvanic Corrosion

This occurs when two different metals are in electrical contact within an electrolyte, causing one metal (the anode) to corrode faster than it would alone. Microbial activities can influence the electrochemical conditions that accelerate galvanic corrosion (Chen *et al.,* 2021).

Intergranular Corrosion

This type occurs along the grain boundaries of metals, often as a result of microbial processes altering the chemical composition around these boundaries, making them anodic compared to the grain interiors. Mitigating the impacts of bio-corrosion involves a combination of material selection, protective coatings, biocides, and design considerations to minimize biofilm formation and microbial activity. Understanding the specific bacteria and their mechanisms of action is the key to developing targeted and effective corrosion management strategies (Liu *et al.,* 2023).

THE PREVENTION AND MITIGATION OF MICROBIAL INDUCED CORROSION (MIC)

The prevention and mitigation of microbial-induced corrosion (MIC) requires a multidisciplinary approach that combines material science, microbiology, and engineering. Here are some notable case studies and examples demonstrating successful strategies to combat MIC across various industries

Cleaning procedure

Maintaining a clean system is a foundational principle in preventing microbially induced corrosion (MIC) in industrial settings, though implementing this practice can be challenging. The choice of a cleaning procedure should take into account factors such as the purpose of cleaning, which is typically to eliminate surface deposits like scaling and biofilms. Scaling, consisting of substances like calcium carbonates, sulfates, or silicates, forms from the precipitation of dissolved chemicals in water and can be influenced by factors like pH, temperature, and water quality (Singh and Singh, 2020). Treatments to reduce scaling include adding inorganic acids such as HCl, H2SO4, or sulfamic acid. Biofilms or slimy deposits comprised of mud, oil, and bacterial slimes, may be removed through flushing, albeit with limited success. For thorough cleaning, especially in complex systems, mechanical methods alongside filters, brushing, pigging, or water jetting are recommended to avoid incomplete cleaning that could lead to recontamination and localized corrosion (Kokilaramani *et al.,* 2021).

In cases where mechanical cleaning is insufficient, especially for removing thick biofilms or accessing remote areas, chemical cleaning is advised post-mechanical cleaning. This involves using mineral acids with corrosion inhibitors to prevent damage to metal surfaces or organic acids and chelating agents like EDTA for their less corrosive properties and ability to form complexes with metal ions, aiding in the removal of oxide layers. However, caution is advised when cleaning stainless steel welds with acid, as it may lead to stress corrosion cracking unless the steel has been heat-treated or solution-annealed (Skovhus and Eckert, 2014). For systems with heavy fouling, a combination of mechanical cleaning followed by chemical treatments with dispersant chemicals like polyacrylates can effectively remove deposits. This integrated approach ensures the removal of both inorganic and biological deposits, thereby mitigating the risk of MIC (Howell and Saxon, 2005).

Biocides

Biocides, encompassing both oxidizing and non-oxidizing compounds, play a critical role in controlling microbial growth in industrial settings, thereby preventing microbially induced corrosion (MIC). Common biocides include chlorine, ozone, bromine, isothiozoles, and glutaraldehyde. Each biocide targets different microorganisms, such as bacteria, fungi, and algae, and their effectiveness can vary depending on the microbe strain. Determining the optimal dosage for effective action is crucial (Yazdi, 2022).

Oxidizing biocides like chlorine, bromine, ozone, and hydrogen peroxide are popular for their ability to disinfect, but their use requires consideration of potential side effects, including interactions with other chemicals, corrosion of metals, and damage to non-metal materials. The effectiveness of chlorine, for example, is influenced by pH levels, with an ideal range being 6.5-7.5 for optimal biocidal action. However, chlorine's efficacy can be reduced by biofilms, which decrease its concentration significantly (Cuerda-Correan *et al.,* 2019).

Bromine functions effectively across a broader pH range than chlorine, making it a more versatile biocide. Ozone is emerging as a preferable alternative due to its high oxidative power and lower corrosivity towards metals, besides being an effective anti-scaling agent (Bediako *et al.,* 2023).

Non-oxidizing biocides, such as glutaraldehyde and THPS, offer pH-independent action and are often used in combination with oxidizing biocides for comprehensive microbial control. THPS, in particular, is favored in the oil industry for its effectiveness against a broad spectrum of microorganisms and its ability to dissolve FeS, reducing sulfate-reducing bacteria (SRB) induced corrosion. However, the environmental toxicity of biocides demands adherence to environmental regulations, underlining the need for careful management and selection of biocides to balance microbial control with environmental safety (Abioye *et al.,* 2022).

Coating

Applying a protective coating over metal surfaces is a key strategy in preventing chemical and microbial-induced corrosion by blocking direct or indirect contact between aggressive agents and the metal. Effective coatings should be electrically non-conductive, compact to limit ion diffusion, adhere well to the metal substrate, and be continuous without defects like cracks that could lead to localized corrosion (Jack, 2021). Materials for corrosion-resistant coatings can include stainless steel, titanium, antifouling paints, plastics, ceramics, and others that are not degraded by bacteria or release corrosive products upon degradation. Among various coatings, coal tar, and epoxy resin have shown effectiveness, whereas PVC-based coatings have performed poorly. Cement linings, while reducing microbial fouling, are vulnerable to sulfur-oxidizing bacteria like Thiobacillus (Zade and Patil, 2024).

Recent advancements include adding natural additives to oil-based coatings, like alkyd, and developing electrodeposited Zn-Ni-chitosan coatings. Studies have demonstrated that adding natural additives from olive oil and fish oil to alkyd coatings can significantly reduce microbial corrosion and biofilm formation on mild steel surfaces, with the fish oil blend showing the most protection (Singh and Singh, 2020). Electrodeposited Zn-Ni-chitosan coatings offer an environmentally friendly alternative to toxic cadmium coatings and have been explored for their resistance against sulfate-reducing bacteria (SRB)-induced corrosion and biofouling in marine environments. Chitosan, known for its biocidal properties, can disrupt bacterial cell membranes when included in the Zn-Ni alloy, enhancing the coating's corrosion resistance and antibacterial efficacy. The incorporation of chitosan has shown promising results in reducing bacterial concentration and corrosion rates, with higher chitosan concentrations improving both corrosion resistance and antibacterial properties (Singh and Singh, 2020).

Polymers

As the disadvantages of using biocides for mitigating biocorrosion become more recognized, industries are exploring alternative methods. One such method involves creating a protective barrier between the metal surface and the microbial environment. This can be achieved through passivation, where metals like stainless steel and titanium develop an inorganic coating under anodic polarization, and through the application of organic or polymer coatings, which offer better corrosion resistance (Nazari *et al.,* 2022).

However, polymer coatings face challenges such as susceptibility to scratches and cracks that allow bacterial colonization, leading to localized MIC. Additionally, weak bonding between the coating and the substrate can create spaces that foster bacterial growth under anaerobic conditions, promoting SRBs and corrosion. To address microbial degradation, recent innovations include polymer coatings with biocidal functions that prevent cell attachment and growth (Ates, 2016).

There are three main types of polymers used to combat MIC: traditional polymers mixed with biocides, antibacterial polymers with quaternary ammonium compounds (quats), and conductive polymers. Traditional polymers like polyurethane, fluorinated compounds, and epoxy resins have shown effectiveness against biocorrosion, especially when integrated with biocides to inhibit biofilm formation (Kamaruzzaman *et al.,* 2019). Quats, known for their corrosion inhibition and antimicrobial properties, have been applied to alloys to reduce bacterial concentration and corrosion rates in marine environments. Conductive polymers, such as polypyrrole and polyaniline, are emerging as environmentally friendly alternatives to hazardous coatings, with some exhibiting antibacterial properties and effectiveness in preventing SRB growth and corrosion (Namivandi-Zangeneh *et al.,* 2021).

Recent developments in conductive polymer coatings, such as nitrogen-rich dual-layer coatings and bromo-substituted polyaniline, have demonstrated significant antibacterial and anticorrosion performance, even in challenging conditions involving aggressive anions and specific bacteria like Desulfovibrio desulfuricans. These advancements suggest a promising future for using antibacterial conductive polymer coatings as a viable strategy for biocorrosion control, offering a potential replacement for biocide-based methods (Singh and Singh, 2020).

Cathodic protection

As the limitations and environmental concerns associated with biocide use for combating biocorrosion are increasingly acknowledged, industries are turning towards alternative protective strategies. These strategies focus on creating a barrier to separate metal surfaces from microbial environments, effectively preventing biocorrosion. This can be achieved through techniques like passivation, where an inorganic layer forms on metals such as stainless steel and titanium through anodic polarization, and the application of organic or polymer coatings known for their enhanced corrosion resistance (Machuca Suarez *et al.,* 2019).

Despite their effectiveness, polymer coatings encounter challenges, including vulnerability to physical damage that can permit microbial colonization and localized MIC. Weak bonds between coatings and metal substrates can also facilitate bacterial growth under anaerobic conditions, further encouraging corrosion. Innovations in polymer coatings now incorporate biocidal functionalities to thwart microbial attachment and proliferation (Echeverria *et al.,* 2020).

Additionally, the integration of cathodic protection systems with coatings on marine vessels offers a cost-effective and efficient antifouling solution. Trials with electrolytic systems on ship hulls have demonstrated the effectiveness of using chlorine generated on-site as an antimicrobial agent. This combination of cathodic protection and specialized coatings is emerging as the most comprehensive approach to preventing biofouling on ships, showcasing the potential of combining various methodologies for enhanced biocorrosion control (Wang *et al.,* 2023).

FUTURE DIRECTIONS AND RESEARCH CHALLENGES

There may be new bacterial species with distinct mechanisms that are still unknown, even if some of the bacterial species responsible for metal rusting have been thoroughly investigated. Finding and describing these species may help to provide information regarding possible biotechnological uses as well as other corrosion mechanisms (Li *et al.,* 2017). The composition and variety of microbial communities in various situations can influence corrosion rates and mechanisms. Similarly, a thorough knowledge of the role that bacteria play in metal rusting can be obtained by examining the diversity of microbes in diverse environments, including soil, sea, and industrial facilities (Enning and Garrelfs, 2014).

The dynamic interactions between bacteria and metal surfaces cannot be fully captured by the methods used to research bacterial corrosion. In order to help create efficient corrosion mitigation measures, real-time insights into microbial activities on metal surfaces can be obtained through advanced imaging, spectroscopic, and molecular technologies (Xia *et al.,* 2016). Bacterial biofilms on metal surfaces can potentially accelerate the rate of corrosion and present difficulties for industrial system maintenance and operation. Another essential component of cutting down on corrosion-related expenses and downtime is the development of measures to prevent or decrease biofilm growth, such as surface changes or biocide treatments (Beech and Sunner, 2004).

CONCLUSION

Microbially Induced Corrosion (MIC) is a complex problem affecting various fields, causing the breakdown of metals, concrete, and polymers; resulting in monetary losses, pollution, and safety hazards. Biocides are commonly used in the hood mold mitigation process, but these come with environmental and operational challenges, hence encouraging innovational approaches. New generations of protective measures such as passivation, biocidal epoxy coatings, and both sacrificial and impressed current anode systems, together with ultra-high build epoxies, represent novel ways of dealing with MIC. However, key knowledge gaps remain the detailed processes of how microbes are involved in the MIC, the formation process of the biofilm, how the biofilm is affected by environmental factors, the difference between materials in biofilm formation, and the method of detection. These areas can, however only be addressed by dedicated research on microbial behavior, biofilms, environment, and material responses. Moreover, specific long-term innovations are still forced, such as work on the creation of new, highly effective means for the early detection of threats in real-time. In order to increase the knowledge on and control over the course of MIC, close collaboration between clinicians, researchers, and industry is needed, an increase of practice-based research, creating new prevention strategies, optimized training of health care professionals, and better data exchange. It will assist in closing the gap between knowledge and application of the theory and, consequently, improve MIC management strategies.

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