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Review Article

Green Corrosion Inhibition by Biogenesis - An Innovative Way: A Review

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ABSTRACT

One innovative phase of science and corrosion science is giving way to another. Utilizing inhibitors is the most effective way to stop corrosion on metals and alloys. Organic corrosion inhibitors are toxic to the environment, so researchers have been looking for greener alternatives that are biodegradable and free of toxic metals and chemicals and are both environmentally advantageous and environmentally acceptable. There are a lot of microorganisms in the environment, and they can both speed up and partially prevent the corrosion of materials. The published research on microorganisms as green corrosion inhibitors is summarized in this review article.

Keywords: *green corrosion inhibitor, environment, microorganism, toxic, corrosion.*

INTRODUCTION

The term "corrosion" describes how metals and alloys deteriorate as a consequence of chemical or electrochemical contact with their surroundings. To put it another way, materials age through corrosion when they interact chemically with their environment (Roberge, 2019). Although corrosion frequently refers to metals, it is also occasionally used to explain how polymers, concrete, and wood deteriorate. The process that needs to be addressed the most regularly in daily life is this one, as opposed to other types of metal deterioration like fatigue and creep (Cwalina, 2014). Naturally, alloys and the metals they are made carry the risk of corrosion (Virtanen, 2011). Constructions made of metal and alloy are susceptible to severe corrosion damage, which can have financially disastrous effects on product losses, replacement costs, maintenance costs, and environmental and public safety risks (Koch et al., 2005). Corrosion studies are significant in the following three categories.

- Economics—economic issues, such as direct and indirect losses.
- Safety—increased safety of operating tools and equipment.
- Metal and resource conservation (Raja et al., 2016).

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The socioeconomic implications of corrosion are significant on a global scale. Corrosion is an unfavourable phenomenon that should be avoided. It is difficult to completely resolve since it's a continuous problem. Preventive measures would be more practical and realistic than total eradication (Shokri et al., 2022).

2. Corrosion environment:

Without making a reference to the environment, corrosion cannot be defined. To some extent, every environment is corrosive. In general, metals deteriorate when exposed to moisture/water, bases (NaOH, $CaCO_3$, $NaHCO_3$, etc.), acids (HCl, H_2SO_4, HNO_3, etc.), salts (NaCl), liquid chemicals, harsh metal polishes, and gases (formaldehyde, ammonia and gases that contain sulphur).

The list of typical corrosive environments is as follows:

- The humidity and air.
- Natural, urban, maritime, and industrial atmosphere
- fresh, salt, and marine water
- Steam and gases such as chlorine, hydrogen sulphide, ammonia, Sulphur dioxide, nitrogen oxides, etc.
- Soils
- Acids
- Alkalis
- Fuel gases.

Therefore, it can be seen that corrosion is a powerful force that weakens economies, depletes resources, and ultimately results in the failure of components, equipment, and machinery (Brynjolfsson et al., 2012).

3. Consequences of corrosion:

Today's society is impacted by corrosion in almost every way. However, estimating its impact in many of these areas can be challenging. Corrosion has a wide range of effects, many of which are more severe than the straightforward loss of mass of metal and have an impact on the reliable, efficient, and safe operation of machinery or structures. Even when only a small amount of metal is destroyed, failures of various kinds and the need for expensive replacements may still arise. The brief impact of corrosion is shown in Figure 1. (Ljungberg et al., 2007).

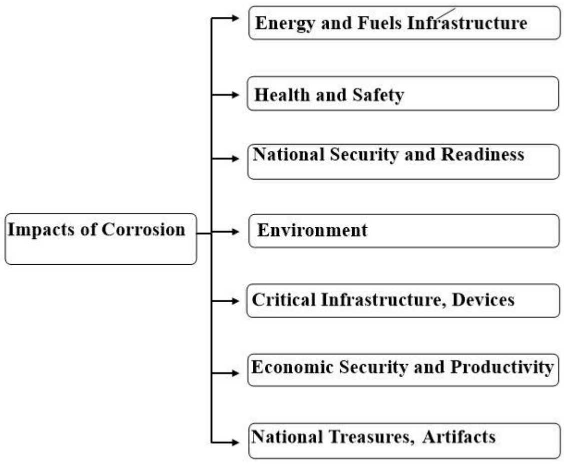

Figure 1. Diagram to show of corrosion impact

4. Cost of corrosion:

According to estimates, the global cost of corrosion is US$2.5 trillion, or 3.4% of the global gross domestic product (2013). By employing the available corrosion control practices, the cost of corrosion is anticipated to be reduced by between 15% and 35%, or between US$375 and $875 billion annually on a global scale (Koch, 2017). Most of the time, neither the environment nor personal safety are considered when calculating these costs. A number of industries have discovered that poor corrosion management can be very expensive, whereas good corrosion management can result in significant cost savings over the course of an asset's lifetime through near-misses, incidents, forced shutdowns (outages), accidents, and so on.

India's economy is currently regarded as one of the few that is expanding and adding to the global GDP. It is anticipated that the current administration's renewed focus on solving the economy's problems may lead to GDP growth above 8% in the years to come (Ray et al., 2022). Corrosion is unpredictably one of the main issues limiting economic expansion. Metal oxidation, also known as corrosion in metals, may be such a serious issue that it could have a negative impact on the economy's overall growth and raise concerns across the country. Despite its apparent insignificance, this problem could have serious repercussions for society. This might sound like a marketing gimmick or be difficult to believe. It's a sad fact, but it's true. Corrosion-related losses total more than $1 lac crore annually, including direct and indirect losses.

The estimated worldwide cost of corrosion is $2,505 billion, or 3.4% of global GDP (2013). Additionally, these costs frequently do not consider personal safety issues or environmental effects. Incorporating the costs associated with safety and environmental consequences into a country's or the world's corrosion cost can be difficult. The aforementioned global cost of corrosion is based on studies with sufficient sector-specific detail for a global sector analysis to be conducted. The current cost of corrosion is estimated to be between US$375 and $875 billion worldwide. However, previous studies have shown that this amount could be reduced by as much as 35% if current corrosion control practices were used. In order to address the economic sectors for various regions of the world, the global economy has been divided into regions with comparable economies (according to the World Bank). The United States, India, the European Region, the Arab World (as defined by the World Bank), China, Russia, Japan, the Four Asian Tigers-Macau, and the rest of the world were included. As shown in figure 2. (Aubert et al., 2003).

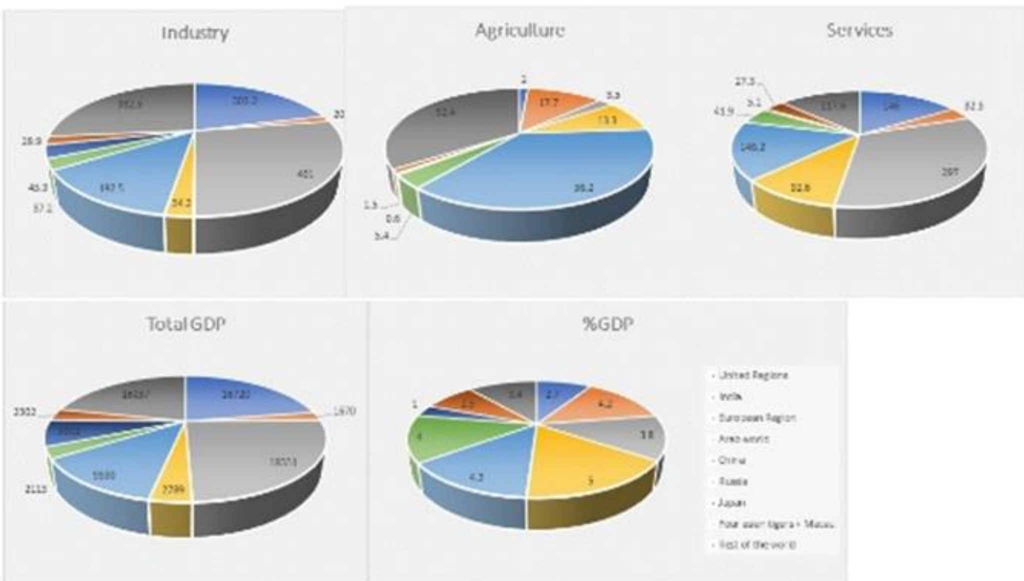

Figure2. Economic Sectors for the five countries used in the Global Cost of Corrosion Study

5. Types of corrosion:

The most frequent type of corrosion is shown in Figure 3. Uniform or general attack corrosion, whereby a chemical or electrochemical reaction thins the metal's surface and corrodes the entire metal surface. Two different types of metals exposed to a corrosive environment with electrode potentials that differ from one another are said to be experiencing galvanic or two-metal corrosion. Corrosion that occurs in metal crevices or on the metal's protected surface is also referred to as localized corrosion. An intergranular type of corrosion is one that is more prone to occurring along metal boundaries than on the inner surface. The unaffected part serves as a cathode, and the pitted part is an anode in the pitting corrosion process caused by random attack. When exposed to a corrosive environment, one element in a metal alloy is separated from the alloy through selective leaching. Corrosion fatigue developed as a result of the interaction between corrosion and cyclic loading. When filiform corrosion occurs, threadlike filaments are created and dispersed throughout the metal's surface. Stress corrosion occurs when corrosive media and stress are both present simultaneously. The metal is in an inert environment, but corrosion is brought on by the stress being applied. In the case of corrosion caused by erosion, the attack was accelerated by the movement of the corrosive fluid on the metal surface, causing corrosion. Fretting corrosion damages the metal surface by causing vibration between two contacting surfaces (Shreir, 2013).

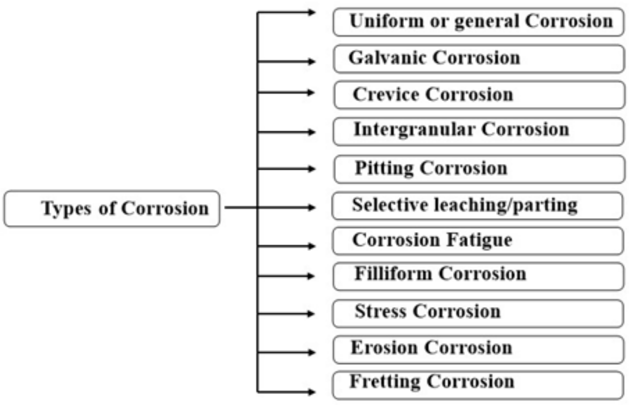

Figure3. Types of corrosion found in the environment

6. Corrosion inhibitors:

The most extensively studied subject in the field of corrosion protection has been discovered to be inhibitors. Inhibition is a defence strategy to avoid corrosive harm to metallic materials. For instance, chemical compounds are required for the inhibition process to reduce the rate of metallic corrosion. A chemical component of a corrosion system slows the rate of corrosion and prevents the diffusion of corrosive ions into the surrounding environment. A corrosion inhibitor is the term used to describe this substance. To put it another way, it significantly contributes to the protection of metal against corrosion attack (Vaysburd et al., 2004).

We may, therefore, conclude that inhibitors are straightforward to apply to the outside of metal and offer the benefit of in-situ application without significantly disrupting the process.

7. Types of corrosion inhibitors:

Corrosion inhibitors are added to the host materials as a powder or solution to inhibit corrosion. For instance, in order to start the inhibition, a corrosive environment must be set up, consisting of an electrolyte or other corrosive solution and the metal's surface charge, respectively. It is a fascinating aspect of the research on corrosion inhibition and its applications that has drawn significant attention from a number of researchers. The effectiveness and adaptability of corrosion inhibitors, respectively, aid in the reduction of corrosion. (Saremi et al., 2014).

Since corrosion is a surface phenomenon, adding a very small amount of corrosion inhibitor to the interfacial layer can stop or slow a metal's corrosion rate in a corrosive environment. Following is a list of the three main mechanisms that prevent corrosion:

- Adsorption: After chemically adhering to the surface of the metal, the inhibitor forms a protective thin coating that slows down the process.
- The formation of an oxide film at the metal surface's surface layer serves as protection.
- Passivation: The inhibitor forms protective precipitates when it interacts with corrosive components in aqueous media (Zhou et al., 2020).

According to the aforementioned corrosion inhibitor mechanism, cathodic, anodic, mixed, and adsorption type inhibitors can all be categorized. Cathodic inhibitors are corrosion preventers that last a long time. Similarly, anodic inhibitors reduce the rate of the anodic reaction. Inhibitors that affect both anodic as well as cathodic reactions are mentioned as mixed inhibitors. Adsorption inhibitors are the name given to these inhibitors because they typically work through an adsorption mechanism. Inorganic inhibitors typically have one of these two types of actions, as opposed to organic inhibitors, which have dual action on both cathodic and anodic (Kaskah et al., 2017). The Mapping chart of corrosion inhibitors as a prevention way is shown in Figure 4.

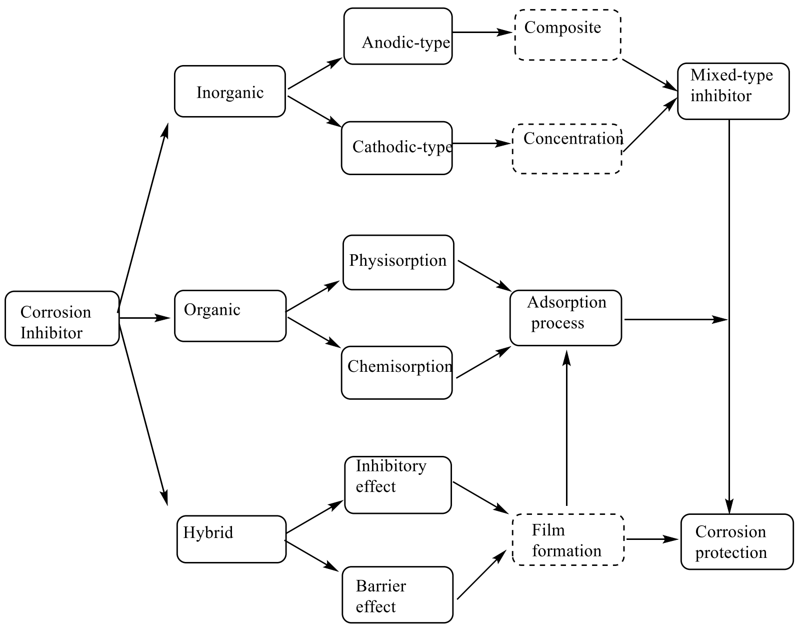

Figure4. Mapping chart of corrosion inhibitor as prevention way of corrosion

8. Inhibitory mechanism for corrosion:

The adsorption process on a metal surface is a reliable and consistent mechanism for the inhibition of corrosion. The inhibitor's chemical structure and the metal's surface charge influence the adsorption phenomenon. The metal possesses a surface charge due to the electrical charge that forms at its interface when it is submerged in the electrolyte. The electrochemical reaction of the corrosion process was slowed by the adsorbed inhibitor molecules that covered the surface at the electrolyte/metal surface due to the probable interaction between a corrosion inhibitor and a metal atom.

The direct or indirect adsorption of inhibitor molecules onto the metal surface, which reduces the metal surface's contact with the aggressive media, is the basis for how corrosion inhibitors work. Most metallic materials are naturally unstable, so when exposed to harsh environmental elements like H^+, Cl^-, etc., they often react chemically or electrochemically to produce more stable materials as a corrosion byproduct (Wei et al., 2020).

Assuming steel as the substrate, the anodic and cathodic reactions outlined below apply:

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

$$2H^+ + 2e^- \longrightarrow H_2$$

Incorporating corrosion inhibitors into corrosive media, they bind to the metal's active sites (regions of higher energy), where they form a protective film, as shown in Figure 5. This layer prevents corrosion by isolating the metal's surface from its hostile surroundings.

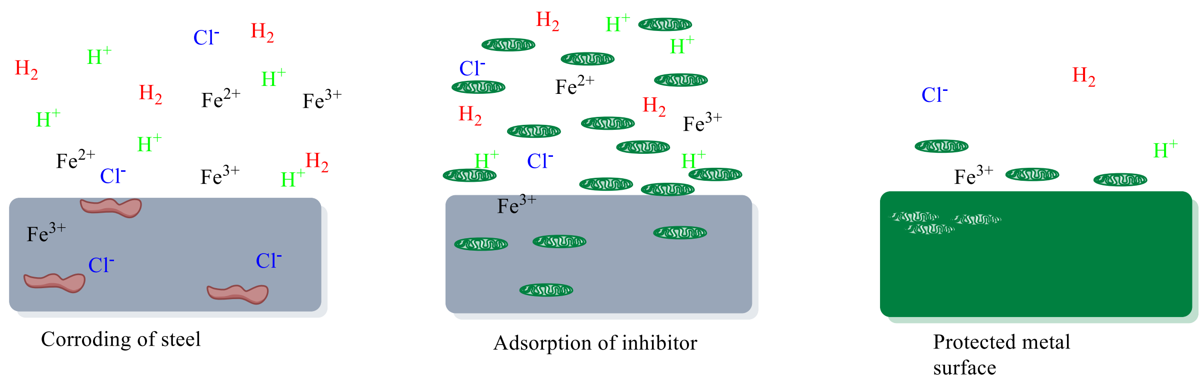

Figure5. Schematically demonstrates the creation of the protective film

Using organic inhibitors to passivate metal surfaces has a number of advantages over using inorganic inhibitors. Passive layers from extremely durable inhibitors passivate the surface uniformly, resulting in the highest level of protection. Inhibitors can be adsorbed physically, chemically, or through a combination of the two processes (i.e., mixed mode). In either of these two modes, the substrate's surface charge determines the interaction of inhibitor molecules with metal surfaces. (Goyal et al., 2018).

9. Need for green inhibitor:

The toxicity of organic and inorganic corrosion inhibitors to the environment and to humans has prompted the search for safer corrosion inhibitors, also known as "green corrosion inhibitors." The development of green corrosion inhibitors and green inhibition methods has recently become critical due to the increasing demand for green chemistry in science and industry. Green chemistry application has recently surpassed all other goals for chemists for the sake of the environment and human health. The reduction of toxic and hazardous waste is one of the main objectives. Additionally, even though there has been a lot of research and literature on green corrosion inhibitors, it is still an unresolved subject for technologists (Soenen et al., 2015).

It is alarming that plant scientists have advised against using plants. As plant materials are used more and more for their ability to resist corrosion, the plant kingdom will progressively disappear. We are protecting our metals by wiping out the plant kingdom. (Chivian, 2002).

Green inhibitors or eco-friendly inhibitors are chemicals that are environmentally and biologically compatible. A few examples of green inhibitors include amino acids, alkaloids, polyphenols, plant extracts, various essential oils, agro-industry byproducts and wastes, and bacterial EPS/biofilms.

10. Microbes' dual function in corrosion: Microbiologically Influenced Corrosion and corrosion inhibitors

10.1 Microbial Communities Related to Corrosion:

Since the beginning of the 20th century, scientists have known that microorganisms influence the corrosion of metals. Microorganism’s ability to form biofilms at the metal-solution interface has the potential to significantly alter the interface's electrochemical conditions. Depending on the nature of the adjustments, corrosion speed-up or corrosion inhibition may result.

The majority of the numerous definitions of microbiologically influenced corrosion (MIC) are interchangeable. Considering that "microorganisms" can include bacteria, cyanobacteria, algae, lichens, and fungi, the following are some examples of the MIC definition:

- Through the interaction of this system's three components — metal, solution, and microorganisms — microorganisms may initiate, facilitate, or accelerate corrosion reactions. This process is known as corrosion initiated by microorganisms (MIC).
- When corrosion is started, accelerated, or both by the actions of microorganisms, the phenomenon is known as MIC (Javaherdashti, 2017).

Rarely are biocorrosion and the process that counteracts it (microbial inhibition) related to the same mechanism or to the same species of microorganisms. At biofilm-covered metal surfaces, complex interactions between the biofilm and protective films take place, leading to either the development of corrosive or inhibitory bacterial actions. Microorganisms alter the ion concentrations and type, pH levels, oxygen levels, and other environmental factors, resulting in substantial changes to the environmental physical and chemical properties and the electrochemical parameters used to measure the corrosion rate. (Videla et al.,2009).

MIC-associated microorganisms include but are not limited to, the following: sulfate-reducing bacteria (Zuo, 2007), iron-oxidizing bacteria (Susan et al., 1994), iron-reducing bacteria (Susan et al., 1994), acid-producing bacteria (Mansour & Elshafei, 2016), and fungus as well as shown by table 1.

Table 1: Shows corrosion causing bacteria along with mechanism

s.no.	Bacteria	Trait	Mode	Ref
1.	*Sulphide reducers*	Use H_2 to reduce SO_4^{-2} to S_2, precipitation of H_2S and FeS	Anodic depolarization by corrosive iron sulphides and cathodic depolarization by hydrogen uptake.	(Wikieł, A. J. et al., 2014) (Venzlaff, H. et al., 2013)
2.	*Iron oxidizers/ manganese oxidizers*	Fe^{2+} to Fe^{3+} and Mn^{2+} to Mn^{3+}: Iron oxide and manganese dioxide formation	Cathodically reactive iron and manganese oxides being deposited	(Lee, J. et al., 2013)
3.	*Iron reducers*	Reduce Fe^{3+} to $Fe^{2+,}$ manganese or iron oxide	Oxides of iron and manganese are reduced	(Kopteva, Z. P. et al, 2004)
4.	*sulphide oxidizers*	Oxidizes S_2 and SO_3^{-2} to H_2SO_4	Metal corrosion by acid production	(Li, S. et al., 2008)
5.	*Acid producing bacteria and fungi*	production of acids like sulfuric acid, nitric acid, and organic acid	Dissolve metal	(Uchiyama, T. et al., 2010)
6.	*Slime forming bacteria*	the creation of extracellular polymeric materials (biofilm)	Exopolymers with metal ion-binding properties	(Vollertsen, J. et al., 2008)

This article aims to provide an overview of recent advancements in this novel strategy, potential mechanisms, and worthwhile directions for its application. This is a result of the abundance of available reviews discussing recent advancements in the field of using microbial biofilms to inhibit corrosion.

10.2 TYPES OF BACTERIA ASSOCIATED WITH CORROSION INHIBITION:

Four main types of bacteria can prevent corrosion:

1) Heterotrophic bacteria,

2) Aerobic bacteria,

3) Methanotrophic bacteria,
4) Phosphate solubilizing microorganisms (Ponmariappan et al., 2004).

There are general mechanisms by which microorganisms can inhibit corrosion or a combination of both:

- Bacterial physiological processes reduce the environment's corrosive elements (e.g., aerobic respiration).
- They are forming protective films on a metal or preserving already-existing protective films.
- Biofilms produce antimicrobials that prevent corrosion-causing bacteria from growing. (Videla et al., 2004).

If this new tactic is used effectively, several authors have reported that the rates of corrosion of various materials are reduced in the presence of microorganisms. In the literature, the anticorrosive potential of bacterial biofilm is explored. This table lists the various microorganisms and details how they exhibit anticorrosive effects on various materials like:

For brass, as shown in Table 2:
For aluminium, as shown in Table 3:
For copper, as shown in Table 4:
For nickel, as shown in Table 5:
For steel, as shown in Table 6:

Table 2: Shows bacteria as corrosion inhibitor for brass

S.no.	microorganism	medium	Metal	Mode of respiration / stain (+/-)	mechanism	outcome	Ref.
1.	*Bacillus licheniformis*	Vataanen nine salts solution (VNSS) and Luria Bertani(LB) medium	cartridge brass	Anaerobic /Gram Positive (+)	reduction of the rates of the cathodic reaction	significant reduction	(Örnek, D. et al., 2002) (Mansfeld, F.et al., 2002)
2.	*Shewanella*	VNNS	cartridge brass	Anaerobic /Gram Negative (-)	-	greatly decreased	(Nagiub, A., et al., 2002) (Mansfeld, F., 2007)

Table 3: Shows bacteria as corrosion inhibitors for aluminium

S.no.	microorganism	Medium	Material	Mode of respiration / stain (+/-)	mechanism	outcome	Ref.
1.	*Bacillus subtilis WB600*	LB medium +VNSS	aluminum 2024	Anaerobic / (+)	production of polyaspartate	Significant decrease	(Örnek, D. et al., 2002). (Ornek, D. et al., 2002). (Mansfeld, F.et al., 2002)
2.	*Bacillus licheniformis*	LB medium +VNSS	aluminum 2024	Anaerobic / (+)	extracellular product is primarily γ-polyglutamate	90% reduction	(Örnek, D. et al., 2002). (Ornek, D. et al., 2002). (Mansfeld, F.et al., 2002)
3.	*Pseudomonas fragi K*	modified Baar's medium + sulfate-reducing bacterium (SRB) Desulfovibrio vulgaris	aluminum alloy 2024	Anaerobic / (-)	protective biofilm	lessen corrosion 4-7-fold decrease	(Jayaraman, A. et al., 1999)
4.	*Escherichia coli*	artificial seawater (VNSS) and LB medium	Al 2024-T3	Aerobic / (-)	biofilm that produced polyphosphate	Significant decrease	(Ornek, D. et al., 2002). (Mansfeld, F.et al., 2002)
5.	*Shewanella*	VNSS	Al 2024	Anaerobic / (-)	-	excellent corrosion protection	(Nagiub, A. et al., 2002) (Mansfeld, F. 2007).

Table 4: Shows bacteria as corrosion inhibitor for copper

S.no.	Microorganism	medium	material	Mode of respiration / stain (+/-)	mechanism	outcome	Ref.
1.	Pseudomonas fragi K	modified Baar's medium (MBM) + Desulfovibrio vulgaris	unalloyed copper	Anaerobic / (-)	protective biofilm	20 fold decrease	(Jayaraman, A. et al., 1999)
2..	Pseudomonas aeruginosa ZK	minimal salt medium (NaCl)	copper alloy (Cu–Ni 70:30	Aerobic / (-)	production of Extracellular polymeric substances (EPS) by bacteria	corrosion inhibition	(Wadood, H. Z. et al., 2020)
3.	Bacillus subtilis strain S1X	minimal salt medium (NaCl)	copper alloy (Cu–Ni 70:30	Anaerobic/ (-)	production of EPS by bacteria	corrosion inhibition observed	(Wadood, H. Z. et al., 2020)
4.	Pantoea agglomerans	LB culture	copper	Aerobic / (-)	Biofilm production + EPS	prevented corrosion	(Garcia et al., 2012)
5.	Alcaligenes faecalis	LB culture	copper	Anaerobic / (-)	Biofilm production + EPS	prevented corrosion	(Garcia et al., 2012)
6.	Bacillus cereus	LB culture	copper	facultative aerobe	Biofilm production + EPS	prevented	(Garcia et al.,

				/ (+)		corrosion	2012)
7.	Brucellaceae bacterium	LB culture	copper	Aerobic / (-)	Biofilm and EPS production	No long-term inhibition	(Garcia et al., 2012)
8.	Enterobacter cloacae	LB culture	copper	facultatively-anaerobic / (-)	Biofilm and EPS production	No long-term inhibition	(Garcia et al., 2012)
9.	Delftia tsuruhatensis	LB culture	copper	Aerobic / (-)	Biofilm and EPS production	prevented corrosion	(Garcia et al., 2012)
10.	Pseudochrobactrum asaccharolyticum	LB culture	copper	obligate aerobic / (-)	Biofilm and EPS production	No long-term inhibition	(Garcia et al., 2012)
11.	B. vietnamensis	artificial seawater	Pure copper	Aerobic / (+)	Protease enzyme activity + oxygen unavailability	Corrosion inhibition	(Moradi et al., 2019)

Table 5: Shows bacteria as corrosion inhibitor for nickel

S.no.	Microorganism	Medium	material	Mode of respiration / stain (+/-)	mechanism	outcome	Ref.
1.	*Pseudomonas aeruginosa*	Nutrient broth (NB) medium	nickel–zinc	Aerobic / (-)	Extensive and compact biofilm formation	Corrosion decreased significantly	(San, N. O. et al., 2014)
2.	*Pseudomonas aeruginosa*	NB medium	nickel–copper	Aerobic / (-)	-	Corrosion accelerated	(San, N. O. et al., 2014)

Table 6: Shows bacteria as corrosion inhibitor for steel

S.no.	microorganism	medium	material	Mode of respiration / stain (+/-)	mechanism	outcome	Ref.
1.	*Geobacter sulfurreducens*	Medium + acetate+ fumarate + phosphate	carbon steel	Anaerobic / (+)	formation of an iron (II) phosphate compact layer	Corrosion inhibition seen	(Cote, C.et al., 2015)
2.	*Pseudomonas flava*	Basal salts solution (BSS)	Mild steel	facultative anaerobe / (-)	formation of Fe–EPS and phosphate layer	significant reduction	(Gunasekaran, G. et al., 2004)
3.	*Pseudomonas stutzeri*	Artificial seawater (ASTMD 1141–98)	X80 pipeline steel	Aerobic / (-)	Compact mineralization film	decline in corrosion rates	(Liu, H. et al. 2023) (Liu, H. et al., 2022)
4.	*Serratia marcescens*	VNSS	Mild steel	facultative anaerobe / (-)	formation of a natural biofilm	decrease in the rate of corrosion	(Hernandez et al., 1994)
5.	*Pseudomonas S9*	VNSS	Mild steel	Anaerobic / (-)	bacteria, exopolymers, and metabolic byproducts forming a protective layer.	decrease in the rate of corrosion	(Hernandez et al., 1994)
6.	*Pseudomonas fragi*	LB medium and VNSS + kanamycin/ tetracycline	SAE 1018 steel	Anaerobic / (-)	Uniform biofilm	2·3–6·9 fold inhibition	(A. Jayaraman et al., 1998)
7.	*Escherichia coli DH5a*	LB Medium +VNSS + kanamycin/ tetracycline	SAE 1018 steel	Aerobic / (-)	Uniform biofilm layer	2·3–6·9 fold inhibition	(A. Jayaraman et al., 1998)
8.	*Rhodococcus sp. C125*	Mineral medium + benzoate	Mild Steel	Aerobic / (+)	bacterial phosphating	Corrosion reduced	(Volkland et al., 2001)
9.	*Pseudomonas putida MT2*	Mineral medium + benzoate	Mild Steel	obligate aerobe / (-)	bacterial phosphating	Corrosion reduced	(Volkland et al., 2001)
10.	*Pseudomonas putida*	Minimal Broth	mild steel	obligate aerobe / (-)	Formation of sturdy Fe-EPS and stable vivianite layers	long term protection	(Suma, M. S et al., 2019)
11.	*Bacillus subtilis c2*	VNSS	cold rolled steel	Aerobic and anerobic / (+)	Formation of thick and compact biofilm	First, accelerate after retarded	(Qu, Q. et al., 2015)
12.	*Bacillus licheniformis*	saline axenic culture	Steel	Anaerobic / (+)	adhesion of compact and dense biofilm	Reduce significantly	(Eduok, U.et al., 2016)
13.	*Bacillus subtilis strain S1X*	1.5% NaCl (corrosive agent)	Stainless Steel 304	Anaerobic/ (-)	a compact and thick biofilm formed	Corrosion rate decreased	(Wadood, H. Z., et al., 2015)
14.	*Pseudomonas aeruginosa strain ZK*	1.5% NaCl (corrosive agent)	Stainless Steel 304	Aerobic / (-)	thick and heterogeneous biofilms	Corrosion rate decreased	(Wadood, H. Z., et al., 2015)
15.	*P. fluorescens 495*	NaCl 0.15M solution.	AISI 304 stainless steel	Aerobic / (-)	e biosurfactant produced and oxide layer both act as barriers	Corrosion rate decreased	(Dagbert, C.et all., 2006) Dagbert, C. et al., 2008)
16.	*Pseudomonas alcaligenes*	BSS	Mild steel	Anaerobic / (-)	acidic groups in EPS	Low corrosion inhibition	Dagbert, C. et al., 2008)
17.	*Pseudomonas cichorii.*	BSS	Mild steel	Facultative aerobic / (-)	phosphate inhibiting film	significant reduction	(Chongdar, S. et al., 2005)
18.	*Pseudomonas putida*	LB medium	SAE 1018 carbon steel	obligate aerobe / (-)	good biofilm formation	decreased by 2- to 15 fold	(Jayaraman, A. et al., 1997)
19.	*Pseudomonas mendocina KR1*	VNSS	SAE 1018 carbon steel	Anaerobic / (-)	-	Corrosion inhibition observed	(Jayaraman, A. et al., 1997)
20.	*Vibrio neocaledonicus sp*	VNSS	carbon steel	Anaerobic / (+)	EPS biofilm layer	Sixty-fold corrosion inhibition efficiency	(Moradi, M. et al., 2015)
21.	*Marinobacter salsuginis*	marine environment	X80 steel	Anaerobic / (-)	biofilm and EPS layer	high corrosion resistance	(Khan, M. S. et al., 2020)
22.	*Shewanella*	VNSS	mild steel	Anaerobic / (-)	-	No significant	38, 39

						changes	
23.	*Bacillus brevis*	Baars' medium	Mild steel	Aerobic/ (+)	gramicidin S layer and biofilm	17- to 34-fold	(Zuo, R. et al., 2004), (Zuo, R., et al., 2004)
24.	*Bacillus subtilis WB600*	cooling service water of the AmerGen Three-Mile-Island (TMI) nuclear plant	Mild steel	Anaerobic / (+)	by lowering the oxygen concentration	19- to 40-fold	(Zuo, R. et al., 2004), (Zuo, R., et al., 2004)
25.	*P. fragi K*	MBM + D.vulgaris	Mild steel SAE 1018	Anaerobic / (-)	Ampicillin + biofilm	50-fold by	(Jayaraman et al., 1999)
26.	*B. brevis*	MBM + D. vulgaris	Mild steel SAE 1018	Aerobic/ (+)	gramicidin S prior		(Jayaraman et al., 1999)
27.	*B. subtilis*	MBM + D. vulgaris	Mild steel SAE 1018	Anaerobic / (+)	Chloramphenicol+ subtilin biofilm		(Jayaraman et al., 1999)
28.	*V. natriegens*	seawater	Carbon steel	Aerobic / (-)	lipids and proteins EPS formation	Corrosion inhibition	(Dong, Y. H. et al., 2016)
29.	*Spirulina platensis*	3.5% NaCl solution	Carbon steel	Aerobic / (-)	Protective biofilm	Inhibition was observed	(Mert, B. D. et al., 2011)
30.	*Bacillus subtilis*	seawater	low-alloy steel plate	Anaerobic / (+)	film formed compact, uniform, and free of cracks	resistance to further corrosion	(Guo, Z. et al., 2017)

11. Eps and bacterial biofilm:

Extracellular polymeric substances, extracellular polysaccharides, exopolymers, and EPS have all been referred to by the acronym "EPS." In early biofilm research, polysaccharides were frequently thought to make up the majority of the EPS. The presence of proteins, nucleic acids, and amphiphilic materials like phospho-lipids in significant amounts or even predominating in EPS has also been shown. Extracellular polymeric substances, or "EPS," is a more inclusive term for various classes of organic macromolecules that have been found to exist in the intercellular spaces of microbial aggregates. These compounds include polysaccharides, proteins, nucleic acids, phospholipids, and other polymeric substances. (Wingender et al., 1999) These compounds have been studied for decades because of their many potential applications in the field of biotechnology. The use of EPS has been studied extensively in order to develop new technologies and products. For example, they can be used as a coating on surfaces or as an adhesive for various materials. Additionally, they can be used to create novel biocatalysts and biosensors. Furthermore, their ability to form complexes with other molecules makes them valuable for drug delivery systems.

12. Commentary:

Microorganisms significantly impact metal corrosion. Most of the literature on interactions between microorganisms and metals describes microbiologically accelerated corrosion (MAC) and microbiologically influenced corrosion inhibition (MICI). MAC is caused by microorganisms that cause corrosion directly, whereas MICI is caused by biofilm formation and metabolic processes that cause corrosion inhibition indirectly. This paper discusses the causes of MICI and potential anti-corrosion measures. The different mechanisms and organisms that cause MIC can vary based on the materials and operating conditions for the same materials. There are numerous accounts of biofilms inhibiting corrosion. Most assert that biofilms completely prevent corrosion.

The fact that organisms and mechanisms implicated in microbially induced corrosion (MIC) have also been reported to inhibit corrosion complicates the situation. To effectively address corrosion issues, it is essential to comprehend how these organisms and mechanisms interact with one another. Compared to sterile conditions, it has been suggested that Pseudomonas and Serratia accelerate the corrosion of iron and nickel. Researchers have demonstrated that, depending on the circumstances, Pseudomonas and Serratia are capable of shielding certain metals. (Jayaraman et al., 1999).

Aerobic biofilms in Luria-Bertani complex liquid media with pure cultures of seven bacterial genera decreased mass loss by a factor of two to fifteen compared to sterile controls, as reported by Jayaraman et al. The extent to which corrosion was inhibited varied between genera and depended on the biofilm's composition: a higher proportion of living cells slowed corrosion. The conclusion was that corrosion could be prevented only by a layer of living cells. (Jayaraman et al., 1999).

For a period of 6 days in the presence of axenic aerobic biofilms, copper's low-frequency impedance value increased twentyfold, while aluminium's polarisation resistance increased four to sevenfold. (Jayaraman et al., 1999).

To culture Bacillus brevis or Pseudomonas fragi in a modified Baar's medium Ennoblement, or increases in corrosion potential (Ecorr) were observed alongside decreased corrosion rates, indicating the presence of compounds that inhibit corrosion. (Kuklinski, 2017).

Antimicrobials targeting sulfate-reducing bacteria (SRB) were developed using genetically modified biofilms in a complex, nutrient-rich medium (modified Baar's) by Jayaraman et al. Because corrosion of stainless steel was drastically reduced when SRB growth was halted by in-situ production of gramicidin, the substance was eventually discovered to have antimicrobial properties. (Jayaraman et al., 1999).

Ismail et al. found that mild steel that had been exposed to P. fragi had 20 times less corrosion. (Volkland et al., 2000).

The corrosion resistance of carbon steel was increased by more than 60 times when treated with the novel bacterium Vibrio neocaledonicus sp. This is the highest-reported effect at inhibiting bacterial corrosion, comparable to certain industrial coatings such as electroless nickel. (Moradi et al., 2015).

Volkland et al. discovered that mild steel incubated in a bacterial-rich medium (Rhodococcus sp. C125 or Pseudomonas putida mt2) could develop a vivianite ($Fe_3(PO_4).28H_2O$) surface film. Biofilms can inhibit oxygen diffusion, decreasing the metal surface's oxygen concentration. The organic material in biofilms can chelate ferrous ions and promote vivianite formation. No vivianite formation was observed in sterile solution, so it was hypothesized that oxygen-consuming biofilms were responsible for the deposition of vivianite. (Volkland et al., 2000).

Corrosion of mild steel in Pseudomonas flava and Pseudomonas stutzeri-containing basal salt solutions (BSSs) was studied by Gunasekaran et al. P. flava, but not P. stutzeri was found to aid in the deposition of dense phosphate layer on mild steel, significantly lowering the corrosion rate. (Gunasekaran et al., 2004).

Zuo and Wood reported corrosion inhibition by gramicidin S-producing Bacillus biofilm on mild steel despite the presence of numerous corrosive bacteria. (Zuo et al., 2004).

To design organic, non-toxic, and economically advantageous systems for controlling corrosion processes, it is necessary to have expert knowledge of the composition, structure, and wettability of biofilms and their effects on corrosion. To ensure the long life and secure operation of machinery, MIC protection technology for materials is essential. Coatings and corrosion inhibitors are two common methods for protecting against corrosion, but they also pose a threat to the environment. Eco-friendly corrosion protection technology MICI provides fresh perspectives and ideas for advancing corrosion control techniques.

CONCLUSION

Corrosion is a major threat to metal substrates, leading to structural damage and costly repairs. To protect metal from corrosion, corrosion inhibitors are one of the best solutions. Corrosion inhibitors are not only effective in protecting metal substrates from corrosion but also have a positive impact on the environment if they are green and environment-friendly. This article will discuss how corrosion inhibition can help protect metal substrates and how it can be used in an environmentally friendly manner.

Green corrosion inhibitors are an important step forward in our green chemistry for a more secure and safe environment. A variety of articles are presented in this study that have the ability to limit corrosion in varied environments. Microbially influenced corrosion inhibition (MICI) has become a research hotspot as a new environmentally friendly anti-corrosion measure. The primary focus was on bacterial biofilms, which offer a safe and cost-effective alternative for inhibitory action, with the added benefit of being renewable and toxic-free. Such significant elements make this a fascinating issue for scholars to pursue additional investigation at the industrial level. It was also established that no mechanism is responsible for metal corrosion inhibition and that several elements contribute to the anticorrosive feature of biofilm. Various bacteria of such kind are yet unknown. Pseudomonas and Bacillus reduced corrosion in many metals and alloys. As a result, additional research in this field is required for various conclusions.

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