Review

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The role of microbes in the inhibition of the atmospheric corrosion of steel caused by air pollutants

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Abstract: Due to the presence of corrosive contaminants in the air, metals naturally corrode when exposed to the environment. Air pollution, in conjunction with climate conditions, may significantly deteriorate outdoor materials, especially metals and hence, the need for corrosion control. Using inhibitors is a powerful strategy that is frequently employed for corrosion prevention and control. Chemical inhibitors are often used. However, due to their low effectiveness and stringent environmental regulations, the majority of chemical corrosion inhibition techniques are becoming less desirable. For this reason, there is an increasing interest in and focus on biological inhibition approaches, which most recently have included the use of microbes. Microbiologically-influenced corrosion inhibition (MICI) is apparently far more complex than traditional corrosion inhibition procedures. A current overview of the mechanisms that have been used or may be efficient for MICI technologies is important in order to facilitate the advancement of MICI and its practical industrial applications, especially for atmospheric corrosion caused by air pollutants, for which there is little information in the reviewed literature. Therefore, this review addresses the role of microbes, like *Pseudomonas putida*, in the inhibition of atmospheric corrosion of metals and brings the reader up-to-date on the few literatures existing on the subject. The review describes and characterizes MICI for atmospheric corrosion as a developing field still in need of enthusiastic researchers to further investigate the area in order to establish useful methodologies, procedures, and technologies for later adoption in industrial terrains and applications.

Keywords: air pollution; atmospheric corrosion; corrosion control; metallic corrosion; microbiologically influenced corrosion inhibition; *Pseudomonas putida*

1 Introduction

Corrosion is the deterioration or degradation of a material due to interaction with its environment (Pedeferri and Ormellese 2018). Corrosion translates to heavy losses. As at 2013, the global cost of corrosion is estimated to be US$2.5 trillion, which is equivalent to 3.4 % of the global GDP for that year (Koch 2017). This makes the study of corrosion of utmost economic significance. Corrosion can also result in terrible tragedies such as train derailments, oil spills, collapsed bridges, gas shortages and severe power outages (Curtin University 2009) due to the failure of corroded structural members, making it an exigent subject matter of health, safety and the environment (HSE) as depicted in Figure 1.

Although nearly all materials corrode, metals are most susceptible to corrosion. Metallic corrosion occurs in various environments or media ranging from aqueous acidic, basic and noxious gaseous environments. Naturally, metals corrode when exposed to the atmosphere due to the presence of corrosive pollutants in the air. Air pollution is a major environmental issue of concern due to the harmful effects it has on human health and the environment (Liu et al. 2015). When combined with climatic effects, air pollution can cause extensive deterioration of outdoor

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Figure 1: Health, safety and environment (HSE) concerns of corrosion.

materials, including metals (Nord et al. 2001). According to Liu et al. (2015), previous study shows that atmospheric corrosion could account for 50 % of the total corrosion loss. Substantial deterioration of materials caused by corrosion could lead to direct metal loss and reduction of lifetime of materials. Hence, the need for preventive techniques for the control of metallic corrosion.

The potent way mostly adopted for the prevention and control of corrosion is the use of inhibitors. Corrosion inhibitors of chemical (organic and inorganic) origin have gained widespread use as cathodic, anodic or mixed inhibitors (Pedeferri and Ormellese 2018). However, most chemical corrosion inhibition methods are becoming unattractive due to poor efficiency and strict environmental regulations (Suma et al. 2019); hence the growing interest and focus on biological inhibition approaches.

Put in another way, corrosion refers to the degradation or deterioration of materials, such as iron and steel, resulting from electrochemical reactions on the surface of the materials initiated by a medium or agent which may be chemical or biological. Biologically-influenced corrosion or “biocorrosion” results from electrochemical reactions that are influenced or driven by microorganisms, which are often present as biofilms (Kip and van Veen 2015). In recent years, research has shown that microbes do not only cause corrosion, but they can also inhibit or protect against corrosion (Potekhina et al. 1999; Karn et al. 2017; Kip and van Veen 2015; Videla and Herrera 2005; Videla and Herrera 2009; Volkland et al. 2000). Thus, the terms “microbiologically influenced corrosion” (MIC) and “microbiologically influenced corrosion inhibition” (MICI) have now emerged to refer to corrosion caused by microbes and corrosion inhibited by microbes respectively (Zuo 2007).

MICI has been shown to have great potential (Kip and van Veen 2015; Potekhina et al. 1999; Videla and Herrera 2005) with a number of microbes, such as *Shewanella algae* (Nagiub and Mansfeld 2002), *Pseudomonas* sp. and *Escherichia coli* (Jayaraman et al. 1997a, b, c), *Aspergillus niger* and *Aspergillus alliaceae* (Joseph et al. 2011), being investigated for this purpose. Recent works provide evidence that *Pseudomonas* bacteria species can inhibit corrosion (Cai et al. 2021; Chongdar et al. 2005; Lan et al. 2017; Shainy et al. 2016; Suma et al. 2019; Volkland et al. 2000). Particularly, *Pseudomonas putida* species has been established and demonstrated as a MICI agent which can inhibit corrosion in metals (Suma et al. 2019). Although *P. putida*’s role as a MICI agent has been researched, its effectiveness as a potential inhibitor has not been investigated for atmospheric corrosion but has only been examined for use in aqueous corrosive media (Suma et al. 2019; Volkland et al. 2000). The effectiveness of *P. putida* in metals under the corrosive influence of air pollutants like sulphur dioxide (SO_2) is a study that has not been well-presented in literature and thus warrants further research and attention.

Enhanced corrosion resistivity and inhibition by microbiological means, as proposed in this research, will lead to cost savings and aid longevity of large metallic structures, installations and buildings within the automotive, locomotive and real estate industries (Nazir et al. 2017). It has been confirmed that employing corrosion prevention and control practices, like microbial inhibition, could result in global savings of between 15 and 35 % of the cost of damage amounting to about US$375–875 billion (Pedeferri and Ormellese 2018). This promissory savings makes the study of corrosion inhibition a worthwhile adventure for global good.

2 Air pollutants and corrosion in metals

2.1 Ambient air quality and pollution

The ambient air is, by nature, the source and store of life-supporting constituent gases for human respiration and existence as well as the life-support for the flora and fauna. The quality of the ambient air is of utmost importance as it affects the health and wellbeing of living things and their environment.

Due to human activities like industrialization (Adeniran et al. 2019; Fakinle et al. 2021; Odekanle et al. 2021), burning of fuels and vehicular activities (Fakinle et al. 2018), the ambient air quality can be compromised by the introduction of certain substances (which may become harmful when present beyond certain allowable quantities). These substances, over time, accumulate in the air and lead to the "contamination" of the ambient air. A number of substances are implicated in this "contamination" and in the consequent lowering of the air quality. These include gases like sulphur dioxide (SO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM). The particulate matter ranges in sizes from soot, to pollen, human air to fine beach sand. In more professionally accurate terminology, the "contamination" of the ambient air is known as *air pollution*, and the harmful "contaminants" introduced into the air by human activities are known as *air pollutants*.

2.2 Impact of air pollution

Air pollution is an issue of global concern which has undeniable impact on the atmosphere. Its impact transcends the local ambient air and often has far-reaching consequences on the tropospheric chemistry of the lower atmosphere, which has negative effects on the global climate.

From an engineering point of view, the impact of air pollution can be viewed in the light of the global professional practice of HSE (health, safety and environment). Air pollution affects the environment negatively, has harmful impact on human health and can lead to devastating outcome on the safety of structures. This tripodal impact is considered in this section.

2.2.1 Impact on the environment

The environment suffers the consequence of the impact of air pollution most readily. This impact and its effects result in certain environmental issues such as acid rain, greenhouse effect, photochemical smog formation, episodes and climate change.

2.2.1.1 Acid rain

Key air pollutants like SO_2 and NO_2 can cause acid rain. Acid rain loosely refers to rainwater with pH value less than 5.6 (Walter 1991). The oxidation of SO_2 and NO_2 in the atmosphere causes acidification of rainfall. The acidified rainfall can have devastating effects on plants and animals.

2.2.1.2 Greenhouse effect

Due to their warming or heat-trapping effect on the Earth, some of the gaseous air pollutants like CO_2 and methane are known as "greenhouse gases". The way that these "greenhouse gases" trap heat near to the Earth's surface is known as the *greenhouse effect*. These heat-trapping gases can be imagined as a "blanket" covering the Earth, keeping it warmer than it would be otherwise. Human activities release greenhouse gases into the atmosphere which in turn trap the sun's heat radiation thereby creating the greenhouse effect.

2.2.1.3 Photochemical smog

Some secondary pollutants are produced when the two main primary pollutants, nitrogen oxides and volatile organic compounds (VOCs), combine to change in sunlight through a series of chemical reactions. The ozone that develops at ground level and peroxyacetyl nitrate (PAN) are the secondary contaminants that raises the most alarm. When nitrogen oxides and VOCs combine with sunlight, a mixture of pollutants called *photochemical smog* is produced, which explains why there is a brown cloud above cities sometimes. Due to the fact that the most sunshine occurs in the summer, photochemical smog tends to happen more frequently in summer (EPA 2004).

2.2.2 Impact on human health

The impacts of some air pollutants on the human health is summarized in Table 1.

Table 1: Some air pollutants and their effects on the human health. Adapted from Wysocka (2018) and EPA (2004).

Pollutant	Effects
Nitrogen oxides	Can contribute to problems with heart and lungs; links to decreased resistance to infection
Volatile organic compounds (VOCs)	Eye irritation; respiratory problems; some compounds are carcinogens
Ozone	Coughing and wheezing; eye irritation; respiratory problems (particularly for conditions such as asthma)
Peroxyacetyl nitrate (PAN)	Eye irritation; respiratory problems
PM10, PM2.5	Carcinogenic, allergic and irritating effects
Carbon dioxide (CO_2)	Fainting, headaches, rapid breathing and breathing difficulties, blurred vision, increased pressure and faster heart rate
Carbon monoxide (CO)	Highly toxic, combining with haemoglobin causes permanent tissue hypoxia, damage to the heart and nervous system, and eventually death
Microorganisms	Allergic reactions (asthma, runny nose, sneezing, skin rashes); headaches, pneumonia and bronchitis, carcinogenic

2.2.3 Impact on safety of engineering structures

Engineering structures are made of different materials, most of which are metals, especially steel. Mild steel, as an engineering material, is widely used in various applications such as bridges, frame structures, architectural industry and automobile industry (Chen et al. 2021; Singh et al. 2019), due to its excellent mechanical properties and low cost (Wang et al. 2021). However, when exposed to outdoor environments, it suffers extensive and severe degradation (Wang et al. 2021) as a result of atmospheric corrosion. The atmospheric corrosion is caused by the presence of harmful pollutants which degrade the metals. The phenomenon of atmospheric corrosion of mild steel, and indeed steel structures in general, has drawn increasing attention for the past few decades due to the consequential catastrophic accidents associated with it (Abbas and Shafiee 2020; Chen et al. 2021).

2.3 Atmospheric corrosion of steel in polluted atmospheres

In recent years, several authors have studied the atmospheric corrosion of steel in different industrial atmospheric environments with a view to aid the understanding of the underlying corrosion mechanism(s) or to explore a protective method against corrosion for the materials or to propose a prediction model. Table 2 gives a summary of recent works which studied the effect of different polluted atmospheres on the corrosion of steel materials and the different purposes why the studies were conducted.

3 Inhibition of atmospheric corrosion caused by air pollutants

The main causes of corrosion are chemical and electrochemical reactions. Chemical corrosion occurs in nonconductive liquids and dry gases devoid of current or electron flow. An oxide layer that develops as a result of oxidation in the air is the primary result of chemical corrosion. Due to redox reactions and varying potentials on the surface of the corroded metal, electrochemical corrosion occurs in solution between metallic materials and electrolytes (Brycki et al. 2018). The anode is a portion of the metal where oxidation and ionization occur. The cathode is the other component. Here, depolarization occurs mostly by reduction of oxygen and hydrogen cation (Koch 2017).

Atmospheric corrosion of metals (especially mild steel and galvanised steel) caused by air pollutants can be inhibited by different methods which can be broadly classified into two: chemical and biological, as summarised in Figure 2. Taking SO_2 as a case study of corrosion-causing air pollutant, the inhibition of its electrochemical scheme of degradation reactions can be achieved by the use of chemical inhibitors and biological inhibitors.

3.1 Cathodic inhibitors

The cathodic corrosion inhibitors stop the metal from reacting cathodically during the corrosion process. These inhibitors contain metal ions that, in the presence of

Table 2: Recent works on the corrosion of steel in polluted atmospheres.

References	Material	Atmospheric corrosion environment	Purpose of study		
			Corrosion mechanism study	Corrosion protection/prevention study	Corrosion prediction model
Fan et al. (2020)	Carbon steel, weathering steel	High humidity and heat marine atmospheric environment	Yes	No	No
Chen et al. (2021)	Mild steel	Tropical coastal atmosphere	No	Yes	No
Lazareva et al. (2021)	Carbon steel	CO_2 corrosion environment	Yes	No	No
Wang et al. (2021)	Mild steel	Simulated coastal atmosphere	Yes	No	No
Wu et al. (2021)	Structural steel	Urban industrial atmosphere and accelerated simulated corrosion environment	No	No	Yes
Song et al. (2022)	Carbon steel	Dynamic atmospheric corrosion environment	No	No	Yes

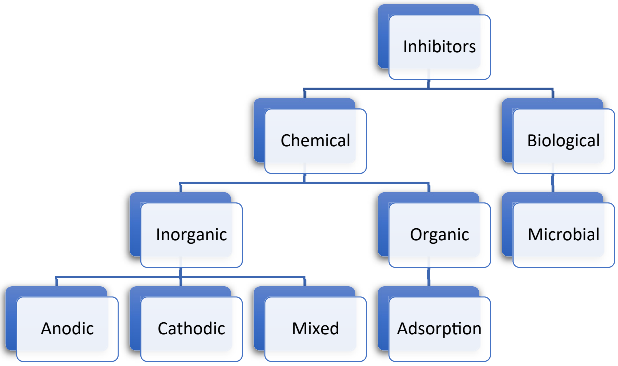

Figure 2: Atmospheric corrosion inhibition methods.

alkalinity, can trigger a cathodic reaction, resulting in the formation of insoluble compounds that precipitate only on cathodic sites. They create a tight, adherent coating over the metal to prevent the diffusion of reducible species there. As a result, the surface impedance and diffusion restriction of the reducible species—specifically, oxygen diffusion and electron conductivity in these regions—increase. High cathodic inhibition is caused by these inhibitors (Dariva and Galio 2014).

3.2 Anodic inhibitors

Anodic inhibitors, also known as passivation inhibitors, work by blocking the anode reaction and promoting the natural passivation of metal surfaces. This is accomplished by creating a coating that is adsorbed on the metal. In general, when inhibitors and corrosion products interact, a cohesive and insoluble layer is produced on the metal surface (Dariva and Galio 2014).

3.3 Organic inhibitors

The adsorption on the surface to form a protective coating that pushes water away from the metal surface and shields it from deterioration is the basis for the mechanism of action of organic corrosion inhibitors. It is not just physical or solely chemical adsorption in this process. The distribution of charge in the molecule, the nature and surface charge, the chemical structure of organic inhibitors, and the type of hostile media (pH and/or electrode voltage) all have an impact on adsorption. The charged metal surface and charged inhibitor molecule interact electrostatically to cause physical adsorption. Chemical adsorption is related to the donor-acceptor interactions between unoccupied, low energy metal d-orbitals and free electron pairs (Brycki et al. 2018).

The adsorption of organic corrosion inhibitors on metal surfaces is a complex process that depends on several factors. Organic corrosion inhibitors with appropriate functional groups can form chemical bonds with metal surfaces and provide effective protection against corrosion. The concentration of the inhibitor and the pH of the solution are important parameters that influence the adsorption process. Some recent works (Chugh et al. 2021; Murmu et al. 2019; Saha et al. 2022) provide more insight on adsorption of organic corrosion inhibitors on metal surfaces.

As a side comment and for completeness' sake, it is worthy of mention to note that a recent trend in the use of organic inhibitors is the burgeoning use of green inhibitors utilizing plant extracts for corrosion control (Oyewole et al. 2021, 2022, 2023). These environmentally-friendly extracts have been copiously deployed for the inhibition of metal corrosion in different acidic media (Elabbasy et al. 2023; Iorhuna and Ayuba 2023; Nesane et al. 2023; Othman et al. 2023). However, there is little work reported on their deployment for atmospheric corrosion.

Cathodic, anodic, and mixed corrosion inhibitors of inorganic or organic origin are now widely used (Pedeferri and Ormellese 2018). However, due to ineffectiveness and stringent environmental laws, the majority of chemical corrosion inhibition methods are losing appeal (Suma et al. 2019); this is why biological inhibition approaches are receiving more attention.

4 Microbial inhibition of atmospheric corrosion of metals

4.1 Microbes and atmospheric corrosion

An early evidence of the involvement of microbes in atmospheric corrosion and rather a common one is the influence of airborne microorganisms which settle on exposed metallic surfaces and thrive on the favourable conditions of humidity, and other environmental nutrients favourable for their growth which are found in the air like chlorides, phosphates and sulphates (Jeffrey and Melchers 2011). While this may be a common occurrence, there is little information on how the microbes cause atmospheric corrosion of metals. Only recently, in the work of Victoria et al. (2021), was a comprehensive review carried out on the mechanism of microbiologically-induced corrosion. This work however contained little to no information on microbiologically-induced atmospheric corrosion. However, since most of the microbes involved in MIC of metallic corrosion in other media are similar to those involved in MIC in the atmospheric environment or air medium, the former's mechanisms can be taken as a basis or starting point for the study of the latter's mechanisms. The study of the mechanisms of microbiologically-induced atmospheric corrosion in polluted air medium is a problem calling for further attention and the intervention of corrosion investigators and inquirers.

4.2 Mechanisms of microbial inhibition of atmospheric corrosion

The mechanism of microbiologically-influenced corrosion inhibition (MICI) is presumably significantly more intricate than conventional corrosion inhibition techniques, whether in industrial or natural settings. Numerous microbial impacts are present in this heterogeneous process, including oxygen consumption, competition for electron donors, blocking of corrosive species, and corrosion inhibitor secretion.

Zuo (2007) suggested categorizing MICI mechanisms into three groups: (i) the removal of corrosive agents, (ii) the inhibition of the adhesion or growth of dangerous microorganisms, and (iii) the production of protective layers by biofilms. Similar opinions and theories have been put forth by others, which claim that microorganisms play two roles in corrosion and can, in some circumstances, be used as a green strategy to prevent or mitigate corrosion.

A deeper understanding of the functions of microorganisms in corrosion processes has led to some interesting new breakthroughs and opportunities in the field of MICI in recent years. In order to facilitate the advancement of MICI and its practical industrial applications, Lou et al. (2021) offered an updated overview of the mechanisms that have been employed or may be effective for MICI technologies. The authors of the review divided MICI mechanisms into five kinds, as depicted in Figure 3. Of these five MICI mechanisms, mineralization has been found to be the major process of inhibitive action of *Pseudomonas* and is thus of interest to this work. However, other mechanisms have also been reported for some species of *Pseudomonas*.

Numerous mineral deposition processes involve microorganisms, and microbiologically induced mineralization is essential to chemical cycling in the environment. Numerous studies have demonstrated that various types of mineralized layers to differing degrees lower the danger of metal corrosion. A number of mineralized layers have been observed in the mechanisms of MICI which include phosphate mineralized layer, iron oxide mineralized layer and carbonate mineralized layer (Lou et al. 2021).

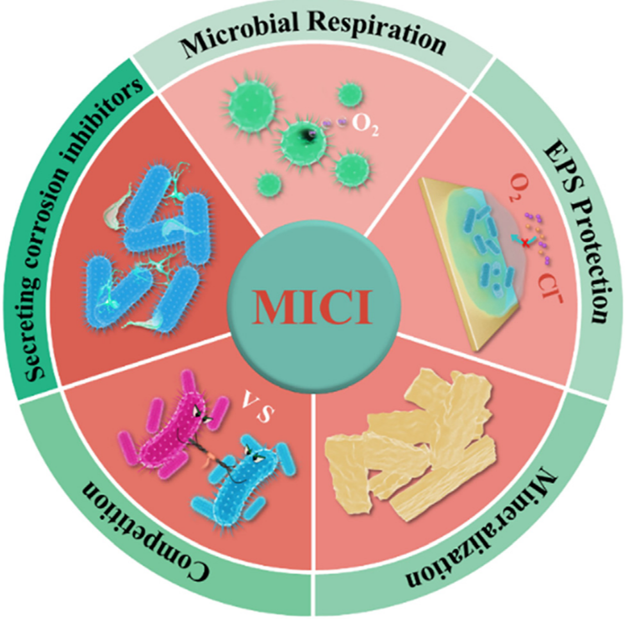

Figure 3: Classification of MICI mechanisms (Lou et al. 2021). Reprinted from Lou et al. (2021), with permission from Elsevier (copyright 2021).

Phosphate mineralized layer formation is the key mechanism observed for MICI by *Pseudomonas*. A phosphate conversion coating is created through the chemical and electrochemical reaction known as phosphating. Under natural circumstances, some bacteria develop a layer of phosphate mineralization on material surfaces, showing a similar result to chemical phosphate treatment. Volkland et al. (2000) discovered that mild steel incubated in media containing various microorganisms (*Rhodococcus* sp. C125 or *P. putida* mt2) might develop a protective vivianite ($Fe_3(PO_4)_2.8H_2O$) surface coating.

The other four MICI mechanisms mentioned by Lou et al. (2021) include: microbial respiration to consume corrosive substances, formation of an extracellular polymeric substance (EPS) protective layer, competitive microbial corrosion inhibition, and the secretion of corrosion inhibitors by bacteria. Besides the formation of microbiologically-induced mineralized layer, MICI can also occur as a result of these other four mechanisms.

In some cases, corrosion-inhibiting microbes operate through competition with other corrosion-causing microbes. For example, in the oil and gas industry, nitrate injection into oil fields creates a competition which helps to combat sulphate-reducing bacteria. This is because nitrate is an important source of nitrogen for microorganisms, as such; the introduction of nitrates into oil fields stimulates the growth of nitrate-reducing bacteria which compete with sulphate-reducing bacteria for the available nitrate. Hence, this makes the former a very potent inhibitor of the corrosion that would have been caused by sulphate-reducing bacteria.

Sometimes, when microbes inhibit corrosion, they secrete substances which act as inhibitors. For instance, some bacteria secrete biosurfactants which have been found to have better biodegradability, lower toxicity, and higher environmental compatibility than conventional chemical surfactants. Zin et al. (2018) studied the inhibitive effect of rhamnolipid biosurfactant secreted by *Pseudomonas* sp. PS-17 on the corrosion of Al–Cu–Mg aluminium alloy under artificial acid rain conditions. The authors found the biosurfactant to be effective in inhibiting the aluminium alloy corrosion under the synthetic acid rain conditions, with the inhibition efficiency increasing with biosurfactant concentration.

Another way microbes inhibit corrosion is through the use of dissolved oxygen for their respiration. Dissolved oxygen acts as a depolarizing agent and promotes corrosion in aqueous environments. Microorganisms that are aerobic or facultatively anaerobic can get energy through aerobic respiration. A low-oxygen or oxygen-free region is created when oxygen is consumed close to a metal surface, which prevents the cathode reaction and prevents corrosion. In Jayaraman et al. (1997c), the researchers' findings showed that *Pseudomonas fragi* protection reduced steel corrosion losses by 10–50 % compared to those in the sterile media. The biofilm of the live bacteria provided a low-oxygen barrier that prevents the metal substrate from corroding or oxidizing.

Perhaps, the earliest known mechanism of MICI is the formation of protective biofilms containing extracellular polymeric substances (EPS). The cultivation of non-corrosive microbes to create a natural EPS protective layer on the material surface to prevent corrosion was the major focus of early work on MICI.

4.3 MICI by *Pseudomonas* bacteria species

Table 3 summarises previous works which had utilized *Pseudomonas* to inhibit corrosion of metals in different media ranging from aqueous, acidic, sea-water and seawater-mimicking media. However, there are limited (if any) literature evidence for the use of the microbe to inhibit corrosion in gaseous corrosive media, especially under polluted atmospheric conditions.

Table 3: Literature evidence of the use of *Pseudomonas* sp. for the inhibition of metallic corrosion.

References	Microbe	Corrosive medium	Material
Pedersen and Hermansson (1991)	*Pseudomonas* sp. S9	Artificial sea water	Steel
Jayaraman et al. (1997a)	*Pseudomonas fragi*	Seawater-mimicking medium	Steel
Jayaraman et al. (1997b)	*P. putida and Pseudomonas mendocina* KR1	Complex liquid medium and seawater-mimicking medium	Carbon steel
Jayaraman et al. (1997c)	*Pseudomonas fragi*	Complex liquid medium	Carbon steel
Jayaraman et al. (1999)	*Pseudomonas fragi* K	Baar's medium	Copper and aluminium
Volkland et al. (2000)	*P. putida* mt 2	Aqueous medium	Mild steel
Gunasekaran et al. (2004)	*Pseudomonas flava and Pseudomonas stutzeri*	Aqueous medium	Mild steel
Chongdar et al. (2005)	*Pseudomonas cichorii* and *Pseudomonas alcaligenes*	Aqueous medium	Mild steel
Shainy et al. (2016)	*Pseudomonas aeruginosa*	0.5 M HCl	Mild steel
Lan et al. (2017)	*Pseudonomas* sp. SWP-4	Aqueous medium	Carbon steel
Suma et al. (2019)	*P. putida* RSS	Aqueous solution	Mild steel

4.4 MICI by *P. putida*

P. putida is a Gram-negative bacterium that has a wide range of uses and applications as shown in Figure 4 (Volke et al. 2020). Besides its significance as biofilm-forming bacteria, it has been explored for industrial uses which include bioremediation, cell factory and biopolymer accumulation, among others.

As a bioremediation agent, *P. putida* can be used to degrade hydrocarbons found in oil spills and thus has a major application in the oil and gas industry.

P. putida has also found application as a cell factory. Engineered microbes with biosynthetic pathways that are streamlined to manufacture desired compounds from renewable carbon sources are known as *microbial cell factories* (Cho et al. 2022). *P. putida* has demonstrated to be a superior bacterial host for the production of medicines, bulk chemicals, and polymers (Weimer et al. 2020).

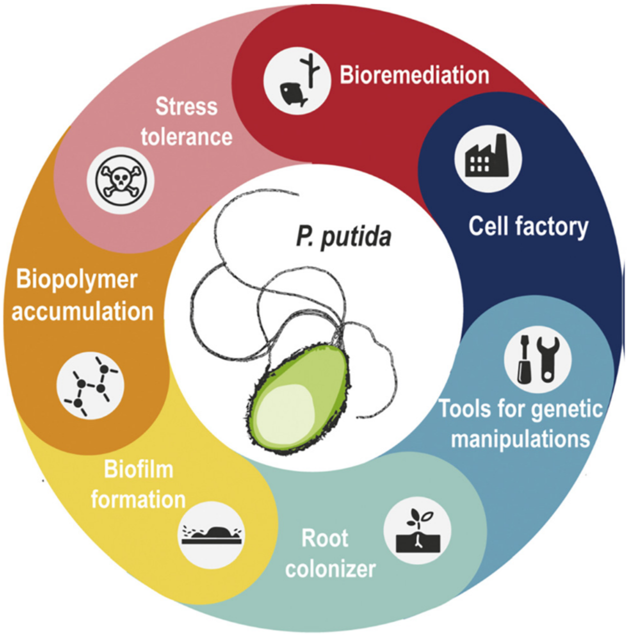

Figure 4: The significant scientific and industrial uses of *P. putida* (Volke et al. 2020). Reprinted from Volke et al. (2020), with permission from Elsevier (copyright 2020).

In this work, *P. putida* would be investigated as a MICI agent owing to its promising performance in inhibiitng corrosion in recent works (Suma et al. 2019) by forming a protective biofilm on the surface of metals. This bacterium produces an extracellular polymeric substance (EPS) that can form a protective film on the surface of metals, preventing them from coming into contact with corrosive agents. The EPS produced by *P. putida* contains proteins, polysaccharides, and lipids, which can interact with metal surfaces and inhibit corrosion.

Several studies have investigated the potential of *P. putida* as a corrosion inhibitor, including the use of *P. putida* biofilms and EPS as protective coatings on metal surfaces. These studies have demonstrated the effectiveness of *P. putida* in inhibiting corrosion in various environments, including marine environments, oil and gas pipelines, and cooling water systems (Li et al. 2023).

The earliest work found in utilizing *P. putida* to inhibit corrosion in metals was that by Jayaraman et al. (1997b). Later in 2000, Volkland et al. incubated mild steel coupons with a medium containing the microbe and found out that the corrosion rate was reduced significantly. Recently, Suma et al. (2019) passivated mild steel with the biofilm of the microbe and observed that the corrosion rate of mild steel was decreased by 28-fold in comparison with the control.

4.5 The mechanism of MICI exhibited by *P. putida*

P. putida has been shown to inhibit MIC through several mechanisms. One of the most important mechanisms is the formation of a protective biofilm on the metallic surface. The biofilm acts as a physical barrier between the metal and the corrosive environment, thereby reducing the rate of corrosion.

P. putida also produces extracellular polymeric substances (EPS), which are polymers that form a matrix around the bacterial cells. The EPS can bind to the metallic surface and form a protective layer that prevents corrosion. In addition, the EPS can adsorb corrosive species, such as hydrogen sulfide and iron ions, reducing their availability for corrosion reactions.

Another mechanism by which the microbe inhibits corrosion is by consuming corrosive species. For example, it can oxidize iron ions, producing iron oxide, which is a less reactive species than iron ions. Similarly, it can oxidize hydrogen sulfide, producing sulfate, which is less corrosive than hydrogen sulfide. It can also induce the precipitation of metal sulfides, which are less corrosive than metallic surfaces. For example, *P. putida* can induce the precipitation of iron sulfide on steel surfaces, which protects the steel from corrosion.

Finally, *P. putida* can produce molecules that inhibit the growth of other microorganisms that are involved in corrosion. For example, it can produce antibiotics that kill or inhibit the growth of sulfate-reducing bacteria, which are known to cause MIC.

4.6 Application of *P. putida* for corrosion inhibition in outdoor structures

Corrosion-inhibiting microorganisms, like *P. putida*, are a promising approach to mitigating the effects of atmospheric corrosion on outdoor metallic structures. These microorganisms can produce a biofilm on the surface of the metal, which acts as a protective layer against corrosion-causing agents in the environment.

To apply corrosion-inhibiting microorganisms to outdoor metallic structures, a few steps can be taken. First, the metal surface must be cleaned thoroughly to remove any dirt, rust, or other contaminants that could interfere with the adhesion of the microorganisms. Then, a solution containing the microorganisms can be applied to the surface of the metal. This solution can be sprayed, brushed, or otherwise distributed across the surface.

Once the microorganisms are applied, they will begin to grow and produce a biofilm on the surface of the metal. The growth and activity of the microorganisms can be monitored over time to ensure that they are effectively inhibiting corrosion. It may also be necessary to periodically reapply the microorganisms to maintain their effectiveness.

Overall, the use of corrosion-inhibiting microorganisms shows great potential for protecting outdoor metallic structures from the effects of atmospheric corrosion. However, further research is needed to determine the optimal conditions for the application and maintenance of these microorganisms.

4.7 Climate effects on microbial inhibition of atmospheric corrosion

Atmospheric corrosion is a major challenge faced by industries that rely on metallic materials. Microbial activity has been found to be a contributing factor to atmospheric corrosion, as it can create corrosive environments by producing acidic metabolites. However, the relationship between microbial activity and corrosion is complex, and it is influenced by a variety of factors, including climate.

Climate can affect the rate and extent of microbial inhibition of atmospheric corrosion. For example, temperature and humidity can affect the growth and activity of microorganisms, with some microbial species thriving in warm and humid environments, while others preferring cooler and drier conditions. Additionally, rainfall can wash away microbial colonies from metallic surfaces, reducing their corrosive impact.

Understanding the impact of climate on microbial inhibition of atmospheric corrosion is crucial for developing effective corrosion mitigation strategies. By considering the environmental factors that influence microbial activity, it is possible to design materials and coatings that are resistant to microbial-induced corrosion. Therefore, research into this area is important for developing sustainable and long-lasting solutions to the problem of atmospheric corrosion.

During a rain event, the corrosion-inhibiting microbes on metallic structures will continue to function as they do under normal conditions. These microbes consume oxygen and create a protective layer on the surface of the metal, preventing the formation of rust and corrosion. During an extended dry period, the corrosion-inhibiting microbes may become less effective due to a lack of moisture. Without water, the microbes may become dormant and not consume enough oxygen to maintain their protective function. Additionally, the absence of rain may cause dust and debris to accumulate on the surface of the metal, which can create a barrier and prevent the microbes from accessing the metal.

To prevent these issues, it is important to ensure that the microbial treatment is properly maintained and that moisture is available to the microbes, even during dry periods. This may involve periodic watering of the metal surface or the use of a supplemental moisture source. Additionally, regular cleaning and maintenance of the surface can help to prevent the accumulation of debris and ensure that the microbes can access the metal.

5 Challenges in the use of *P. putida* for inhibiting the atmospheric corrosion of metals

Although *P. putida* has potential to prevent metal atmospheric corrosion, however, there are several problems and challenges encountered in using or hampering its use for this purpose.

One major challenge is its limited effectiveness. Although *P. putida* has been shown to reduce corrosion in laboratory studies, its effectiveness in real-world conditions is limited. The bacteria require specific environmental conditions, such as high humidity and access to nutrients, to thrive and prevent corrosion. These conditions may not always be present in the atmosphere, making it challenging to rely on *P. putida* for corrosion prevention.

Another challenge which may hinder the seamless use of the microbe is the unpredictability of outcomes. Generally, the use of live bacteria to prevent corrosion is unpredictable, as the bacteria can evolve and adapt to their environment over time. This means that the effectiveness of *P. putida* may vary depending on factors such as temperature, humidity, and the presence of other microorganisms in the environment.

Furthermore, safety concerns may pose a challenge in the usage of the microbe. There are potential safety concerns associated with using live bacteria to prevent corrosion, as the bacteria can potentially cause health problems if they come into contact with humans. Additionally, there are concerns about the environmental impact of introducing live bacteria into the atmosphere.

Cost is another challenge that may hinder the deployment of microbes for industrial use. It is commonly agreeable that the use of live bacteria for corrosion prevention is relatively expensive, as it requires the ongoing cultivation and distribution of the bacteria to the sites where corrosion prevention is needed.

Finally, the lack of regulatory approval may also pose a challenge for the use of microbes for corrosion control. The use of live bacteria for corrosion prevention is not currently regulated, which means that there are no established guidelines or standards for its use. This can create uncertainty for companies and organizations that may be considering using *P. putida* for corrosion prevention.

6 Future outlook and recommendations

As corrosion is a significant challenge faced by many industries which can result in equipment failure, increased maintenance costs, and decreased operational efficiency, the use of corrosion-inhibiting microbes like *P. putida* is a promising approach to mitigate this problem. Here are comments on the future outlook and recommendations on the use of these microbes for industrial applications.

6.1 Future outlook

The use of corrosion-inhibiting microbes like *P. putida* is still in the early stages of development. However, with advances in biotechnology, there is a growing interest in using these microbes for industrial applications. The potential benefits of using *P. putida* include reduced maintenance costs, improved equipment lifespan, and increased operational efficiency. As research in this field progresses, we may see an increasing adoption of these microbes in various industries.

6.2 Recommendations

Here are a few recommendations on the use of *P. putida* for industrial applications.

(1) Conduct thorough research: Before using *P. putida* or any other microbial-based corrosion inhibitor, it is essential to conduct thorough research to understand its effectiveness, limitations, and potential risks.
(2) Consider the application: Different industries may have different requirements for corrosion inhibition, and it is essential to consider the specific application when selecting a microbial-based inhibitor. For instance, the microbial-based inhibitor may work well in some applications but may not be effective in others.
(3) Monitor performance: It is crucial to regularly monitor the performance of the microbial-based inhibitor to ensure that it is effective in preventing corrosion. This can involve testing the equipment or infrastructure for corrosion, as well as monitoring the microbial population.
(4) Follow best practices: When using *P. putida* or any other microbial-based inhibitor, it is important to follow best practices for handling, storage, and application. This can help to ensure that the inhibitor is effective and safe to use.

7 Conclusions

Recent trend in research has shown that microbes can be effective in the inhibition of metallic corrosion. However, there is limited research demonstrating their effectiveness for atmospheric corrosion, especially those mediated by air pollutants. Furthermore, the mechanisms by which they carry out their inhibitive actions on metallic surfaces under the influence of corrosive air pollutants media, can be said to be similar to those established mechanisms for MICI in aqueous media (which has been extensively studied by researchers).

Essentially, *P. putida* inhibits corrosion through several mechanisms, including the formation of a protective biofilm, production of EPS, consumption of corrosive species, induction of precipitation of metal sulfides, and production of antibiotics that inhibit the growth of other microorganisms involved in corrosion. Overall, the research on the use of *P. putida* as a corrosion inhibitor is promising, and further studies are needed to fully understand its potential for practical applications in corrosion control.

Conclusively, this review outlines and identifies the field of MICI for atmospheric corrosion as a burgeoning subject still calling for enthusiastic inquirers to further explore the area in order to establish practical methodologies, procedures and technologies for onward adoption in industrial terrains and applications. The use of corrosion-inhibiting microbes like *P. putida* is a promising approach to mitigate corrosion in various industries. However, it is essential to conduct thorough research, consider the specific application, monitor performance, and follow best practices to ensure the effectiveness and safety of these inhibitors.

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