Comprehensive Review on Carbon Steels Corrosion in Chloride-Rich Media

Abstract
Corrosion is a serious engineering and economic problem that affects metals and alloys, particularly carbon steel, which is widely used in many industrial applications. This review provides a comprehensive overview of the corrosion of carbon steels in rich chloride media, starting with corrosion mechanisms and factors that influence corrosion, types of corrosion, and types of the main corrosion products (rust). It also explores the main methods used in studying and monitoring corrosion (non-electrochemical and electrochemical techniques), starting from laboratory experiments to advanced analytical techniques. Among the strategies to mitigate corrosion, the use of corrosion inhibitors plays a crucial role in reducing the corrosion rate of carbon steels. This is especially true in harsh environments rich in chloride, known for accelerating metal degradation. This review also presents previous studies on corrosion in chloride-rich waters and evaluates the effectiveness of different inhibitors in controlling corrosion, contributing to the development of efficient protective solutions for metals under harsh and aggressive conditions.

Keywords Corrosion, Carbon Steels, Chlorides Ions, Corrosion Products, Inhibitors.

1.Introduction

Metal corrosion creates a significant risk to environmental and human health. Corrosion may release hazardous metals, including lead, cadmium, and chromium, into soil and water, resulting in pollution that impacts ecosystems and penetrates the food chain. Moreover, infrastructure deterioration can lead to dangerous leaks, impacting water quality and presenting immediate health hazards. Corrosion is not only a matter of material degradation; it also poses significant environmental and public health risks.

The corrosion of metals significantly affects several industrial sectors [1–5]. Metals, such as steels and alloys, have been widely utilized in industrial and technical applications. Moreover, metals are utilized in the offshore petroleum, power generation, nuclear energy, aerospace, shipping, and building industries [6–11]. Corrosion is the irreversible deterioration of a metal surface as a result of chemical reactions, whereby pure metal is converted into more chemically stable forms such as metal oxide, hydroxide or oxyhydroxide within a corrosive environment. These environments can exist in solid, liquid or gaseous states and are commonly referred to as electrolytes [12]. Corrosion is a surface process that occurs on the outer layer of the metal and manifests itself in several forms: An initial attack on the surface may cause general corrosion, leading to a gradual reduction in thickness, or it may cause localized damage, leaving only specific areas corroded, as sometimes seen at grain boundaries or in areas of weakness resulting from differences in the metal's resistance to the corrosive environment [13]. This process is slow, but over time it causes the deterioration of metal machinery and equipment, reducing their production efficiency. The annual economic losses resulting from various forms of corrosion in India are estimated at US$6.5 billion, while direct waste in the United States amounts to about 3.2% of gross domestic product [14]. A good understanding of corrosion and the application of appropriate and timely solutions are essential for controlling it [15]. Furthermore, a special type of corrosion can occur in relatively pure water at temperatures reaching around 1300°C on the product side, known as classic hot spot corrosion [16]. Corrosion is widely recognized as a universal phenomenon. Carbon steels (CS), due to their excellent mechanical properties [17-19]. In addition to the possibilities for processing (welded

[20], chipped [21], deformed [22]), are an appropriate choice for use in the manufacture of different parts of machines [23], accessories of fall arrest systems such as carabiners, hooks, and pythons [24,25], vehicle bodies [26], shipbuilding [27], or in use in buildings, bridges, rails, water, gas, and industrial pipes, cooling tower parts [28-31].

This study focuses on carbon steels with carbon at or below ~ 0.35% to facilitate welding. A subsequent differentiation can be established based on carbon content. Low carbon steels (containing fewer than 0.15% carbon) possess insufficient carbon to undergo hardening and are commonly utilized in hot-working or to achieve maximum ductility in the annealed state. Steels containing less than 0.25% carbon, commonly known as mild-steel, exhibit increased strength as they approach the maximum limit of carbon content. Medium carbon steels (0.25–0.55% carbon) are frequently subjected to heat treatment (quenching and tempering) to attain greater strength; however, this review focuses mainly on compositions below 0.35% carbon [32]. CS may get corroded during industrial operations; thus, corrosion inhibition sometimes is crucial for safe and economical operations for prolonged use of CS. This review examines CS as the most suitable alloy for constructing pipelines that transport water, oil, and gas. The majority of corrosion problems in the water, the oil and gas industries are related to pipelines and their exposure environments of CS, which determine the appropriate kind of CS selection. The present article offers an extensive examination of the corrosion characteristics of CS in saline solutions, emphasizing the fundamental electrochemical processes, significant influencing variables, and different experimental methodologies employed to evaluate corrosion rates. Furthermore, it analyzes various mitigation measures, including the use of corrosion inhibitors. This study examines recent research to identify contemporary difficulties, knowledge deficiencies, and emerging trends in corrosion science. The insights provided attempt to enhance the effectiveness as well as sustainability of corrosion prevention techniques, especially in shipping, industrial, and oil and gas sectors.

2. Corrosion mechanism

Corrosion is characteristics due to chemical (dry corrosion) or electrochemical (wet corrosion) interactions with its surroundings. Nonmetals are excluded from the current definition [32]. The breaking down of reactions into partial oxidation and reduction processes is referred to as electrochemical [33]. For corrosion, these reactions must be performed [34]:

Corrosion happens at the anode. At the point of the anode, oxidation or the loss of electrons from the metal occurs. The metal with the greater reduction potential is often referred to as the anode. The anodic metal is transformed into its equivalent ion by the loss of electrons.

$$M \rightarrow M + ne^{-} \tag{1}$$

At the cathode, reduction occurs, wherein the metal receives electrons from the anode. This may occur through the evolution of hydrogen and/or the absorption of oxygen.

2.1 By hydrogen evolution

It is the corroding process which hydrogen is released during it. The process often occurs in an acidic or alkaline media, when (H^+) ions absorb anodic electrons and release hydrogen.

$$2H^{+} + 2e^{-} \rightarrow H^{2}(gas) \tag{2}$$

For example, Fe metal reaction at anode:

$$Fe \rightarrow Fe^{2+} + 2e\square \tag{3}$$

And reaction at cathode:

$$2H\square O + 2e^{-} \rightarrow H\square\ (gas) \tag{4}$$

Overall cell reaction:

$$Fe + 2H_2O \rightarrow Fe^{2+} + H_2(gas) \tag{5}$$

2.2 By absorption of oxygen

It is the corrosion process involving the absorption of oxygen. This typically occurs in a neutral liquid, with NaCl being employed as the conducting medium, as seen in Fig. 1 in which (O_2) is absorbed to give (OH^-) ions.

$$\frac{1}{2}O\square + H\square O + 2e\square \rightarrow 2OH\square \tag{6}$$

For example, at anode the carbon steel reaction is:

$$Fe \rightarrow Fe^{2+} + 2e\square \tag{7}$$

And at cathode is:

$$\frac{1}{2}O\square + H\square O + 2e\square \rightarrow 2OH\square \tag{8}$$

Overall reaction:

Formation of Fe^{2+} ions at anode and OH^- ions released at cathode which come to form iron hydroxide [Fe $(OH)_2$] [35].

$$Fe^{2+} + 2OH\square \rightarrow Fe(OH)\square \tag{9}$$

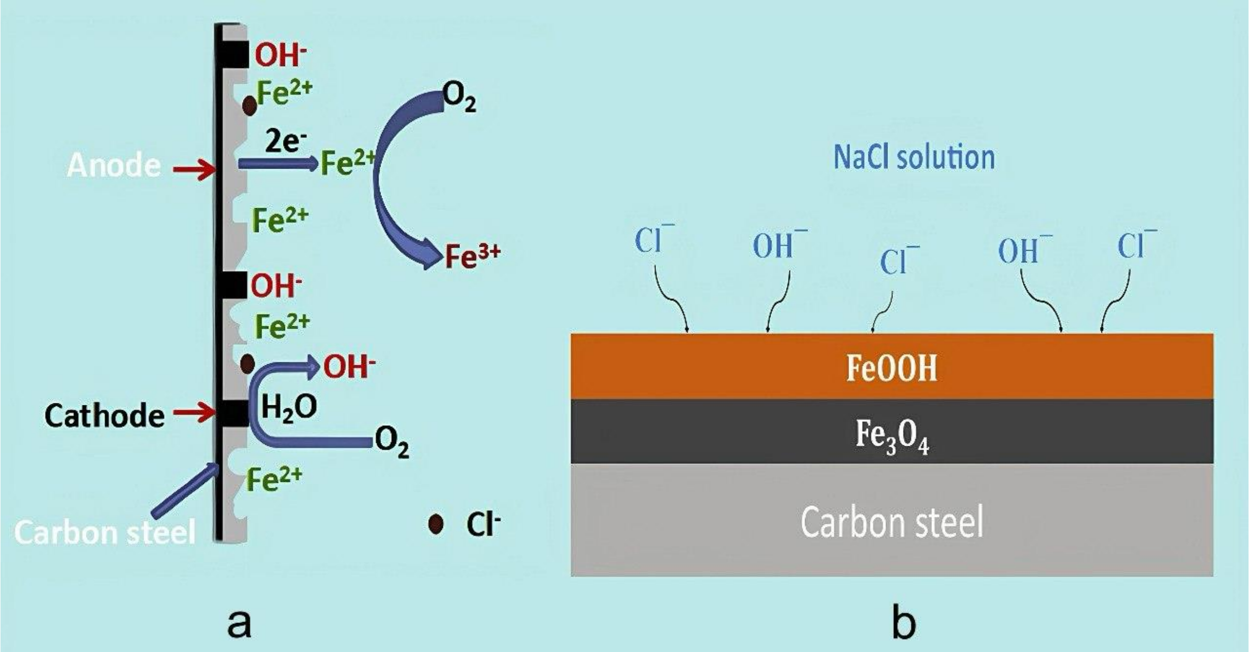


Fig. 1. Schematic representation of carbon steel immersed in NaCl solution (a) Mechanism [36], (b**)** Corrosion layer formation on the steels surface

3. Factors affecting corrosion process

Numerous internal and environmental variables directly or indirectly influence corrosion; some of these elements are illustrated in Fig. 2. We will focus on the nature of the metal and natural corrosion environment. Additional elements influencing corrosion include metal purity, characteristics of the surface coating, properties of the corrosive product, temperature, concentration of dissolved salts in the a medium, air humidity, and the pH of the electrolyte.

3-1 Nature of alloy or metal

It further depends upon:

3-1-1 Galvanic series position: When different metals are electrically connected in a specific electrolytic medium, the metal with higher oxidation potential, or the one higher in the electrochemical series, corrodes, while the other metal remains protected. The rate of corrosion depends directly on the electrochemical difference between the two metals; the greater the difference, the faster the corrosion. The susceptibility of metals to corrosion is shown in Fig 3. For example, in the presence of copper and cast iron in the same electrolytic medium, the cast iron corrodes first while the copper is protected from corrosion.

3-1-2 Purity of alloy or metal: The corrosion rate typically increases with rising impurity levels. This occurs because impurities create small electrochemical cells in which the anodic component undergoes corrosion. For instance: Zinc with impurities such as iron or lead exhibits accelerated corrosion.

3-1-3 Nature of the surface film: A thin layer of oxides forms on the surface of all metals in aerated environments. The effectiveness of this layer is determined by the volume ratio between the metal oxide and the original metal, known as the ‘specific volume ratio.’ In light of this, the higher this ratio, the lower the rate of metal oxidation.

*3-1-4 Nature of corrosion product**:*** The rate of corrosion accelerates when the corrosion product is soluble in the corrosive medium, as this allows the reaction to continue on the metal surface. The volatile product evaporates immediately after formation, exposing the metal to further attack and thus increasing rust formation.

3-1-5 Alloy or metal grain size: The mechanical characteristics of low carbon steel are predominantly influenced by ferrite particle size, with finer grains being advantageous for mechanical characteristics [37-39]. Nevertheless, the high energy and chemical reactivity of grain boundaries result in a larger density of these boundaries, which enhances surface reactivity through improved electron activity and diffusion, so influencing corrosion resistance. Enhanced corrosion resistance leads to prolonged durability of steel buildings [40–45]. Consequently, examining the effects of grain size on the corrosion resistance of low carbon steel is a significant topic.

3-2 Nature of corrosive environment

It further requires:

- *High temperature:* The rate of corrosion increases sharply with rising temperature, doubling with every 10 °C increase, provided that other biological and chemical factors remain constant [46]. This behavior is often depicted as an exponential curve showing the direct effect of heat, but the reality is more complex, as thermal changes also affect the effectiveness of other factors such as ion transport, gas dissolution (especially oxygen), and the properties of the protective layer formed on the metal surface. The effect of increased temperature is evident in two main ways: First, by accelerating electrochemical reactions thanks to increased molecular energy and more frequent effective collisions, and second, by modifying intermediate factors, such as solubility, ion transport, and microbial activity adding further depth and complexity to the underlying exponential curve.
- *Media humidity:* The rate of corrosion increases significantly when a certain level of relative humidity, known as critical humidity, is exceeded, as the ability of the iron oxide layer to absorb water from atmospheric humidity enhances electrochemical corrosion. The available moisture provides the metal surface with the electrolyte necessary to form an effective electrochemical cell, which accelerates oxidation and recovery reactions at the metal interface.
- *Effect of dissolved salts in media:* The rate of corrosion initially increases with increasing salt content, then gradually decreases until it becomes lower than the rate of corrosion in distilled water once the concentration reaches saturation. Different types of salts such as sodium chloride, alkali metal salts, alkaline earth metal salts, and acid salts affect the corrosion behavior of iron and steel in various ways related to their ability to alter the properties of the oxide layer and the conductivity of ions in solution [47].
- *Effect of pH in media:* pH is the most important factor in determining the rate of corrosion; a decrease in pH is usually accompanied by a significant increase in the rate of corrosion, indicating that acidic media (with a pH below seven) are more corrosive than neutral or alkaline media [48].
- *Effect of dissolved oxygen in media:*
  Dissolved oxygen plays a critical and complicated function in the corrosion of metals. Oxygen participates in cathodic processes on the metal surface in neutral, alkaline, and acidic environments. Therefore, the presence of corrosion is necessary for its occurrence. In the absence of dissolved oxygen, corrosion in neutral and alkaline solutions diminishes to nearly nothing. An increase in dissolved oxygen content, due to its participation in cathodic processes, promotes corrosion. What would occur if we were to inject increasing amounts of water infused with oxygen? It was established that oxygen, under specific conditions (in high-purity water) and elevated temperatures, may lead to the production of a thick passive protective coating of metal oxides on the metal surface, hence reducing corrosion [49].

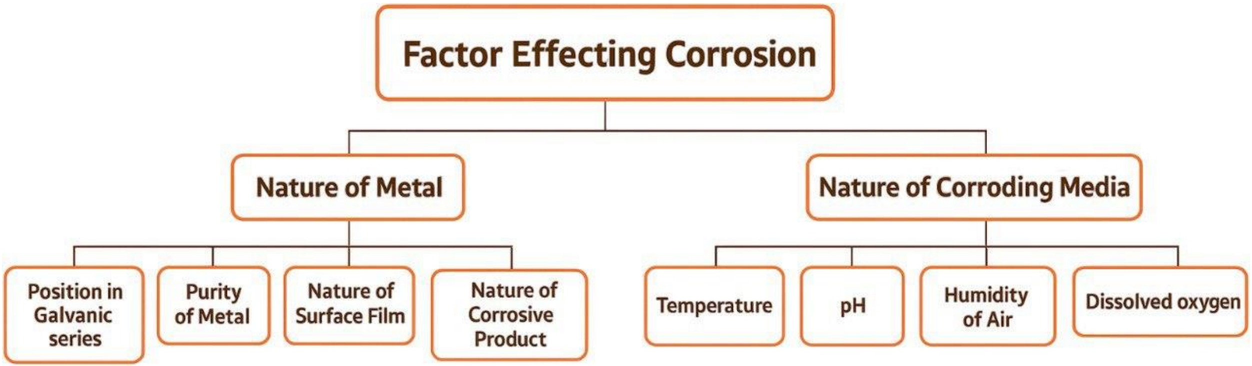


Fig. 2. Some of the factors affecting corrosion process

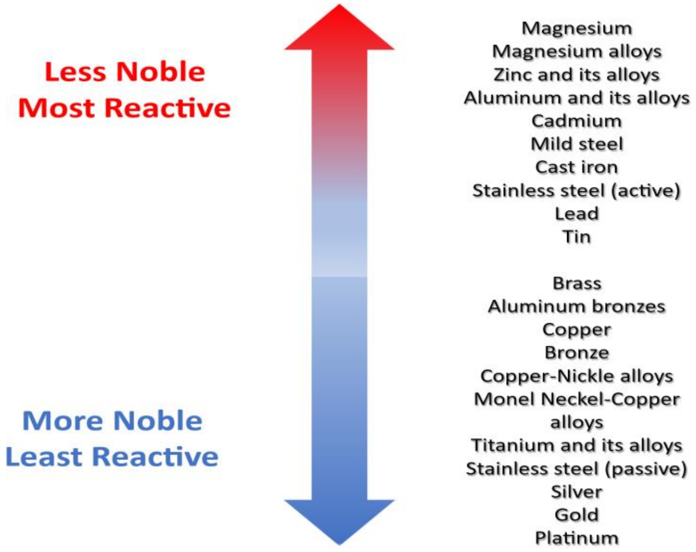


Fig. 3. Corrosion susceptibility of the metal

4- Methods for studying corrosion

4-1 Non-electrochemical technique (weight loss method)

This is a gravimetric technique where the weight of a carbon steel sample is measured before and after exposure to a corroding environment (e.g., saline solution). The difference in weight is used to calculate the corrosion rate according to the following equation [50]:

$$Corrosion\ rate = \frac{K\ W}{D \times T \times A} \tag{10}$$

The corrosion rate can be characterized as an increase per unit in the depth of corrosion over time, measured in mils per year (mpy) or as weight loss per unit area per time, often in milligrams per square decimeter per day (mdd) or as the corrosion current (mA.cm^{-2}). The standard SI metric for denoting the corrosion rate is millimeter per year (mm/y) or inch per year (inch/y). Table 1 illustrates the resistance of corrosion classification of CS.

Table 1. The comparison resistance of corrosion classification of CS [51]

Relative corrosion resistance	**Approximate corrosion rate**	
	mpy	**mm/y**
Outstanding	More than 1	More than 0.02
Excellent	1-5	0.002-0.1
Good	5-20	0.1-0.5
Fair	20-50	0.5-1
Poor	50-200	1-5
Unacceptable	Less than 200	Less than 5

Many researchers (52-58) have been measured the corrosion rate of different types of carbon steel in different chloride media at $25^{o}C$ of immersion as shown in Table 2.

Table 2. Corrosion rates of various types of carbon steels in different chloride media

Types of carbon steel	**Type of salt solution**	**Total Immersion Time**	**Corrosion Rate**	**Reference**
Low carbon steel	Marine water	24 months	500 mm/y	[52]
Low carbon steel	Seawater	28 days	0.037 mm/y	[53]
Low carbon steel	Lake Water	28 days	0.045 mm/y	[53]
Low carbon steel	Tap Water	28 days	0.04 mm/y	[53]
Medium carbon steel	Banda Aceh's	12 months	0.015 mpy	[54]
Carbon steel	Seawater	288 hours	0.18 mm/h	[55]
Carbon steel	Beibu Gulf Tidal Zone	360 days	600 mm/day	[56]
Mild Steel	1% NaCl	28 days	0.788 mpy	[57]
Mild Steel	3% NaCl	28 days	0.687 mpy	[57]
Mild Steel	5% NaCl	28 days	0.360 mpy	[57]
Mild Steel	7% NaCl	28 days	0.779 mpy	[57]
Mild Steel	10% NaCl	28 days	0.315 mpy	[57]
Mild Steel	Salt water	5 weeks	1.0622 mm/y	[58]

4-2 Electrochemical Techniques for Studying Corrosion of Carbon Steel

The most common employed electrochemical techniques are the potentiodynamic polarization technology (Tafel) combined with electrochemical impedance spectroscopy (EIS) [59,60]. The primary benefit of electrochemical methods exceed weight loss techniques is the ability to investigate additional information relating to corrosion mechanisms. Electrochemical procedures are typically conducted using a three electrode established consisting of a working electrode, a reference electrode, and a counter electrode [61]. The impact of corrosion inhibitors has been investigated by modifying the extract concentration, testing temperature, and liquid flowrate. Electrochemical analysis is efficient, rapid, and simple to use [62]. Potentiodynamic polarization yields many electrochemical characteristics, including corrosion potential (Ecorr.), current density of corrosion (Icorr.), anodic slope (βa), and cathodic slope (βc). Electrochemical impedance spectroscopy is capable of accurately estimating the rate of corrosion with minimal impact on the electrode. Different electrochemical techniques exist to assess the process and corrosion degree of the metal, as well as the efficiency and mechanisms of corrosion inhibitors to a certain extent.

4-2-1 Potentiodynamic Polarization (Tafel)

The potentiodynamic polarization technique is widely employed and consists of polarization current density and electrode potential [63,64]. Polarization curves (Anodic and cathodic) represent the relationship between polarization electrical current density and electrode potential. However, when the potentiodynamic polarization utilizing the potentiodynamic polarization curve technique is excessively high, significant curve deviations arise, preventing from getting hold of a standard potentiodynamic polarization curve. Fig. 4 illustrates a diagram of the potentiodynamic polarization curve.

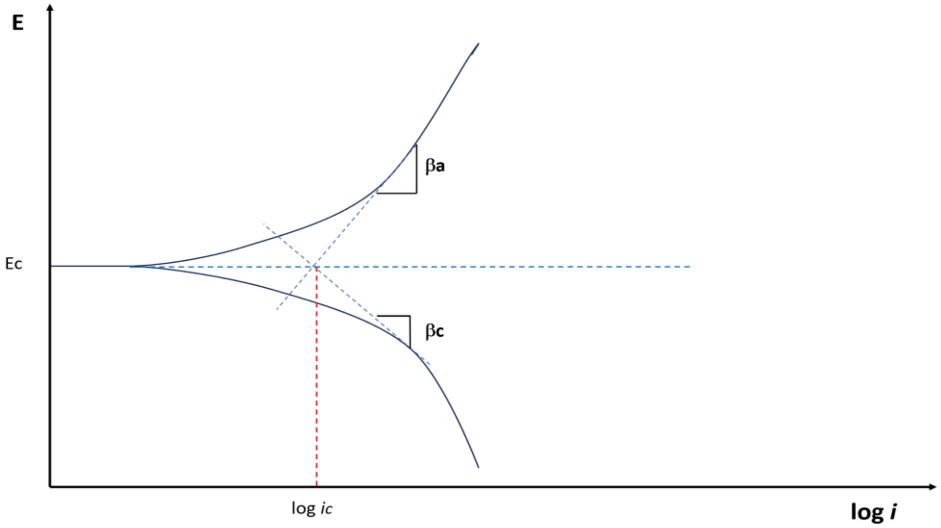


Fig. 4. Potentiodynamic polarization curve diagram

4-2-2 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) quantifies the impedance spectra of an electrode system throughout an extensive frequency range, employing a small amplitude sinusoidal potential as the perturbation signal to provide a nearly linear correlation between the system's responses. EIS is a prevalent testing method that little affects the electrode surface condition. Consequently, it is extensively utilized in scientific research and constitutes a significant methodology in electrochemical testing approaches [65,66]. In the analogous circuit, R_s denotes the resistance of electrolyte solution between the working electrode and reference electrode, R_{ct} signifies the charge transfer resistance associated with the corrosion process at the metal-electrolyte interface, and CPE represent the constant phase element. In corrosion science, EIS provides data on corrosion resistance, variations surface roughness of electrodes, adsorption of corrosion inhibitors, and the generation of corrosion products. In contrast to other conventional electrochemical techniques, such as potentiodynamic polarization curves, EIS offers enhanced insights into corrosion kinetics as seen in Fig. 5.

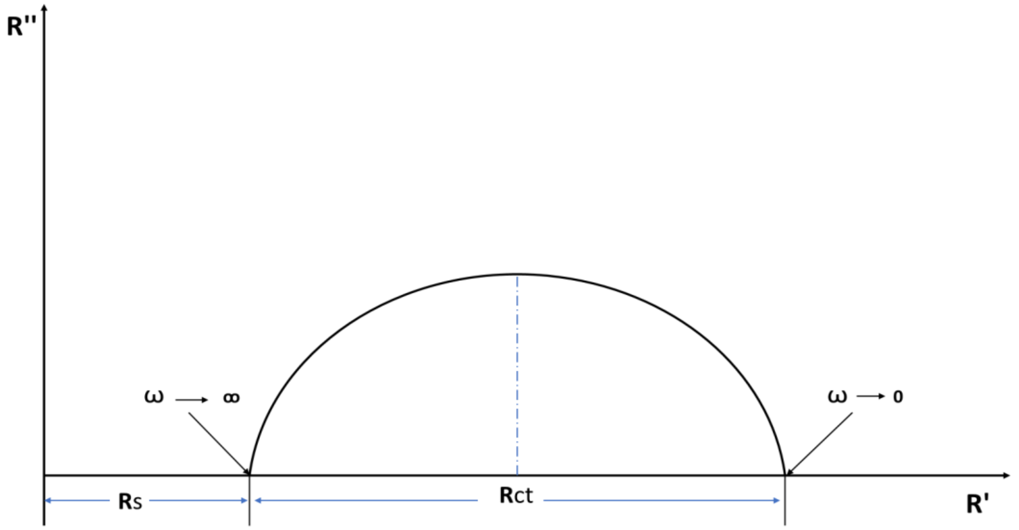


Fig. 5. Schematic diagram of electrochemical impedance spectroscopy

4-3 Surface characterization techniques

This portion of the article examines surface analytical approaches for characterizing carbon steel surfaces, both treated and untreated (e.g., corrosion inhibitors) in corrosive environments. The discussion addresses aspects affecting the use of certain approaches in carbon-steel corrosion research, including high surface roughness under corrosive circumstances [67].

4.3.1. Scanning electrochemical microscopy (SEM)

Employing scanning electron microscopy (SEM), an accurate imaging technique capable of giving high-resolution images of metallic surfaces, enables a comprehensive examination of corrosion, protective films, and the underlying substrates of metals [68,69] This approach involves directing an electron beam at a sample, resulting in the production of secondary electrons by surface contact. The electrons are subsequently collected to provide a high-quality image [70] A key benefit of scanning electron microscopy is its flexibility, allowing application in environmental chambers, both high and low vacuum environments, and the investigation of corrosion processes under different conditions [71]. SEM may be utilized with various techniques, such as X-ray spectroscopy, for the chemical evaluation of corrosion products to determine the kind of corrosion and its source. SEM is an essential tool for examining corrosion; it may potentially identify localized corrosion sites and yield data on the concentration of active corrosion species, hence advancing study into localized corrosion at particular areas. It also offers helpful understanding into inhibitors to improve protective methods and enhance the useful lifetime of metal structures. Research evaluated the performance of a newly developed organic corrosion inhibitor by SEM testing.

4.3.2 Energy dispersive X-ray spectroscopy (EDX)

EDX is a chemical analysis method that employs a high-energy electron beam to target substances, excite electrons from inner shells, and concurrently emit X-ray photons. The energy content of these photons is characteristic to the emitting element, facilitating the examination of the sample's chemical structure. SEM-EDX is a high magnification, stereoscopic microscopy technique employed for the analysis of healing products. It employs a concentrated high energy electron beam to examine materials, revealing physical information on the surface topography of the specimen. This technique is frequently employed to ascertain crystal structure, shape, dimensions, and distribution. The interface composition is assessed by backscattered SEM images. SEM/EDX is a method that offers an optical representation of a surface together with the elemental composition of selected regions [72-76].

4-3-3 Atomic force microscopy (AFM)

Atomic force microscopy facilitates the examination of surface topography, involving measures of surface roughness. Assessing the adhesion of the inhibitor or corrosive coating on the substrate (metal or alloys) only using topographical imaging has consistently posed challenges. Moreover, capturing topographical photos might be challenging due to the irregular film development. Consequently, AFM current pictures and force versus distance curves are employed for providing further insights into the characteristics of surface layers, such as the adherence of corrosion inhibitors and coatings [77,78]. AFM offers the capability to function in different liquid conditions and facilitates real-time surface monitoring in corroding environments [79,80].

4-3-4 X-ray diffraction spectroscopy (synchrotron-sourced)

Grating-induced X-ray diffraction (GI-XRD) is an effective method for studying interfacial chemistry at the solid-liquid interface, but its traditional application suffers from a low signal-to-noise ratio that can lead to inaccurate conclusions about phase evolution. This challenge is exacerbated when analysing thin films—such as corrosion inhibitor layers—on carbon steel, as surface roughness in corrosive environments contributes to a reduction in the received signal. Synchrotron-radiation-induced X-ray diffraction (SR-XRD) addresses these limitations by providing a high signal-to-noise ratio sufficient for examining thin films on carbon steel even under aggressive corrosion conditions. SR-XRD has high resolution due to the use of a parallel beam that reduces peak broadening at low angles, as well as high brightness, high intensity, tight collimation, and low emission polarisation, making it the preferred choice of crystallographers [81].

It is also necessary to monitor the transformations undergone by corrosion products under different conditions and to conduct in situ corrosion tests. In carbon dioxide environments, where oxygen is consumed, it has been observed that carbon steel produces iron carbonate as a by-product, which may oxidise when subsequently exposed to oxygen-rich conditions. It has also been demonstrated that combining field SR-GI-XRD with additional electrochemical methods such as cyclic voltammetry and electrochemical impedance spectroscopy provides a deeper mechanistic understanding of electrochemical reactions on copper surfaces [82,83].

4-3-5 X-ray photoelectron spectroscopy (XPS)

XPS is a quantitative spectroscopic method that provides information on the elemental composition at parts-per-thousand levels depending on the electronic and chemical state of the surface being examined. This technique has been widely used in corrosion research to describe the composition of metal surfaces, particularly in the study of corrosion products. For example, researchers applied it to carbon steel exposed to seawater, and three-dimensional analyses revealed the absence of an iron signal in the spectrum, indicating that the surface was completely covered with a layer of corrosion products [84]. The presence of iron in its metallic and oxidised states was associated with the production of oxides, and techniques such as Raman spectroscopy and X-ray diffraction confirmed these results. In addition, XPS was used in the qualitative analysis of surface films to measure the effectiveness of protective layers, such as studying the formation of iron carbonates on carbon steel surfaces [85] and examining the presence of hydroxide ions within the layer to assess its cohesion and protective properties [86].

4-3-6 Raman spectroscopy (IR)

Raman spectroscopy (IR) has been acknowledged as a crucial surface characterization technique for corrosion investigations, applicable for assessing both single layer and multilayer surface characteristics. Raman spectroscopy offers insights into surface connecting (vibrational data), hence giving structural information regarding the contact between the metal substrate and corrosion inhibitor [87].

4-3-7 Fourier transform infrared spectroscopy (FTIR)

Unique molecular fingerprints can be formed based on the absorption and transmission of infrared light. The quality and quantity of individual components in samples may be determined using FTIR. IR recognized as the dispersive IR method, was employed in previous investigations. Currently, FTIR is widely utilized because to its several benefits, including accurate measurement, rapid data collection, high sensitivity, non-destructive analysis, and the absence of a need for external calibration. Conventional FTIR, usually examined in the mid IR wavelength range, has been effectively utilized in the analysis of surface coatings on CS substrates. The existence or nonexistence of certain bands of the corrosion inhibitor molecule correlates with the molecule's orientation on the CS surface and/or inside the film of inhibitor. This helps in understanding how corrosion inhibitors adsorbed on steel surfaces [88].

To evaluate and examine the corrosion of metals and alloys, monitoring alterations in the color of electrolyte solutions may serve as a simple way, but alternative approaches such as the Standard Immersion Test (SIT) should also be studied. Fig. 6 illustrates the flowchart of the experimental approach based on SIT. At the conclusion of the SIT, the corrosion behavior of metals subjected to corrosive solutions is assessed by measuring the corrosion rate (mm/y).

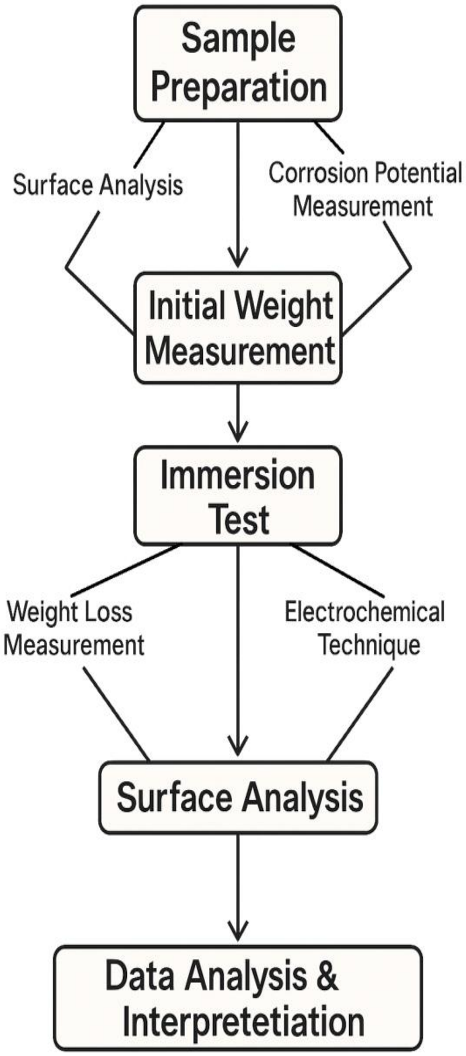


Fig. 6. Flowchart of an experimental methodology employed to examine corrosion behavior of steels

5. Types of corrosion

Corrosion interactions are classified into two types based on the characteristics of the corrosive environments: wet corrosion and dry corrosion. Corrosion can be categorized into several types [89-97] as shown in Fig. 7, they depend on the environment, the substrate type, or the chemical procedure.

5-1 General Corrosion: It is also known as uniform corrosion, is distinct from dry corrosion; this type of corrosion degrades the metal's untreated surface very consistently. It may also be characterized as a form of corrosion that progresses uniformly throughout the entire exposed surface. Oxygen serves as the primary catalyst for this corrosion. The main materials exhibiting general corrosion are steel and cast iron. When subjected to a humid environment, they exhibit a rust-like appearance.

5-2 Intergranular Corrosion: Intergranular corrosion is highly pertinent to the brewing industries. It involves a localized attack, wherein a restricted pathway is preferentially corroded along the grain boundaries of a metal. This form of corrosion can significantly impact mechanical qualities, leading to decreases in strength and ductility.

5-3 Galvanic Corrosion: Galvanic corrosion often arises when different conductive materials are electrically interconnected and subjected to an electrolyte. Consequently, the subsequent essential criteria must be satisfied for galvanic corrosion:
1. Various metals or alternative conductors, such as graphite.
2. Electrical contact between dissimilar conductive materials, which may occur by direct contact or an alternative connection, such as a shared grounding pathway.
3. Electrolyte (the corrosive media) in contact with different conductive materials.

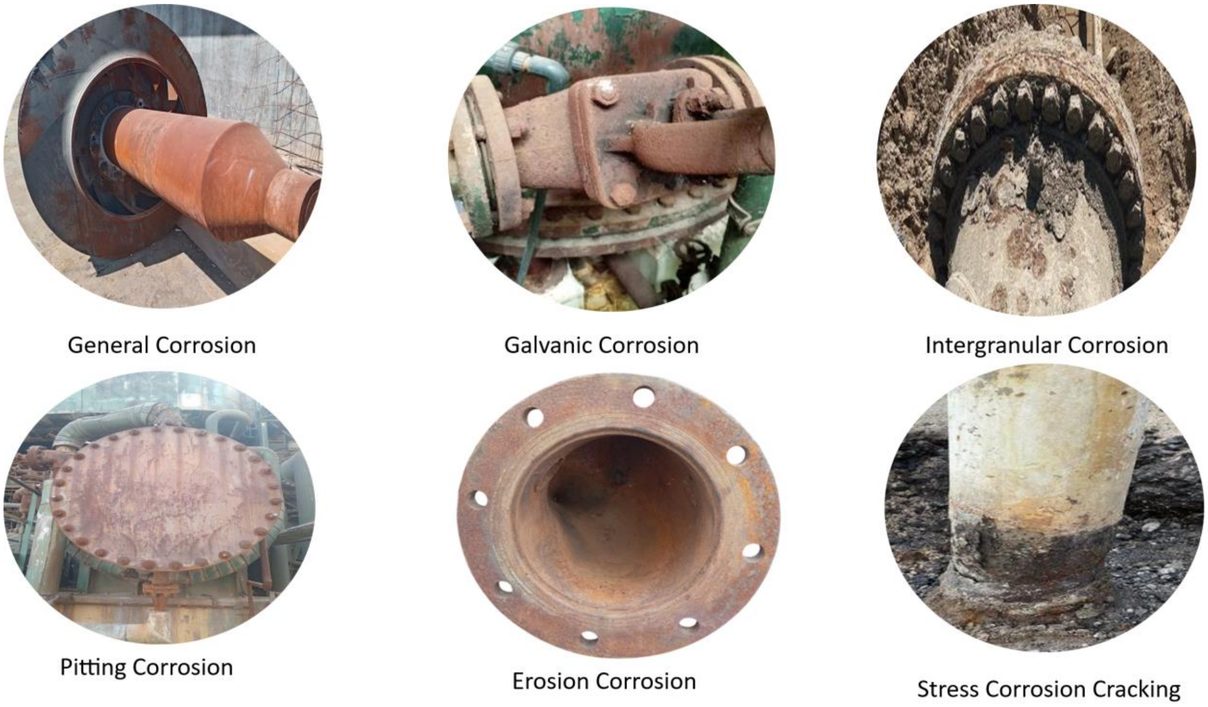
5-4 Pitting Corrosion: Pitting corrosion is considered more hazardous than uniform corrosion damage because to its challenging detection, prediction, and design reduction. Pitting corrosion can result in pits that are either open or enveloped by a semipermeable barrier of corrosion byproducts. Pits can be either hemispherical or cup-shaped [97].

5-5 Crevice Corrosion: This type of corrosion is represented a localized type. Crevice corrosion happens in small voids or interstices between two metallic surfaces or between metals and non-metallic surfaces. A concentration cell is established with the crevice lacking oxygen. The differential aeration between the cracking (micro-environment) and the exterior surface (bulk environment) imparts an anodic aspect to the crevice. This may lead to a very corrosive environment within the cracks. Instances of crevices involve flanges, deposits, washers, ends of rolled tube, and threaded connections as shown in Fig. 8 [98].

5-6 Erosion Corrosion: Erosion Corrosion is the accelerated degradation or attack on a metal resulting from the relative motion between a corrosive liquid and the metal surface.

5-7 Stress Corrosion Cracking (SCC): It denotes cracking resulting from the simultaneous existence of tensile stress and a corroding environment. The influence of SCC on a material often occurs between dry cracking and the material's fatigue threshold [99].

5-8 Selective Leaching: Also referred to as "parting" or "dealloying," it is the specific elimination of one element from a steel alloy, resulting in a modified residual structure. A common instance is the selective extraction of zinc from brass alloy, known as dezincification as shown in Fig. 8 [100].



General Corrosion

Galvanic Corrosion

Intergranular Corrosion

Pitting Corrosion

Erosion Corrosion

Stress Corrosion Cracking

Fig. 7. Different corrosion patterns in carbon steels manufactured parts as observed at the thermal power station and refinery of Al-Dora-Baghdad, Iraq

Crevice Corrosion

Selective Leaching

Fig. 8. Crevice corrosion and selective leaching [98,100]

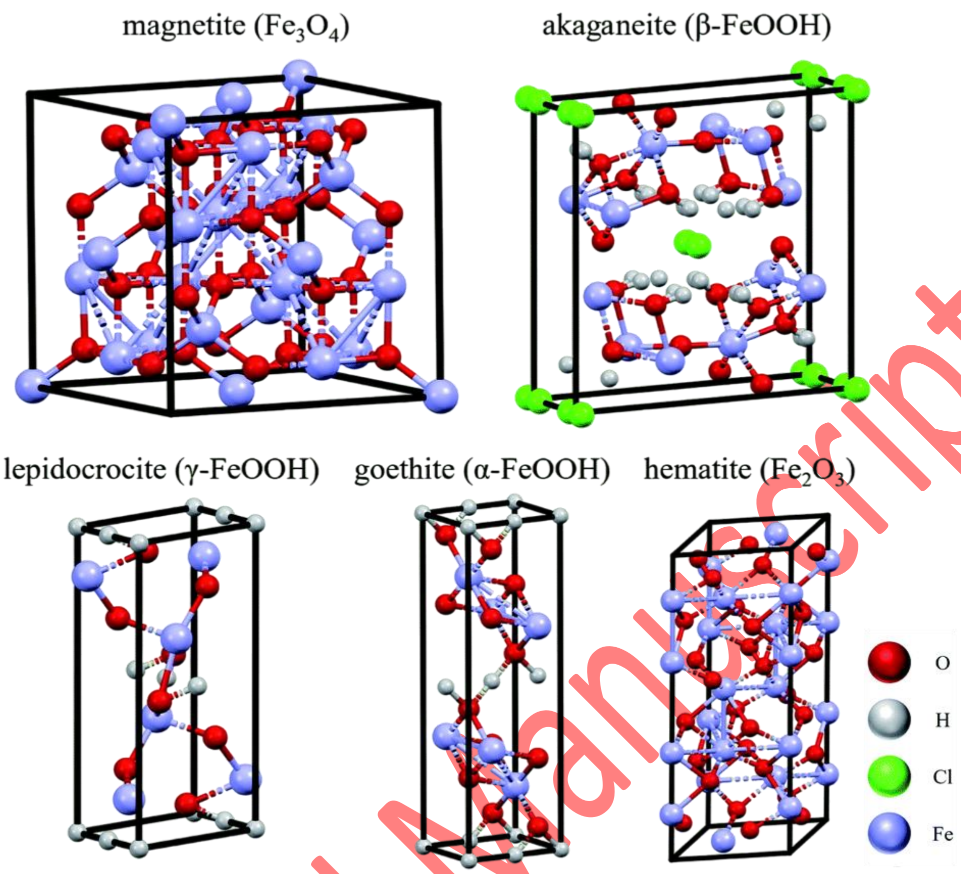
6-The types of corrosion product producing on CS

The corrosion products that develop on the steel alloy surface are the principal results of the metal's dissolution. They can significantly influence the current corrosion process. Primarily, they establish a physical barrier between the alloy and the environment, therefore protecting the metal by preventing the transfer of dissolved oxygen from saltwater to the metal surface [101,102]. Secondly, their porous nature provides a unique home for micro-organisms that may exist in a particular environment [103-107]. Thirdly, some phases are used as electronic conductors, such as magnetite [108,109] and iron sulfides [110,111], which can enhance galvanic cells. The composition of the corrosion product layer varies according to the exposure zone and may alter over time. The layers, developed on steel alloy surfaces during laboratory tests or at seaport exposure locations, illustrate the complex nature of iron chemistry in natural saltwater. Their composition varies in regions (anodic and cathodic), hence actively contributing to the maintenance of corrosion cells and promoting localized corrosion processes [112].

Many research investigations have been performed on corrosion products that developed in different atmospheres utilizing XRD and IR. The corrosion product of CS typically consists of crystalline compounds of iron oxide, hydroxide, and oxide-hydroxides [113,114]. The shape and dimensions of the crystals created are depending upon the varying conditions under which they create. The chemical composition [115-121] and morphologies of solid corrosion products were examined according to characteristics given in Table 3. Some of crystals are shown in Fig. 9.

Table 3. Chemical composition and morphology of corrosion products [54,122-129]

Corrosion product	**Composition**	**Crystal structure**	**Morphology**
Goethite	α-FeOOH	Orthorhombic	Cloudy-shaped, flat and thin sheet, Needle-shaped, filiform, whiskers, bipyramids, cubes, thin rods cotton balls, tiny rods, nest-like, star-like, cotton ball.
Lepidocrocite	γ-FeOOH	Orthorhombic	Dense plates, granular, thick sheet Laminar, spherical, sandy granules, worm burrow, birds nest, plumage or shattered glass, floral, sandy mixture.
Hematite	α-Fe_2O_3	Hexagonal	-
Feroxyhyte	δ-FeOOH	Hexagonal	Flowery, bent plates.
Akageneite	β-FeOOH	Monoclinic	cylinder, tube, cigar-shaped, plate-like morphology.
maghemite	γ-Fe_2O_3	Cubic	Dark flat layer, circular grain, donuts-like, Black circular rings.
Magnetite	Fe_3O_4	Cubic	-
Wustite	FeO	Cubic	-


magnetite (Fe_3O_4)

akaganeite (β-FeOOH)

lepidocrocite (γ-FeOOH)

goethite (α-FeOOH)

hematite (Fe_2O_3)

Fig. 9. Some of crystals cell of carbon steel corrosion [128]

7- Corrosion inhibition

The solubility of metal in the solution affects weight loss, corrosion, and metal instability. The addition of inhibitors results in a linear decrease in the weight loss in the specimens proportional to the corrosion rate [129].

Corrosion inhibition is the most cost-effective, practical, and easy method for controlling corrosion on metals in saltwater environments [130]. Corrosion inhibitors control metal dissolution and acid consumption. Inhibitors are adsorbed onto the metallic surface; Inhibitors inhibit the solubility of metals. Inhibitors adsorb onto the metal surface, creating a physical protective barrier, and interact with anodic and/or cathodic reaction sites to prevent oxidation and/or reduction of corrosion reactions [131].

Corrosion inhibitors are natural or chemical substances added in low concentrations into corrosive environments to prevent or minimize (control) corrosion without significantly reacting with surrounding components [132]. Concentration ranges from (1 to 15,0000) ppm [133]. Corrosion inhibitors are crucial in many chemical industries such as oil extraction, processing. The use of corrosion inhibitors into the system minimizes the corrosion process or inhibits the metal oxidation rate [134]. Inhibition is the method that prevents the damage caused by of corrosive substances by adsorbing inhibitors onto a whole metallic substrate [135,136].

The inhibitors can be categorized into both inorganic and organic types [51]. Inorganic inhibitors indicate either anodic or cathodic behaviors. The organic inhibitors have mixed cathodic and anodic activity together with adsorption properties. Figure 10 illustrates how to classify of the inhibitors. Inorganic corrosion inhibitors have superior effectiveness over an additional temperature spectrum and for longer periods of time in comparison to organic corrosion inhibitors. Organic corrosion inhibitors, while more expensive than their inorganic different forms, indicate less toxicity.

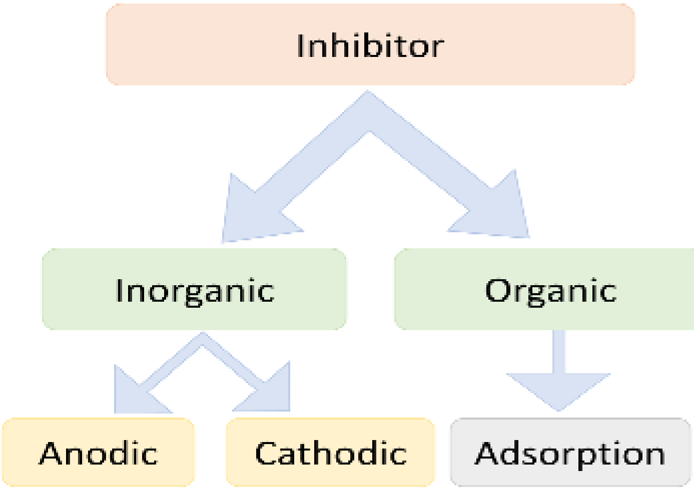


Fig. 10. Classification of Inhibitors

The inhibition efficiency of inhibitors is determined by the structure and chemical properties of the film formed over the substrate surface [137]. The efficiency of the inhibitor is affected by the state of the substrate surface, the type of corrosive media, the steel composition, and the chemical structure of the inhibitor [138]. Physical-chemical properties induced by the functional group the and strength of the inhibitor-metal bond in the molecule affect the adsorption of organic inhibitors [139]. The variety of organic and inorganic corrosion inhibitors as well as some green eco-friendly, some biobased corrosion inhibitors are explored for the carbon steel application.

Recent research conducted by many authors on the efficiency of inhibition of different types of carbon steels in rich chloride solutions are shown in Table 4.

Table 4. Efficiency of some corrosion inhibitors for different types of carbon steel in salt water at 25^{o}C.

Corrosion Inhibitor	**Concentration of inhibitors**	**Type of Media**	**Steel type**	**Efficiency %**	**References**
4-[6-bromo-benzothiazolylazo] thymol BTAT	70 ppm	seawater	Low Carbon Steel	94.6	[140]
Syzygium cumini fruit	500 ppm	seawater	Low Carbon Steel	92.99	[141]
Coriandrum sativum	10 µL 30 µL	138 and 200 mg/L	Mild Steel	83.6 78.5	[142]

Aloe vera	50 µL 300 ppm	seawater	API 5L Carbon steel	86.6 83.75	[143]
Silicate	1.2 g was dissolved in 100 ml of 3 mol/L NaOH	Saline solution	Carbon steel	94	[144]
Alkanol ammonium salts	From [5×10^{-4} to 5×10^{-3}] mol/L	3 % NaCl	Carbon steel	96	[145]
Amino Acid L-Histidine	250 ppm 500 ppm 1000 ppm	3.5 %NaCl	AISI 1018 carbon steel	Up to 89	[146]
New organic ammonium salts	Different concentrations	3.5 % Saline solution	Mild steel	High	[147]
Morinda citrifolia	300 ppm	Saline environment	Mild steel	85.1	[148]
plum tree gum	25 mg/L 50 mg/L 100 mg/L 250 mg/L 500 mg/L	3.5% saline water	Carbon steel	94 95 96 97 97	[149]
4-(dimethylamino) -1-nonylpyridin-1 -ium Bromide((4DMN)	Different concentrations	3.5 %NaCl	Carbon steel	94	[150]
4-(dimethylamino)-1 -(prop-2-yn-1-yl)pyridine -1-ium Iodide (4DMP)	Different concentrations	Saline medium	Carbon steel	92	[150]
Sodium silicate	0.1, 0.5, 1, 5, 10 and 20 mmol/L	3 % NaCl	Carbon steel	Up to 99.8	[151]
Cassava leaf (DNA)	20 ppm	3.5% NaCl	AISI 1015 low carbon steel	96.4	[152]
Ficus (FIC) leaf	2 ppm	Saline medium	Carbon steel	87	[153]
Bis(2-ehylhexyl) phosphate (BEP)	500 ppm	1 % NaCl	Carbon steel	93.07	[154]

Curcuma longa	200 ppm	Seawater	Mild steel	98	[155]
Octylsilanol and Ce(III) ions	400 ppm	0.1 NaCl mol/L	Carbon steel	>96	[156]
(1-{[5-(2 Chloro-phenylazo)-2-hydroy-benzylidene]-amino}-4,7-dimethyl -6-nitro- 1H quinolin-2-one (CPHAQ2O))	5 ppm 10 ppm 20 ppm	3.5% NaCl	carbon steel	86.82 87.05 90.55	[157]
Imidazole and Benzimidazole	50 ppm	3% NaCl	AISI 1010 carbon steel	73	[158]
coconut oil-modified imidazoline	20 ppm	3% NaCl	Carbon steel	85	[159]

8- Conclusions and Future Prospects

Corrosion of carbon steel in salty environments is a serious concern due to its extensive use in oceanic building materials, pipelines, and industrial applications. Temperature, pH, chloride concentrations, and exposure length have significant effects on corrosion. In order to limit the degradation of materials, it is necessary to have a thorough understanding of these variables. A variety of approaches have been used to investigate corrosion behavior, including weight loss, electrochemical techniques (potentiodynamic polarization, electrochemical impedance spectroscopy) and surface analysis instruments (SEM, EDX, XRD, AFM). The weight loss method allows for direct measurement of corrosion rate, electrochemical methods can provide real-time information, and surface analysis methods can provide insight into morphological and chemical changes in corrosion-damaged materials. The prevention of corrosion has been achieved by employing various protective strategies, including corrosion inhibitors, protective coatings, cathodic protection, and nanotechnology-based materials. It is becoming increasingly essential for early detection of corrosion symptoms and averting structural failures to employ real-time corrosion monitoring techniques, such as electrochemical sensors and acoustic emission techniques. It should be noted, however, that progress in corrosion research continues, but obstacles remain in creating eco-friendly inhibitors, increasing coating longevity, and developing real-time monitoring systems. By developing environmentally friendly corrosion inhibitors and self-healing coatings, by implementing intelligent monitoring systems that utilize artificial intelligence and Internet of Things-based sensors, and by developing alloys and nanotechnology-based coatings, future corrosion research must focus on sustainable corrosion mitigation. With the incorporation of emerging technologies and sustainable materials, carbon steel structures are able to last longer, require fewer repairs, and provide increased operational safety in adverse conditions. Industrial applications benefit from improved material durability and environmental sustainability as a result.

Nomenclature

CR	Average corrosion rate (mm/y)
K	Conversion factor (3650) of the corrosion rate (mm/y)
W	Weight loss (g)
D	Density (g/cm^3)
T	Corrosion exposure time (Day)
A	Surface area of the sample (cm^2)

References:

[1] Exbrayat L, Salaluk S, Uebel M, Jenjob R, Rameau B, Koynov K, Landfester K, Rohwerder M, Crespy D. Nanosensors for monitoring early stages of metallic corrosion. ACS Applied Nano Materials. 2019 Jan;2(2):812–818. https://doi.org/10.1021/acsanm.8b02045

[2] Nwanonenyi SC, Obasi HC, Obidiegwu MU, Chukwujike IC. Anticorrosion response of polymer mixture on mild steel in hydrochloric acid environment. Emergent Materials. 2020 Aug 18;3(5):663–673. https://doi.org/10.1007/s42247-020-00120-2

[3] Fayyad EM, Abdullah AM, Hassan MK, Mohamed AM, Jarjoura G, Farhat Z. Recent advances in electroless-plated Ni-P and its composites for erosion and corrosion applications: a review. Emergent Materials. 2018 Aug 15;1(1-2):3–24. https://doi.org/10.1007/s42247-018-0010-4

[4] Babouri L, Belmokre K, Kabir A, Abdelouas A, Khettabi R, El Mendili Y. Microstructure and crystallographic properties of $Cu_{77}Zn_{21}$ alloy under the effect of heat treatment. Material at High Temperature. 2019 Jul 23;36(2):165–172. https://doi.org/10.1080/09603409.2018.1499243

[5] Gollapudi S, Cai W, Patibanda S, Rajulapati KV, Neelakantan L. Correlating corrosion inhibition to grain size in electrodeposited Ni-18Co. Emergent Materials. 2020 Oct 30;3:989–997. https://doi.org/10.1007/s42247-020-00135-9

[6] Ali AA. An Investigation to the Abrasive Wear in Pipes Used for Oil Industry. Journal of Engineering. 2013 Nov 1;19(11):1382-1394. https://doi.org/10.31026/j.eng.2013.11.03

[7] Nsaif HJ, Majeed NS, Salman RH, Abed KM. Elimination of phenol by sonoelctrochemical process utilizing graphite, stainless steel, and titanium anodes: optimization by taguchi approach. Iraqi Journal of Chemical and Petroleum Engineering. 2024 Sep 30;25(3):21-30. https://doi.org/10.31699/IJCPE.2024.3.3

[8] Ahmed SA, Makki HF. Corrosion rate optimization of mild-steel under different cooling tower working parameters using Taguchi design. Journal of Engineering. 2019;26(1):174-185. http://doi.org/10.31026/j.eng.2020.01.13

[9] Bahrami Panah N, Danaee I. Effect of Structural Changes on Corrosion Inhibition Behavior of Synthesized N2O4 Imine Compounds for Steel Pipelines in Oil and Gas Wells. Journal of Chemical and Petroleum Engineering. 2019 Jun 1;53(1):1-10. https://doi.org/10.22059/jchpe.2019.232647.1193

[10] Amin MA, Abd El Rehim SS, El-Lithy AS. Corrosion, passivation and breakdown of passivity of Al and Al–Cu alloys in gluconic acid solutions. Electrochimica Acta. 2010 Aug 1;55(20):5996–6003. https://doi.org/10.1016/j.electacta.2010.05.055

[11] Jasim RA, Salman RH. Use of nano Co-Ni-Mn composite and aluminum for removal of artificial anionic dye congo red by combined system. Ecological Engineering & Environmental Technology. 2024 Jun 1;25(7):133-149. https://doi.org/10.12912/27197050/188266

[12] Fernandes JS, Montenor F. Corrosion. Materials for Construction and Civil Engineering. 2015 Jan 1;2:679-71. http://doi.org/10.1007/978-3-319-08236-3_15

[13] Singh DD. Various forms of water side Corrosion: Causes & Prevention. In: Proceedings of the National Workshop on Boiler Corrosion. 1995 April;16-23. https://eprints.nmlindia.org/3557

[14] Kumar R, Kumar R, Kumar S. Erosion corrosion study of HVOF sprayed thermal sprayed coating on boiler tubes: a review. IJSMS. 2018;1(3):1-6. https://www.ijsmsjournal.org/2018/volume-1%20issue-3/ijsms-v1i3p101.pdf

[15] Palanisamy G. Corrosion inhibitors. In Corrosion Inhibitors. 2019 July 23:44-53. http://doi.org/10.5772/intechopen.80542

[16] Abdulsada SA, Al□Mosawi AI. Surface Characteristics and Corrosion Tendency of TIG□Welded Low Carbon Steel Sheet Affected Cold Galvanizing and Processed by Immersion in Sodium Chloride Solution. Journal of Bio- and Tribo-Corrosion. 2024 April 9;10(34). https://doi.org/10.1007/s40735-024-00838-0

[17] Odusote JK, Ajiboye TK, Rabiu AB. Evaluation of Mechanical Properties of Medium Carbon Steel Quenched in Water and Oil. AU Journal of Technology. 2012 April;15(4):218-224. https://assumptionjournal.au.edu/index.php/aujournaltechnology/article/view/1375/1209

[18] Chen Y, Zheng S, Zhou J, Wang P, Chen L, Qi Y. Influence of H2S interaction with prestrain on the mechanical properties of high-strength X80 steel. International journal of hydrogen energy. 2016 Jun 29;41(24):10412-10420. https://doi.org/10.1016/j.ijhydene.2016.01.144

[19] Javidan F, Heidarpour A, Zhao XL, Minkkinen J. Application of high strength and ultra-high strength steel tubes in long hybrid compressive members: Experimental and numerical investigation. Thin-Walled Structure. 2016 May;102;273-285. https://doi.org/10.1016/j.tws.2016.02.002

[20] Boumerzoug Z, Derfouf C, Baudin T. Effect of Welding on Microstructure and Mechanical Properties of an Industrial Low Carbon Steel. Engineering. 2010 July;2:502–506. http://doi.org/10.4236/eng.2010.27066

[21] Panda A, Duplak J, Hatala M, Krenicky T, Vrabel P. Research on the Durability of Selected Cutting Materials in the Process of Turning Carbon Steel. MM Science Journal. 2016 Oct;10: 1086–1089. https://doi.org/10.17973/MMSJ.2016_10_201660

[22] Karavaeva MV, Nurieva SK, Zaripov NG, Ganeev AV, Valiev RZ. Microstructure and mechanical properties of medium-carbon steel subjected to severe plastic deformation. Metal Science and Heat Treatment. 2012 July 21;54; 155–159. https://doi.org/10.1007/s11041-012-9473-8

[23] Kimapong K, Poonayom P, Wattanajitsiri V. Microstructure and wear resistance of hard-facing weld metal on JIS-S50C carbon steel in agricultural machine parts. Materials Science Forum. 2016 Sep; 872: 55–61. https://doi.org/10.4028/www.scientific.net/MSF.872.55

[24] Burduhos-Nergis DP, Baciu C, Vizureanu P, Lohan NM, Bejinariu C. Materials types and selection for carabiners manufacturing: A review. In Proceedings of the IOP Conference Series: Materials Science and Engineering. 2019;572:012027. http://doi.org/10.1088/1757-899X/572/1/012027

[25] Bejinariu C, Darabont DC, Baciu ER, Georgescu IS, Bernevig-Sava MA, and Baciu C. Considerations on applying the method for assessing the level of safety at work. Sustainability. 2017; 9(7):1263. https://doi.org/10.3390/su9071263

[26] Hamidinejad SM, Kolahan F, Kokabi AH. The modeling and process analysis of resistance spot welding on galvanized steel sheets used in car body manufacturing. Material & Design. 2012 Feb;34:759–767. https://doi.org/10.1016/j.matdes.2011.06.064

[27] Sekban DM, Aktarer SM, Xue P, Ma ZY, Purcek G. Impact toughness of friction stir processed low carbon steel used in shipbuilding. Materials Science and Engineering A, 2016 Aug 30; 672: 40–48. https://doi.org/10.1016/j.msea.2016.06.063

[28] Usher KM, Kaksonen AH, Cole I, Marney D. Critical review: Microbially influenced corrosion of buried carbon steel pipes. International Biodeterioration and Biodegradation. 2014 Sept; 93: 84–106. https://doi.org/10.1016/j.ibiod.2014.05.007

[29] Ouda EH, Khazaal SH, Abbas J. An Application of Cooperative Game Theory in Oil Refining Sites: Case Study of Dora Refinery in Iraq. In International Conference on Intelligent and Fuzzy Systems 2023 Aug 17:592-599. https://doi.org/10.1007/978-3-031-39777-6_69

[30] Bharatiya U., Gal P., Agrawal A., Shah M., and Sircar A., Effect of Corrosion on Crude Oil and Natural Gas Pipeline with Emphasis on Prevention by Ecofriendly Corrosion Inhibitors: A Comprehensive Review, Journal of Bio- and Tribo-Corrosion, (2019), 5(35) https://doi.org/10.1007/s40735-019-0225-9

[31] Gandy D. Carbon Steel Handbook. Carbon. 2007 March; 3(3): 172. http://gang.josen.net/uploads/allimg/20230415/1-2304151923021a.pdf

[32] Uhlig HH. Corrosion Control in Water Systems. Industrial & Engineering Chemistry. 1952 Aug;44(8):1736-40. https://pubs.acs.org/doi/pdf/10.1021/ie50512a017

[33] Abdulsada SA, Al-Mosawi AI. Corrosion behaviour and surface topography for steel plates used in automotive industry exposed to salty corrosive thermo-accelerated medium. Journal of Silicate Based and Composite Materials. 2022;74(6):38–41. https://doi.org/10.14382/epitoanyag-jsbcm.2022.31

[34] Harsimran S, Santosh K, Rakesh K. Overview of Corrosion and Its Control: a Critical Review. Proceedings on Engineering Sciences. 2021; 3(1); 13–24. https://doi.org/10.24874/PES03.01.002

[35] Ahmed SA, Makki HF. Corrosion behavior of mild-steel in cooling towers using high salinity solution. AIP Conference Proceedings. 2020 March 25;2213(1):020178. https://doi.org/10.1063/5.0000274

[36] Vorobyova V, Skiba M. Peach Pomace Extract as efficient Sustainable Inhibitor for carbon Steel against Chloride-Induced corrosion. Journal of Bio- and Tribo-Corrosion. 2020 Nov 16;7(1):11 https://doi.org/10.1007/s40735-020-00450-y

[37] Liu MY, Shi B, Wang C, Ji SK, Cai X, Song HW. Normal Hall–Petch behavior of mild steel with submicron grains. Materials letters. 2003 Jun 1;57(19):2798-802. https://doi.org/10.1016/S0167-577X(02)01377-0

[38] Chigondo M, Chigondo F. Recent Natural Corrosion Inhibitors for Mild Steel: An Overview. Journal of chemistry. 2016 Jul 14;2016(6208937):7. https://doi.org/10.1155/2016/6208937

[39] Nouroozi M, Mirzadeh H, Zamani M. Effect of microstructural refinement and intercritical annealing time on mechanical properties of high-formability dual phase steel. Materials Science and Engineering: A. 2018 Oct 24;736:22-26. https://doi.org/10.1016/j.msea.2018.08.088

[40] Ralston KD, Birbilis N. Effect of grain size on corrosion: a review. Corrosion. 2010 Jul 1;66(7):075005. https://doi.org/10.5006/1.3462912

[41] Ralston KD, Birbilis N, Davies CH. Revealing the relationship between grain size and corrosion rate of metals. Scripta Materialia. 2010 Dec 1;63(12):1201-1204. https://doi.org/10.1016/j.scriptamat.2010.08.035

[42] Chen YT, Zhang KG. Influence of grain size on corrosion resistance of a HSLA steel. Advanced Materials Research. 2012 Oct 10;557:143-146. https://doi.org/10.4028/www.scientific.net/AMR.557-559.143

[43] Soleimani M, Mirzadeh H, Dehghanian C. Unraveling the Effect of Martensite Volume Fraction on the Mechanical and Corrosion Properties of Low□Carbon Dual□Phase Steel. Steel research international. 2020 Feb;91(2):1900327. https://doi.org/10.1002/srin.201900327

[44] Li Y, Wang F, Liu G. Grain size effect on the electrochemical corrosion behavior of surface nanocrystallized low-carbon steel. Corrosion. 2004 Oct 1;60(10):891-896. https://doi.org/10.5006/1.3287822

[45] Soleimani M, Mirzadeh H, Dehghanian C. Processing route effects on the mechanical and corrosion properties of dual phase steel. Metals and Materials International. 2020 Jun;26:882-890. https://doi.org/10.1007/s12540-019-00459-0

[46] Levy AV. Erosion and erosion-corrosion of metals. Corrosion. 1995 Nov 1;51(11):872-883. https://doi.org/10.5006/1.3293564

[47] Chappell C. The influence of carbon on the corrodibility of iron. Journal of the American Society for Naval Engineers. 1912 Aug;24(3):1061. https://doi.org/10.1111/j.1559-3584.1912.tb04648.x

[48] Décarie E, Boatman TG, Bennett N, Passfield W, Gavalás□Olea A, Siegel P, Geider RJ. Predictions of response to temperature are contingent on model choice and data quality. Ecology and evolution. 2017 Dec;7(23):10467-10481. https://doi.org/10.1002/ece3.3576

[49] Zehra S, Mobin M, Aslam J. An overview of the corrosion chemistry. Environmentally Sustainable Corrosion Inhibitors. 2022 Jan 1:3-23. https://doi.org/10.1016/B978-0-323-85405-4.00012-4

[50] Standard practice for preparing, cleaning, and evaluating corrosion test specimens, ASTM Standard G1-03. ASTM. 2017.

[51] Fontana MG. Corrosion Engineering. McGraw-Hill Book Company. New York. 1986. https://www.osti.gov/biblio/5741236

[52] Ma Y, Li Y, Wang F. Corrosion of low carbon steel in atmospheric environments of different chloride content. Corrosion science. 2009 May 1;51(5):997-1006. https://doi.org/10.1016/j.corsci.2009.02.009

[53] Mahzan S, Rusli RI. Corrosion Behaviour of a Low Carbon Steel Piping Exposed to Different Water Conditions. Research Progress in Mechanical and Manufacturing Engineering. 2023 Aug 1;4(1):413-419. https://doi.org/10.30880/rpmme.2023.04.01.047

[54] Fonna S, Ibrahim IB, Huzni S, Ikhsan M, Thalib S. Investigation of corrosion products formed on the surface of carbon steel exposed in Banda Aceh's atmosphere. Heliyon. 2021 Apr 1;7(4). https://doi.org/10.1016/j.heliyon.2021.e06608

[55] Liu Y, Wang Z, Wei Y. Influence of seawater on the carbon steel initial corrosion behavior. International Journal of Electrochemical Science. 2019 Feb 1;14(2):1147-1162. https://doi.org/10.20964/2019.02.36

[56] He S, He S, Yu P, Li H, Feng J, Liao P, Liao J, Huang X. Corrosion behaviour of carbon steel in Beibu Gulf tidal zone. Corrosion Engineering, Science and Technology. 2023 Apr;58(2):116-123. https://doi.org/10.1080/1478422X.2022.2149426

[57] May M. Corrosion behavior of mild steel immersed in different concentrations of NaCl solutions. Journal of Sebha University-(Pure and Applied Sciences)-Vol. 2016;15(1):1-12. https://www.researchgate.net/publication/317502595_Corrosion_behavior_of_mild_steel_immersed_in_different_concentrations_of_NaCl_solutions?enrichId=rgreq-18c023c9e280142136eebcc8fd70d6d4-XXX&enrichSource=Y292ZXJQYWdlOzMxNzUwMjU5NTtBUzo1MDQ1NjYwMzY2NTYxMjhAMTQ5NzMwOTMyNTEzNw%3D%3D&el=1_x_2&_esc=publicationCoverPdf

[58] Odio BO, Chinwuko EC, Chukwuneke JL, Sinebe JE. Investigation of the effect of corrosion on mild steel in five different environments. International Journal of Scientific & Technology Research. 2014;3(7):306-310. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=6ac40b3b0bc0f357ce11e38703415788727f97cc

[59] Berradja A. Electrochemical techniques for corrosion and tribocorrosion monitoring: methods for the assessment of corrosion rates. Corrosion inhibitors. 2019 Jul 2; 26. https://doi.org/10.5772/intechopen.86743

[60] Suzuki S. Surface analysis of oxides and corrosion products formed on surfaces of iron-based alloys. In Characterization of Corrosion Products on Steel Surfaces. 2006 Oct 6:131-158. https://doi.org/10.1007/978-3-540-35178-8_7

[61] Popoola LT. Organic green corrosion inhibitors (OGCIs): a critical review. Corrosion Reviews. 2019 Mar 26;37(2):71-102. https://doi.org/10.1515/corrrev-2018-0058

[62] Li H, Zhang S, Qiang Y. Corrosion retardation effect of a green cauliflower extract on copper in H2SO4 solution: Electrochemical and theoretical explorations. Journal of Molecular Liquids. 2021 Jan 1;321:114450. https://doi.org/10.1016/j.molliq.2020.114450

[63] Şahin EA, Solmaz R, Gecibesler İH, Kardaş G. Adsorption ability, stability and corrosion inhibition mechanism of phoenix dactylifera extrat on mild steel. Materials Research Express. 2020 Jan 27;7(1):016585. https://doi.org/10.1088/2053-1591/ab6ad3

[64] Al-Ghaban AM, Abdullah HA, Anaee RA, Naser SA, Khadom AA. Expired butamirate drug as eco-friendly corrosion inhibitor for aluminum in seawater: Experimental and theoretical studies. Journal of Engineering Research. 2024 Sep 1;12(3):299-309. https://doi.org/10.1016/j.jer.2023.11.020

[65] Zhang K, Xu B, Yang W, Yin X, Liu Y, Chen Y. Halogen-substituted imidazoline derivatives as corrosion inhibitors for mild steel in hydrochloric acid solution. Corrosion Science. 2015 Jan 1;90:284-295. https://doi.org/10.1016/j.corsci.2014.10.032

[66] Khormali A. Using a New Mixture of Reagents for Effective Inhibition of Corrosion and Salt Precipitation in the Petroleum Industry. Journal of Chemical and Petroleum Engineering. 2021 Dec 1;55(2):257-276. https://doi.org/10.22059/jchpe.2021.322527.1349

[67] Shwetha KM, Praveen BM, Devendra BK. A review on corrosion inhibitors: types, mechanisms, electrochemical analysis, corrosion rate and efficiency of corrosion inhibitors on mild steel in an acidic environment. Results in Surfaces and Interfaces. 2024 Aug 1;16:100258. https://doi.org/10.1016/j.rsurfi.2024.100258

[68] Sabbaghi S, Bazargan Lari R, Zeraatkar M. Multilayer nano films for corrosion control. International Journal of Nanoscience and Nanotechnology. 2011 Jun 1;7(2):72-77. https://www.ijnnonline.net/article_3943_0.html

[69] Martinez-Lombardia E, Maurice V, Lapeire L, De Graeve I, Verbeken K, Kestens L, Marcus P, Terryn H. In situ scanning tunneling microscopy study of grain-dependent corrosion on microcrystalline copper. The Journal of Physical Chemistry C. 2014 Oct 8;118(44):25421-25428. https://doi.org/10.1021/jp507089f

[70] Bokati KS, Dehghanian C. Adsorption behavior of 1H-benzotriazole corrosion inhibitor on aluminum alloy 1050, mild steel and copper in artificial seawater. Journal of Environmental Chemical Engineering. 2018 Apr 1;6(2):1613-1624. https://doi.org/10.1016/j.jece.2018.02.015

[71] Lopez DA, Schreiner WD, De Sánchez SR, Simison SN. The influence of carbon steel microstructure on corrosion layers: an XPS and SEM characterization. Applied surface science. 2003 Feb 28;207(1-4):69-85. https://doi.org/10.1016/S0169-4332(02)01218-7

[72] Scimeca M, Orlandi A, Terrenato I, Bischetti S, Bonanno E. Assessment of metal contaminants in non-small cell lung cancer by EDX microanalysis. European journal of histochemistry: EJH. 2014 Sep 12;58(3):2403. https://doi.org/10.4081/ejh.2014.2403

[73] Scimeca M, Giannini E, Antonacci C, Pistolese CA, Spagnoli LG, Bonanno E. Microcalcifications in breast cancer: an active phenomenon mediated by epithelial cells with mesenchymal characteristics. BMC cancer. 2014 Dec;14:1-0. https://doi.org/10.1186/1471-2407-14-286

[74] Scimeca M, Feola M, Romano L, Rao C, Gasbarra E, Bonanno E, Brandi ML, Tarantino U. Heavy metals accumulation affects bone microarchitecture in osteoporotic patients. Environmental Toxicology. 2017 Apr;32(4):1333-1342. https://doi.org/10.1002/tox.22327

[75] Barba T, Wach J, Lustig S, Laurent F, Devouassoux-Shisheboran M, Valour F, Chidiac C, Ferry T. Metallosis-associated prosthetic joint infection. Médecine et maladies infectieuses. 2015 Nov 14;45(11-12):484-487. https://doi.org/10.1016/j.medmal.2015.09.009

[76] Khan H, Hurworth M, Kop A. Metallosis following a dual coat porous hydroxyapatite shoulder hemiarthroplasty. journal of orthopaedics. 2015 Dec 1;12(4):266-271. https://doi.org/10.1016/j.jor.2015.02.005

[77] Aljaafari HA, Ali SB, Abbas MA, Ali HB, Anaee RA, Naser SA, Mahdi RI, Anaee MA. Improvement in the Corrosion Behavior of Al-Si-xWC Composites Prepared by Casting Technique. Journal of Bio-and Tribo-Corrosion. 2024 Sep 5;10(100). https://doi.org/10.1007/s40735-024-00902-9

[78] Li J, Lampner D. In-situ AFM study of pitting corrosion of Cu thin films. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 1999 Aug 1;154(1-2):227-237. https://doi.org/10.1016/S0927-7757(98)00901-7

[79] Ataeefard M, Moradian S. Surface properties of polypropylene/organoclay nanocomposites. Applied Surface Science. 2011 Jan 1;257(6):2320-2326. https://doi.org/10.1016/j.apsusc.2010.09.096

[80] Bowen WR, Hilal N. Atomic force microscopy in process engineering: An introduction to AFM for improved processes and products. Butterworth-Heinemann; 2009 Jun 30. https://books.google.com/books?hl=en&lr=&id=XKByFSz316sC&oi=fnd&pg=PP1&dq=Atomic+force+microscopy+in+process+engineering:+An+introduction+to+AFM+for+improved+processes+and+products&ots=bR7SilpY6P&sig=7IKJr55qYhJZNrmtBX4x-z1EfK8

[81] Al-Hassan S, Mishra B, Olson DL, Salama MM. Effect of microstructure on corrosion of steels in aqueous solutions containing carbon dioxide. Corrosion. 1998 Jun 1;54(06):480–491. https://doi.org/10.5006/1.3284876

[82] Kautek W, Geuß M, Sahre M, Zhao P, Mirwald S. Multi□method Analysis of the Metal/Electrolyte Interface: Scanning Force Microscopy (SFM), Quartz Microbalance Measurements (QMB), Fourier Transform Infrared Spectroscopy (FTIR) and Grazing Incidence X□ray Diffractometry (GIXD) at a Polycrystalline Copper Electrode. Surface and Interface Analysis: An International Journal devoted to the development and application of techniques for the analysis of surfaces, interfaces and thin films. 1997 Jun;25(7□8):548-560. https://doi.org/10.1002/(SICI)1096-9918(199706)25:7/8%3C548::AID-SIA269%3E3.0.CO;2-B

[83] Sathiyanarayanan S, Sahre M, Kautek W. In-situ grazing incidence X-ray diffractometry observation of pitting corrosion of copper in chloride solutions. Corrosion science. 1999 Oct 15;41(10):1899-1909. https://doi.org/10.1016/S0010-938X(99)00021-9

[84] Qiu JH, Chua PH. EIS and XPS study of the corrosion of carbon steel in inhibited natural seawater. Surface and Interface Analysis: An International Journal devoted to the development and application of techniques for the analysis of surfaces, interfaces and thin films. 1999 Aug;28(1):119-122. https://doi.org/10.1002/(SICI)1096-9918(199908)28:1%3C119::AID-SIA631%3E3.0.CO;2-T

[85] Xiang Y, Yan M, Choi YS, Young D, Nesic S. Time-dependent electrochemical behavior of carbon steel in MEA-based CO_2 capture process. International Journal of Greenhouse Gas Control. 2014 Nov 1;30:125-132. https://doi.org/10.1016/j.ijggc.2014.09.003

[86] Lopez DA, Schreiner WH, De Sanchez SR, Simison SN. The influence of inhibitors molecular structure and steel microstructure on corrosion layers in CO_2 corrosion: An XPS and SEM characterization. Applied Surface Science. 2004 Sep 15;236(1-4):77-97. https://doi.org/10.1016/j.apsusc.2004.03.247

[87] Gutiérrez C, Melendres CA, editors. Spectroscopic and diffraction techniques in interfacial electrochemistry. Springer Science & Business Media; 2012 Dec 6;320. https://books.google.com/books?hl=en&lr=&id=IsjrCAAAQBAJ&oi=fnd&pg=PR9&dq=Spectroscopic+and+Diffraction+Techniques+in+Interfacial+Electrochemistry&ots=6LuQSzhiUB&sig=KaliDx8lDlQvbgUeY7H6BS7pb_4

[88] Dwivedi D, Lepkova K, Becker T. Emerging surface characterization techniques for carbon steel corrosion: a critical brief review. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2017 Mar 31;473(2199):20160852. https://doi.org/10.1098/rspa.2016.0852

[89] Adejoro IA, Ojo FK, Obafemi SK. Corrosion inhibition potentials of ampicillin for mild steel in hydrochloric acid solution. Journal of Taibah University for Science. 2015 Apr 1;9(2):196-202. https://doi.org/10.1016/j.jtusci.2014.10.002

[90] Singh R. Corrosion control for offshore structures: cathodic protection and high-efficiency Coating. Gulf Professional Publishing; 2014 Aug 12:41–44. https://books.google.com/books?hl=en&lr=&id=4QF0AwAAQBAJ&oi=fnd&pg=PP1&dq=Corrosion+control+and+monitoring,+in+Corrosion+Control+for+Offshore+Structures:+Cathodic+Protection+and+High+Efficiency+Coating&ots=j0ZIDLpw10&sig=XRJDIwfwMZhs0NL3wCXYymvhXhc

[91] Zinad DS, Jawad QA, Hussain MA, Mahal A, Mohamed L, Al-Amiery AA. Adsorption, temperature and corrosion inhibition studies of a coumarin derivatives corrosion inhibitor for mild steel in acidic medium: gravimetric and theoretical investigations. International Journal of Corrosion and Scale Inhibition. 2020;9(1):134-151. https://dx.doi.org/10.17675/2305-6894-2020-9-1-8

[92] Hashim FG, Salman TA, Al-Baghdadi SB, Gaaz T, Al-Amiery A. Inhibition effect of hydrazine-derived coumarin on a mild steel surface in hydrochloric acid. Tribologia-Finnish Journal of Tribology. 2020 Dec 11;37(3–4):45-53. https://doi.org/10.30678/fjt.95510

[93] Al-zyadi JM, Kadhim AA, Yao KL. Electronic and magnetic properties of the (001) surface of the CoNbMnSi Heusler alloy: First-principles calculations. Journal of Electron Spectroscopy and Related Phenomena. 2018 Jul 1;226:17-21. https://doi.org/10.1016/j.elspec.2018.04.005

[94] Mohammed DA, Fakhri MA, Kadhim A. Reduction the corrosion rate of 304 stainless steel using pulsed laser shock penning method. In IOP Conference Series: Materials Science and Engineering 2018 Dec 1;454(1):012162. IOP Publishing. http://doi.org/10.1088/1757-899X/454/1/012162

[95] Al-Zyadi JM, Kadhim AA, Yao KL. Half-metallicity of the (001),(111) and (110) surfaces of CoRuMnSi and interface half-metallicity of CoRuMnSi/CdS. RSC advances. 2018;8(45):25653-25663. https://doi.org/10.1039/C8RA02918K

[96] Abass RH, Haleem AM, Hamid MK, Kadhim A, Jawad RS. Antimicrobial activity of TiO2 NPs against Escherichia coli ATCC 25922 and Staphylococcus aureus ATCC 25923. Int. J. Comput. Appl. Sci. 2017 Feb 15;2(1):6-10. https://www.researchgate.net/publication/312587095_Antimicrobial_Activity_of_TiO2_NPs_against_Escherichia_coli_ATCC_25922_and_Staphylococcus_aureus_ATCC_25923?enrichId=rgreq-240a54832fff67c68e2dd0cc2ecff1d2-XXX&enrichSource=Y292ZXJQYWdlOzMxMjU4NzA5NTtBUzo0NjgyMDcxOTE0OTg3NTJAMTQ4ODY0MDcwMTI1Ng%3D%3D&el=1_x_2&_esc=publicationCoverPdf

[97] Obeyesekere NU. Pitting corrosion. Trends in oil and gas corrosion research and technologies. 2017 Jan 1:215-248. https://doi.org/10.1016/B978-0-08-101105-8.00009-7

[98] Yadla SV, Sridevi V, Lakshmi MV, Kumari SK. A review on corrosion of metals and protection. International Journal of Engineering Science & Advanced Technology. 2012;2(3):637-644. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=52d9b8f53fef6032c14ba1f3ccd93e893b825301

[99] Panahi H, Eslami A. An Investigation on Corrosion and Stress Corrosion Cracking initiation of a Ferritic Stainless Steel in a Tertiary Amine Solution. Journal of Chemical and Petroleum Engineering. 2019 Dec 1;53(2):203-210. https://doi.org/10.22059/jchpe.2019.271003.1258

[100] White L. Selective Leaching: Prevention and Testing. Technical Report. Degradation and Surface Engineering. 2015 Dec.

[101] Melchers RE. Mathematical modelling of the diffusion controlled phase in marine immersion corrosion of mild steel. Corrosion science. 2003 May 1;45(5):923-940. https://doi.org/10.1016/S0010-938X(02)00208-1

[102] Melchers RE, Jeffrey R. Early corrosion of mild steel in seawater. Corrosion Science. 2005 Jul 1;47(7):1678-1693. https://doi.org/10.1016/j.corsci.2004.08.006

[103] Pineau S, Sabot R, Quillet L, Jeannin M, Caplat C, Dupont-Morral I, Refait P. Formation of the Fe (II–III) hydroxysulphate green rust during marine corrosion of steel associated to molecular detection of dissimilatory sulphite-reductase. Corrosion Science. 2008 Apr 1;50(4):1099-1111. https://doi.org/10.1016/j.corsci.2007.11.029

[104] Boudaud N, Coton M, Coton E, Pineau S, Travert J, Amiel C. Biodiversity analysis by polyphasic study of marine bacteria associated with biocorrosion phenomena. Journal of

applied microbiology. 2010 Jul 1;109(1):166-179. https://doi.org/10.1111/j.1365-2672.2009.04643.x

[105] Usher KM, Kaksonen AH, MacLeod ID. Marine rust tubercles harbour iron corroding archaea and sulphate reducing bacteria. Corrosion Science. 2014 Jun 1;83:189-197. https://doi.org/10.1016/j.corsci.2014.02.014

[106] Lanneluc I, Langumier M, Sabot R, Jeannin M, Refait P, Sablé S. On the bacterial communities associated with the corrosion product layer during the early stages of marine corrosion of carbon steel. International Biodeterioration & Biodegradation. 2015 Apr 1;99:55-65. https://doi.org/10.1016/j.ibiod.2015.01.003

[107] Stipanicev M, Turcu F, Esnault L, Rosas O, Basseguy R, Sztyler M, Beech IB. Corrosion of carbon steel by bacteria from North Sea offshore seawater injection systems: Laboratory investigation. Bioelectrochemistry. 2014 Jun 1;97:76-88. https://doi.org/10.1016/j.bioelechem.2013.09.006

[108] Rlinger MI, Samokhvalov AA. Electron conduction in magnetite and ferrites. physica status solidi (b). 1977 Jan 1;79(1):9-48. https://doi.org/10.1002/pssb.2220790102

[109] Lopez Maldonado KL, De La Presa P, De La Rubia MA, Crespo P, De Frutos J, Hernando A, Matutes Aquino JA, Elizalde Galindo JT. Effects of grain boundary width and crystallite size on conductivity and magnetic properties of magnetite nanoparticles. Journal of nanoparticle research. 2014 Jun 17;16(2482):1-12. https://doi.org/10.1007/s11051-014-2482-3

[110] Dong ZH, Shi W, Ruan HM, Zhang GA. Heterogeneous corrosion of mild steel under SRB-biofilm characterised by electrochemical mapping technique. Corrosion Science. 2011 Sep 1;53(9):2978-2987. https://doi.org/10.1016/j.corsci.2011.05.041

[111] Enning D, Venzlaff H, Garrelfs J, Dinh HT, Meyer V, Mayrhofer K, Hassel AW, Stratmann M, Widdel F. Marine sulfate-reducing bacteria cause serious corrosion of iron under electroconductive biogenic mineral crust. Environmental microbiology. 2012 Jul;14(7):1772-1787. https://doi.org/10.1111/j.1462-2920.2012.02778.x

[112] Refait P, Grolleau AM, Jeannin M, François E, Sabot R. Localized corrosion of carbon steel in marine media: Galvanic coupling and heterogeneity of the corrosion product layer. Corrosion Science. 2016 Oct 1;111:583-595. https://doi.org/10.1016/j.corsci.2016.05.043

[113] Ezzati M, Gélinas YA. Methodological Study on the Analysis of Organic Matter Associated with Iron Oxides in Marine Sediments. Applied Geochemistry. 2025 Jan 22;180:106295. https://doi.org/10.1016/j.apgeochem.2025.106295

[114] Cornell RM, Schwertmann U. The iron oxides: structure, properties, reactions, occurrences, and uses. Weinheim: Wiley-vch; 2003 Oct 17;664. https://doi.org/10.1515/CORRREV.1997.15.3-4.533

[115] Antunes RA, Costa I, Faria DL. Characterization of corrosion products formed on steels in the first months of atmospheric exposure. Materials research. 2003 Jun;6(3):403-408. https://doi.org/10.1590/S1516-14392003000300015

[116] Abdulsada SA, Al-Mosawi AI. Analysis of corrosion rate, inhibition efficiency, and economic cost of XD3 reinforced concrete related to inhibitor and plasticiser types. Engineering Research Express. 2023 Aug 17;5(3):035032. https://doi.org/10.1088/2631-8695/acee46

[117] Wang R, Chu G, Zhang J, Liu R, Wang Y, Sun L, Cao Z, Song L, Ma F. Influence of stress on corrosion behavior and evolution model of Q235 steel in marine environments.

International Journal of Pressure Vessels and Piping. 2025 Apr 1;214:105388. https://doi.org/10.1016/j.ijpvp.2024.105388

[118] Oh SJ, Cook DC, Townsend HE. Characterization of iron oxides commonly formed as corrosion products on steel. Hyperfine interactions. 1998 Dec;112(1):59-66. https://doi.org/10.1023/A:1011076308501

[119] Ding K, Cheng W, Zhang P, Guo W, Fan L, Xu L, Hou J. Study on corrosion behavior of typical carbon steel and low alloy steel in deep sea of different sea areas. Corrosion Reviews. 2024 Feb 26;42(1):75-83. https://doi.org/10.1515/corrrev-2022-0113

[120] Pornpibunsompob T, Saidarasamoot S, Phabjanda S, Pornyungyuen T, Gositanon A, Chalermboon S, Nakaracha P. Corrosion of Low Carbon Steel in Chloride Containing Environment. ASEAN Journal of Scientific and Technological Reports. 2022 Nov 20;25(4):21-29. https://doi.org/10.55164/ajstr.v25i4.247174

[121] Thalib S, Ikhsan M, Fonna S, Huzni S, Ridha S. Identification of corrosion product on medium carbon steel under the exposure of Banda Aceh's atmosphere. In IOP Conference Series: Materials Science and Engineering 2018 May 1;352(1):012004. http://doi.org/10.1088/1757-899X/352/1/012004

[122] Kumar V, Sharma N, Tiwari SK, Kango S. Atmospheric corrosion of materials and their effects on mechanical properties: A brief review. Materials Today: Proceedings. 2021 Jan 1;44(6):4677-4681. https://doi.org/10.1016/j.matpr.2020.10.939

[123] Gao J, Wang N, Chen H, Xu X. The Influence of 1 wt.% Cr on the corrosion resistance of low-alloy steel in marine environments. Metals. 2023 May 30;13(6):1050. https://doi.org/10.3390/met13061050

[124] Wang D, Li Y, Li Z, Zhang L, Zhang Q, Dong H, Zhang J. Corrosion behaviour and mechanical property degradation of Q355b steel under coupled environmental loads. KSCE Journal of Civil Engineering. 2025 Jun 1;29(6):100119. https://doi.org/10.1016/j.kscej.2024.100119

[125] Alcántara J, Chico B, Simancas J, Díaz I, De la Fuente D, Morcillo M. An attempt to classify the morphologies presented by different rust phases formed during the exposure of carbon steel to marine atmospheres. Materials Characterization. 2016 Aug 1;118:65-78. https://doi.org/10.1016/j.matchar.2016.04.027

[126] Song Y, Jiang G, Chen Y, Zhao P, Tian Y. Effects of chloride ions on corrosion of ductile iron and carbon steel in soil environments. Scientific reports. 2017 Jul 31;7(1):6865. https://doi.org/10.1038/s41598-017-07245-1

[127] Cui Y, Liu S, Smith K, Yu K, Hu H, Jiang W, Li Y. Characterization of corrosion scale formed on stainless steel delivery pipe for reclaimed water treatment. Water Research. 2016 Jan 1;88:816-825. https://doi.org/10.1016/j.watres.2015.11.021

[128] Qi G, Qin X, Xie J, Han P, He B. Electrochemical corrosion behaviour of four low-carbon steels in saline soil. RSC advances. 2022;12(32):20929-20945. https://doi.org/10.1039/D2RA03200G

[129] Rao P, Mulky L. Microbially influenced corrosion and its control measures: A critical review. Journal of Bio-and Tribo-Corrosion. 2023 Jun 26;9(57). https://doi.org/10.1007/s40735-023-00772-7

[130] Solomon MM, Umoren SA. Enhanced corrosion inhibition effect of polypropylene glycol in the presence of iodide ions at mild steel/sulphuric acid interface. Journal of environmental chemical engineering. 2015 Sep 1;3(3):1812-1826, https://doi.org/10.1016/j.jece.2015.05.018

[131] Singh P, Srivastava V, Quraishi MA. Novel quinoline derivatives as green corrosion inhibitors for mild steel in acidic medium: electrochemical, SEM, AFM, and XPS studies. Journal of Molecular Liquids. 2016 Apr 1;216:164-173, https://doi.org/10.1016/j.molliq.2015.12.086

[132] Verma C, Ebenso EE, Quraishi MA. Corrosion inhibitors for ferrous and non-ferrous metals and alloys in ionic sodium chloride solutions: A review. Journal of Molecular Liquids. 2017 Dec 1;248:927-942. https://doi.org/10.1016/j.molliq.2017.10.094

[133] Kelly RG, Scully JR, Shoesmith D, Buchheit RG. Electrochemical techniques in corrosion science and engineering. CRC Press; 2002 Sep 13. https://doi.org/10.1201/9780203909133

[134] Chitra S, Parameswari K, Sivakami C, Selvaraj A. Sulpha Schiff Bases as corrosion inhibitors for mild steel in 1M sulphuric acid. Chemical Engineering Research Bulletin. 2010 Feb 7;14(1):1-6. https://doi.org/10.3329/cerb.v14i1.3766

[135] Bentiss F, Lagrenee M, Traisnel M, Hornez JC. The corrosion inhibition of mild steel in acidic media by a new triazole derivative. Corrosion science. 1999 Apr 1;41(4):789-803. https://doi.org/10.1016/S0010-938X(98)00153-X

[136] Jasim ZI, Rashid KH, AL-Azawi KF, Khadom AA. Synthesis of schiff-based derivative as a novel corrosion inhibitor for mild steel in 1 M HCl solution: optimization, experimental, and theoretical investigations. Journal of Bio-and Tribo-Corrosion. 2023 Jun 20;9(54).https://doi.org/10.1007/s40735-023-00774-5

[137] El-Rehim SA, Refaey SA, Taha F, Saleh MB, Ahmed RA. Corrosion inhibition of mild steel in acidic medium using 2-amino thiophenoland 2-cyanomethyl benzothiazole. Journal of Applied Electrochemistry. 2001 Apr;31:429-435. https://doi.org/10.1023/A:1017592322277

[138] El Azhar M, Mernari B, Traisnel M, Bentiss F, Lagrenée M. Corrosion inhibition of mild steel by the new class of inhibitors [2, 5-bis (n-pyridyl)-1, 3, 4-thiadiazoles] in acidic media. Corrosion Science. 2001 Dec 1;43(12):2229-2238. https://doi.org/10.1016/S0010-938X(01)00034-8

[139] Samide A, Bibicu I, Rogalski MS, Preda M. Study of the corrosion inhibition of carbon-steel in dilute ammoniacal media using N-ciclohexil-benzothiazole-sulphenamida. Corrosion science. 2005 May 1;47(5):1119-1127. https://doi.org/10.1016/j.corsci.2004.06.018

[140] Mohammed RA, Hussein SZ. Corrosion inhibition of carbon steel in saline water using an azo dye at various concentrations. Int. J. Corros. Scale Inhib. 2024;13(1):241-253. https://dx.doi.org/10.17675/2305-6894-2024-13-1-12

[141] Ali N, Fonna S, Nurdin N, Saputra Y, Arifin AK. Assessment of Syzygium cumini (Jamblang) fruit extract as an eco-friendly corrosion inhibitor for low-carbon steel in 3.5% NaCl medium. Int. J. Corros. Scale Inhib. 2024;13:223-240. http://doi:/10.17675/2305-6894-2024-13-1-11

[142] Francis SM, Venugopal T. Investigation of biocorrosion on mild steel in cooling tower water and its inhibition by C. sativum. AIMS Molecular Science. 2024 Oct 1;11(4):395–414. https://doi.org/10.3934/molsci.2024024

[143] Royani A, Hanafi M, Mubarak NM, Priyotomo G, Aigbodion VS, Musabikha S, Manaf A. Unveiling green corrosion inhibitor of Aloe vera extracts for API 5L steel in seawater environment. Scientific reports. 2024 Jun 18;14(1):14085. https://doi.org/10.1038/s41598-024-64715-z

[144] Namus RM, Abass MH, Alali M, Zedin NK. Using green corrosion inhibitor to reduce maintenance cost for carbon steel saline water storage systems in the oil industry. Koroze a Ochrana Materiálu. 2024;68(1):43-50. https://doi.org/10.2478/kom-2024-0005

[145] Crisan M, Muntean C, Chumakov Y, Plesu N. Investigating the corrosion inhibition mechanisms of alkanolammonium salts: a case study with ethylethanolammonium 4-nitrobenzoate on carbon steel in saline solution. Applied Sciences. 2024 Feb 23;14(5):1832. https://doi.org/10.3390/app14051832

[146] Moura MJ, Vasques RB, Levy MM, Magalhães SJ, Pascoal CV, Almeida-Neto FW, Lima-Neto P, Medeiros SL, Salomão FC, Barros EB, Araújo WS. Study of the Efficiency of the Amino Acid L-Histidine as a Corrosion Inhibitor of 1018 Carbon Steel in Saline Solution Without and with CO 2 Saturation. Materials Research. 2024 May 31;27:e20240135. https://doi.org/10.1590/1980-5373-MR-2024-0135

[147] Mahmood M, Shihab M. New organic ammonium salts as corrosion inhibitors for mild steel in saline solution. Egyptian Journal of Chemistry. 2024 Mar 1;67(3):209-214. https://doi.org/10.21608/ejchem.2023.227330.8369

[148] Royani A, Hanafi M, Haldhar R, Manaf A. Evaluation of Morinda citrifolia extract as sustainable inhibitor for mild steel in saline environment. Journal of Engineering Research. 2024 Sep 1;12(3):321-327. https://doi.org/10.1016/j.jer.2024.01.013

[149] Husseini M, Latief BH, Khudhair NA, Huseeni MD, Al-Saadi FA. Investigation of Corrosion Inhibition of Carbon Steel by Using Natural Iraqi Plum Tree Gum in a Saline Medium. Iraqi Journal of Science. 2024 Oct 30:5349-5356. https://doi.org/10.24996/ijs.2024.65.10.1

[150] Messali M, Almutairi SM, Ait Mansour A, Salghi R, Lgaz H. Exploring the mechanisms of eco-friendly pyridinium ionic liquids for corrosion inhibition of carbon steel in saline mediums: Unveiling deeper understanding through experimental and computational approaches. Journal of Materials Research and Technology. 2023 Nov 1;27:8292-8307. https://doi.org/10.1016/j.jmrt.2023.11.219

[151] De Ketelaere E, Moed D, Vanoppen M, Verliefde AR, Verbeken K, Depover T. Sodium silicate corrosion inhibition behaviour for carbon steel in a dynamic salt water environment. Corrosion Science. 2023 Jun 1;217:111119. https://doi.org/10.1016/j.corsci.2023.111119

[152] Ekere IE, Agboola O, Fayomi SO, Ayeni AO, Ayodeji A. Investigation of corrosion inhibition by Cassava leaf DNA on AISI 1015 low carbon steel in sodium chloride solution. Int J Corros Scale Inhib. 2023;12:424-437. https://doi.org/10.17675/2305-6894-2023-12-2-3

[153] Al-Mashhadani HA, Alshujery MK, Khazaal FA, Salman AM, Kadhim MM, Abbas ZM, Farag SK, Hussien HF. Anti-corrosive substance as green inhibitor for carbon steel in saline and acidic media. In Journal of Physics: Conference Series. 2021 Mar 1;1818(1):012128. https://doi.org/10.1088/1742-6596/1818/1/012128

[154] Hu J, Xiong Q, Chen L, Zhang C, Zheng Z, Geng S, Yang Z, Zhong X. Corrosion inhibitor in CO2-O2-containing environment: Inhibition effect and mechanisms of Bis (2-ehylhexyl) phosphate for the corrosion of carbon steel. Corrosion Science. 2021 Feb 1;179:109173. https://doi.org/10.1016/j.corsci.2020.109173

[155] Mahalakshmi P, Rajendran S, Nandhini G, Joycee SC, Vijaya N, Umasankareswari T, Renuga DN. Inhibition of corrosion of mild steel in sea water by an aqueous extract of turmeric powder. International Journal of Corrosion and Scale Inhibition. 2020;9(2):706-725. https://doi.org/10.17675/2305-6894-2020-9-2-20

[156] Cotting F, Aoki IV. Octylsilanol and Ce (III) ions–alternative corrosion inhibitors for carbon steel in chloride neutral solutions. Journal of Materials Research and Technology. 2020 Jul 1;9(4):8723-8734. https://doi.org/10.1016/j.jmrt.2020.06.011

[157] Mohammed MA, Kubba RM. Experimental Evaluation for the inhibition of carbon steel corrosion in salt and acid media by new derivative of quinolin-2-one. Iraqi Journal of Science. 2020 Aug 28:1861-1873. http://doi.org/10.24996/ijs.2020.61.8.2

[158] Moreira RR, Soares TF, Ribeiro J. Electrochemical investigation of corrosion on AISI 316 stainless steel and AISI 1010 carbon steel: study of the behaviour of imidazole and benzimidazole as corrosion inhibitors. Advances in Chemical Engineering and Science. 2014 Sep 17;4(4):503-514. http://dx.doi.org/10.4236/aces.2014.44052

[159] Rivera-Grau LM, Casales M, Regla I, Ortega-Toledo DM, Gonzalez-Rodriguez JG, Gomez LM. CO_2 Corrosion inhibition by imidazoline derivatives based on coconut oil. International Journal of Electrochemical Science. 2012 Dec 1;7(12):13044-13057. https://doi.org/10.1016/S1452-3981(23)16607-7