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Comprehensive Review on Carbon Steels Corrosion in Chloride-Rich Media

Shaymaa H. Khazaal, Hasan F. Makki *

1. Department of Chemical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq. E-mail: shaimaa.hasan2107m@coeng.uobaghdad.edu.iq
   Department of Applied Chemistry, College of Applied Sciences, University of Technology, Baghdad, Iraq. E-mail: Shaymaa.H.AlKhasraji@uotechnology.edu.iq
2. Department of Chemical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq. E-mail: drhasanf.m@coeng.uobaghdad.edu.iq

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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, beginning with an examination of corrosion mechanisms and factors that influence corrosion, as well as the types of corrosion and the primary corrosion products (rust). It also explores the primary methods used to study and monitor corrosion (non-electrochemical and electrochemical techniques), ranging 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, which accelerates metal degradation. This review also presents previous studies on corrosion in chloride-rich waters. It evaluates the effectiveness of various inhibitors in controlling corrosion, thereby contributing to the development of efficient protective solutions for metals under harsh, aggressive conditions.

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, polluting ecosystems and contaminating the food chain. Moreover, infrastructure deterioration can lead to hazardous leaks, compromising water quality and posing immediate health risks. Corrosion is not only a matter of material degradation; it also poses significant environmental and public health risks.

The corrosion of metals has a significant impact on several industrial sectors [1–5]. Metals, such as steels and alloys, have been widely utilized in industrial and technical applications. Moreover, metals are used in the offshore petroleum, power generation, nuclear energy, aerospace, shipping, and building industries [6–11]. Corrosion is the irreversible deterioration of a metal surface resulting from chemical reactions in which pure metal is converted into more chemically stable forms, such as metal oxides, hydroxides, or oxyhydroxides, in a corrosive environment. These environments can exist in solid, liquid, or gaseous states and are commonly

* Corresponding Author: H.F. Makki (E-mail address: drhasanf.m@coeng.uobaghdad.edu.iq)

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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 $6.5 billion. At the same time, direct waste in the United States accounts for approximately 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 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, chipped, deformed), are an appropriate choice for use in the manufacture of different parts of machines, accessories of fall arrest systems such as carabiners, hooks, and pythons, vehicle bodies, shipbuilding, or in use in buildings, bridges, rails, water, gas, and industrial pipes, cooling tower parts [20-31].

This study focuses on carbon steels with carbon at or below ~0.35% to facilitate welding. Subsequent differentiation can be based on carbon content. Low-carbon steels (containing fewer than 0.15% carbon) have insufficient carbon to harden and are commonly used for 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 heat-treated (quenching and tempering) to attain greater strength; however, this review focuses mainly on compositions below 0.35% carbon [32]. CS may become corroded during industrial operations; thus, corrosion inhibition is sometimes crucial for safe, economical operations, enabling prolonged use of CS. This review examines CS as the most suitable alloy for pipeline construction to transport water, oil, and gas. The majority of corrosion problems in the water, oil, and gas industries are related to pipelines and their exposure environments, which determine the appropriate CS type. This article presents an in-depth examination of the corrosion characteristics of CS in saline solutions, focusing on the fundamental electrochemical processes, key influencing variables, and various experimental methodologies used to assess corrosion rates. Furthermore, it analyzes multiple mitigation measures, including the use of corrosion inhibitors. This study reviews recent research to identify contemporary challenges, knowledge gaps, and emerging trends in corrosion science. The insights provided aim to enhance the effectiveness and sustainability of corrosion prevention techniques, particularly in the shipping, industrial, and oil and gas sectors.

Corrosion Mechanism

Corrosion is characteristic 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 oxidized to its corresponding cation by losing electrons.

$$M \rightarrow M + ne^{-} \quad (1)$$

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.

By Hydrogen Evolution

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

$$2H^{+} + 2e^{-} \rightarrow H_2(gas) \quad (2)$$

For example, Fe metal reaction at anode:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (3)$$

And reaction at the cathode:

$$2H_2O + 2e^{-} \rightarrow H_2\ (gas) \quad (4)$$

Overall cell reaction:

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

By Absorption of Oxygen

It is the corrosion process involving the absorption of oxygen. This typically occurs in a neutral liquid, with NaCl serving as the conducting medium, as shown in Fig. 1, where O_2 is absorbed to produce OH^- ions.

$$\frac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \quad (6)$$

For example, at the anode, the carbon steel reaction is:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (7)$$

and at the cathode is:

$$\frac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \quad (8)$$

Overall reaction:

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

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2 \quad (9)$$

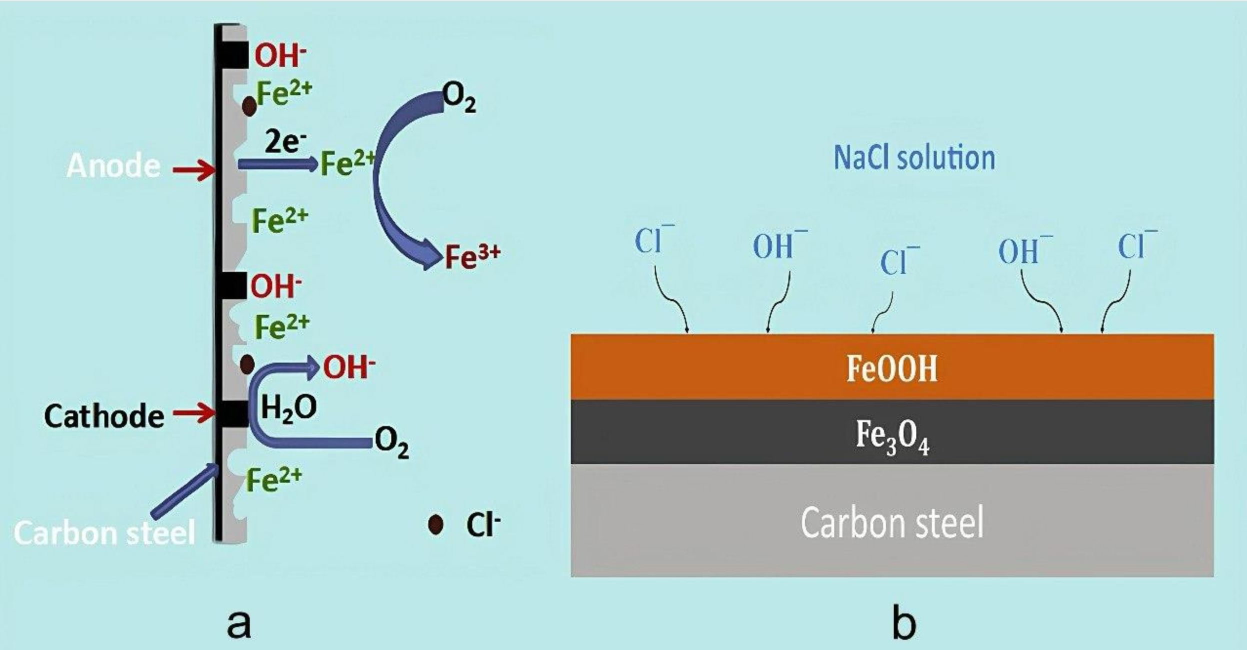

Fig. 1. Schematic representation of carbon steel immersed in NaCl solution (a) Mechanism [36], and (b) Corrosion layer formation on the steel's surface

Factors Affecting the 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 factors influencing corrosion include metal purity, surface coating characteristics, properties of the corrosive product, temperature, dissolved salt concentration, air humidity, and electrolyte pH.

Nature of Alloy or Metal

It further depends upon:

Galvanic Series Position

When different metals are electrically connected in a specific electrolyte, the metal with the higher oxidation potential (i.e., 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 illustrated in Fig. 3. For example, in the presence of copper and cast iron in the same electrolytic medium, the cast iron corrodes first. In contrast, the copper remains protected from corrosion.

Purity of Alloy or Metal

The corrosion rate typically increases with rising impurity levels. This occurs because impurities form small electrochemical cells in which the anodic component corrodes. For instance, zinc with impurities such as iron or lead exhibits accelerated corrosion.

Nature of the Surface Film

A thin layer of oxides forms on the surfaces of all metals in an aerated environment. 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.

Nature of Corrosion Product

The corrosion rate accelerates when the corrosion product is soluble in the corrosive medium, as this allows the reaction to continue at the metal surface. The volatile product evaporates immediately after formation, exposing the metal to further attack and thereby increasing the rate of rust formation.

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 traits [37-39]. Nevertheless, the high energy and chemical reactivity of grain boundaries result in a higher density of these boundaries, which enhances surface reactivity by improving electron activity and diffusion, thereby influencing corrosion resistance. Enhanced corrosion resistance extends the 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.

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; however, 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 through higher 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 the critical humidity, is exceeded, as the iron oxide layer's ability to absorb atmospheric humidity enhances electrochemical corrosion. The available moisture provides the metal surface with the electrolyte needed to form an effective electrochemical cell, thereby accelerating oxidation and recovery reactions at the metal interface.

Effect of dissolved salts in media: The corrosion rate initially increases with increasing salt content, then gradually decreases to a value lower than that 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, depending on their ability to alter the properties of the oxide layer and the ion conductivity in solution [47].

Effect of pH in media: pH is the most critical factor in determining corrosion rate; a decrease in pH is usually accompanied by a significant increase in corrosion rate, indicating that acidic media (pH below 7) 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, 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 has been established that oxygen, under specific conditions (in high-purity water) and at elevated temperatures, can form a thick, protective coating of metal oxides on the metal surface, thereby reducing corrosion [49].

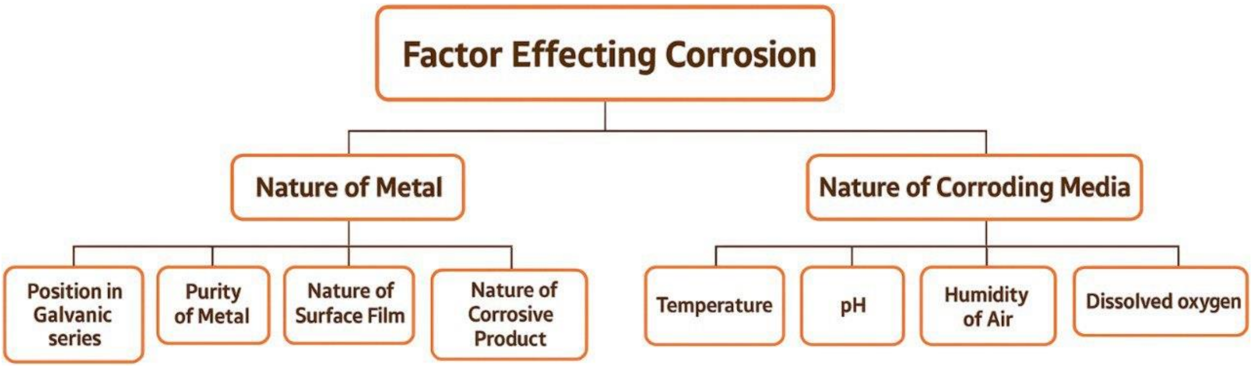

Fig. 2. Some of the factors affecting the corrosion process

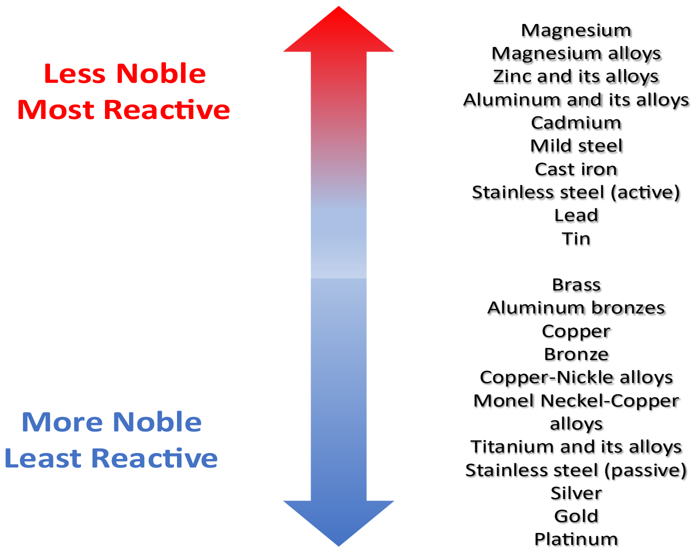

Fig. 3. Corrosion susceptibility of the metal

Methods for Studying Corrosion

Non-Electrochemical Technique (Weight Loss Method)

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

$$Corrosion\ rate = \frac{K\ W}{D \times T \times A} \quad (10)$$

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 unit for denoting corrosion rate is millimeters per year (mm/y) or inches per year (in/y). Table 1 illustrates the corrosion resistance classification of CS.

Table 1. The comparison of the corrosion resistance 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 measured the corrosion rate of different types of carbon steel in different chloride media at 25 °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	Ref.
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]

Electrochemical Techniques for Studying Corrosion of Carbon Steel

The most commonly employed electrochemical techniques are the potentiodynamic polarization technology (Tafel) combined with electrochemical impedance spectroscopy (EIS) [59, 60]. The primary benefit of electrochemical methods, beyond weight-loss techniques, is the ability to obtain additional information on corrosion mechanisms. Electrochemical procedures are typically conducted in a three-electrode setup comprising 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 flow rate. Electrochemical analysis is an efficient, rapid, and straightforward method [62]. Potentiodynamic polarization yields several electrochemical characteristics, including corrosion potential (Ecorr.), corrosion current density (Icorr.), anodic slope (βa), and cathodic slope (βc). Electrochemical impedance spectroscopy can accurately estimate corrosion rate with minimal impact on the electrode. Various electrochemical techniques are available to assess the extent of corrosion in metals and the efficiency and mechanisms of corrosion inhibitors.

Potentiodynamic Polarization (Tafel)

The potentiodynamic polarization technique is widely employed, consisting of applying a polarization current density and measuring the resulting 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 curve is excessively steep, significant deviations occur, preventing the formation of a standard potentiodynamic polarization curve. Fig. 4 shows a potentiodynamic polarization curve.

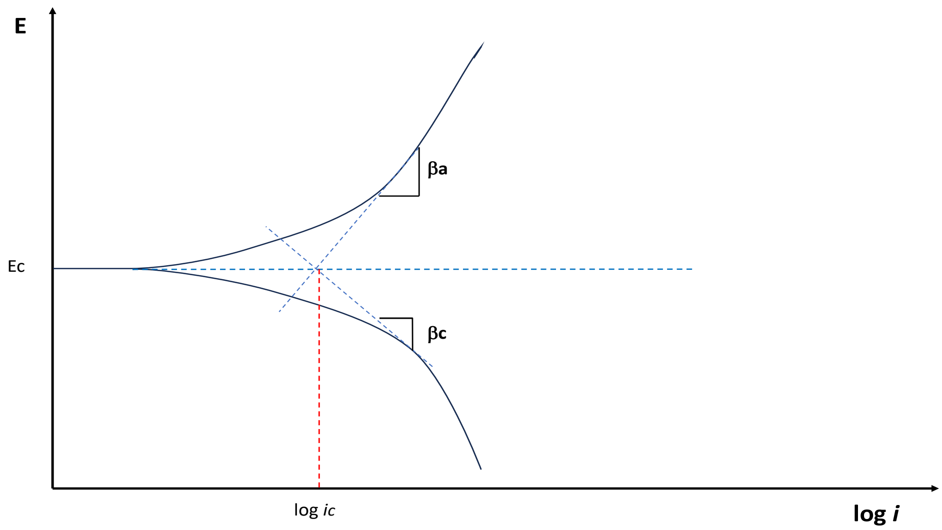

Fig. 4. Potentiodynamic polarization curve diagram

Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) quantifies the impedance of an electrode system over an extensive frequency range, employing a small-amplitude sinusoidal potential as the perturbation signal to achieve a nearly linear relationship between the system's response and the perturbation. EIS is a prevalent testing method that has little effect on the electrode surface condition. Consequently, it is widely used in scientific research and constitutes a significant methodology for electrochemical testing [65, 66]. In the analogous circuit, R_s denotes the resistance of the electrolyte solution between the working electrode and the reference electrode, Rct denotes the charge-transfer resistance associated with the corrosion process at the metal-electrolyte interface, and CPE denotes the constant phase element. In corrosion science, EIS provides data on corrosion resistance, variations in electrode surface roughness, adsorption of corrosion inhibitors, and the formation of corrosion products. In contrast to other conventional electrochemical techniques, such as potentiodynamic polarization curves, EIS provides enhanced insights into corrosion kinetics, as shown in Fig. 5.

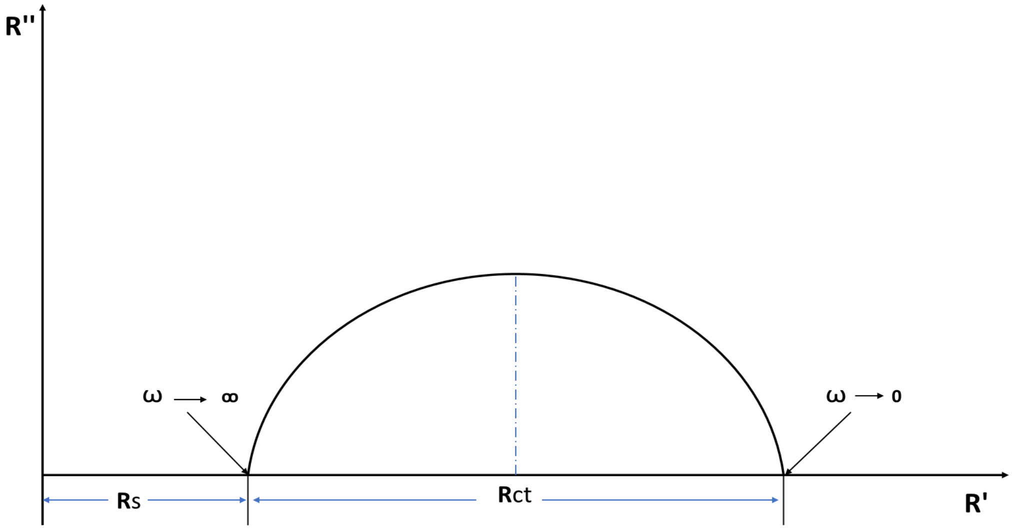

Fig. 5. Schematic diagram of electrochemical impedance spectroscopy

Surface Characterization Techniques

This section examines surface analytical methods for characterizing carbon steel surfaces, both treated and untreated (e.g., corrosion inhibitors), in corrosive environments. The discussion addresses aspects that affect the use of specific approaches in carbon-steel corrosion research, including high surface roughness under corrosive conditions [67].

Scanning Electrochemical Microscopy (SEM)

Employing scanning electron microscopy (SEM), an accurate imaging technique that provides high-resolution images of metallic surfaces, enables a comprehensive examination of corrosion, protective films, and the underlying metal substrates [68, 69]. This approach involves directing an electron beam at a sample, which produces secondary electrons via 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 applications in environmental chambers, both high- and low-vacuum environments, and the investigation of corrosion processes under various conditions [71]. SEM can be used in conjunction with multiple techniques, such as X-ray spectroscopy, to chemically analyze corrosion products and determine the type of corrosion and its source. SEM is a crucial tool for examining corrosion, as it can potentially identify localized corrosion sites and provide data on the concentration of active corrosion species, thereby advancing the understanding of localized corrosion in specific areas. It also provides valuable insights 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 using SEM.

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 of 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 uses a high-energy, concentrated electron beam to examine materials, revealing physical information about the specimen's surface topography. This technique is frequently employed to ascertain crystal structure, shape, dimensions, and distribution. Backscattered SEM images are used to assess the interface composition. SEM/EDX is a method that offers an optical representation of a surface together with the elemental composition of selected regions [72-76].

Atomic Force Microscopy (AFM)

Atomic force microscopy enables the examination of surface topography, including measurements of surface roughness. Assessing the adhesion of an inhibitor or corrosive coating on a substrate (metal or alloy) using topographical imaging alone has consistently posed challenges. Moreover, capturing topographical photos might be challenging due to the irregular film development. Consequently, AFM current images and force-distance curves are used to provide further insights into the characteristics of surface layers, including the adhesion of corrosion inhibitors and coatings [77, 78]. AFM can operate under various liquid conditions and enables real-time surface monitoring in corrosive environments [79, 80].

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; however, its traditional application suffers from a low signal-to-noise ratio, which can lead to inaccurate conclusions about phase evolution. This challenge is exacerbated when analyzing thin films—such as corrosion inhibitor layers—on carbon steel, as surface roughness in corrosive environments reduces 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, which reduces peak broadening at low angles of incidence. Additionally, it features high brightness, high intensity, tight collimation, and low emission polarization, 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, carbon steel forms iron carbonate as a by-product, which may oxidize 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].

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 characterize the composition of metal surfaces, particularly 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 corrosion product layer [84]. The presence of iron in both metallic and oxidized states was associated with the formation of oxides, as confirmed by Raman spectroscopy and X-ray diffraction. 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].

Raman Spectroscopy (IR)

Raman spectroscopy (IR) has been recognized as a crucial surface characterization technique for corrosion investigations, applicable to assessing both single-layer and multilayer surface properties. Raman spectroscopy provides insights into surface interactions (vibrational data), thereby offering structural information regarding the contact between the metal substrate and corrosion inhibitor [87].

Fourier Transform Infrared Spectroscopy (FTIR)

Unique molecular fingerprints can be generated from the absorption and transmission of infrared light. The quality and quantity of individual components in samples may be determined using FTIR. IR, a dispersive IR method, was employed in previous investigations. Currently, FTIR is widely used for its several benefits, including accurate measurements, rapid data collection, high sensitivity, non-destructive analysis, and the absence of external calibration. Conventional FTIR, typically measured in the mid-IR, has been widely used to study surface coatings on CS substrates. The presence or absence of specific bands of the corrosion inhibitor molecule correlates with the molecule's orientation on the CS surface and/or within the inhibitor film. This helps in understanding how corrosion inhibitors adsorb on steel surfaces [88].

To evaluate metal and alloy corrosion, monitoring color changes in electrolyte solutions is a simple method; however, alternative approaches, such as the Standard Immersion Test (SIT), should also be considered for more accurate results. Fig. 6 illustrates the flowchart of the SIT-based experimental approach. At the conclusion of the SIT, the corrosion behavior of metals subjected to corrosive solutions is assessed by measuring the corrosion rate (mm/y).

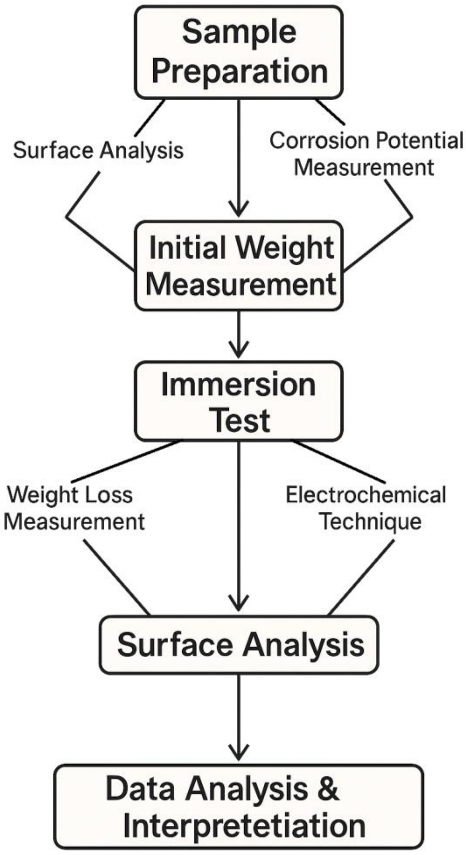

Fig. 6. Flowchart of an experimental methodology employed to examine corrosion behavior of steels

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, which depend on the environment, substrate type, or chemical procedure.

General Corrosion

It is also known as uniform corrosion, distinct from dry corrosion; this type of corrosion uniformly degrades the metal's untreated surface. 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 primary materials susceptible to general corrosion are steel and cast iron. When subjected to a humid environment, they exhibit a rust-like appearance.

Intergranular Corrosion

Intergranular corrosion is highly pertinent to the brewing industry. It involves a localized attack in which a restricted pathway is preferentially corroded along a metal's grain boundaries. This form of corrosion can significantly affect mechanical properties, leading to reductions in strength and ductility.

Galvanic Corrosion

Galvanic corrosion typically occurs when two dissimilar conductive materials are electrically connected and exposed 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.

Pitting Corrosion

Pitting corrosion is considered more hazardous than uniform corrosion damage due to its challenging detection, prediction, and mitigation in design and construction. 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].

Crevice Corrosion

Localized corrosion is a type of corrosion. 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. Crevices occur at flanges, deposits, washers, the ends of rolled tubes, and threaded connections, as shown in Fig. 8 [98].

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.

Stress Corrosion Cracking (SCC)

It denotes cracking caused by the simultaneous presence of tensile stress and a corrosive environment. The influence of SCC on a material often occurs between dry cracking and the material's fatigue threshold [99].

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 typical instance is the selective extraction of zinc from brass alloy, known as dezincification, as shown in Fig. 8 [100].

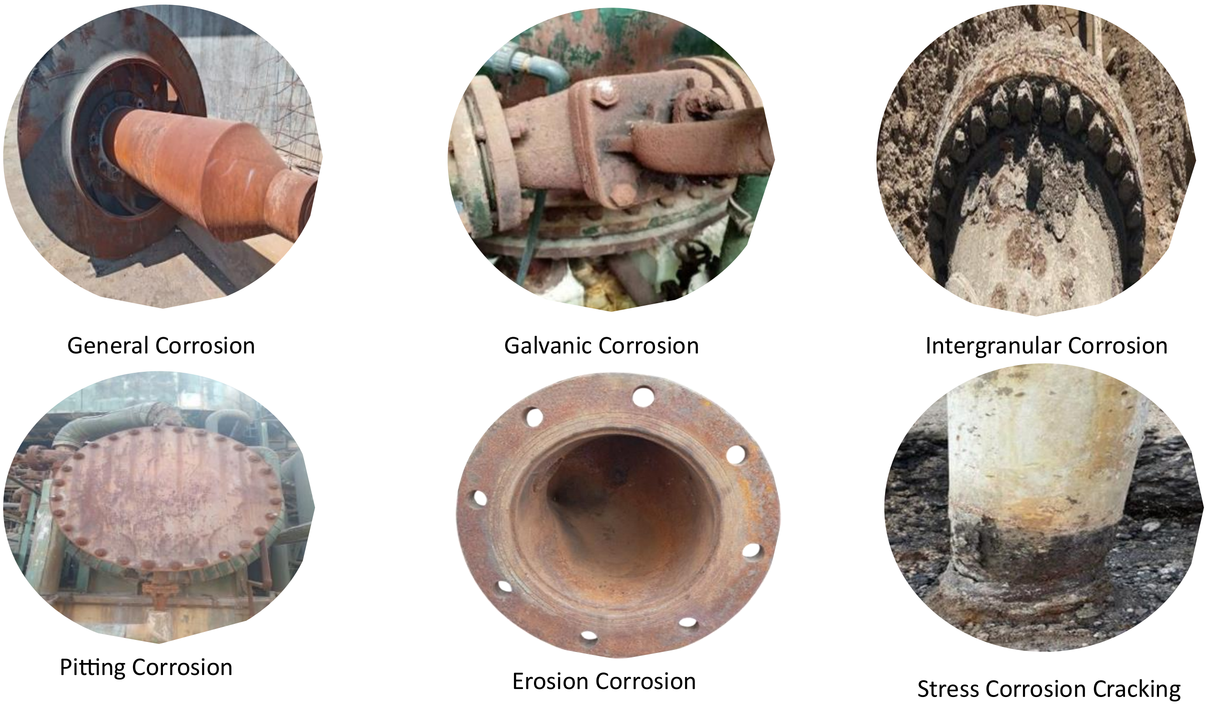

Fig. 7. Different corrosion patterns in carbon steel manufactured parts as observed at the thermal power station and refinery of Al-Dora-Baghdad, Iraq

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

Types of Corrosion Product Produced 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 habitat for microorganisms present in a particular environment [103-107]. Thirdly, some phases serve as electronic conductors, such as magnetite [108, 109] and iron sulfides [110, 111], thereby enhancing the performance of galvanic cells. The composition of the corrosion product layer varies with the exposure zone and may change 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 by region (anodic and cathodic), thereby actively maintaining corrosion cells and promoting localized corrosion processes [112].

Many research investigations have been conducted on corrosion products formed in various atmospheres using XRD and IR. The corrosion product of CS typically consists of crystalline iron oxides, hydroxides, and oxide-hydroxides [113, 114]. The shape and dimensions of the crystals formed depend on the conditions under which they are made. The chemical composition [115-121] and morphologies of the solid corrosion products were examined based on the characteristics listed in Table 3. Some of the 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, bird nests, 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, donut-like, Black circular rings.
Magnetite	Fe_3O_4	Cubic	-
Wustite	FeO	Cubic	-

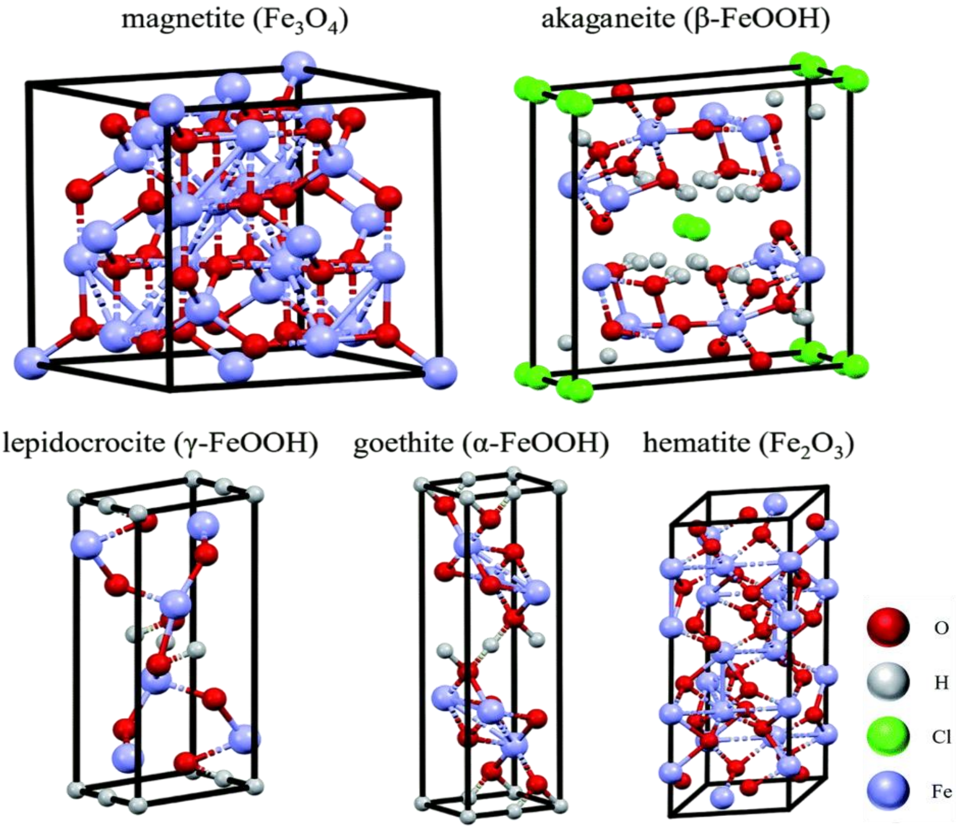

Fig. 9. Some of the crystal cellس of carbon steel corrosion [128]

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 various chemical industries, including oil extraction and processing. The use of corrosion inhibitors in the system minimizes corrosion or slows the oxidation rate of the metal [134]. Inhibition is a method that prevents damage caused by corrosive substances by adsorbing inhibitors onto the entire metallic substrate [135, 136].

Inhibitors can be categorized into inorganic and organic types [51]. Inorganic inhibitors indicate either anodic or cathodic behaviors. The organic inhibitors exhibit mixed cathodic and anodic activity, as well as adsorption properties. Fig. 10 illustrates the classification of inhibitors. Inorganic corrosion inhibitors exhibit superior effectiveness over a wider temperature range and for longer periods than organic corrosion inhibitors. Organic corrosion inhibitors, while more expensive than their inorganic counterparts, indicate less toxicity.

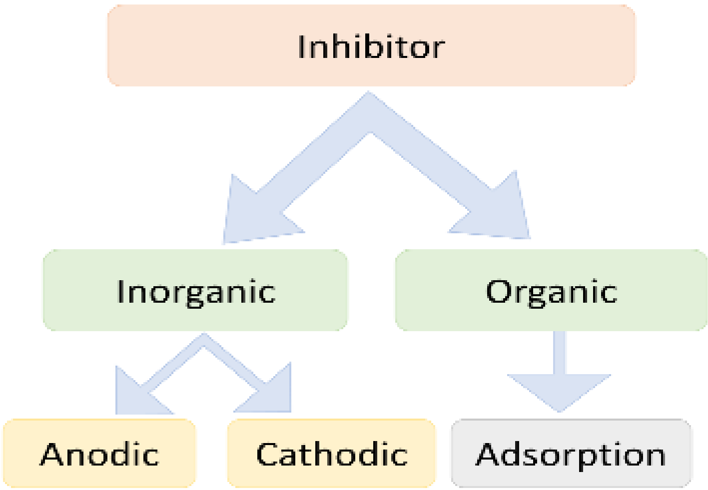

Fig. 10. Classification of inhibitors

Inhibitor efficiency is determined by the structure and chemical properties of the film formed on the substrate surface [137]. The inhibitor's efficiency is affected by the substrate surface condition, the type of corrosive medium, the steel composition, and the inhibitor's chemical structure [138]. The physical-chemical properties induced by the functional group and the 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, biobased corrosion inhibitors, has been explored for carbon steel applications.

Recent research conducted by various authors on the efficiency of inhibiting different types of carbon steels in rich chloride solutions is presented in Table 4.

Table 4. Efficiency of some corrosion inhibitors for different types of carbon steel in salt water at 25 °C

Corrosion Inhibitor	Concentration of Inhibitors	Type of Media	Steel Type	Efficiency%	Ref.
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 50 µL	138 and 200 mg/L	Mild steel	83.6 78.5 86.6	[142]
Aloe vera	300 ppm	Seawater	API 5L Carbon steel	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	5×10^{-4} - 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-ethylhexyl) 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]

Conclusion and Future Prospects

Corrosion of carbon steel in saline environments is a serious concern due to its extensive use in oceanic structures, pipelines, and industrial applications. Temperature, pH, chloride concentrations, and exposure length have significant effects on corrosion. To limit material degradation, it is essential 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 direct measurement of the corrosion rate. Electrochemical methods can provide real-time information, and surface analysis methods can offer insight into morphological and chemical changes in corrosion-damaged materials. Corrosion prevention has been achieved through a range of protective strategies, including corrosion inhibitors, protective coatings, cathodic protection, and nanotechnology-based materials. It is increasingly essential to employ real-time corrosion monitoring techniques, such as electrochemical sensors and acoustic emission methods, to detect corrosion early and prevent structural failures. 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, implementing intelligent monitoring systems that leverage artificial intelligence and Internet of Things-based sensors, and developing alloys and nanotechnology-based coatings, future corrosion research must focus on sustainable corrosion mitigation. By incorporating emerging technologies and sustainable materials, carbon steel structures can last longer, require fewer repairs, and provide greater operational safety in adverse conditions. Industrial applications benefit from improved material durability and environmental sustainability.

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)

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