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Comprehensive Review on Carbon Steels Corrosion in Chloride-Rich Media

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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 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. It evaluates the effectiveness of different inhibitors in controlling corrosion, contributing to the development of efficient protective solutions for metals under harsh and 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, resulting in pollution that impacts ecosystems and penetrates 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, whereby pure metal is converted into more chemically stable forms, such as metal oxides, hydroxides, or oxyhydroxides, 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

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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 amounts to approximately 3.2% of the 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, 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. 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 become corroded during industrial operations; thus, corrosion inhibition is sometimes crucial for safe and economical operations, allowing for the 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, oil, and gas industries are related to pipelines and their exposure environments, which determine the appropriate type of CS selection. 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 the field of 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 transformed into its equivalent ion by losing 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.

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.

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

For example, Fe metal reaction at anode:

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

And reaction at the cathode:

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

Overall cell reaction:

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

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.

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

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

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

and at the cathode is:

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

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].

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

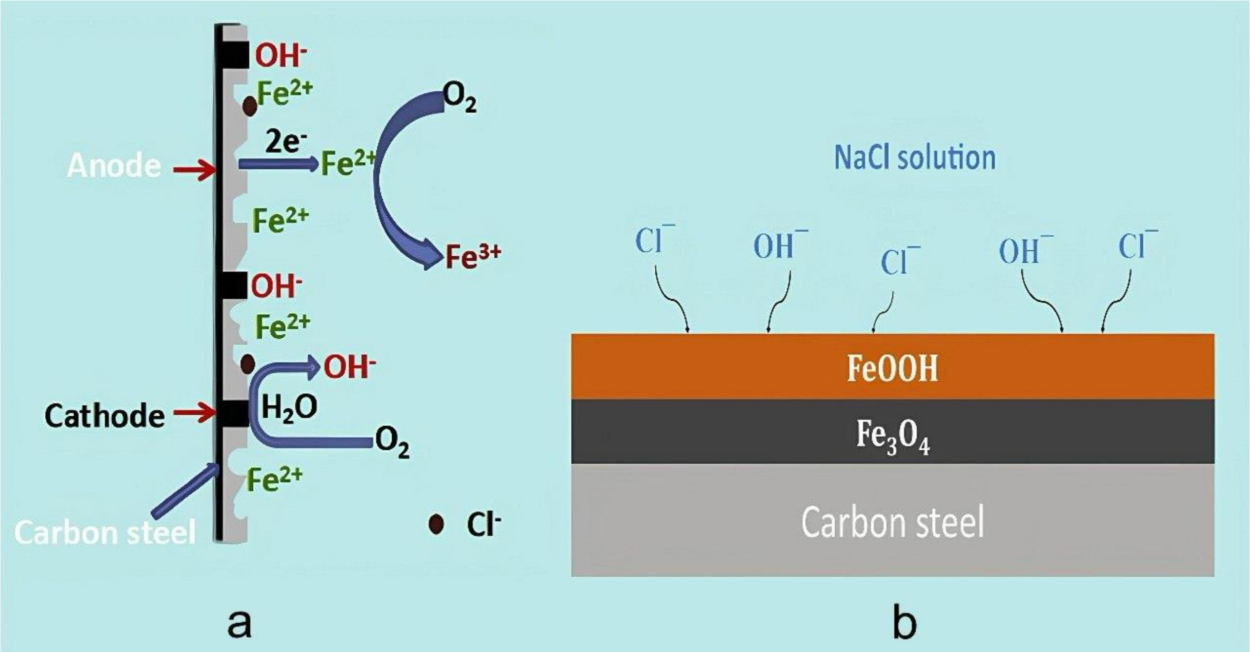

Fig. 1. Schematic representation of carbon steel immersed in NaCl solution (a) Mechanism [36], and (b) Corrosion layer formation on the steel's surface

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 elements influencing corrosion include metal purity, surface coating characteristics, properties of the corrosive product, temperature, concentration of dissolved salts in the medium, air humidity, and the pH of the electrolyte.

Nature of Alloy or Metal

It further depends upon:

Galvanic Series Position

When different metals are electrically connected in a specific electrolytic medium, the metal with the 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 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 create small electrochemical cells in which the anodic component undergoes corrosion. 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 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.

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 attack further 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 larger density of these boundaries, which enhances surface reactivity through improved electron activity and diffusion, thus 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.

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 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 critical 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 has been established that oxygen, under specific conditions (in high-purity water) and at elevated temperatures, can lead to the formation of a thick, passive protective coating of metal oxides on the metal surface, thereby reducing corrosion [49].

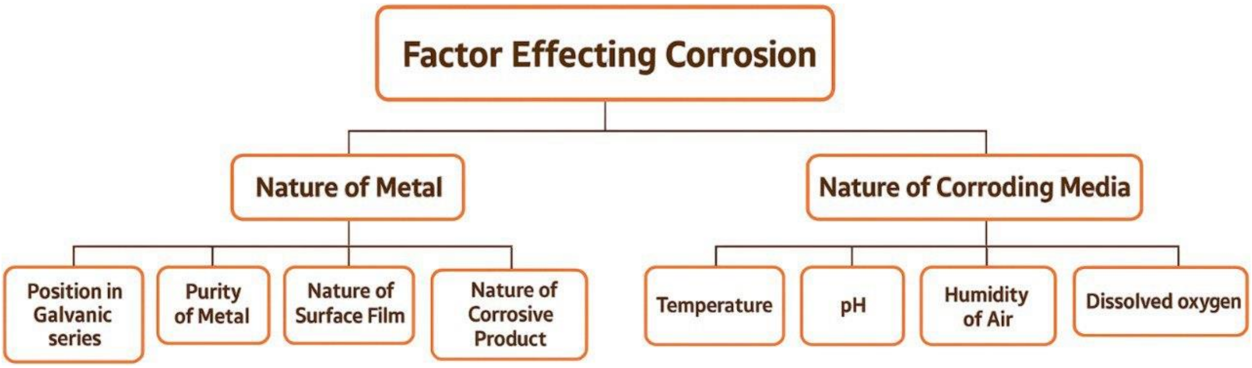

Fig. 2. Some of the factors affecting the corrosion process

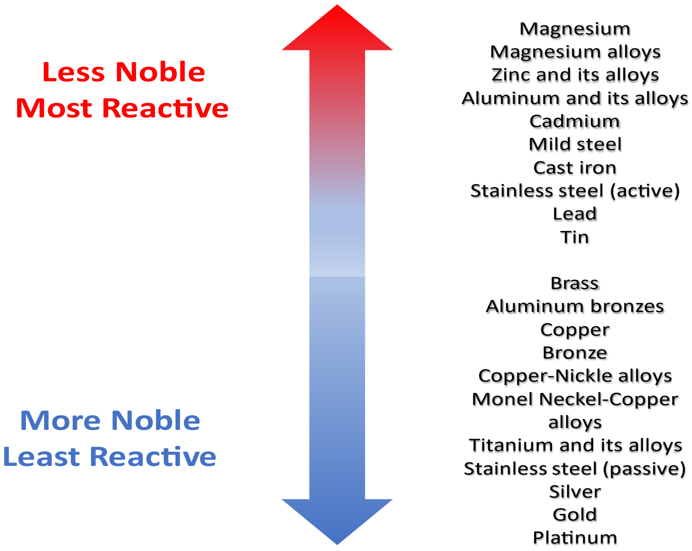

Fig. 3. Corrosion susceptibility of the metal

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]:

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

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 millimeters per year (mm/y) or inches per year (inch/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 investigate additional information relating to corrosion mechanisms. Electrochemical procedures are typically conducted using a three-electrode setup 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 flow rate. Electrochemical analysis is an efficient, rapid, and straightforward method [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 corrosion rate with minimal impact on the electrode. Various electrochemical techniques are available to assess the process and degree of corrosion in metals, as well as the efficiency and mechanisms of corrosion inhibitors to some extent.

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 utilizing the potentiodynamic polarization curve technique is excessively high, significant curve deviations arise, preventing the formation of a standard potentiodynamic polarization curve. Fig. 4 illustrates a diagram of the potentiodynamic polarization curve.

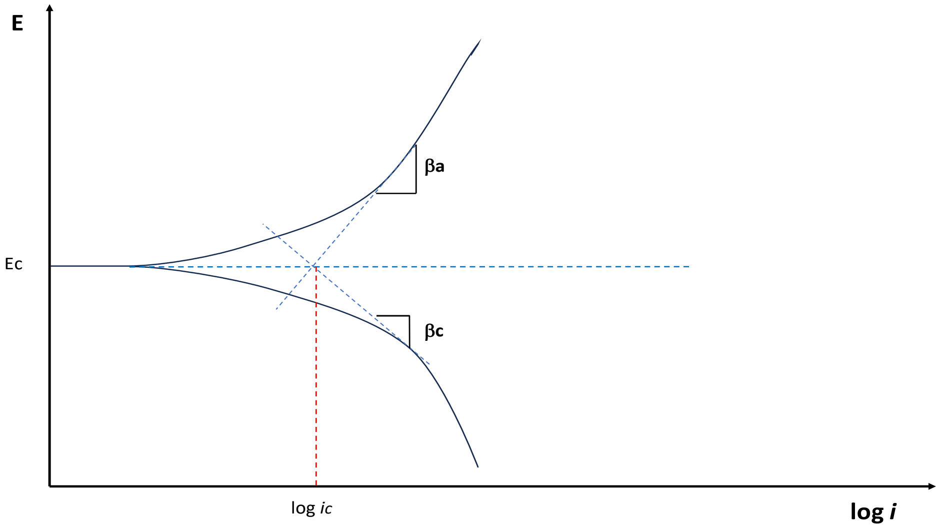

Fig. 4. Potentiodynamic polarization curve diagram

Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) quantifies the impedance spectra of an electrode system over 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 has little effect on 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 the 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 represents the constant phase element. In corrosion science, EIS provides data on corrosion resistance, variations in 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 provides enhanced insights into corrosion kinetics, as shown in Fig. 5.

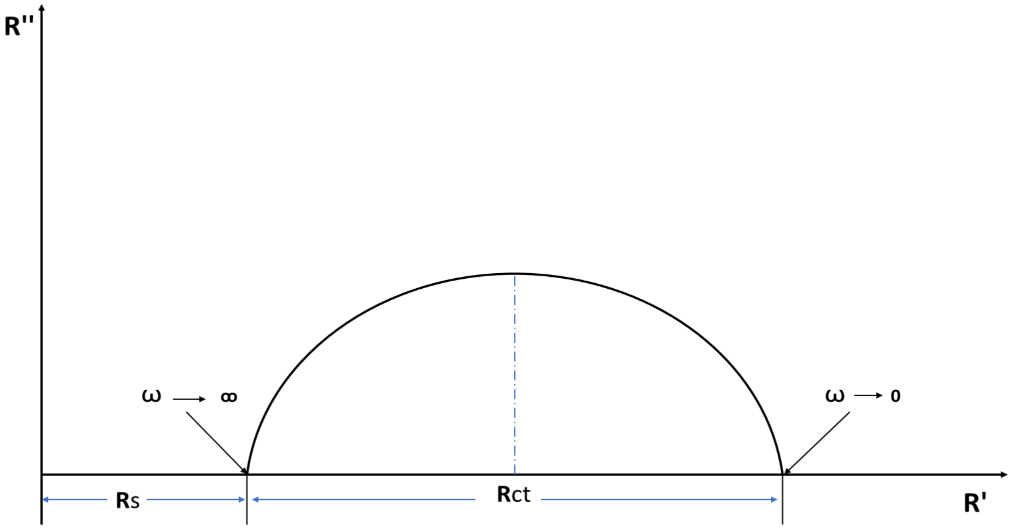

Fig. 5. Schematic diagram of electrochemical impedance spectroscopy

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 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 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 for applications in environmental chambers, as well as in 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 offers a helpful knowledge of inhibitors to improve protective methods and enhance the valuable lifetime of metal structures. Research evaluated the performance of a newly developed organic corrosion inhibitor by SEM testing.

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 utilizes a concentrated, high-energy 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 versus distance curves are employed to provide 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].

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 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, 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, it has been observed that carbon steel produces 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 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 oxidized 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].

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 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 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 due to its several benefits, including accurate measurement, rapid data collection, high sensitivity, non-destructive analysis, and the absence of the need for external calibration. Conventional FTIR, usually examined in the mid-IR wavelength range, has been effectively utilized in the study of surface coatings on CS substrates. The existence or nonexistence of specific 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 adsorb on steel surfaces [88].

To evaluate and examine the corrosion of metals and alloys, monitoring alterations in the color of electrolyte solutions can serve as 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 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).

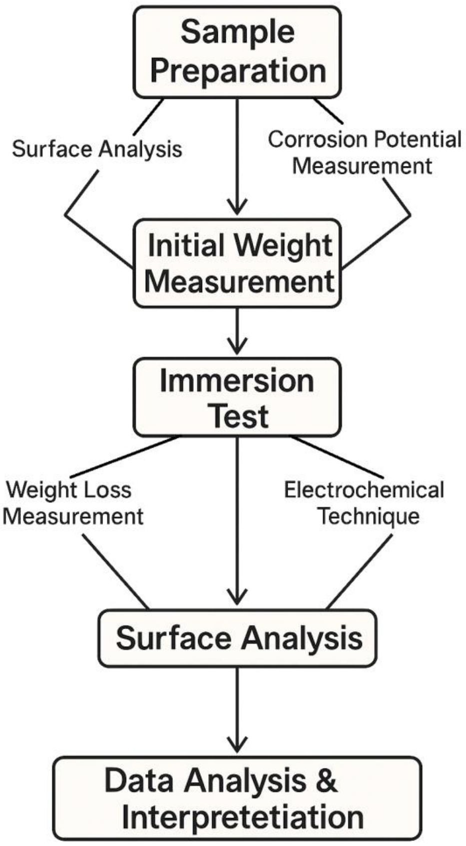

Fig. 6. Flowchart of an experimental methodology employed to examine corrosion behavior of steels

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, which is distinct from dry corrosion; this type of corrosion degrades the metal's untreated surface 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 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, 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.

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

A localized type represents this 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. Instances of crevices involve 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 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].

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].

General Corrosion Galvanic Corrosion Intergranular Corrosion

Pitting Corrosion Erosion Corrosion Stress Corrosion Cracking

Fig. 7. Different corrosion patterns in carbon steel 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]

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 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 the performance of 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 by region (anodic and cathodic), thereby actively contributing to the maintenance of 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 compounds of iron oxide, hydroxide, and oxide-hydroxides [113, 114]. The shape and dimensions of the crystals created depend upon the varying conditions under which they are made. The chemical composition [115-121] and morphologies of solid corrosion products were examined according to the characteristics given 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	-

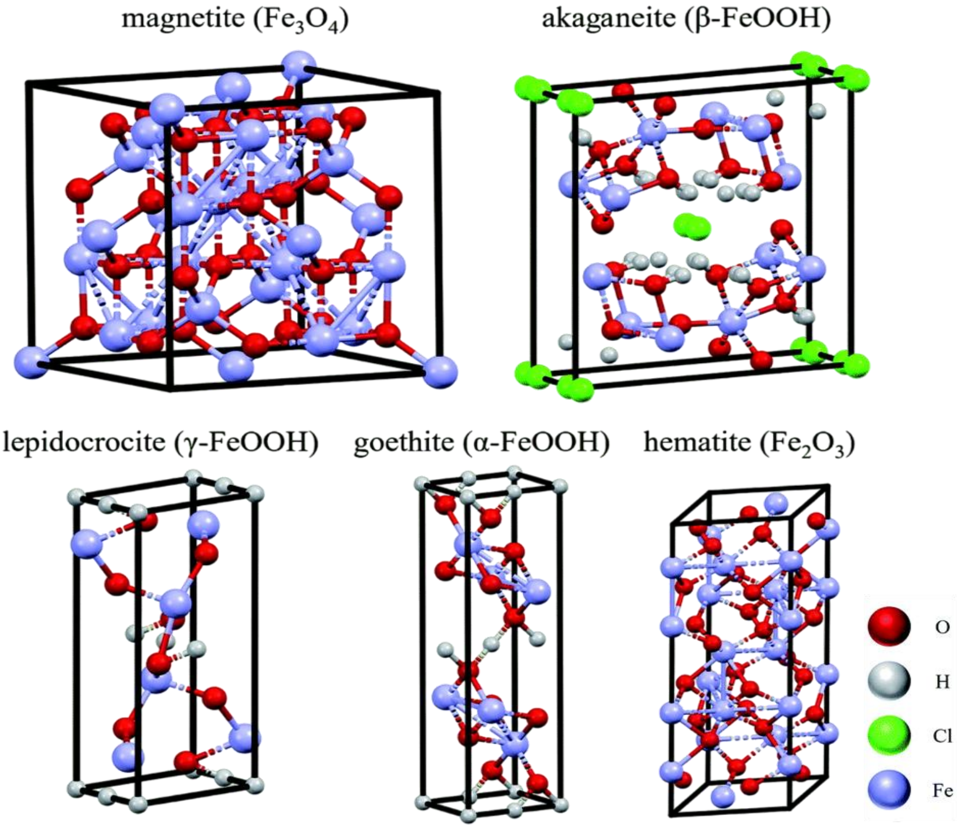

Fig. 9. Some of the crystal cellس of carbon steel corrosion [128]

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 the corrosion process or inhibits 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].

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. Fig. 10 illustrates the classification of inhibitors. Inorganic corrosion inhibitors exhibit superior effectiveness over a wider temperature range and for more extended periods compared to organic corrosion inhibitors. Organic corrosion inhibitors, while more expensive than their inorganic counterparts, indicate less toxicity.

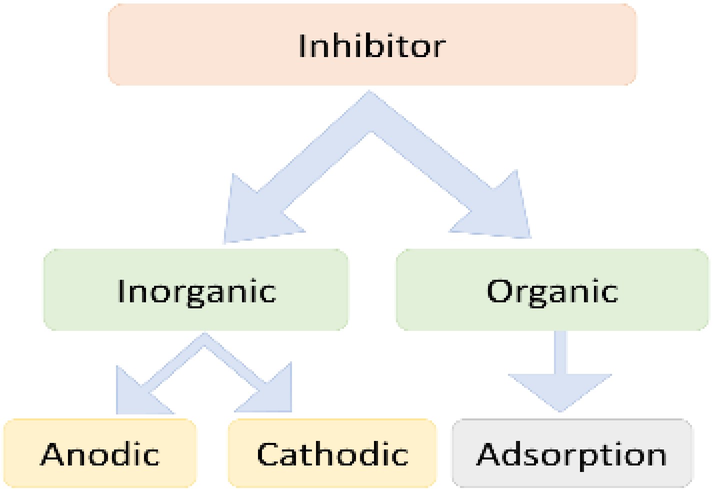

Fig. 10. Classification of inhibitors

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]. 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 ºC

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 for 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. The prevention of corrosion has been achieved through the employment of various protective strategies, including corrosion inhibitors, protective coatings, cathodic protection, and nanotechnology-based materials. It is becoming increasingly essential to employ real-time corrosion monitoring techniques, such as electrochemical sensors and acoustic emission methods, for early detection of corrosion symptoms and averting 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, 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 can 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)

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