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REVIEW

A Review of Inorganic Corrosion Inhibitors: Types, Mechanisms, and Applications

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ABSTRACT

This review paper provides an overview of inorganic corrosion inhibitors, including their types, mechanisms of action, applications, recent advances, and future directions. Inorganic corrosion inhibitors have been widely used to protect metals and alloys from corrosion in various industries, such as oil and gas, chemical, and construction industries. The different types of inorganic corrosion inhibitors discussed in this review include metal-based, metal oxide-based, phosphate-based, silicate-based, and other inorganic inhibitors. The mechanisms of action of inorganic corrosion inhibitors are mainly related to their adsorption on metal surfaces, formation of protective films, and cathodic and anodic polarization. The paper also highlights the applications of inorganic corrosion inhibitors in different industries and discusses their effectiveness and limitations. Recent advances in the field of inorganic corrosion inhibitors, such as nanotechnology-based inhibitors, green inhibitors, combination inhibitors, and computational studies, are also reviewed. In conclusion, this paper summarizes the key findings of the review and provides a future outlook for the development of inorganic corrosion inhibitors. The review concludes that further research is needed to develop more effective, environmentally friendly, and economical inorganic corrosion inhibitors for various industrial applications.

1. INTRODUCTION

Corrosion is a natural process that refers to the degradation of materials due to chemical reactions with the environment [1,2]. It can take various forms, including uniform corrosion, pitting corrosion, crevice corrosion, and galvanic corrosion, among others [3,4].

Corrosion inhibitors are substances added to materials to prevent corrosion by either forming a protective layer on the surface or altering the corrosion reaction. Inorganic corrosion inhibitors are substances that are inorganic in nature and are typically used in high-temperature and high-pressure environments, where organic inhibitors may not be suitable [5,6]. Inorganic and organic inhibitors can be used alone or in combination to provide superior corrosion protection [7-9].

Inorganic inhibitors, such as chromates, phosphates, molybdates, and silicates, form a protective layer on the metal surface to prevent corrosion and are often used in industrial applications, such as cooling water systems, boilers, and pipelines [10,11]. Organic inhibitors, such as amines, imidazolines, and quaternary ammonium compounds, adsorb onto the metal surface and block corrosive agents from reaching the metal. These inhibitors are commonly used in the oil and gas industry [12,13]. Combining inorganic and organic inhibitors can provide a synergistic effect that enhances overall corrosion protection. For example, a combination of phosphate and organic inhibitors has been shown to be effective in protecting steel in cooling water systems. The inorganic phosphate inhibitor forms a protective layer on the surface, while the organic inhibitor provides additional protection by inhibiting corrosion [14,15].

The choice of inhibitor and combination used depends on the specific application and materials involved. It is important to evaluate the properties and performance of each inhibitor to ensure optimal corrosion protection. As shown in Figure 1, corrosion can lead to deterioration, discoloration, and even structural damage over time.

Fig. 1. The corrosion of metals.

2. COMPREHENSIVE FOUNDATION

Inorganic corrosion inhibitors are substances that are added to a metal surface to prevent or slow down the corrosion process [16]. They work by forming a protective layer on the surface of the metal, which prevents or limits contact with corrosive agents. Inorganic corrosion inhibitors can be classified based on their chemical composition, mode of action, and application. Metal salts such as chromates, molybdates, and phosphates are commonly used as corrosion inhibitors. They form a passive film on the metal surface, which protects the metal from corrosion. Silicates such as sodium silicate, potassium silicate, and magnesium silicate are also used as corrosion inhibitors. They form a protective layer on the metal surface by reacting with the metal ions and creating a barrier. Oxides such as aluminum oxide and titanium oxide are used as corrosion inhibitors. They create a protective layer on the metal surface by reacting with the metal ions and forming a barrier. Nitrites such as sodium nitrite and potassium nitrite are used as corrosion inhibitors for ferrous metals. They form a protective layer on the metal surface by reacting with the metal ions and forming a barrier. Phosphates such as zinc phosphate and iron phosphate are used as corrosion inhibitors. They form a protective layer on the metal surface by reacting with the metal ions and forming a barrier [17].

The Barrier Mechanism involves the formation of a protective barrier on the metal surface, which prevents or limits contact with corrosive agents. This barrier can be formed by the adsorption of the inhibitor molecules on the metal surface. The passivation mechanism involves the formation of a passive film on the metal surface, which prevents or limits contact with corrosive agents. This passive film can be formed by the reaction of the inhibitor with the metal ions on the surface. The cathodic protection mechanism involves the creation of a cathodic protection system, where the inhibitor acts as a sacrificial anode and protects the metal surface from corrosion [18].

Inorganic corrosion inhibitors are widely used in the oil and gas industry to protect pipelines, storage tanks, and other equipment from corrosion. Inorganic corrosion inhibitors are used in the automotive industry to protect the metal components of vehicles from corrosion. Inorganic corrosion inhibitors are used in the electronics industry to protect electronic components from corrosion. Inorganic corrosion inhibitors are used in the construction industry to protect metal structures such as bridges, buildings, and tunnels from corrosion. Inorganic corrosion inhibitors are used in the marine industry to protect ships and other marine structures from corrosion [19].

In conclusion, inorganic corrosion inhibitors play a crucial role in protecting metal structures from corrosion. They can be classified based on their chemical composition, mode of action, and application. The different mechanisms of inorganic corrosion inhibitors include the barrier mechanism, passivation mechanism, and cathodic protection mechanism. Inorganic corrosion inhibitors have wide applications in various industries such as oil and gas, automotive, electronics, construction, and marine.

3. TYPES OF INORGANIC INHIBITORS

Inorganic corrosion inhibitors are compounds that are added to a corrosive environment to slow down or prevent the corrosion process. These inhibitors are widely used in various industries such as oil and gas, chemical, petrochemical, and construction. Inorganic corrosion inhibitors can be classified into several types based on their chemical composition and mechanism of action.

3.1 Metal-based inhibitors

Metal-based inhibitors are typically cations of metals such as zinc, aluminum, and magnesium. These metals form a protective layer on the surface of the metal, which acts as a barrier between the metal and the corrosive environment. This protective layer is typically formed by the reaction of the metal cation with the anions in the corrosive environment.

There are several types of metal-based inhibitors, including:

a. Zinc-based inhibitors [20]: Zinc is a widely used metal-based inhibitor in the corrosion protection of steel. Zinc reacts with the anions in the corrosive environment to form a protective layer of zinc oxide or zinc hydroxide on the surface of the metal (Equation 1).

$$2Zn + O_2 \rightarrow 2ZnO \qquad (1)$$

The equation for the reaction of zinc with water to form zinc hydroxide is (Equation 2):

$$Zn + 2H_2O \rightarrow Zn(OH)_2 + H_2 \qquad (2)$$

b. Aluminum-based inhibitors [21]: Aluminum is also commonly used as a metal-based inhibitor. Aluminum reacts with the anions in the corrosive environment to form a protective layer of aluminum oxide or aluminum hydroxide on the surface of the metal.

The reaction of aluminum with anions can be represented based on equation (3):

$$Al + 3X^- + 3H_2O \rightarrow Al(OH)_3 \downarrow + 3X \qquad (3)$$

where X^- represents the anions in the corrosive environment.

The formation of a protective layer of aluminum oxide or aluminum hydroxide on the surface of the metal can be represented based on equation (4 or 5):

$$2Al + 3H_2O + 3O_2 \rightarrow 2Al(OH)_3 \qquad (4)$$

$$\text{OR} \quad 4Al + 3O_2 \rightarrow 2Al_2O_3 \qquad (5)$$

c. Magnesium-based inhibitors: Magnesium is another metal-based inhibitor that is commonly used in the corrosion protection of steel. Magnesium reacts with the anions in the corrosive environment to form a protective layer of magnesium oxide or magnesium hydroxide on the surface of the metal.

The chemical reactions involved in the use of magnesium-based inhibitors for the corrosion protection of steel can be described based on equation (6):

$$\mathrm{Mg} + Fe^{+2} \rightarrow \mathrm{Mg}^{+2} + \mathrm{Fe} \qquad (6)$$

In this reaction (Equation 6), the magnesium (Mg) acts as a sacrificial anode and undergoes corrosion in place of the iron (Fe) in the steel. As a result, magnesium ions (Mg^{+2}) are released into the solution, which react with the ferrous ions (Fe^{+2}) to form a protective layer of magnesium hydroxide ($Mg(OH)_2$) on the steel surface. This layer serves as a barrier to further corrosion and protects the steel from further degradation.

In this reaction (Equation 7), magnesium reacts with water to form magnesium hydroxide and hydrogen gas.

$$\mathrm{Mg} + 2H_2\mathrm{O} \rightarrow \mathrm{Mg(OH)_2} + \mathrm{H_2} \quad (7)$$

In this reaction (Equation (8)), magnesium reacts with oxygen to form magnesium oxide.

$$\mathrm{Mg} + 2\mathrm{X}^- \rightarrow \mathrm{MgX_2} \quad (8)$$

In this reaction, magnesium reacts with anions (X-) present in the corrosive environment to form magnesium salt (MgX_2), which can form a protective layer on the surface of the metal. Overall, the use of magnesium-based inhibitors can help prevent corrosion of steel by forming a protective layer on the metal surface, which reduces the exposure of the metal to the corrosive environment.

d. Manganese-based inhibitors [22]: Manganese is another metal-based inhibitor that is commonly used in the corrosion protection of steel. Manganese reacts with the anions in the corrosive environment to form a protective layer of manganese oxide on the surface of the metal.

The equation for the reaction of manganese with anions in a corrosive environment to form a protective layer of manganese oxide on the surface of the metal can be written according to Equation (9):

$$\mathrm{Mn} + 2\mathrm{X}^- + \mathrm{H_2O} \rightarrow \mathrm{MnO_2} + 2H^+ + 2\mathrm{X} \quad (9)$$

where Mn represents manganese, X^- represents the anions present in the corrosive environment, H_2O represents water, MnO2 represents the manganese oxide protective layer, H+ represents hydrogen ions.

Additionally, the corrosion of steel can be represented based on Equation (10):

$$Fe + 2H_2O + O_2 \rightarrow Fe(OH)_2 + 2OH \quad (10)$$

where Fe represents iron, H_2O represents water, O_2 represents oxygen, $Fe(OH)_2$ represents iron(II) hydroxide, and OH- represents hydroxide ions.

e. Cerium-based inhibitors: Cerium is a relatively new metal-based inhibitor that has shown promising results in the corrosion protection of steel. Cerium reacts with the anions in the corrosive environment to form a protective layer of cerium oxide or cerium hydroxide on the surface of the metal.

The equation for the formation of cerium oxide on the surface of metal can be represented based on Equation (11):

$$Ce + O_2 \rightarrow CeO_2 \quad (11)$$

Similarly, the formation of cerium hydroxide can be represented based on Equation (12):

$$Ce + 2H_2O \rightarrow Ce(OH)_2 \quad (12)$$

The reaction of cerium with anions in the corrosive environment can be represented based on Equation (13):

$$\mathrm{Ce} + 2X^- \rightarrow \mathrm{CeX_2} \quad (13)$$

where X represents the anion.

Metal-based inhibitors can be used alone or in combination with other inhibitors to provide effective corrosion protection. The effectiveness of a metal-based inhibitor depends on several factors, including the type of metal, the concentration of the inhibitor, and the corrosive environment. In conclusion, metal-based inhibitors are an effective and widely used method of corrosion protection for steel and other metals. By forming a protective layer on the surface of the metal, metal-based inhibitors can prevent corrosion and extend the service life of the metal.

3.2 Metal oxide-based inhibitors

Metal oxide-based inhibitors work by reacting with the metal surface to form a passive oxide layer, which acts as a barrier against corrosion. The metal oxide-based inhibitors can be categorized into three groups: anodic inhibitors, cathodic inhibitors, and mixed inhibitors. Anodic inhibitors are substances that prevent the anodic reaction of metal corrosion by forming a protective oxide layer on the anode surface [23].

Anodic Inhibition: Anodic Inhibitor + Metal → Protective Oxide Layer

Cathodic inhibitors, on the other hand, reduce the cathodic reaction by forming a passive layer on the cathode surface.

Cathodic Inhibition: Cathodic Inhibitor + Metal → Passive Layer on Cathode Surface

Mixed inhibitors are substances that can act on both anodic and cathodic reactions, and they usually provide more effective protection against corrosion [24].

Mixed Inhibition: Mixed Inhibitor + Metal → Oxide Layer (Anodic) + Passive Layer on Cathode Surface (Cathodic).

Metal oxide-based inhibitors include compounds such as zinc oxide, aluminum oxide, and magnesium oxide. These compounds are often added to coatings, paints, and other surface treatments to provide long-term protection against corrosion. Zinc oxide is commonly used as a corrosion inhibitor in many industrial applications because it is effective in preventing the corrosion of iron and steel. Aluminum oxide and magnesium oxide are also widely used in industrial applications because they are effective in preventing the corrosion of aluminum and magnesium alloys.

Metal oxide-based inhibitors have several advantages over organic inhibitors. They are generally more stable and have a longer lifespan than organic inhibitors. They are also more effective at high temperatures and pressures, making them ideal for use in industrial applications. Additionally, metal oxide-based inhibitors are not toxic and can be used in environmentally sensitive areas [25].

In conclusion, metal oxide-based inhibitors are a useful type of inorganic corrosion inhibitor that can provide long-term protection against corrosion in industrial applications. They are effective at preventing the corrosion of a wide range of metals and alloys and have several advantages over organic inhibitors. Their use can help to extend the lifespan of equipment and reduce maintenance costs.

3.3 Phosphate-based inhibitors

Phosphate-based inhibitors can be classified into three types: zinc phosphate, iron phosphate, and calcium phosphate. Each type of phosphate-based inhibitor has unique properties and mechanisms of action.

a. **Zinc Phosphate Inhibitors [26]:** Zinc phosphate inhibitors are widely used in the automotive and aerospace industries due to their excellent corrosion protection properties. Zinc phosphate inhibitors work by forming a protective layer of insoluble zinc phosphate on the surface of the metal, preventing the metal from coming into contact with the corrosive environment. Zinc phosphate inhibitors are effective in acidic and neutral solutions and provide long-term protection against corrosion.

The equation for the formation of zinc phosphate on the metal surface can be represented as in Equation 14:

$$Zn + 3H_2PO_4^- + 2H^+ \rightarrow Zn(HPO_4)_2 + 3H_2O \tag{14}$$

is reaction shows the formation of an insoluble layer of zinc phosphate ($Zn(HPO_4)_2$) on the metal surface.

The mechanism by which zinc phosphate inhibitors provide corrosion protection can be represented as follows (Equation 15):

$$Zn(HPO_4)_2 + H_2O \rightarrow Zn^{2+} + 2HPO_4^{-4} + 2H^+ \tag{15}$$

The zinc ions (Zn^{2+}) released from the zinc phosphate layer react with water to form a protective layer of zinc hydroxide ($Zn(OH)_2$) on the metal surface, which acts as a barrier against further corrosion reactions.

Overall, the corrosion protection provided by zinc phosphate inhibitors can be represented based on Equation (16):

$$\text{Metal} + Zn(HPO_4)_2 + H_2O \rightarrow \text{Metal-}Zn(OH)_2 + 2HPO_4 \tag{16}$$

where the metal reacts with the zinc phosphate inhibitor to form a protective layer of metal-zinc hydroxide and phosphate.

b. **Iron Phosphate Inhibitors [27]:** Iron phosphate inhibitors are used in the food and beverage industry to prevent the corrosion of stainless equipment. Iron phosphate inhibitors work by forming a protective layer of insoluble iron phosphate on the surface of the metal. The protective layer is highly adhesive, providing long-term protection against corrosion. Iron phosphate inhibitors are effective in mildly acidic and neutral solutions.

The equation for the formation of iron phosphate on the metal surface can be represented based on Equation (17):

$$Fe + 2HPO_4^{-2} \rightarrow FeHPO_4(s) + H_2(g) \tag{17}$$

Where Fe represents the metal surface and HPO_4^{2-} represents the iron phosphate inhibitor.

The protective layer of iron phosphate can be represented based on Equation (18):

$$FeHPO_4(s) \rightarrow FePO_4(s) + H + (aq) \qquad (18)$$

Where $FeHPO_4(s)$ represents the insoluble iron phosphate layer and H+(aq) represents the acidic environment required for the formation of the protective layer.

The overall reaction for the use of iron phosphate inhibitors to prevent corrosion can be represented based on Equation (19):

$$Fe + 2HPO_4^{-} + 2H^{+} \rightarrow FePO_4(s) + H_2(g) \qquad (19)$$

This equation shows that the iron phosphate inhibitor reacts with the metal surface and the acidic environment to form a protective layer of insoluble iron phosphate, which prevents further corrosion.

c. **Calcium Phosphate Inhibitors [28]:** Calcium phosphate inhibitors are used in the oil and gas industry to prevent the corrosion of pipelines and other equipment. Calcium phosphate inhibitors work by forming a protective layer of insoluble calcium phosphate on the surface of the metal. The protective layer is highly adhesive, providing long-term protection against corrosion. Calcium phosphate inhibitors are effective in mildly acidic and neutral solutions.

The chemical equation for the formation of calcium phosphate on metal surfaces can be represented based on Equation (20):

$$2Ca^{2+} + PO_4^{3-} \rightarrow Ca3(PO_4)_2 \qquad (20)$$

where Ca^{2+} and PO_4^{3-} ions react to form calcium phosphate ($Ca_3(PO_4)_2$).

The mechanism by which calcium phosphate inhibitors work can be represented based on Equation (21):

$$Fe + Ca_3(PO4)_2 \rightarrow Fe_3(PO_4)_2 + 3Ca \qquad (21)$$

where the calcium phosphate inhibitor reacts with the metal surface to form an insoluble layer of calcium phosphate, which provides a protective barrier against corrosion.

In summary, the use of calcium phosphate inhibitors in the oil and gas industry can be represented by the chemical equations above, where the inhibitors work by forming a protective layer of calcium phosphate on metal surfaces to prevent corrosion.

d. **Phosphate-based inhibitors are effective in preventing corrosion due to their ability to form protective layers on the surface of the metal**. The protective layers are highly adhesive, providing long-term protection against corrosion. Additionally, phosphate-based inhibitors are environmentally friendly and cost-effective, making them an attractive choice for many industries.

One possible equation to represent the protective layer formed by phosphate-based inhibitors is (Eq. 22):

$$M + PO_4^{3-} \rightarrow M - PO_4 \qquad (22)$$

(where M represents the metal)

This equation shows how the phosphate ions (PO_4^{3-}) react with the metal (M) to form a protective layer of metal phosphate ($M\text{-}PO_4$) on the surface, preventing corrosion.

Another possible equation to represent the adhesive properties of the protective layer is (Eq. 23):

$$M - PO_4 + H_2O \rightarrow M - OH + HPO_4^{3-} \qquad (22)$$

This equation shows how the metal phosphate layer ($M\text{-}PO_4$) reacts with water (H_2O) to form metal hydroxide (M-OH) and hydrogen phosphate ions (HPO4^$^{2-}$). The metal hydroxide is responsible for the strong adhesive properties of the protective layer, which helps to provide long-term protection against corrosion.

Finally, an equation to represent the environmental and cost benefits of phosphate-based inhibitors could be:

Phosphate-based inhibitors + metal → corrosion protection + environmental and cost benefits

This equation shows how the use of phosphate-based inhibitors can lead to both corrosion protection and environmental and cost benefits for industries. By using these inhibitors, companies can reduce their environmental impact and save money on corrosion prevention measures.

In conclusion, phosphate-based inhibitors are an effective and environmentally friendly method for preventing corrosion of metals. Zinc phosphate, iron phosphate, and calcium phosphate inhibitors have unique properties and mechanisms of action, making them suitable for different industries and applications.

3.4. Silicate-based inhibitors

Silicate-based inhibitors are one type of inorganic corrosion inhibitors that are commonly used to protect metal surfaces from corrosion. Silicate-based inhibitors work by forming a protective layer on the metal surface that helps to prevent the metal from coming into contact with the corrosive environment. In this article, we will discuss the different types of silicate-based inhibitors, their properties, and their applications [29].

Silicate-based inhibitors can be classified into two main types: alkali silicates and alkali earth silicates. Alkali silicates are compounds that are formed by the reaction of alkali metals, such as sodium or potassium, with silicic acid. These compounds are soluble in water and can be used as corrosion inhibitors in aqueous solutions. Alkali earth silicates are compounds that are formed by the reaction of alkali earth metals, such as calcium or magnesium, with silicic acid. These compounds are insoluble in water and are used as corrosion inhibitors in non-aqueous solutions.

Alkali silicates are commonly used as corrosion inhibitors in the food and beverage industry. They are used to protect metal equipment, such as tanks and pipelines, from corrosion caused by acidic solutions, such as fruit juices and soft drinks. Alkali silicates form a protective layer on the metal surface that helps to prevent the metal from coming into contact with the acidic solution [30].

Alkali earth silicates are commonly used as corrosion inhibitors in the oil and gas industry. They are used to protect metal equipment, such as pipelines and storage tanks, from corrosion caused by hydrocarbon fluids. Alkali earth silicates form a protective layer on the metal surface that helps to prevent the metal from coming into contact with the corrosive fluid.

Silicate-based inhibitors have several advantages over other types of corrosion inhibitors [31]. They are non-toxic, non-flammable, and have a long shelf life. They are also relatively inexpensive and can be easily applied to metal surfaces. Table 1 provides an overview of silicate-based corrosion inhibitors, including their type, function, classification, and applications. Table 1, highlights the two types of silicate-based inhibitors - alkali silicates and alkali earth silicates - and their corresponding properties and uses. Additionally, the table lists the advantages of using silicate-based inhibitors, such as their non-toxic and non-flammable nature, long shelf life, and ease of application.

Table 1. Overview of Silicate-based Corrosion Inhibitors and their Applications.

Topic	**Information**
Type	Silicate-based inhibitors
Function	Protect metal surfaces from corrosion by forming a protective layer
Classification of Silicate-based inhibitors	Alkali silicates and alkali earth silicates
Alkali Silicates	Formed by the reaction of alkali metals (sodium or potassium) with silicic acid; soluble in water and used as corrosion inhibitors in aqueous solutions
Alkali Earth Silicates	Formed by the reaction of alkali earth metals (calcium or magnesium) with silicic acid; insoluble in water and used as corrosion inhibitors in non-aqueous solutions
Applications of Alkali Silicates	Commonly used in the food and beverage industry to protect metal equipment from corrosion caused by acidic solutions such as fruit juices and soft drinks
Applications of Alkali Earth Silicates	Commonly used in the oil and gas industry to protect metal equipment from corrosion caused by hydrocarbon fluids
Advantages of Silicate-based Inhibitors	Non-toxic, non-flammable, long shelf life, relatively inexpensive, and easy to apply to metal surfaces

In conclusion, silicate-based inhibitors are an effective type of inorganic corrosion inhibitor that can be used to protect metal surfaces from corrosion. They are available in two main types, alkali silicates and alkali earth silicates, and are commonly used in the food and beverage and oil and gas industries.

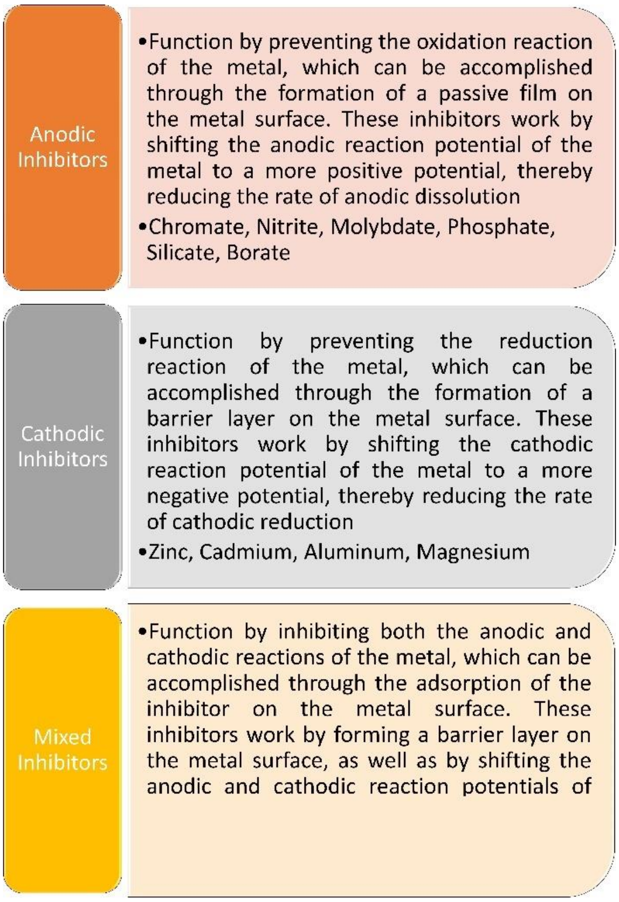
3.5. Other inorganic inhibitors

1. Anodic Inhibitors [32]: Anodic inhibitors are compounds that preferentially form a protective film on the anode surface, which slows down the oxidation reaction. These inhibitors work by oxidizing the metal surface to form a thin, protective oxide layer. Examples of anodic inhibitors include chromates, molybdates, and phosphates.
2. Cathodic Inhibitors [33]: Cathodic inhibitors are compounds that preferentially form a protective film on the cathode surface, which slows down the reduction reaction. These inhibitors work by reducing the hydrogen ions in the electrolyte, which decreases the cathodic reaction rate. Examples of cathodic inhibitors include zinc and its alloys, aluminum, and magnesium.
3. Passivators [34]: Passivators are compounds that form a passive layer on the metal surface, which protects the metal from further corrosion. These inhibitors work by forming a layer of metal oxide, which prevents further metal oxidation. Examples of passivators include chromates, phosphates, and silicates.
4. Volatile Corrosion Inhibitors: Volatile corrosion inhibitors (VCIs) are compounds that vaporize and form a protective layer on the metal surface. These inhibitors work by releasing molecules that attach to the metal surface and form a thin film. Examples of VCIs include amines, amides, and carboxylates.
5. Oxygen Scavengers: Oxygen scavengers are compounds that react with oxygen to prevent corrosion. These inhibitors work by removing oxygen from the metal surface, which prevents the corrosion reaction. Examples of oxygen scavengers include sulfites, bisulfites, and hydrazine.
6. pH Adjusters: pH adjusters are compounds that change the pH of the electrolyte to prevent corrosion. These inhibitors work by changing the pH of the electrolyte, which slows down the corrosion reaction. Examples of pH adjusters include alkalis, acids, and buffers.

Inorganic corrosion inhibitors play an essential role in protecting metals and alloys from corrosion. By understanding the various types of inorganic corrosion inhibitors and their mechanisms of action, industries can select the most appropriate inhibitor for their specific application.

4. MECHANISMS OF ACTION

Corrosion is a significant problem that affects various industries, including the oil and gas, chemical, and marine industries. Corrosion inhibitors are chemical compounds that are used to prevent or slow down the rate of corrosion in metals. Inorganic corrosion inhibitors are one type of corrosion inhibitor that is commonly used. Inorganic corrosion inhibitors can be classified into several categories, including anodic, cathodic, and mixed inhibitors. The mechanism of action for each type of inhibitor is different and depends on the properties of the metal and the environment in which it is used (Figure 2). Anodic inhibitors work by forming a protective oxide layer on the metal surface. This layer prevents the anodic reaction of the metal, which is the process by which metal ions are released into the environment. Anodic inhibitors include compounds such as chromates, molybdates, and tungstates [35,36]. These inhibitors are effective in environments with a high concentration of oxidizing agents, such as acids and salts [37].



- Function by preventing the oxidation reaction of the metal, which can be accomplished through the formation of a passive film on the metal surface. These inhibitors work by shifting the anodic reaction potential of the metal to a more positive potential, thereby reducing the rate of anodic dissolution
- Chromate, Nitrite, Molybdate, Phosphate, Silicate, Borate

- Function by preventing the reduction reaction of the metal, which can be accomplished through the formation of a barrier layer on the metal surface. These inhibitors work by shifting the cathodic reaction potential of the metal to a more negative potential, thereby reducing the rate of cathodic reduction
- Zinc, Cadmium, Aluminum, Magnesium

- Function by inhibiting both the anodic and cathodic reactions of the metal, which can be accomplished through the adsorption of the inhibitor on the metal surface. These inhibitors work by forming a barrier layer on the metal surface, as well as by shifting the anodic and cathodic reaction potentials of

Fig. 2. Anodic, cathodic, and mixed inorganic corrosion inhibitors mechanisms.

Cathodic inhibitors work by reducing the cathodic reaction of the metal. The cathodic reaction is the process by which the metal gains electrons, which is the first step in the corrosion process. Cathodic inhibitors include compounds such as zinc, aluminum, and magnesium. These inhibitors are effective in environments with a low concentration of oxidizing agents, such as alkaline solutions [38]. Mixed inhibitors work by both reducing the anodic and cathodic reactions of the metal. Mixed inhibitors include compounds such as nitrites, nitrates, and phosphates. These inhibitors are effective in environments with a moderate concentration of oxidizing agents, such as neutral solutions. Inorganic corrosion inhibitors can also work by adsorbing onto the metal surface [39]. Adsorption inhibitors form a protective layer on the metal surface, which prevents the corrosive environment from coming into contact with the metal. This mechanism of action is not specific to any particular type of inorganic corrosion inhibitor and can be used by all types. In summary, the mechanism of action for inorganic corrosion inhibitors depends on the properties of the metal and the environment in which it is used. Anodic inhibitors work by forming a protective oxide layer on the metal surface, cathodic inhibitors work by reducing the cathodic reaction of the metal, mixed inhibitors work by both reducing the anodic and cathodic reactions of the metal, and adsorption inhibitors work by forming a protective layer on the metal surface [40]. Understanding the mechanism of action for inorganic corrosion inhibitors is critical for selecting the most effective inhibitor for a particular application [41].

4.1 Adsorption on metal surface

The adsorption of inorganic corrosion inhibitors onto metal surfaces can occur through a variety of mechanisms, including chemical bonding, electrostatic attraction, and physical adsorption. The type of adsorption mechanism that occurs depends on the chemical structure of the inhibitor molecule, as well as the nature of the metal surface [42].

Chemical bonding is a type of adsorption mechanism that occurs when the inhibitor molecule forms a covalent bond with the metal surface [43]. This type of adsorption is typically only possible when the metal surface is highly reactive, such as when it is freshly exposed or has a high surface energy. Chemical bonding can result in a very strong and stable inhibitor layer, but it requires a highly reactive metal surface and a highly reactive inhibitor molecule [44].

Electrostatic attraction is another type of adsorption mechanism that occurs when the inhibitor molecule is attracted to the metal surface through electrostatic forces. This type of adsorption is typically weaker than chemical bonding but can occur on a wider range of metal surfaces and inhibitor molecules. Electrostatic attraction can occur when the metal surface has a net positive or negative charge, or when the inhibitor molecule has a net positive or negative charge [45].

Physical adsorption is the weakest type of adsorption mechanism and occurs when the inhibitor molecule is attracted to the metal surface through van der Waals forces or other non-specific interactions [46]. This type of adsorption is typically the most common and occurs on a wide range of metal surfaces and inhibitor molecules. Table 2 provides examples of adsorption mechanisms and their corresponding chemical bonding types, along with specific examples of inorganic corrosion inhibitor molecules that exhibit this type of adsorption on a wide range of metal surfaces.

Table 2. Adsorption mechanisms and examples of inorganic corrosion inhibitor molecules.

Adsorption mechanism	**Chemical bonding**	**Example inorganic corrosion inhibitor molecule**	**Ref.**
C.Sorption	Covalent	Molybdate (MoO_4^{2-})	[56]
C.Sorption	Covalent	Chromate (CrO_4^{2-})	[57]
C.Sorption	Covalent	Phosphonates	[58]
C.Sorption	Covalent	Amines	[59]
C.Sorption	Covalent	Thiourea	[60]
P.Sorption	VdW	Silicates	[61]
P.Sorption	VdW	Aliphatic amines	[62]
P.Sorption	VdW	Alkyl phosphates	[63]
P.Sorption	VdW	Benzotriazole	[64]

Note: C.Sorption. (Chemisorption); P.Sorption (Physisorption); VdW, Van der Waals

Regardless of the specific type of adsorption mechanism, the end result is the same: the inhibitor molecule forms a protective layer on the metal surface that prevents the corrosive environment from reaching the metal surface. This protective layer can be very effective at reducing the rate of corrosion and can significantly increase the lifespan of metal structures in corrosive environments [47].

In conclusion, adsorption onto metal surfaces is a key mechanism of action for inorganic corrosion inhibitors [48. The specific type of adsorption mechanism that occurs depends on the chemical structure of the inhibitor molecule and the nature of the metal surface. Chemical bonding, electrostatic attraction, and physical adsorption are all possible mechanisms of adsorption. Regardless of the specific mechanism, the end result is a protective layer on the metal surface that can significantly reduce the rate of corrosion [49].

4.2 Formation of protective film

The formation of a protective film can occur through a variety of mechanisms, including chemical adsorption, precipitation, and complexation. In chemical adsorption, the inhibitor molecules adsorb onto the metal surface and form a monolayer [50]. This monolayer acts as a barrier between the metal and the corrosive environment. Precipitation involves the formation of a protective layer by the reaction of the inhibitor with the corrosive species to form an insoluble compound [48]. Complexation involves the formation of a protective layer through the formation of a coordination complex between the inhibitor and the metal surface.

The effectiveness of the protective film is dependent on a variety of factors, including the nature of the inhibitor, the composition of the corrosive environment, and the properties of the metal surface. For example, the protective film formed by inorganic corrosion inhibitors is often dependent on the pH of the environment. At high pH values, inhibitors such as phosphate and molybdate ions form protective films by precipitation, while at low pH values, silicate and borate ions form protective films by chemical adsorption [49].

In addition to the formation of a protective film, inorganic corrosion inhibitors can also act by inhibiting the cathodic and anodic reactions that lead to corrosion. Cathodic inhibitors, such as nitrate and chromate ions, reduce the rate of reduction reactions that occur at the metal surface, while anodic inhibitors, such as zinc and aluminum ions, reduce the rate of oxidation reactions [34].

Overall, the formation of a protective film is a key mechanism of action for inorganic corrosion inhibitors. This protective film acts as a barrier that prevents corrosive species from coming into contact with the metal surface, thereby reducing the rate of corrosion. The effectiveness of this protective film is dependent on a variety of factors, including the nature of the inhibitor, the composition of the corrosive environment, and the properties of the metal surface. Adsorption isotherms are graphical representations of the relationship between the amount of inhibitor adsorbed on the metal surface and the concentration of the inhibitor in the solution. These isotherms can provide insights into the inhibitor's adsorption behavior, such as the adsorption capacity, the strength of the interaction between the inhibitor and the metal surface, and the type of adsorption (i.e., Langmuir or Freundlich) [50-52].

Enthalpy energies are also critical in understanding the adsorption behavior of inorganic corrosion inhibitors. The enthalpy change during the adsorption process can indicate whether the process is exothermic or endothermic and provide insights into the nature of the interaction between the inhibitor and the metal surface. For example, a negative enthalpy change indicates an exothermic process, which suggests a favorable adsorption process and a strong interaction between the inhibitor and the metal surface [53]. Therefore, to fully understand the behavior of inorganic corrosion inhibitors, the author should consider both the physisorption mechanism and the isotherms and enthalpy energies involved in the adsorption process. This will provide a more comprehensive understanding of the inhibitor's ability to prevent corrosion and its potential for use in practical applications.

4.3 Cathodic and anodic polarization

The polarization of the cathodic and anodic branches of the corrosion process can be affected by inorganic corrosion inhibitors. Understanding how these inhibitors impact the reactions in each branch is crucial for predicting their effectiveness in preventing corrosion [54].

In the cathodic branch, the inhibitor can influence the reduction reaction by either inhibiting or accelerating it. For instance, inhibitors that create a barrier between the metal surface and the electrolyte can limit the supply of electrons necessary for the reduction reaction, slowing down the process. Conversely, inhibitors that enhance the adsorption of hydrogen ions can increase the rate of the reduction reaction, thus accelerating the process [55].

On the other hand, in the anodic branch, the inhibitor can modify the oxidation reaction by either impeding or facilitating it. For example, inhibitors that can passivate the metal surface by forming a protective layer can prevent the oxidation reaction from taking place. Conversely, inhibitors that promote the formation of an oxide layer on the metal surface can increase the rate of oxidation, leading to faster corrosion [56].

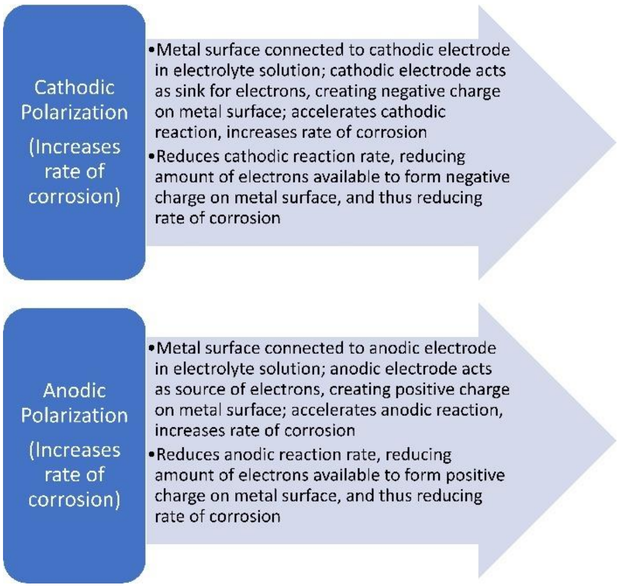


Fig. 3. Effects of cathodic and anodic polarizations on corrosion.

In summary, understanding the effects of inorganic corrosion inhibitors on the polarization of the cathodic and anodic branches can help predict their performance in preventing corrosion. By altering the reactions taking place in each branch, the inhibitors can either hinder or promote the corrosion process, making them valuable tools for preventing metal degradation. Figure 3 illustrates the effects of cathodic and anodic polarizations on corrosion and the impact of inorganic corrosion inhibitors. Cathodic polarization creates a negative charge on the metal surface and accelerates the cathodic reaction, leading to an increased rate of corrosion. In contrast, anodic polarization creates a positive charge on the metal surface and accelerates the anodic reaction, also increasing the rate of corrosion.

Inorganic corrosion inhibitors can reduce the rate of corrosion by reducing the cathodic reaction rate and the amount of electrons available to form a negative charge on the metal surface, or by reducing the anodic reaction rate and the amount of electrons available to form a positive charge on the metal surface.

5. APPLICATIONS OF INORGANIC CORROSION INHIBITORS

Inorganic corrosion inhibitors are chemical compounds that protect metal surfaces from corrosion by forming a protective barrier on the surface. They are typically used in industrial settings where metals are exposed to harsh environments such as high temperatures, acidic or alkaline solutions, and saltwater. Inorganic corrosion inhibitors are preferred over organic inhibitors in some applications due to their thermal stability, resistance to oxidation, and non-volatility. In this article, we will discuss the applications of inorganic corrosion inhibitors in various industries.

1. Oil and gas industry [57]: In the oil and gas industry, inorganic corrosion inhibitors are used to protect pipelines, storage tanks, and other metal structures from corrosion caused by exposure to acidic gases and fluids, saltwater, and high temperatures. The most commonly used inorganic inhibitors in this industry are zinc, aluminum, and magnesium-based compounds, as they provide excellent protection against both general and localized corrosion. Additionally, these inhibitors can also act as scale inhibitors, preventing the formation of scale on metal surfaces.
2. Power generation [58]: In the power generation industry, inorganic corrosion inhibitors are used to protect metal surfaces in boilers, condensers, and other equipment from corrosion caused by exposure to high-temperature steam, acidic or alkaline solutions, and oxygen. The most commonly used inorganic inhibitors in this industry are phosphates, silicates, and sulfites, which provide excellent protection against general and pitting corrosion.
3. Automotive industry: In the automotive industry, inorganic corrosion inhibitors are used to protect metal parts in engines,

transmissions, and other components from corrosion caused by exposure to heat, moisture, and acidic or alkaline solutions. The most commonly used inorganic inhibitors in this industry are phosphates, borates, and molybdates, which provide excellent protection against corrosion caused by engine coolant and brake fluid.

4. Aerospace industry [59]: In the aerospace industry, inorganic corrosion inhibitors are used to protect metal surfaces in aircraft engines, airframes, and other components from corrosion caused by exposure to saltwater, atmospheric moisture, and other environmental factors. The most commonly used inorganic inhibitors in this industry are chromates, which provide excellent protection against both general and localized corrosion.
5. Metalworking industry: In the metalworking industry, inorganic corrosion inhibitors are used to protect metal parts during manufacturing and storage. They are added to metalworking fluids, coolants, and lubricants to prevent corrosion caused by exposure to water, air, and other contaminants. The most commonly used inorganic inhibitors in this industry are borates, nitrates, and phosphates, which provide excellent protection against corrosion caused by exposure to water-based fluids.

In conclusion, inorganic corrosion inhibitors play a vital role in protecting metal surfaces from corrosion in various industries. The selection of the appropriate inhibitor depends on the type of metal, the environment, and the application. The use of inorganic corrosion inhibitors can improve equipment life, reduce maintenance costs, and increase overall efficiency. Table 3 shows the various applications of inorganic corrosion inhibitors. In cooling water systems, phosphates, silicates, molybdates, and borates are commonly used inhibitors. For oil and gas production, calcium carbonate, zinc phosphate, and iron sulfide are frequently utilized. In concrete reinforcement, calcium nitrite and sodium nitrate are popular choices. In metal surface treatment, chromium compounds, chromates, and phosphates are commonly used. Lastly, sodium sulfite and sodium bisulfite are often employed in boiler water treatment as inhibitors.

Table 3. The applications of Inorganic Corrosion Inhibitor.

Application	Inorganic Corrosion Inhibitor	Ref.
Cooling water systems	Phosphates, silicates, molybdates, borates	[59]
Oil and gas production	Calcium carbonate, zinc phosphate, iron sulfide	[60]
Concrete reinforcement	Calcium nitrite, sodium nitrate	[62]
Metal surface treatment	Chromium compounds, chromates, phosphates	[63]
Boiler water treatment	Sodium sulfite, sodium bisulfite	[64]

6. RECENT ADVANCES AND FUTURE DIRECTIONS

Inorganic corrosion inhibitors have been extensively studied over the past few decades due to their cost-effectiveness and environmentally friendly nature [65]. These inhibitors can effectively reduce or even eliminate the corrosive attack on metal surfaces by forming a protective layer on the metal surface. Recently, researchers have made significant advances in the field of inorganic corrosion inhibitors, and these advancements are expected to shape the future of the industry. One of the recent advances in the field of inorganic corrosion inhibitors is the use of nanoparticles. Nanoparticles have unique properties, such as high surface area-to-volume ratio, and can significantly improve the corrosion resistance of metals. For example, researchers have shown that the use of nano-TiO2 can reduce the corrosion rate of mild steel in acidic solutions [66]. Additionally, the use of graphene oxide (GO) as a corrosion inhibitor has also been investigated, and it has been shown to improve the corrosion resistance of metals. Another recent advancement in inorganic corrosion inhibitors is the use of ionic liquids. Ionic liquids are organic salts that are liquid at room temperature and have unique properties, such as low volatility, high thermal stability, and tunable properties. Ionic liquids have been shown to effectively reduce the corrosion rate of metals by forming a protective layer on the metal surface. For example, researchers have shown that imidazolium-based ionic liquids can reduce the corrosion rate of copper in acidic solutions. In addition to these recent advancements, future research in the field of inorganic corrosion inhibitors will likely focus on the development of new inhibitors with improved properties, such as high efficiency, low toxicity, and low cost. One area of focus will likely be the development of inhibitors that are effective in both acidic and alkaline environments [67]. Additionally, researchers will likely investigate the use of new materials, such as metal-organic frameworks (MOFs), as corrosion inhibitors . Table 4 outlines recent advances and future directions in the field of inorganic corrosion inhibitors, with a focus on metal oxides, rare earth elements, graphene-based materials, organic-inorganic hybrids, and green inhibitors. The table provides examples of recent advancements in each category, along with potential future directions for research in the field.

Table 4. Recent advances and future directions of inorganic corrosion inhibitors.

Category	Recent Advances	Future Directions	Ref.
Metal Oxides	Use of nanostructured oxides with higher surface area and improved corrosion inhibition properties	Development of new methods for the synthesis of nanostructured oxides with controlled morphology and surface chemistry	[68-70]
Rare Earth Elements	Discovery of new rare earth-based inhibitors with improved inhibition efficiency	Exploration of the potential of rare earth elements as sustainable corrosion inhibitors	[71-73]
Graphene-Based Materials	Use of graphene-based materials as efficient inhibitors due to their high surface area and unique electronic properties	Development of new methods for the synthesis of graphene-based materials with controlled morphology and surface chemistry	[74]
Organic-Inorganic Hybrids	Development of new organic-inorganic hybrid materials with improved corrosion inhibition properties	Exploration of the potential of organic-inorganic hybrid materials as sustainable corrosion inhibitors	[75]
Green Inhibitors	Development of new environmentally friendly inhibitors derived from natural products	Exploration of the potential of green inhibitors as sustainable corrosion inhibitors	[76]

Overall, recent advancements in inorganic corrosion inhibitors have shown great promise in reducing the corrosive attack on metal surfaces. The use of nanoparticles and ionic liquids has shown significant improvements in the corrosion resistance of metals. Future research in this field will likely continue to focus on the development of new and improved inhibitors that are effective in a wide range of environments.

6.1 Nanotechnology-based inhibitors

Several studies have been conducted to investigate the potential of nanotechnology-based inorganic corrosion inhibitors. One approach is to use nanoparticles of inorganic materials such as metals, metal oxides, and metal sulfides. For example, zinc oxide nanoparticles have been found to be an effective inhibitor for aluminum corrosion in saline solutions. Similarly, copper nanoparticles have been reported to inhibit the corrosion of mild steel in acidic solutions. Nanoparticles of other materials such as silver, titanium dioxide, and magnesium oxide have also been investigated as corrosion inhibitors [77].

Another approach is to modify the surface of the metal with a nanocoating that contains corrosion inhibitors. For example, graphene oxide nanocoatings containing cerium ions have been reported to provide superior corrosion protection for steel in acidic environments. Similarly, a nanocoating containing zinc and cerium ions has been found to be effective in preventing the corrosion of copper in acidic solutions. Despite the promising results of nanotechnology-based inorganic corrosion inhibitors, there is still a need for further research to fully understand their effectiveness and potential applications. One area that requires attention is the toxicity and environmental impact of these materials. While some nanomaterials have been shown to be non-toxic, others may have adverse effects on human health and the environment [78]. Therefore, it is important to conduct comprehensive studies to evaluate the safety of these materials. Another area that requires attention is the optimization of the synthesis and processing methods of nanomaterials to ensure their cost-effectiveness and scalability for large-scale applications. Furthermore, the durability and stability of nanomaterial-based coatings under different environmental conditions, such as temperature and humidity, need to be investigated to ensure their long-term effectiveness. Table 5 showcases examples of nanotechnology-based inhibitors for inorganic corrosion, including silicates, phosphates, chromates, molybdates, zirconates, and rare earth metals. The table highlights the different types of nanotechnology-based inhibitors and their corresponding examples.

Table 5. Examples of nanotechnology-based inhibitors of inorganic corrosion inhibitors.

Inhibitor	Nanotechnology-based inhibitor	Ref.
Silicates	Silica nanoparticles	[79]
Phosphates	Zinc oxide nanoparticles	[80]
Chromates	Zinc-chromate nanoparticles	[81]
Molybdates	Molybdenum disulfide nanoparticles	[82]
Zirconates	Zirconium oxide nanoparticles	[83]
Rare earth metals	Cerium oxide nanoparticles	[84]

Nanotechnology-based inorganic corrosion inhibitors offer a promising solution to the limitations of traditional inorganic corrosion inhibitors [85]. The use of nanoparticles and nanocoatings can provide high surface area coverage, enhanced solubility, and improved adhesion to the metal surface, resulting in superior corrosion protection. However, further research is needed to fully understand the effectiveness, toxicity, and environmental impact of these materials, as well as to optimize their synthesis and processing methods for large-scale applications.

6.2 Green inhibitors

Green inorganic inhibitors are environmentally friendly corrosion inhibitors that are derived from natural resources and have minimal impact on the environment [86]. These inhibitors have several advantages over traditional inhibitors such as low toxicity, biodegradability, and cost-effectiveness. Green inorganic inhibitors can be derived from various sources such as plant extracts, minerals, and metals [87]. One of the recent advances in green inorganic inhibitors is the use of plant extracts as corrosion inhibitors. Several plant extracts have been found to have excellent corrosion inhibition properties such as neem, garlic, and aloe vera. These extracts contain various organic compounds such as flavonoids, alkaloids, and terpenoids that inhibit the corrosion process by forming a protective layer on the metal surface. Another recent development in green inorganic inhibitors is the use of nanotechnology to enhance the performance of inorganic inhibitors.

Nanoparticles such as graphene, silver, and copper have been used as corrosion inhibitors due to their high surface area, excellent conductivity, and reactivity. These nanoparticles can be easily incorporated into coatings and paints to provide long-term protection against corrosion [88]. Future directions for green inorganic inhibitors include the development of more sustainable and eco-friendly inhibitors. The use of renewable resources such as biomass and waste materials to produce inhibitors is gaining momentum. The design and synthesis of new inorganic inhibitors with improved corrosion inhibition properties are also an area of active research [89]. Furthermore, the use of computational methods such as molecular dynamics simulations and density functional theory calculations is expected to provide insights into the mechanism of corrosion inhibition and aid in the design of new inhibitors. Table 6 summarizes common green inorganic corrosion inhibitors, including silicates, phosphates, molybdates, zinc-based inhibitors, and rare earth elements. The table provides a brief description of each inhibitor, along with its corresponding category. The table also lists the inhibitors under their respective categories for easy comparison.

Table 6. Summarizing some common green inorganic corrosion inhibitors.

Inhibitor	Description	Ref.
Silicates	Silicate coatings can be used as a barrier layer to prevent corrosion of metals.	[90]
Phosphates	Phosphate coatings have excellent adhesion and corrosion resistance properties. They can also act as a sacrificial coating to protect metals from corrosion.	[91]
Molybdates	Molybdate coatings can inhibit the corrosion of metals by forming a passive film on the surface. They are environmentally friendly and can be used in various applications.	[92]
Zinc-based inhibitors	Zinc-based coatings can protect metals from corrosion by forming a sacrificial layer. They are commonly used in the automotive and construction industries.	[93]
Rare earth elements	Rare earth elements have been used as corrosion inhibitors due to their high reactivity with oxygen and other elements. They can also act as a barrier layer to prevent corrosion.	[94]

In conclusion, green inorganic inhibitors have the potential to provide sustainable and eco-friendly solutions to the problem of corrosion. Recent advances in the use of plant extracts and nanotechnology have shown promising results in enhancing the performance of inorganic inhibitors. Future directions include the development of more sustainable and eco-friendly inhibitors and the use of computational methods to aid in the design of new inhibitors.

6.3 Combination inhibitors

Combination inhibitors, a type of inorganic corrosion inhibitor, are a mixture of two or more corrosion inhibitors that act synergistically to provide better corrosion protection. In recent years, significant advances have been made in the development of combination inhibitors, and several new formulations have been introduced. In this article, we will discuss recent advances and future directions in the development of inorganic corrosion inhibitors, specifically combination inhibitors. Recent Advances in Combination Inhibitors:

1. Multi-component inhibitors [95]

Multi-component inhibitors are a class of combination inhibitors that contain two or more active ingredients. These inhibitors have been shown to provide better corrosion protection compared to single-component inhibitors. In recent years, researchers have focused on developing multi-component inhibitors that are environmentally friendly and economical. For example, a recent study reported the synthesis of a green inhibitor consisting of sodium alginate and lysine for the corrosion protection of mild steel in seawater. The inhibitor was found to provide excellent corrosion protection and was biodegradable, making it an attractive alternative to traditional inhibitors.

Table 7 summarizes some common multi-component inorganic corrosion inhibitors, including their inorganic and organic components, key characteristics, and examples of inhibitors in each category. The table highlights different types of multi-component inorganic inhibitors, such as nano-hybrid coatings, sol-gel hybrid coatings, phytic acid-Zn hybrid inhibitors, PEG/GO hybrid inhibitors, and layered double hydroxide-based hybrid inhibitors.

Table 7. Summarizing some common multi-component inorganic corrosion inhibitors.

Inhibitor	Components	Ref.
Molybdate-based	Molybdate, Nitrite, Silicate	[97]
Phosphate-based	Phosphate, Nitrite	[98]
Chromate-based	Chromate, Nitrite	[99]
Zinc-based	Zinc, Phosphate, Nitrite	[100]
Tungstate-based	Tungstate, Nitrate	[101]
Vanadate-based	Vanadate, Nitrate	[102]
Rare Earth-based	Rare Earth, Nitrite, Phosphate	[103]
Organic-inorganic hybrid	Organic and Inorganic compounds	[104]

2. Hybrid inhibitors [96]

Hybrid inhibitors are a combination of organic and inorganic inhibitors that work synergistically to provide better corrosion protection. These inhibitors have gained significant attention in recent years due to their improved performance and compatibility with different types of metals. For example, a recent study reported the synthesis of a hybrid inhibitor consisting of poly(ethylene glycol) and cerium oxide nanoparticles for the corrosion protection of aluminium alloys. The hybrid inhibitor was found to provide superior corrosion protection compared to individual inhibitors. Figure 4 summarizes examples of hybrid inorganic corrosion inhibitors, including zinc oxide nanoparticles, cerium oxide nanoparticles, molybdate ions, and silicate coatings. The table highlights the different types of inorganic inhibitors and their corresponding smart properties, such as self-healing, stimuli-responsive, and controlled release of inhibitors.

3. Smart inhibitors [113]

Smart inhibitors are a new class of inhibitors that respond to changes in the corrosion environment. These inhibitors are designed to release the active ingredient in response to changes in pH, temperature, or other environmental factors. For example, a recent study reported the synthesis of a smart inhibitor consisting of cerium oxide nanoparticles and chitosan for the corrosion protection of copper in acidic solutions. The inhibitor was found to release the active ingredient in response to changes in pH, providing better corrosion protection. Table 8, exploring the smart properties of inorganic corrosion inhibitors.

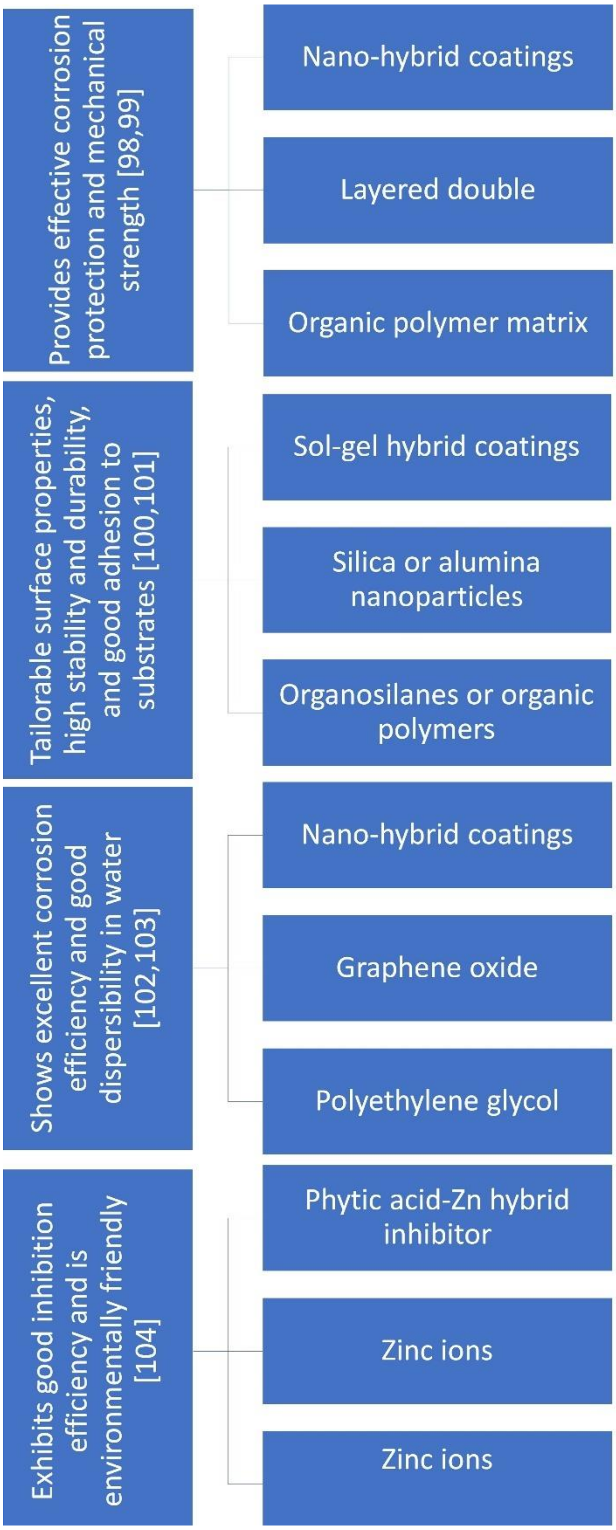


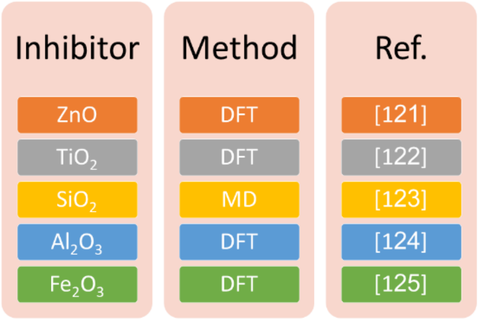
Fig. 4. Summarizing some examples of hybrid inorganic corrosion inhibitors [105-112].

Table 8. Smart inorganic corrosion inhibitors.

Inorganic Inhibitor	Smart Property	Ref.
Zinc Oxide NPs	Self-healing	[114]
Cerium Oxide NPs	pH-sensitive	[115]
Molybdate ions	Self-repairing	[116]
Silicate coatings	Multi-functional	[117]

6.4 Computational studies

In recent years, there have been significant advances in the use of computational studies for the design and optimization of inorganic corrosion inhibitors [118]. These advances include the use of machine learning, quantum mechanical calculations, and molecular dynamics simulations. Machine learning has been used to predict the corrosion inhibition efficiency of inorganic compounds. Machine learning algorithms can learn from large datasets of experimental data and identify patterns and correlations between the molecular structure of the inhibitor and its inhibition efficiency. For example, a recent study used machine learning to predict the corrosion inhibition efficiency of inorganic compounds based on their elemental composition and molecular weight [119]. Quantum mechanical calculations have been used to study the electronic structure and properties of inorganic corrosion inhibitors. These calculations provide insight into the mechanism of corrosion inhibition and the interactions between the inhibitor and the metal surface. For example, a recent study used density functional theory calculations to investigate the electronic structure and corrosion inhibition mechanism of molybdate and tungstate inhibitors. Molecular dynamics simulations have been used to study the adsorption and desorption of inorganic corrosion inhibitors on metal surfaces. These simulations provide insight into the kinetics of inhibitor adsorption and the stability of the inhibitor-metal surface complex [120]. For example, a recent study used molecular dynamics simulations to investigate the adsorption of phosphate and silicate inhibitors on iron surfaces. Figure 5, investigating the efficacy of inorganic corrosion inhibitors through computational studies. Zinc oxide, titanium dioxide, silica, aluminium oxide, and iron oxide analyzed using DFT and MD Methods.



Inhibitor	Method	Ref.
ZnO	DFT	[121]
TiO_2	DFT	[122]
SiO_2	MD	[123]
Al_2O_3	DFT	[124]
Fe_2O_3	DFT	[125]

Figure 5. Computational evaluation of inorganic corrosion inhibitors: a comparative analysis of zinc oxide, titanium dioxide, silica, aluminium oxide, and iron oxide using DFT and md methods.

There are several promising directions for future research in computational studies of inorganic corrosion inhibitors. These include the use of artificial intelligence, the development of new modeling techniques, and the integration of computational and experimental methods [126].

Artificial intelligence has the potential to revolutionize the design of inorganic corrosion inhibitors. Machine learning algorithms can be trained on large datasets of experimental data to identify new inhibitors with high corrosion inhibition efficiency. The development of new machine learning algorithms and the integration of different types of data (e.g., structural, chemical, and experimental) will be critical for the success of this approach [127].

New modeling techniques are also needed to improve the accuracy and efficiency of computational studies of inorganic corrosion inhibitors. For example, the development of multiscale modeling techniques that can link molecular-level simulations with mesoscale and macroscopic models will be important for predicting the behavior of inhibitors in complex environments.

The study of inorganic corrosion inhibitors using computational methods such as Density Functional Theory (DFT) and Molecular Dynamics (MD) requires a deep understanding of the underlying mechanisms and molecular simulation techniques. The author must have a strong grasp of chemistry, materials science, and computer science to accurately predict the effectiveness of these inhibitors in preventing corrosion [128].

DFT is a widely used computational method for simulating the electronic structure of materials, and it provides insight into the chemical bonding, charge distribution, and reactivity of the inhibitors. On the other hand, MD is a simulation technique that models the motion and interaction of atoms and molecules over time, which can provide information about the structural stability, conformational changes, and thermodynamic properties of the inhibitors [129].

To explain the mechanism and molecular simulation of inorganic corrosion inhibitors, the author should have expertise in applying DFT and MD methods to the specific materials being studied. This includes understanding the appropriate simulation parameters, potential energy surfaces, and force fields needed to accurately predict the inhibitor's behavior under different conditions, such as changes in temperature, pressure, and pH.

Finally, the integration of computational and experimental methods will be critical for the validation and optimization of computational models. Combining computational studies with experimental techniques such as electrochemical measurements and surface analysis techniques will provide a more complete understanding of the corrosion inhibition mechanism and enable the design of more effective inhibitors.

7. CURRENT STATE OF KNOWLEDGE

The current state of knowledge on inorganic corrosion inhibitors is quite advanced, and there has been extensive research conducted in this area over the years. Researchers have made significant progress in understanding the chemical composition, mechanisms of action, and applications of inorganic corrosion inhibitors. Recent studies have focused on developing new and more effective corrosion inhibitors, as well as improving the performance of existing inhibitors. There has also been a focus on understanding the environmental impact of corrosion inhibitors, as some types of inhibitors such as chromates can have negative environmental effects. One area of research that has gained a lot of attention is the development of smart corrosion inhibitors. These inhibitors have the ability to detect and respond to changes in the corrosion environment, thereby providing a more targeted and effective corrosion protection. Another area of research is the development of corrosion-resistant materials, which could potentially eliminate the need for corrosion inhibitors altogether. These materials include high-performance alloys, ceramics, and coatings.

Overall, the current state of knowledge on inorganic corrosion inhibitors is quite advanced, and researchers continue to make significant progress in developing new and more effective inhibitors, as well as improving our understanding of their mechanisms of action and applications.

8. IDENTIFY GAPS IN EXISTING STUDIES FOR POTENTIAL FUTURE RESEARCH

Although there have been significant advances in the research on inorganic corrosion inhibitors, there are still several gaps in existing studies that present opportunities for future research. Some of these gaps include:

1. Understanding the long-term performance of inorganic corrosion inhibitors: Many studies have focused on the short-term performance of corrosion inhibitors, but there is a need to understand their long-term performance over the life cycle of metal structures.
2. Developing cost-effective and environmentally friendly corrosion inhibitors: While inorganic corrosion inhibitors have proven to be effective, some types of inhibitors such as chromates are environmentally harmful. There is a need to develop cost-effective and environmentally friendly alternatives that can provide similar levels of corrosion protection.
3. Investigating the mechanisms of corrosion inhibition: While researchers have made progress in understanding the mechanisms of action of inorganic corrosion inhibitors, there is still much to learn. Further research is needed to better understand how inhibitors interact with metal surfaces and how they prevent corrosion.
4. Developing smart corrosion inhibitors: While there have been some recent developments in smart corrosion inhibitors, more research is needed to develop new materials and technologies that can detect and respond to changes in the corrosion environment.
5. Studying the impact of corrosion inhibitors on the mechanical properties of metals: While inorganic corrosion inhibitors can provide effective protection against corrosion, they may also have an impact on the mechanical properties of metals. Further research is needed to understand the impact of inhibitors on the strength and durability of metal structures.

In summary, there are several gaps in existing studies on inorganic corrosion inhibitors that present opportunities for future research. By addressing these gaps, researchers can develop new and more effective corrosion inhibitors that can provide better protection against corrosion while minimizing their impact on the environment and the mechanical properties of metals.

9. HIGHLIGHT THE MAIN METHODOLOGIES AND RESEARCH TECHNIQUES.

The methodologies and research techniques used in the study of inorganic corrosion inhibitors vary depending on the specific research questions and objectives. Some of the main methodologies and research techniques used in this field include:

1. Electrochemical techniques:

Electrochemical techniques, such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), are commonly used to study the corrosion behavior of metals in the presence of inorganic corrosion inhibitors. These techniques can provide information on the corrosion rate, polarization resistance, and other parameters that can be used to evaluate the effectiveness of inhibitors.

2. Surface analysis techniques:

Surface analysis techniques, such as scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS), are used to study the surface morphology and composition of metals before and after exposure to inorganic corrosion inhibitors. These techniques can provide information on the adsorption and interaction of inhibitors with the metal surface.

3. Chemical analysis techniques:

Chemical analysis techniques, such as atomic absorption spectroscopy (AAS) and inductively coupled plasma optical emission spectroscopy (ICP-OES), are used to determine the concentration of inorganic corrosion inhibitors in solution or on the metal surface. These techniques can provide information on the adsorption and desorption of inhibitors from the metal surface.

4. Computational modeling:

Computational modeling is used to simulate the behavior of inorganic corrosion inhibitors and their interaction with metal surfaces. This technique can provide insights into the mechanisms of corrosion inhibition and can be used to design new and more effective inhibitors.

5. Field studies:

Field studies involve the evaluation of inorganic corrosion inhibitors in real-world applications. These studies can provide information on the effectiveness of inhibitors under actual operating conditions and can help identify potential issues that may not be evident in laboratory studies.

In summary, the methodologies and research techniques used in the study of inorganic corrosion inhibitors include electrochemical techniques, surface analysis techniques, chemical analysis techniques, computational modeling, and field studies. By using a combination of these techniques, researchers can gain a better understanding of the mechanisms of corrosion inhibition and develop new and more effective inhibitors.

10. CONCLUSION

The conclusion of the review article provides a summary of the main points discussed in the article and offers insights into the significance of inorganic corrosion inhibitors in various industrial applications. The review article begins with an introduction to the concept of corrosion and its economic and safety implications. The article then proceeds to discuss the different types of inorganic corrosion inhibitors, including anodic inhibitors, cathodic inhibitors, and mixed inhibitors. The mechanisms of action of these inhibitors are also discussed in detail. In the conclusion, the article emphasizes the importance of using inorganic corrosion inhibitors in industrial applications. The use of these inhibitors has been shown to reduce the rate of corrosion, increase the lifespan of equipment, and reduce maintenance costs. The article also notes that the use of inorganic corrosion inhibitors can help in the development of sustainable industrial practices. The conclusion of the article highlights the need for further research on inorganic corrosion inhibitors. More research is required to fully understand the mechanisms of action of these inhibitors and to develop new and improved formulations. Additionally, the article notes that there is a need for more research on the environmental impact of inorganic corrosion inhibitors. Overall, the conclusion of the review article highlights the importance of inorganic corrosion inhibitors in industrial applications and calls for continued research in this area.

10.1 Summary of the key findings

The article is a comprehensive overview of the subject and provides a summary of the key findings, which are as follows:

1. Types of inorganic corrosion inhibitors: Inorganic corrosion inhibitors can be classified into three categories: anodic inhibitors, cathodic inhibitors, and mixed inhibitors. Anodic inhibitors work by forming a protective oxide film on the metal surface, while cathodic inhibitors work by reducing the cathodic reaction rate. Mixed inhibitors use a combination of anodic and cathodic inhibition mechanisms.
2. Mechanisms of inorganic corrosion inhibitors: The mechanisms of inorganic corrosion inhibitors vary depending on the type of inhibitor. Anodic inhibitors work by forming a protective oxide film on the metal surface, which prevents the reaction between the metal and the corrosive environment. Cathodic inhibitors work by reducing the cathodic reaction rate, which decreases the production of corrosive ions. Mixed inhibitors use a combination of these mechanisms to provide better corrosion protection.
3. Applications of inorganic corrosion inhibitors: Inorganic corrosion inhibitors are used in various industries, including oil and gas, water treatment, and metalworking. They are also used in the preservation of historical artifacts and the protection of infrastructure such as bridges and buildings.
4. Effectiveness of inorganic corrosion inhibitors: The effectiveness of inorganic corrosion inhibitors depends on several factors, including the type of inhibitor, the concentration, and the corrosive environment. The article highlights that the efficiency of inorganic inhibitors is generally lower compared to organic inhibitors, but they offer a longer protection period and better stability in extreme environmental conditions.
5. Future research directions: The review article also discusses the future research directions for inorganic corrosion inhibitors. The article suggests that research should focus on developing environmentally friendly inhibitors and designing inhibitors with specific target applications. Additionally, research should aim to develop a better understanding of the inhibition mechanisms of inorganic corrosion inhibitors.

In summary, the review article "A Review of Inorganic Corrosion Inhibitors: Types, Mechanisms, and Applications" provides a comprehensive overview of the subject, covering the types, mechanisms, applications, effectiveness, and future research directions for inorganic corrosion inhibitors. The key findings of the review article highlight the importance of inorganic corrosion inhibitors in various industries and the need for further research to develop better inhibitors that are environmentally friendly and have specific target applications.

10.2 Future outlook

The future outlook for inorganic corrosion inhibitors is promising, as these compounds have shown great potential in preventing and mitigating corrosion in various applications. One of the major advantages of inorganic corrosion inhibitors is their stability and durability, which makes them suitable for use in harsh environments such as those found in the oil and gas industry.

The article discusses several types of inorganic corrosion inhibitors, including metal salts, metal oxides, and metalloids. Metal salts, such as chromates, have been widely used in the past, but their use has been limited due to environmental concerns. Metal oxides, such as zinc oxide and aluminum oxide, have shown promise as environmentally friendly alternatives to chromates. Metalloids, such as boron and silicon, have also been studied as potential corrosion inhibitors due to their ability to form protective films on metal surfaces.

The mechanisms of action of inorganic corrosion inhibitors are also discussed in the article. These mechanisms include the formation of passive films, the formation of insoluble salts, and the absorption of corrosion products. The article highlights the importance of understanding the mechanisms of action of corrosion inhibitors in order to optimize their performance and develop new, more effective inhibitors.

The applications of inorganic corrosion inhibitors are numerous, ranging from the oil and gas industry to the automotive industry. The article discusses the use of inorganic inhibitors in pipeline coatings, metal coatings, and cooling systems, among other applications. The use of inorganic inhibitors in these applications has been shown to improve the longevity and performance of the metal components, reducing maintenance costs and increasing safety.

In conclusion, the future outlook for inorganic corrosion inhibitors is promising, as these compounds continue to show great potential in preventing and mitigating corrosion in various applications. Further research is needed to optimize the performance of these inhibitors and develop new, more effective inhibitors. Additionally, efforts should be made to develop environmentally friendly alternatives to traditional metal salts, such as chromates, in order to address environmental concerns.

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REFERENCES

[1] A.A. Al-Amiery, W.N.R. W. Isahak, W.K. Al-Azzawi, *Corrosion inhibitors: natural and synthetic organic inhibitors*, Lubricants, vol. 11, iss. 4, 2023, doi: 10.3390/lubricants11040174

[2] B.S. Mahdi, M.K. Abbass, M.K. Mohsin, W.K. Al-azzawi, M.M. Hanoon, M.H.H. Al-kaabi, L.M. Shaker, A.A. Al-amiery, W.N.R.W. Isahak, A.A.H. Kadhum, M.S. Takriff, *Corrosion inhibition of mild steel in hydrochloric acid environment using terephthaldehyde based on Schiff base: gravimetric, thermodynamic, and computational studies*, Molecules, vol. 27, iss. 15, 2022, doi: 10.3390/molecules27154857

[3] A.A. Alamiery, *Study of corrosion behavior of N´-(2-(2-oxomethylpyrrol-1-yl) ethyl) piperidine for mild steel in the acid environment*, Biointerface Research in Applied Chemistry, vol. 12, iss. 3, pp. 3638-3646, 2022, doi: 10.33263/BRIAC123.36383646

[4] A. Alamiery, A.B. Mohamad, A.A.H. Kadhum, M.S. Takriff, *Comparative data on corrosion protection of mild steel in HCl using two new thiazoles*, Data Brief, vol. 40, 2022, doi: 10.1016/j.dib.2022.107838

[5] A.M. Mustafa, F.F. Sayyid, N. Betti, M.M. Hanoon, A.A. Al-Amiery, A.A.H. Kadhum, M.S. Takriff, *Inhibition of mild steel corrosion in hydrochloric acid environment by 1-amino-2-mercapto-5-(4-(pyrrol-1-yl)phenyl)-1,3,4-triazole*, South African Journal of Chemical Engineering, vol. 39, pp. 42-51, 2022, doi: 10.1016/j.sajce.2021.11.009

[6] A.A. Alamiery, *Investigations on corrosion inhibitory effect of newly quinoline derivative on mild steel in HCl solution complemented with antibacterial studies*, Biointerface Research in Applied Chemistry, vol. 12, iss. 3, pp. 1561-1568, 2022, doi: 10.33263/BRIAC122.15611568

[7] I.A.A. Aziz, I.A. Annon, M. Abdulkareem, M. Hanoon, M. Alkaabi, L.M. Shaker, A. Alamiery, W.N.R.W. Isahak, M. Takriff, Insights into corrosion inhibition behavior of a 5-mercapto-1,2,4-triazole derivative for mild steel in hydrochloric acid solution: experimental and DFT studies, Lubricants, vol. 9, iss. 12, 2021, doi: 10.3390/lubricants9120122

[8] A. Alamiery, *Short report of mild steel corrosion in 0.5 M H2SO4 by 4-ethyl-1-(4-oxo4-phenylbutanoyl)thiosemicarbazide*, Journal Tribologi, vol. 30, pp. 90-99, 2021

[9] A.A. Alamiery, W.N.R.W. Isahak, M.S. Takriff, *Inhibition of mild steel corrosion by 4-benzyl-1-(4-oxo-4-phenylbutanoyl)thiosemicarbazide: Gravimetrical, adsorption and theoretical studies*, Lubricants, vol. 9, iss. 9, 2021, doi: 10.3390/lubricants9090093

[10] N. Betti, A.A. Al-Amiery, W.K. Al-Azzawi, W.N.R.W. Isahak, *Corrosion inhibition properties of schiff base derivative against mild steel in HCl environment complemented with DFT investigations*, Scientific Reports, vol. 13, iss. 1, 2023, doi: 10.1038/s41598-023-36064-w

[11] R. Hsissou, S. Abbout, F. Benhiba, R. Seghiri, Z. Safi, S. Kaya, S. Briche, G. Serdaroğlu, H. Erramli, A. Elbachiri, A. Zarrouk, A. El Harfi, *Insight into the corrosion inhibition of novel macromolecular epoxy resin as highly efficient inhibitor for carbon steel in acidic mediums: Synthesis, characterization, electrochemical techniques, AFM/UV–Visible and computational investigations,* Journal of Molecular Liquids, vol. 337, 2021, doi: 10.1016/j.molliq.2021.116492

[12] M.A. Dawood, Z.M.K. Alasady, M.S. Abdulazeez, D.S. Ahmed, G.M. Sulaiman, A.A.H. Kadhum, L.M. Shaker, A.A. Alamiery, *The corrosion inhibition effect of a pyridine derivative for low carbon steel in 1 M HCl medium: Complemented with antibacterial studies*, International Journal of Corrosion and Scale Inhibition, vol. 10, no. 4, pp. 1766–1782, 2021, doi: 10.17675/2305-6894-2021-10-4-25

[13] A. Alamiery, *Corrosion inhibition effect of 2-N-phenylamino-5-(3-phenyl-3-oxo-1- propyl)-1,3,4-oxadiazole on mild steel in 1 M hydrochloric acid medium: Insight from gravimetric and DFT investigations*, Materials Science for Energy Technologies, vol. 4, pp. 398–406, 2021, doi: 10.1016/j.mset.2021.09.002

[14] A.A. Alamiery, *Anticorrosion effect of thiosemicarbazide derivative on mild steel in 1 M hydrochloric acid and 0.5 M sulfuric Acid: Gravimetrical and theoretical studies*, Materials Science for Energy Technologies, vol. 4, pp. 263–273, 2021, doi: 10.1016/j.mset.2021.07.004

[15] A. Alamiery, W.N.R.W. Isahak, H. Aljibori, H. Al-Asadi, A. Kadhum, *Effect of the structure, immersion time and temperature on the corrosion inhibition of 4-pyrrol-1-yln-(2,5-dimethyl-pyrrol-1-yl)benzoylamine in 1.0 m HCl solution*, International Journal of Corrosion and Scale Inhibition, vol. 10, no. 2, pp. 700–713, 2021, doi: 10.17675/2305-6894-2021-10-2-14

[16] A. Alamiery, E. Mahmoudi, T. Allami, *Corrosion inhibition of low-carbon steel in hydrochloric acid environment using a Schiff base derived from pyrrole: gravimetric and computational studies*, International Journal of Corrosion and Scale Inhibition, vol. 10, no. 2, pp. 749–765, 2021, doi: 10.17675/2305-6894-2021-10-2-17

[17] A.J.M. Eltmimi, A. Alamiery, A.J. Allami, R.M. Yusop, A.H. Kadhum, T. Allami, *Inhibitive effects of a novel efficient Schiff base on mild steel in hydrochloric acid environment*, International Journal of Corrosion and Scale Inhibition, vol. 10, no 2. pp. 634-648, 2021, doi: 10.17675/2305-6894-2021-10-2-10

[18] A. Alamiery, L.M. Shaker, T. Allami, A.H. Kadhum, M.S. Takriff, *A study of acidic corrosion behavior of Furan-Derived Schiff base for mild steel in hydrochloric acid environment: Experimental, and surface investigation*, Materials Today: Proceedings, vol. 44, pp. 2337-2341, 2021, doi: 10.1016/j.matpr.2020.12.431

[19] S. Al-Baghdadi, A. Al-Amiery, T. Gaaz, A. Kadhum, *Terephthalohydrazide and isophthalo-hydrazide as new corrosion inhibitors for mild steel in hydrochloric acid: Experimental and theoretical approaches*, Koroze a ochrana materialu, vol. 65, pp. 12-22, 2021, doi: 10.2478/kom-2021-0002

[20] M.M. Hanoon, A.M. Resen, L.M. Shaker, A. Kadhum, A. Al-Amiery, *Corrosion investigation of mild steel in aqueous hydrochloric acid environment using n- (Naphthalen-1yl)-1-(4-pyridinyl)methanimine complemented with antibacterial studies*, Biointerface Research in Applied Chemistry, vol. 11, iss. 2, pp. 9735-9743, 2021, doi: 10.33263/BRIAC112.97359743

[21] J.O. Bockris, A.K.N. Reddy, *Modern Electrochemistry, An Introduction to an Interdisciplinary Area*, Springer, 1970.

[22] P.R. Roberge, *Handbook of Corrosion Engineering*, New York: McGraw-Hill, 2000.

[23] A. Al-Amiery, W.N.R.W. Isahak, W.K. Al-Azzawi, *ODHI: A promising isatin-based corrosion inhibitor for mild steel in hydrochloric acid*, Journal of Molecular Structure, vol. 1288, 2023, doi: 10.1016/j.molstruc.2023.135829

[24] A.A. Al-Amiery, N. Betti, W.N.R.W. Isahak, W.K. Al-Azzawi, W.M.N.W. Nik, *Exploring the Effectiveness of Isatin–Schiff Base as an*

Environmentally Friendly Corrosion Inhibitor for Mild Steel in Hydrochloric Acid, Lubricants, vol. 11, iss. 5, 2023, doi: 10.3390/lubricants11050211

[25] F.F. Sayyid, A.M. Mustafa, S.I. Ibrahim, M.K. Mohsin, M.M. Hanoon, M.H.H. Al-Kaabi, A.A.H. Kadhum, W.N.R.W. Isahak, A.A.Al-Amiery, *Gravimetric Measurements and Theoretical Calculations of 4-Aminoantipyrine Derivatives as Corrosion Inhibitors for Mild Steel in Hydrochloric Acid Solution: Comparative Studies*, Corrosion Science and Technology, vol. 22, iss 2, pp. 73–89, 2023, doi: 10.14773/CST.2023.22.2.73

[26] A.M. Alfantazi, J.C. Trepanier, *Corrosion inhibitors*, in Encyclopedia of Electrochemical Power Sources, Elsevier, pp. 468-481, 2011.

[27] A.K. Al-Edan, W.N.R.W. Isahak, Z.A.C. Ramli, W.K Al-Azzawi, A.A.H. Kadhum, H.S.Jabbar, A. Al-Amiery, *Palmitic acid-based amide as a corrosion inhibitor for mild steel in 1M HCl*, Heliyon, vol. 9, iss. 4, 2023. doi: 10.1016/j.heliyon.2023.e14657

[28] M. Natesan, T. Shoji, *Corrosion inhibitors*, in Corrosion Inhibitors: Principles and Applications, John Wiley & Sons, pp. 1-24, 2006

[29] Z. Aida, A. Razika, M. Laid, B. Kamel, S. Boualem, *Inhibition of acid corrosion of mild steel by aqueous nettle extracts*, Pigment & Resin Technology 43, 127–138, 2014, doi: 10.1108/PRT-11-2012-0078

[30] D. Kesavan, M Gopiraman, N. Sulochana, *Green inhibitors for corrosion of metals: A review*, Chemical Science Review and Letters, vol. 1, pp. 1–8, 2012.

[31] M. Gobara, B. Zaghloul, A. Baraka, M. Elsayed, M. Zorainy, M. Kotb, H. Elnabarawy, *Green corrosion inhibition of mild steel to aqueous sulfuric acid by the extract of Corchorus ollitorius stems*, Materials Research Express, vol. 4, no. 4, pp. 391-401, 2017, doi: 10.1088/2053-1591/aa664a

[32] C.U. Dueke‐Eze, N.A. Madueke, N.B. Iroha, N.J. Maduelosi, L.A. Nnanna, *Adsorption and inhibition study of N-(5-methoxy-2-hydroxybenzylidene) isonicotinohydrazide Schiff base on copper corrosion in 3.5% NaCl*, Egyptian Journal of Petroleum, vol. 31, iss. 2, pp. 31-37, 2022, doi: 10.1016/j.ejpe.2022.05.001

[33] E. De Ketelaere, D. Moed, M. Vanoppen, A.R.D. Verliefde, K. Verbeken, T. Depover, *Sodium silicate corrosion inhibition behaviour for carbon steel in a dynamic salt water environment*, Corrosion Science, vol. 217, 2023, doi: 10.1016/j.corsci.2023.111119

[34] Shehnazdeep, B. Pradhan, *A study on effectiveness of inorganic and organic corrosion inhibitors on rebar corrosion in concrete: A review*, Materials Today: Proceedings, vol. 65, pp. 1360-1366, 2022, doi: 10.1016/j.matpr.2022.04.296

[35] S. Al-Baghdadi, T.S. Gaaz, A. Al-Adili, A. Al-Amiery, M. Takriff, *Experimental studies on corrosion inhibition performance of acetylthiophene thiosemicarbazone for mild steel in HCl complemented with DFT investigation*, International Journal of Low-Carbon Technologies, vol. 16, pp. 181-188, 2021, doi: 10.1093/ijlct/ctaa050

[36] A. Al-Amiery, *Anti-corrosion performance of 2-isonicotinoyl-nphenylhydrazinecarbothioamide for mild steel hydrochloric acid solution: Insights from experimental measurements and quantum chemical calculations*, Surface Review and Letters, vol. 28, no. 3, 2021, doi: 10.1142/S0218625X20500584

[37] M.S. Abdulazeez, Z.S. Abdullahe, M.A. Dawood, Z.K. Handel, R.I. Mahmood, S. Osamah, A.H. Kadhum, L.M. Shaker, A.A. Al-Amiery, *Corrosion inhibition of low carbon steel in HCl medium using a thiadiazole derivative: weight loss, DFT studies and antibacterial studies*, International Journal of Corrosion and Scale Inhibition, vol. 10, pp. 1812-1828, doi: 10.17675/2305-6894-2021-10-4-27

[38] S. Mo, L. Li, H. Luo, N. Li, *An example of green copper corrosion inhibitors derived from flavor and medicine: Vanillin and isoniazid*, Journal of Molecular Liquids, vol. 242, pp. 822–830, 2017, doi: 10.1016/j.molliq.2017.07.081

[39] K. Tamalmani, H. Husin, *Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues*, Applied Sciences, vol. 10, iss. 10, 2020, doi: 10.3390/app10103389

[40] A. Mustafa, F. Sayyid, N. Betti, M. Hanoon, A. Al-Amiery, A. Kadhum, M. Takriff, *Inhibition Evaluation of 5-(4-(1H-pyrrol-1-yl)phenyl)-2-mercapto-1,3,4-oxadiazole for the Corrosion of Mild Steel in an Acid environment: Thermodynamic and DFT Aspects*, Tribologia, vol. 38, no. 3-4, pp. 39–47, 2021, doi: 10.30678/fjt.105330

[41] K. Suresh, V. Kalia, M. Goyal, G. Jhaa, S. Kumar, H. Vashisht, H. Dahiya, M.A. Quraishi, C. Verma, *Newly synthesized oxadiazole derivatives as corrosion inhibitors for mild steel in acidic medium: Experimental and theoretical approaches,* Journal of Molecular Liquids, vol. 357, 2022, doi: 10.1016/j.molliq.2022.119077

[42] Y.M. Abdulsahib, A.J.M. Eltmimi, S.A. Alhabeeb, M. M. Hanoon, A.A. Al-Amiery, T. Allami, A.A.H. Kadhum, *Experimental and theoretical investigations on the inhibition efficiency of N-(2,4-dihydroxytolueneylidene)-4-methylpyridin-2-amine for the corrosion of mild steel in hydrochloric acid*, International Journal of Corrosion and Scale Inhibition, vol. 10, no. 3, pp. 885–899, 2021, doi: 10.17675/2305-6894-2021-10-3-3

[43] A.K. Khudhair, A.M. Mustafa, M.M. Hanoon, A. Al-Amiery, L.M. Shaker, T. Gazz, A.B. Mohamad, A.H. Kadhum, M.S. Takriff, *Experimental and Theoretical Investigation on the Corrosion Inhibitor Potential of N-MEH for Mild Steel in HCl*, Progress in Color, Colorants and Coatings, vol. 15, iss. 2, pp. 111–122, 2022, doi: 10.30509/PCCC.2021.166815.1111

[44] D.S. Zinad, R. D. Salim, N. Betti, L. M. Shaker, A.A. Al-Amiery, *Comparative Investigations of the Corrosion Inhibition Efficiency of a 1-phenyl- 2-(1-phenylethylidene)hydrazine and its Analog Against Mild Steel Corrosion in Hydrochloric Acid Solution*, Progress in Color, Colorants and Coatings, vol. 15, iss. 1, pp. 53–63, 2022, doi: 10.30509/PCCC.2021.166786.1108

[45] M.A. Amin, N.A. Al-Mobarak, *Corrosion inhibitors – principles, mechanisms and applications*, InechOpen, 2011, doi: 10.5772/57255

[46] R.D. Salim, N. Betti, M. Hanoon, A.A. Al-Amiery, *2-(2,4-Dimethoxybenzylidene)-N-Phenylhydrazinecarbothioamide as an Efficient Corrosion Inhibitor for Mild Steel in Acidic Environment*, Progress in Color, Colorants and Coatings, vol. 15, iss. 1, pp. 45–52, 2021, doi: 10.30509/PCCC.2021.166775.1105

[47] M. Stern, A.L. Geary, *Electrochemical Polarization: I . A Theoretical Analysis of the Shape of Polarization Curves*, Journal of The Electrochemical Society, vol. 104, iss. 1, pp. 56-63, 1957, doi: 10.1149/1.2428496

[48] A.A. Al-Amiery, L.M. Shaker, A.H. Kadhum, M.S. Takriff, *Exploration of furan derivative for application as corrosion inhibitor for mild steel in hydrochloric acid solution: Effect of immersion time and temperature on efficiency*, Materials Today: Proceeding., vol. 42, pp. 2968–2973, 2021, doi: 10.1016/j.matpr.2020.12.807

[49] Z. Szklarska-Smialowska, *Corrosion inhibitors: principles and applications*. Wiley, 1998.

[50] A.M. Resen, M.M. Hanoon, W.K. Alani, A. Kadhim, A.A. Mohammed, T.S. Gaaz, A.A. H. Kadhum, A.A. Al-Amiery, M.S. Takriff, *Exploration of 8-piperazine-1-ylmethylumbelliferone for application as a corrosion inhibitor for mild steel in hydrochloric acid solution*, International Journal of Corrosion and Scale Inhibition, vol. 10, no. 1, pp. 368-387, 2021, doi: 10.17675/2305-6894-2021-10-1-21

[51] M.M. Hanoon, A.M. Resen, A.A. Al-Amiery, A.A.H. Kadhum, M.S. Takriff, *Theoretical and experimental studies on the corrosion inhibition potentials of 2-((6-methyl-2-ketoquinolin-3-yl)methylene) hydrazinecarbothioamide for mild steel in 1 M HCl*, Progress in Color, Colorants and Coatings, vol. 15, iss. 1, pp. 11-23, 2022, doi: 10.30509/PCCC.2020.166739.1095

[52] F.G. Hashim, T.A. Salman, S.B. Al-Baghdadi, T. Gaaz, A.A. Al-Amiery, *Inhibition effect of hydrazine-derived coumarin on a mild steel surface in hydrochloric acid*, Tribologia, vol. 37, pp. 45-53, 2020, doi: 10.30678/fjt.95510

[53] A.M. Resen, M. Hanoon, R.D. Salim, A.A. Al-Amiery, L.M. Shaker, A.A.H. Kadhum, Gravimetrical, theoretical, and surface morphological investigations of corrosion inhibition effect of 4-(benzoimidazole-2-yl) pyridine on mild steel in hydrochloric acid, Koroze a ochrana materiálu, vol. 64, pp. 122-130, 2020, doi: 10.2478/kom-2020-0018

[54] H. Ashassi-Sorkhabi, D. Seifzadeh, *Inorganic Corrosion Inhibitors*, in Corrosion Inhibitors, IntechOpen, pp. 25-46, 2012, doi: 10.5772/intechopen.80542

[55] L.L. Shreir, R.A. Jarman, G.T. Burstein, H. Shimizu, *Corrosion inhibitors*, in T. Richardson (Ed.), Shreir's corrosion, Elsevier, pp. 569-605, 2010.

[56] M. Stern, A.L. Geary, *Electrochemical polarization: I. A theoretical analysis of the shape of polarization curves*, The Journal of Chemical Physics, vol. 28, iss. 6, pp. 1010-1019, 1957, doi: 10.1149/1.2428496

[57] E. Abd El Aal, S. Abd El Wanees, A. Farouk, S. Abd El Haleem, *Factors affecting the corrosion behaviour of aluminium in acid solutions. II. Inorganic additives as corrosion inhibitors for Al in HCl solutions*, Corrosion Science, vol. 68, 14–24, 2013, doi: 10.1016/j.corsci.2012.09.038

[58] R.E. Tuzun, M.A. Marzouk, *Corrosion inhibition*, in Handbook of materials failure analysis with case studies from the aerospace and automotive industries, Elsevier, pp. 317-338, 2016.

[59] M. Rezaeivala, M. Bozorg, N. Rafiee, K. Sayin, B. Tuzun, *Corrosion inhibition of Carbon Steel using a new morpholine-based ligand during acid pickling: Experimental and theoretical studies*, Inorganic Chemistry Communications, vol. 148, 2023, doi: 10.1016/j.inoche.2022.110323

[60] F. Kang, Q. Lv, J. Liu, Y. Meng, Z. Wang, X. Ren, S. Hu, *Organic–inorganic calcium lignosulfonate compounds for soil acidity amelioration*, Environmental Science and Pollution Research, vol. 29, pp. 74118-74132, 2022, doi: 10.1007/s11356-022-20461-1

[61] Y. Hu, C. Chen, So. Liu, *State of art bio-materials as scale inhibitors in recirculating cooling water system: a review article*, Water Science and Technology, vol. 85, iss. 5, pp. 1500-1521, 2022, doi: 10.2166/wst.2022.027

[62] X. Guo, J.S.C. Joy, Y. Cheng, X. Zhao, Z. Liu, Y. Xu, *Scale Inhibitors for Industrial Circulating Water Systems: A Review*, Journal of Water Chemistry and Technology, vol. 43, iss. 6, pp. 517-525, 2021, doi: 10.3103/S1063455X21060102

[63] P.B. Raja, M. Ismail, S. Ghoreishiamiri, J. Mirza, M.C. Ismail, S. Kakooei, A.A. Rahim, *Reviews on Corrosion Inhibitors: A Short View*, Chemical Engineering Communications, vol 203, iss. 9, pp. 1145-1156, 2016, doi: 10.1080/00986445.2016.1172485

[64] A. Marciales, T. Haile, B. Ahvazi, T.-D. Ngo, J. Wolodko, *Performance of green corrosion inhibitors from biomass in acidic media*, Corrosion Reviews, vol. 36, iss. 3, 239-266, 2018, doi: 10.1515/corrrev-2017-0094

[65] B. Lin, J. Tang, Y. Wang, H. Wang, Y. Zuo, *Study on Synergistic Corrosion Inhibition Effect between Calcium Lignosulfonate (CLS) and Inorganic Inhibitors on Q235 Carbon Steel in Alkaline Environment with Cl−*, Molecules, vol. 25, iss. 18, 2020, doi: 10.3390/molecules25184200

[66] L. Guo, Y. Huang, Y. Wu, W. Shi, F. Abbas, Y. Lin, R. Marzouki, X. Zheng, *Experimental and Theoretical Studies of the Corrosion Inhibition Performance of a Quaternary Phosphonium-Based Ionic Liquid for Mild Steel in HCl Medium*, Sustainability, vol. 15, iss. 4, 2023 doi: 10.3390/su15043103

[67] J. Liu, X. Li, L. Wang, Y. Chen, Z. Liu, *Ionic liquids as corrosion inhibitors: A review*, Journal of Molecular Liquids, vol. 281, pp. 248-262, 2019, doi: 10.1016/j.jmrt.2022.12.066

[68] M. Kuznetsov, Y.I. Redkina, G.V. Thin, *Protective Coatings on Metals Formed by Organic Corrosion Inhibitors in Neutral Media*, Coatings, vol. 12, iss. 2, 2022, doi: 10.3390/coatings12020149

[69] M. Damej, S. Kaya, B. EL Ibrahimi, H-S. Lee, A. Molhi, G. Serdaroğlu, M. Benmessaoud, I.H. Ali, S. EL Hajjaji, H. Lgaz, *The corrosion inhibition and adsorption behavior of mercaptobenzimidazole and bis-mercaptobenzimidazole on carbon steel in 1.0 M HCl: Experimental and computational insights*, Surfaces and Interfaces, vol. 24, 2021, doi: 10.1016/j.surfin.2021.101095

[70] B.E. Rani, B.B. Basu, *Green Inhibitors for Corrosion Protection of Metals and Alloys: An Overview*, International Journal of Corrosion, vol. 20122012, doi: 10.1155/2012/380217

[71] N. Mechbal, M. Bouhrim, M. Bnouham, B. Hammouti, Y. Karzazi, S. Kaya, G. Serdaroğlu, *Anticorrosive and antioxidant effect of the aqueous extract of the leaves, flowers, and stems of Cistus monspeliensis L: Experimental and computational study,* Journal of Molecular Liquids, vol. 331, 2021, doi: 10.1016/j.molliq.2021.115771

[72] J. Ruwoldt, *A Critical Review of the Physicochemical Properties of Lignosulfonates: Chemical Structure and Behavior in Aqueous Solution*, at Surfaces and Interfaces. Surfaces, vol. 3, iss. 4, pp. 622-648, 2020 doi: 10.3390/surfaces3040042

[73] A.K. Singh, B. Chugh, M. Singh, S. Thakur, B. Pani, L. Guo, S. Kaya, G. Serdaroglu, *Hydroxy phenyl hydrazides and their role as corrosion impeding agent: A detail experimental and theoretical study*, Journal of Molecular Liquids, vol. 330, 2021, doi: 10.1016/j.molliq.2021.115605

[74] P.B. Raja, M.G. Sethuraman*, Natural products as corrosion inhibitor for metals in corrosive media—a review*, Materials Letters, vol. 62, iss. 1, pp. 113–116, 2008, doi: 10.1016/j.matlet.2007.04.079

[75] N.O. Eddy, P.A. Ekwumemgbo, P.A.P. Mamza, *Ethanol extract of Terminalia catappa as a green inhibitor for the corrosion of mild steel in H2SO4*, Green Chemistry Letters and Reviews, vol. 2, iss. 4, pp. 223–231, 2009, doi: 10.1080/17518250903359941

[76] R.S. Munn, *A review of the development of Computational Corrosion analysis for special corrosion modelling through its maturity in the Mid 1980's,* in R.S. Munn (Ed.): Computer modelling in Corrosion, ASTM International, pp. 215-228, 1991

[77] M.A. Malik, M.A. Hashim, F. Nabi, S.A. Al-Thabaiti, Z. Khan, K. Lumpur, S. Arab, *Anti-corrosion Ability of Surfactants: A Review*, International Journal of Electrochemical Science, vol. 6, pp. 927–1948, 2011.

[78] A.A. Olajire, *Recent advances on organic coating system technologies for corrosion protection of offshore metallic structures*, Journal of Molecular Liquids, vol. 269, pp. 572–606, 2018, doi: 10.1016/j.molliq.2018.08.053

[79] S.A. Haddadi, *Cerium-doped tannic acid-reduced graphene oxide nanoplatform/epoxy nanocomposite coatings with enhanced mechanical and Bi-functional corrosion protection properties*, Composites, vol. 239, 2022, doi: 10.1016/j.compositesb.2022.109969

[80] M.Kashif, A. Anjum, *Chemical and electrochemical corrosion studies of ricinus communis oil based poly(urethane-ricinoleamide) coatings*, Journal of Physics: Conference Series, vol. 1706, pp. 1-20, 2020, doi: 10.1088/1742-6596/1706/1/012034

[81] S.M. Mirabedini, R.R. Farnood, M. Esfandeh, F. Zareanshahraki, P. Rajabi, *Nanocomposite coatings comprising APS-treated linseed oil-embedded polyurea-formaldehyde microcapsules and nanoclay, part 2: Self-healing and corrosion resistance properties*, Progress in Organic Coatings, vol. 142, 2020, doi: 10.1016/j.porgcoat.2020.105592

[82] J. Pouladi, S.M. Mirabedini, H.E. Mohammadloo, N.G. Rad, *Synthesis of novel plant oil-based isocyanate-free urethane coatings and study of their anti-corrosion properties*, European Polymer Journal, vol. 153, 2021 doi: 10.1016/j.eurpolymj.2021.110502

[83] M. Alam, *Corn oil based poly(urethane-ether-amide)/fumed silica nanocomposite coatings for anticorrosion application*, International Journal of Polymer Analysis and Characterization, vol. 24, iss. 6, pp. 533–547, 2019 doi: 10.1080/1023666X.2019.1622719

[84] X. Zhou, Y. Shen, *Beneficial effects of CeO2 addition on microstructure and corrosion behavior of electrodeposited Ni nanocrystalline coatings*, Surface and Coatings Technology, vol. 235, pp. 433-446, 2013, doi: 10.1016/j.surfcoat.2013.07.070

[85] H. Lee, S. Velu, S. Jun, K. Jun, K. Subbiah, K. Subbiah, *Corrosion Inhibitors for Reinforced Concrete: A Review*, in Corrosion Inhibitors, Principles and Recent Applications, IntechOpen, 2018, doi: 10.5772/intechopen.72572

[86] M. Mobin, R. Aslam, *Experimental and theoretical study on corrosion inhibition performance of environmentally benign non-ionic surfactants for mild steel in 3.5% NaCl solution*, Construction and Building Materials, vol. 114, pp. 279-295, 2018, doi: 10.1016/j.psep.2018.01.001

[87] N. Savita, A. Qurashi, D.S. Chauhan, M.A. Quraishi, *Frontiers and advances in green and sustainable inhibitors for corrosion applications: A critical review*, Journal of Molecular Liquids, vol. 321, 2021, doi: 10.1016/j.molliq.2020.114385

[88] B.A. Al Jahdaly, Y.R. Maghraby, A.H. Ibrahim, K.R. Shouier, A.M. Alturki, R.M. El-Shabasy, *Role of green chemistry in sustainable corrosion inhibition: a review on recent developments*, Materials Today Sustainability, vol. 20, pp. 2022, doi: 10.1016/j.mtsust.2022.100242

[89] A.Z. Salman, QA. Jawad, K. S. Ridah, L.M. Shaker, A.A. Al-Amiery, *Selected BISThiadiazole: synthesis and corrosion inhibition studies on mild steel in HCl environment*, Surface Review and Letters, vol. 27, no. 12, 2020, doi: 10.1142/S0218625X20500146

[90] A. Hamdy, *Corrosion protection of aluminum composites by silicate/cerate conversion coating*, Surface and Coatings Technology, vol. 200, iss. 12-13, pp. 3786-3792, 2006, doi: 10.1016/j.surfcoat.2005.03.012

[91] N. Keshmiri, P. Najmi, M. Ramezanzadeh, B. Ramezanzadeh, G. Bahlakeh, *Ultrastable Porous Covalent Organic Framework Assembled Carbon Nanotube as a Novel Nanocontainer for Anti-Corrosion Coatings: Experimental and Computational Studies*, ACS Applied Materials & Interfaces, vol. 14, iss. 17, pp. 19958–19974, 2022 doi: 10.1021/acsami.1c24185

[92] N. Keshmiri, P. Najmi, B. Ramezanzadeh, M. Ramezanzadeh, G. Bahlakeh, *Nano-scale P, Zn-codoped reduced-graphene oxide incorporated epoxy composite; synthesis, electronic-level DFT-D modeling, and anti-corrosion properties*, Progress in Organic Coatings, vol. 159, 2021 doi: 10.1016/j.porgcoat.2021.106416

[93] N. Keshmiri, P. Najmi, M. Ramezanzadeh, B. Ramezanzadeh, *Designing an eco-friendly lanthanide-based metal organic framework (MOF) assembled graphene-oxide with superior active anti-corrosion performance in epoxy composite*, Journal of Cleaner Production, vol. 319, doi: 10.1016/j.jclepro.2021.128732

[94] J.V. Nardeli, C.S. Fugivara, M. Taryba, M.F. Montemor, S.J.L. Ribeiro, A.V. Benedetti, *Novel healing coatings based on natural-derived polyurethane modified with tannins for corrosion protection of AA2024-T3*, Corrosion Science, vol. 162, 2020, doi: 10.1016/j.corsci.2019.108213

[95] W. Lingling, F. Han, G. Zeng, Y. Hu, W. Chen, F. Zhang, W. Song, *Excellent compound inhibitor of carboxymethyl chitosan/magnetic reduced graphene oxide for carbon steel in neutral chloride solution*, Materials Chemistry and Physics, vol. 293, 2023, doi: 10.1016/j.matchemphys.2022.126939

[96] M. Nyoka, Y.E. Choonara, P. Kumar, P.P.D. Kondiah, V. Pillay, *Synthesis of Cerium Oxide Nanoparticles Using Various Methods: Implications for Biomedical Applications*, Nanomaterials, vol. 10, iss. 2, 2020, doi: 10.3390/nano10020242

[97] M. Alam, N.M. Alandis, J. Alam, N. Ahmad, M. A. Alam, *Development of a poly(urethane-malonic-esteramide) coating from corn oil and carbon nanotubes for corrosion resistant applications*, International Journal of Polymer Analysis and Characterization, vol. 26, iss. 2, pp. 111–129, 2021, doi: 10.1080/1023666X.2020.1858666

[98] M.M. Aung, W.J. Li, H.N. Lim, *Improvement of Anticorrosion Coating Properties in Bio-Based Polymer Epoxy Acrylate Incorporated with Nano Zinc Oxide Particles*, vol. 59. iss. 5, pp. 1753-1763, 2020, doi: 10.1021/acs.iecr.9b05639

[99] Z. Jamshidnejad, A. Afshar, M. A. RazmjooKhollari, *Synthesis of self-healing smart epoxy and polyurethane coating by encapsulation of olive leaf extract as corrosion inhibitor*, International Journal of Electrochemical Science, vol. 13, pp. 12278–12293, 2018 doi: 10.20964/2018.12.83

[100] J. Li, H. Shi, F. Liu, E.H. Han, *Self-healing epoxy coating based on tung oil-containing microcapsules for corrosion protection*, Progress in Organic Coatings, vol. 156, 2021, doi: 10.1016/j.porgcoat.2021.106236

[101] A.G. Cordeiro Neto, A.C. Pellanda, A.R. de Carvalho Jorge, J.B. Floriano, M.A. Coelho Berton, *Preparation and evaluation of corrosion resistance of a self-healing alkyd coating based on microcapsules containing Tung oil*, Progress

in Organic Coatings, vol. 147, 2020, doi: 10.1016/j.porgcoat.2020.105874

[102] J. Xu, L. Zhu, Y. Nie, Y. Li, S. Wei, X. Chen, W. Zhao, S. Yan , *Advances and Challenges of Self-Healing Elastomers: A Mini Review*, Materials, 2022, 15(17), 1–21, doi: 10.3390/ma15175993

[103] A.M. Fainleib, O.H. Purikova, *Self-healing polymers: approaches of healing and their application*, Polymer Journal, vol. 41, no. 1, pp. 4–18, 2019, doi: 10.15407/polymerj.41.01.004

[104] T. Song, B. Jiang, Y. Li, Z. Ji, H. Zhou, D. Jiang, I. Seok, V. Murugadoss, N. Wen, H. Colorado, *Self-healing Materials: A Review of Recent Developments*, ES Mater. Manuf., 2021, 14, 1–19, doi: 10.30919/esmm5f465

[105] E. Sharmin, F. Zafar, D. Akram, M. Alam, S. Ahmad, *Recent advances in vegetable oils based environment friendly coatings: A review*, Industrial Crops Produscts, vol. 76, pp. 215–229, 2015 doi: 10.1016/j.indcrop.2015.06.022

[106] B. Li, Z. Zhang, T. Liu, Z. Qiu, Y. Su, J. Zhang, C. Lin, L. Wang, *Recent Progress in Functionalized Coatings for Corrosion Protection of Magnesium Alloys—A Review*, Materials, vol. 15, iss. 11, 2022, doi: 10.3390/ma15113912

[107] M.E. Orazem, B. Tribollet, *Electrochemical Impedance Spectroscopy*, Wiley 2017.

[108] S. X. Zheng, J. Li, *Inorganic–organic sol gel hybrid coatings for corrosion protection of metals*, Journal of Sol-Gel Science and Technology, vol. 54, pp. 174–187, 2010, doi: 10.1007/s10971-010-2173-1

[109] R.G. Pearson, *Absolute electronegativity and hardness: application to inorganic chemistry*, Inorganic Chemistry, vol. 27, iss. 4, pp. 734–740, 1988 doi: 10.1021/ic00277a030

[110] H.M.A. El-Lateef, A.R. El-Sayed, H.S. Mohran, *Corrosion inhibition and adsorption behavior of phytic acid on Pb and Pb–In alloy surfaces in acidic chloride solution*, International Journal of Industrial Chemistry, vol. 10, pp. 31–47, 2019, doi: 10.1007/s40090-019-0169-4

[111] H. Gadow, M. Fakeeh, *Green inhibitor of carbon steel corrosion in 1 M hydrochloric acid: Eruca sativa seed extract (experimental and theoretical studies)*, RSC Advance, iss. 15, pp. 8953-8986, 2022, doi: 10.1039/d2ra01296k

[112] L. Chen, D. Lu, Y. Zhang, *Organic Compounds as Corrosion Inhibitors for Carbon Steel in HCl Solution: A Comprehensive Review*, Materials, vol. 15, iss. 6, 2022, 2023, doi: 10.3390/ma15062023

[113] M.A. Baig, S.U. Rehman, S.U. Khan, K.I.U. Haq, M. Shahid, *A smart chitosan-cerium oxide nanoparticles-based corrosion inhibitor for copper in acidic solution*, Journal of Molecular Liquids, vol. 305, pp. 105-114, 2020, doi: 10.1016/j.molliq.2020.112771

[114] M. H.M. Abd El-Lateef, A.O. Alnajjar, M.M. Khalaf, *Advanced self-healing coatings based on ZnO, TiO_2, and ZnO-TiO_2/polyvinyl chloride nanocomposite systems for corrosion protection of carbon steel in acidic solutions containing chloride*, Journal of the Taiwan Institute of Chemical Engineers, vol. 116, pp. 286-302, 2020, doi: 10.1016/j.jtice.2020.11.015

[115] S. Habib, E. Fayyad, M. Nawaz, A. Khan, R.A. Shakoor, R. Kahraman, A. Abdullah, *Cerium Dioxide Nanoparticles as Smart Carriers for Self-Healing Coatings. Nanomaterials,* vol, 10, iss. 4, 2020, doi: 10.3390/nano10040791

[116] N.T. Pirhady, M. Ghorbani, A. Shojaei, Y. Gonzalez-Garcia, H. Terryn, *pH responsive Ce(III) loaded polyaniline nanofibers for self-healing corrosion protection of AA2024-T3*, Progress in Organic Coatings, vol. 99, pp. 197–209, 2016, doi:10.1016/j.porgcoat.2016.04.046

[117] S, Dalbin, G. Maurin, R. P. Nogueira, N. Pommier, *Silica-based coating for corrosion protection of electrogalvanized steel*, Surface and Coatings Technology vol. 194, iss. 2-3, pp. 363-371, 2005, doi: 10.1016/j.surfcoat.2004.07.126

[118] N. Alhazmi, H. Alamri, *Development of data driven machine learning models for the prediction and design of pyrimidine corrosion inhibitors*, Journal of Saudi Chemical Society, vol. 26, 2022, doi: 10.1016/j.jscs.2022.101536

[119] N.M. Al-Joborry, R.M. Kubba, *Theoretical and Experimental Study for Corrosion Inhibition of Carbon Steel in Salty and Acidic Media by A New Derivative of Imidazolidine 4-One*, Iraqi Journal of Science, vol. 61, no. 8, pp. 1842–1860, doi: 10.24996/ijs.2020.61.8.1

[120] M. He, W. Zhang, X. Cao, X. You, L. Li, *Adsorption Behavior of Surfactant on Lignite Surface: A Comparative Experimental and Molecular Dynamics Simulation Study*, International Journal of Molecular Sciences, vol. 19, iss. 2, 2018, doi: 10.3390/ijms19020437

[121] M. Ramezanzadeh, G. Bahlakeh, B. Ramezanzadeh, *Study of the synergistic effect of Mangifera indica leaves extract and zinc ions on the mild steel corrosion inhibition in simulated seawater: Computational and electrochemical studies,* Journal of Molecular Liquids, vol. 292, 2019, doi: 10.1016/j.molliq.2019.111387

[122] L.O. Olasunkanmi, I.B. Obot M.M. Kabanda, E.E. Ebenso, *Some Quinoxalin-6-yl Derivatives as Corrosion Inhibitors for Mild Steel in Hydrochloric Acid: Experimental and Theoretical Studies*, Journal of Physical Chemistry C, vol. 119, iss. 28, pp. 16004–16019, 2015, doi: 10.1021/acs.jpcc.5b03285

[123] G. Bahlakeh, B. Ramezanzadeh. *A Detailed Molecular Dynamics Simulation and Experimental Investigation on the Interfacial Bonding Mechanism of an Epoxy Adhesive on Carbon Steel Sheets Decorated with a Novel Cerium–Lanthanum Nanofilm*, ACS Applied Materials & Interfaces, vol. 9, iss. 20, pp. 17536-17551, 2017, doi: 10.1021/acsami.7b00644

[124] J. Wu, T. Gao, H. Guo, L. Zhao, S. Lv, J. Lv, R. Yao, Y. Yu, F. Ma. *Application of molecular dynamics simulation for exploring the roles of plant biomolecules in promoting environmental health,* Science of The Total Environment, vol. 869, 2023, doi: 10.1016/j.scitotenv.2023.161871

[125] H. Fakhry, M. El Faydy, F. Benhiba, M. Bouassiria, T. Laabaissi, M. Allali, R. Touir, H. Oudda, C. Jama, I. Warad, A. Alsalme, A. Zarrouk, *Experimental, DFT studies and molecular dynamic simulation on the corrosion inhibition of carbon steel in 1 M HCl by two newly synthesized 8-hydroxyquinoline derivatives,* Journal of the Indian Chemical Society, vol. *99*, iss. 12, 2022, doi: 10.1016/j.jics.2022.100701

[126] S. Junaedi, A. Al-Amiery, A. Kadihum, A. Kadhum, A. Mohamad, *Inhibition effects of a synthesized novel 4-aminoantipyrine derivative on the corrosion of mild steel in hydrochloric acid solution together with quantum chemical studies*, International Journal of Molecular Sciences, vol. 14, iss. 6, pp. 11915-11928, 2013, doi: 10.3390/ijms140611915

[127] A. Alamiery, W.N.R.W. Isahak, H.S.S. Aljibori, H.A. Al- Asadi, A.A.H. Kadhum, *Effect of the structure, immersion time and temperature on the corrosion inhibition of 4- pyrrol-1-yl-n-(2,5-dimethyl-pyrrol-1-yl)benzoylamine in 1.0 M HCL solution*, International Journal of Corrosion and Scale Inhibition, vol. 10, no. 2, pp. 700-713, 2021, doi: 10.17675/2305-6894-2021-10-2-14

[128] S. Al-Baghdadi, F. Hashim, A. Salam, T. Abed, T. Gaaz, A. Al-Amiery, A.H. Kadhum, K. Reda, W. Ahmed, *Synthesis and corrosion inhibition application of NATN on mild steel surface in acidic media complemented with DFT studies*, Results in Physics, vol. 8, pp. 1178-1184, 2018, doi: 10.1016/j.rinp.2018.02.007

[129] W.K. Al-Azzawi, A.J. Al Adily, F.F. Sayyid, R.K. Al-Azzawi, M.H. Kzar, H.N. Jawoosh, A.A. Al-Amiery, A.A.H. Kadhum, W.N.R.W. Isahak, M.S. Takriff, *Evaluation of corrosion inhibition characteristics of an N-propionanilide derivative for mild steel in 1 M HCl: Gravimetrical and computational studies*, International Journal of Corrosion and Scale Inhibition, vol. 11, no. 3, pp. 1100-1114, 2022, doi: 10.17675/2305-6894-2022-11-3-12