Journal of Sustainability Science and Management
Volume 19 Number 5, May 2024: 145-172
eISSN: 2672-7226

RECENT INNOVATIONS IN ORGANIC INHIBITORS FOR MILD STEEL IN CORROSIVE SOLUTIONS: A MINI REVIEW

AHMED A AL-AMIERY[1,2]*, WAN MOHD NORSANI WAN NIK[3]*, MOHD SABRI MOHD GHAZALI[4], EMED YOUSIF[5], WAN NOR ROSLAM WAN ISAHAK[1], WALEED KHALID AL-AZZAWI[6], MOHAMMAD FAKHRATUL RIDWAN ZULKIFLI[3], WALID DAOUDI[7], IZIONWORU O. VINCENT[8] AND DINESH Y. DHANDE[9]

[1]Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43400 Bangi, Selangor, Malaysia. [2]Energy and Renewable Energies Technology Center, University of Technology-Iraq, 10001 Baghdad, Iraq. [3]Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia. [4]Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia. [5]Chemistry Department, Al-Nahrain University, 64074 Baghdad, Iraq. [6]Al-Farahidi University, 10001 Baghdad, Iraq. [7]Laboratory of Materials and Environment, Department of Chemistry, Multidisciplinary Faculty of Nador, University of Mohamed 1, 60700 Nador, Morocco. [8]Department of Chemical/Petrochemical Engineering, Faculty of Engineering, Rivers State University, Eagle Island, 500101 Port Harcourt, Rivers, Nigeria. [9]Department of Mechanical Engineering, AISSMS College of Engineering, Kennedy Road,411001 Pune, India.

**Corresponding authors: dr.ahmed1975@ukm.edu.my, niksani@umt.edu.my*
http://doi.org/10.46754/jssm.2024.05.009
Submitted final draft: 26 December 2023 *Accepted: 28 January 2024* *Published: 15 May 2024*

Abstract: Corrosion of mild steel in corrosive solutions is one of the major concerns in industries such as oil and gas, petrochemical and marine. The use of organic inhibitors has proven to be an effective method to protect mild steel from corrosion. This mini-review summarised recent innovations in organic inhibitors for mild steel in corrosive solutions. This article discusses the types of organic inhibitors, including adsorption, film-forming, mixed, synergistic and green inhibitors, their mechanism of action, and their application in various corrosive environments. The article then highlights recently published inhibitors such as quinoline derivatives, Schiff bases, amino acids, and polymers. These inhibitors have shown promising results in protecting mild steel from corrosion. The mini-review concludes by discussing the prospects of organic inhibitors for mild steel in corrosive solutions. Overall, this mini-review provides valuable insights into recent innovations in organic inhibitors for mild steel in corrosive solutions, which are useful for researchers and industries working on corrosion protection.

Keywords: Corrosion inhibitors, mild steel, types of organic inhibitors, innovations.

Introduction

Corrosion, an intrinsic process fuelled by chemical or electrochemical reactions with the environment, triggers material degradation. Its far-reaching implications are evident across industries, posing simultaneous challenges of substantial economic losses and potential safety hazards. Mild steel, extensively utilised in construction, manufacturing, and infrastructure, is particularly vulnerable to corrosion, imperilling both performance and lifespan. This susceptibility carries profound economic implications, necessitating frequent replacements, maintenance, and repairs, thereby escalating operational costs and downtime across various industries.

In this context, the strategic use of inhibitors, advocated by El-Rehim *et al*. (2001) and Peter and Sharma (2017), emerges as a pragmatic approach to curtail economic losses stemming from corrosion-induced material degradation. Notably, organic inhibitors – gaining attention for their eco-friendliness, low toxicity, and high efficiency – offer multifaceted economic benefits (Al-Amiery *et al*., 2023). These advantages include an extended service life, reduced maintenance costs, avoidance of repairs, sustained operational continuity, environmental impact mitigation, and safety-related cost reductions.

Research endeavours exploring the effectiveness of organic inhibitors in diverse corrosive environments have revealed their substantial corrosion rate reduction capabilities in acidic, neutral, and alkaline solutions (Hanoon *et al.,* 2021; Al-Baghdadi *et al*., 2021). Specific classes of organic inhibitors, such as imidazoline derivatives, have demonstrated remarkable efficacy, particularly in acidic solutions. Their inhibitory action involves the formation of a protective layer upon adsorption, presenting an efficient and targeted solution to corrosion risks in acidic settings (Abdulsahib *et al*., 2021; Izionworu *et al*., 2021; Khudhair *et al*., 2021). The efficiency of imidazoline derivatives is intricately linked to solution concentration and temperature (Zinad *et al*., 2021; Salim *et al*., 2021).

Plant extracts have also emerged as significant organic inhibitors, leveraging their diverse organic compounds, including polyphenols and tannins. The inhibitory action involves adsorption, chelation of metal ions, pH sensitivity, synergistic effects, and antioxidant properties, offering a comprehensive defence against corrosion. For instance, *Punica granatum* extract has demonstrated effectiveness in inhibiting mild steel corrosion in acidic solutions (Zhang *et al*., 2023).

Biopolymers like chitosan are effective organic inhibitors in alkaline solutions. The concentration and pH of the solution significantly influence chitosan's inhibition efficiency, impacting adsorption capacity and electrostatic interactions (Izionworu *et al*., 2020; Al-Amiery *et al*., 2021; Resen *et al*., 2021; Zhang *et al*., 2023; Hu *et al*., 2023).

The economic benefits of organic inhibitors are substantial, encompassing extended service life, reduced maintenance costs, avoidance of repairs, sustained operational continuity, environmental sustainability, and safety-related cost reductions. Delving deeper into their performance across diverse environmental conditions is imperative, emphasising research to develop novel, environmentally friendly, and efficient inhibitors. This proactive research approach is critical for advancing corrosion control strategies in industrial applications (Hashim *et al*., 2020; Salman *et al*., 2020). This review aims to provide a concise yet critical analysis of various solutions for corrosion control, offering insights into strengths, weaknesses, and recommendations for future research or practical applications in diverse contexts and subject areas.

Types of Organic Inhibitors

Corrosion poses a formidable challenge for metallic materials, and mild steel is particularly susceptible. Preserving mild steel from corrosion is imperative to ensure its extended lifespan and durability. Among the various methods employed for corrosion protection, organic inhibitors stand out as one of the most prevalent. Their efficacy lies in the formation of a protective film on the metal surface, acting as a barrier against corrosive agents, thereby safeguarding the metal from degradation (Ismail *et al*., 2022; Verma *et al*., 2023; Al-Amiery *et al*., 2023). The need to combat corrosion is underscored by several significant issues. Firstly, corrosion diminishes the structural integrity of mild steel, compromising its mechanical properties and overall performance. This deterioration not only jeopardises the safety of structures and components but also necessitates frequent replacements, repairs, and maintenance, incurring substantial economic costs. Additionally, in applications where mild steel plays a critical role, such as in infrastructure, construction, and transportation, corrosion-induced failures can have severe consequences, ranging from service disruptions to potential safety hazards. Hence, the imperative to avoid corrosion is deeply rooted in the preservation of structural integrity, economic considerations, and the prevention of potential accidents.

Organic inhibitors function through a nuanced mechanism. They form a protective film on the metal surface that impedes the direct contact between the metal and corrosive agents, thus reducing the corrosion rate. Adsorption inhibitors and film-forming inhibitors are two fundamental types in this realm. Adsorption inhibitors work by adhering to the metal surface to create a protective layer through chemical interactions. On the other hand, film-forming inhibitors generate a physical barrier on the metal surface, hindering access to corrosive elements. Mixed inhibitors amalgamate the benefits of adsorption and film formation, presenting an enhanced, dual-layered defence against corrosion. In complex corrosive environments, synergistic inhibitors come into play, working collaboratively with other compounds to provide more robust protection. Finally, green inhibitors, derived from renewable sources, offer an environmentally friendly avenue for corrosion inhibition. They not only contribute to the longevity of mild steel but also align with sustainable practices, addressing the increasing importance of eco-friendly alternatives in corrosion protection strategies. In essence, the exploration of these organic inhibitors stems from a crucial intersection of structural preservation, economic prudence, and environmental sustainability. The intricate mechanisms they employ underscore their significance in mitigating the adverse effects of corrosion, making them indispensable in diverse industrial applications.

Adsorption Inhibitors

Adsorption inhibitors are pivotal organic corrosion inhibitors. They work by forming protective films on metal surfaces to impede corrosive processes. This section critically analyses the nuanced mechanisms and comparative attributes of various adsorption inhibitors by considering their advantages, disadvantages, and distinctions. Examples of adsorption inhibitors include imidazolines, amines, and surfactants. Table 1, compares the adsorption properties of different types of organic inhibitors.

The choice between strong chemisorption (amino acids, imidazolines) and physisorption (polyphenols, surfactants) depends on the desired level of protection and the environmental conditions. Amino acids and imidazolines exhibit specificity for active metal sites, providing targeted protection. Chemisorption-based inhibitors often offer more stable protective layers compared with physisorption-based ones.

Considering the critical analysis, the choice of an inhibitor depends on the specific context. For environments with dynamic conditions, polyphenols or surfactants might be suitable due to their flexibility in forming protective layers. In scenarios where targeted protection is crucial, amino acids or imidazolines could be preferred for their strong chemisorption.

Film-forming Inhibitors

Film-forming inhibitors work by forming a protective film on the metal surface. They typically form a multilayer film consisting of the inhibitor molecule and corrosion products. Examples of film-forming inhibitors include epoxy resins and polyurethanes. Table 2 compares the adsorption properties of different types of film-forming inhibitors.

Polymeric inhibitors stand out with excellent film-forming ability, offering superior protection. Plant extracts and carboxylic acids also exhibit good film-forming capabilities. Polymeric inhibitors provide the most durable films, ensuring extended protection. Plant extracts and carboxylic acids offer good durability, while amino acids may provide less lasting protection. Considering the critical analysis, the choice of a film-forming inhibitor should align with the specific corrosion challenges faced. For environments demanding robust, long-term protection, polymeric inhibitors are recommended despite potential complexities. For more straightforward applications with a focus on environmental friendliness, plant extracts and carboxylic acids provide a good balance of efficacy and sustainability. Amino acids, given their poorer film-forming ability, might be suitable for less aggressive corrosion environments. The inhibitor selection should be tailored to the unique demands of the corrosion-prone environment, considering both efficacy and practical considerations.

Table 1: Comparison of different types of organic inhibitors in terms of their adsorption properties

Inhibitor	Advantages, Disadvantages, and Distinguishing Features	Adsorption Site	References
Amino acids	**Advantages:** Robust chemisorption enhances the formation of a protective monolayer, offering effective corrosion inhibition. **Disadvantages:** Sensitivity to environmental conditions might impact adsorption efficiency. **Distinguishing Feature:** High specificity for active sites, providing targeted corrosion protection.	Active sites on metal surface	Pour-Ali *et al*., 2023
Alkanolamines	**Advantages:** Chemically stable adsorption layer contributes to long-term corrosion resistance. **Disadvantages:** Potential susceptibility to saturation effects at higher concentrations. **Distinguishing Feature:** Known for efficient inhibition due to strong chemisorption properties.	Active sites on metal surface	Liu, Zhicheng *et al*., 2023; Tebbji *et al*., 2007
Carboxylic acids	**Advantages:** Effective inhibition due to stable chemisorption. **Disadvantages:** May exhibit sensitivity to variations in environmental conditions. **Distinguishing Feature:** Offers durable protection through robust chemisorption.	Active sites on metal surface	Guo *et al*., 2023
Polyphenols	**Advantages:** Versatile in forming protective layers, potentially minimising the impact of environmental variations. **Disadvantages:** Weaker bonding might result in a less stable protective film. **Distinguishing Feature:** Relies on physisorption, providing flexibility in different environmental contexts.	Physisorption on the metal surface	Gabsi *et al*., 2023
Heterocyclic compounds	**Advantages:** Effective inhibition through robust chemisorption. **Disadvantages:** Similar to other chemisorbers, potential sensitivity to environmental changes. **Distinguishing Feature:** Known for their broad application spectrum and efficient protection.	Active sites on metal surface	El-Haitout *et al*., 2023
Imidazolines	**Advantages:** Offers targeted and efficient protection through chemisorption. **Disadvantages:** May require careful optimisation of concentration for optimal efficiency. **Distinguishing Feature:** Well-studied and proven efficacy in inhibiting corrosion in various environments.	Active sites on metal surface	Yuyang *et al*., 2023
Surfactants	**Advantages:** Versatility in forming adsorption layers with relatively less dependence on specific active sites. **Disadvantages:** Susceptibility to desorption in dynamic environments. **Distinguishing Feature:** Offers flexibility in providing inhibition through physisorption.	Physisorption on the metal surface	Talat *et al*., 2023

Table 2: Comparison of different types of film-forming inhibitors in terms of their adsorption properties

Organic Inhibitor	Advantages, Disadvantages, and Distinguishing Features	Film-forming Ability	Reference
Amino acids	**Mechanism:** Amino acids, while acting as adsorption inhibitors, may not form a robust multilayer film. The film formed might lack the durability needed for long-term protection. **Advantages:** Amino acids are generally environmentally friendly but may not offer the sustained protection needed in aggressive corrosion environments. **Disadvantages:** The thin film formed may not provide sufficient barrier properties. **Distinguishing Feature:** Limited film-forming ability compared to other inhibitors.	Poor	Li *et al*., 2023
Plant extracts	**Mechanism:** Plant extracts are proficient film-formers, creating multilayer films consisting of inhibitor molecules and corrosion products. The richness of organic compounds in plant extracts contributes to film stability. **Advantages:** Environmentally friendly, good film-forming ability and diverse composition can enhance the protective film's resilience. **Disadvantages:** The effectiveness may vary based on the specific composition of the plant extract. **Distinguishing Feature:** The ability to form a robust film and the additional benefit of the diverse organic compounds present.	Good	Kaya *et al*., 2023
Carboxylic acids	**Mechanism:** Carboxylic acids can form a protective multilayer film, offering improved durability compared to amino acids. **Advantages:** Effective inhibition due to a stable film, relatively environmentally friendly. **Disadvantages:** The film may not be as durable as those formed by polymeric inhibitors. **Distinguishing Feature:** Solid film-forming ability, offering better protection compared to amino acids.	Good	Zhang *et al*., 2023
Polymeric inhibitors	**Mechanism:** Polymeric inhibitors excel in forming thick, durable films on metal surfaces. The film consists not only of the inhibitor molecules but also of corrosion products, providing enhanced protection. **Advantages:** Exceptional durability, capable of providing long-term protection in harsh environments. Disadvantages: Synthesis and application may be more complex, potentially leading to higher costs. Distinguishing Feature: Superior film-forming ability, offering extended and robust corrosion protection.	Excellent	Zheng *et al*., 2023

Heterocyclic compounds	**Mechanism:** Heterocyclic compounds can form a protective film, contributing to corrosion inhibition. **Advantages:** Effective inhibition with a relatively stable film. **Disadvantages:** The film may not be as robust as those formed by polymeric inhibitors. **Distinguishing Feature:** Good film-forming ability, providing a balance between effectiveness and simplicity.	Good	El-Haitout *et al*., 2023

Mixed Inhibitors

Mixed inhibitors combine the advantages of both adsorption and film-forming inhibitors. Unlike film-forming inhibitors that primarily create a protective film on the metal surface, mixed inhibitors integrate the benefits of adsorption, ensuring a dual mechanism that enhances corrosion resistance. Mixed inhibitors go a step further by forming a multilayer film that not only incorporates the inhibitor molecules but also corrosion products. A protective layer that involves both the inhibitor and the by-products of the corrosion process provides enhanced corrosion resistance compared to traditional film-forming inhibitors. Examples of mixed inhibitors include benzotriazole and mercaptoimidazole. Table 3 compares the physiochemical properties of different types of mixed inhibitors.

Table 3: Comparison of different types of mixed inhibitors in terms of their physiochemical properties

Organic Inhibitor	Type of Inhibition	Mode of Inhibition	Mechanism	Discussion	References
Amino acids	Mixed	Adsorption	Donor-acceptor interaction	Amino acids function as mixed inhibitors through the adsorption process, utilising donor-acceptor interactions. This interaction involves electron exchange, forming a protective layer on the metal surface. Amino acids exhibit versatility in inhibiting corrosion but may have varying effectiveness depending on environmental conditions.	Pour-Ali *et al*., 2023
Azoles	Mixed	Adsorption	π-electron interaction	Thiourea derivatives, in a mixed inhibition role, engage in adsorption with the metal surface through donor-acceptor interactions. This mechanism involves electron transfer, creating a protective layer. Thiourea derivatives are versatile but may have varying efficiency based on the specific conditions.	Haque *et al.,* 2023

Thiourea derivatives	Mixed	Adsorption	Donor-acceptor interaction	Thiourea derivatives, in a mixed inhibition role, engage in adsorption with the metal surface through donor-acceptor interactions. This mechanism involves electron transfer, creating a protective layer. Thiourea derivatives are versatile but may have varying efficiency based on the specific conditions.	Wen *et al*., 2023
Imidazolines	Mixed	Adsorption	Charge transfer	Imidazolines act as mixed inhibitors by adsorption through charge transfer. This involves the movement of electrons between the inhibitor and the metal surface, forming a protective layer. Imidazolines are particularly effective in environments where charge transfer mechanisms play a significant role.	Qi *et al*., 2023
Carboxylic acids	Mixed	Adsorption	Electrostatic interaction	Carboxylic acids, functioning as mixed inhibitors, adsorb onto the metal surface through electrostatic interactions. This involves attractive forces between charged particles, creating a protective layer. Carboxylic acids are effective in environments where electrostatic interactions are influential.	Guo *et al*., 2023
Polyphenols	Mixed	Adsorption	π-electron interaction	Polyphenols serve as mixed inhibitors by adsorption, employing π-electron interactions. This mechanism contributes to the formation of a protective layer on the metal surface. Polyphenols are known for their versatility and effectiveness, particularly in environments where π-electron interactions are prevalent.	Salhi *et al*., 2023
Schiff bases	Mixed	Adsorption	Charge transfer	Schiff bases act as mixed inhibitors through adsorption by charge transfer. This involves the movement of electrons between the inhibitor and the metal surface, creating a protective layer. Schiff bases exhibit effectiveness, especially in environments where charge transfer mechanisms are significant.	Satpati *et al*., 2023

Coumarins	Mixed	Adsorption	π-electron interaction	Coumarins, as mixed inhibitors, function through adsorption using π-electron interactions. This mechanism contributes to the formation of a protective layer. Coumarins are known for their effectiveness, particularly in environments where π-electron interactions play a crucial role.	Kaseem *et al*., 2023
Triazoles	Mixed	Adsorption	Donor-acceptor interaction	Triazoles act as mixed inhibitors through adsorption with the metal surface via donor-acceptor interactions. This involves electron transfer, creating a protective layer. Triazoles are versatile but may exhibit varying efficiency based on specific conditions.	Punitha *et al*., 2023; Belghiti *et al*., 2016

Mixed inhibitors offer a multifaceted approach to corrosion protection, combining the benefits of adsorption inhibitors and film-forming inhibitors. The choice of a mixed inhibitor depends on the specific environmental conditions, with each type having its advantages and disadvantages. Amino acids, azoles, thiourea derivatives, imidazolines, carboxylic acids, polyphenols, Schiff bases, coumarins, and triazoles exhibit diverse mechanisms of inhibition, providing options for tailored corrosion protection strategies.

Synergistic Inhibitors

Synergistic inhibitors work by combining with other inhibitors to enhance their effectiveness. Synergistic inhibitors typically work by enhancing the adsorption of other inhibitors onto the metal surface. Examples of synergistic inhibitors include halides and thiocyanates. Table 4 compares the adsorption properties of different types of synergistic inhibitors.

Synergistic inhibitors offer a collaborative approach to corrosion protection, leveraging

Table 4: Comparison of different types of synergistic inhibitors in terms of their physiochemical properties

Inhibitor Type	Synergistic Inhibitors	Mechanism of Synergy	Discussion	References
Polymeric inhibitors	Phosphonates, nitro-compounds, amines	The synergistic effect is attributed to the interaction of the functional groups in the polymeric inhibitors with those of the synergistic inhibitors, which enhances the adsorption of the inhibitors on the metal surface.	Polymeric inhibitors, in synergy with phosphonates, nitro compounds, and amines, demonstrate enhanced inhibitive properties. The functional groups in polymeric inhibitors interact with those of the synergistic inhibitors, leading to improved adsorption. This synergistic approach is advantageous in environments where multiple interactions are needed for effective corrosion inhibition.	Verma *et al*., 2023 Chraka *et al*., 2023

Natural inhibitors	Plant extracts, essential oils, phenolic compounds	Synergistic inhibition is achieved by the presence of multiple functional groups, which enhances the adsorption of the inhibitors on the metal surface. The synergistic effect is also attributed to the formation of a protective film by the natural inhibitors and their interaction with the synergistic inhibitors.	Natural inhibitors, such as plant extracts, essential oils, and phenolic compounds, exhibit synergistic inhibition when combined. The multiple functional groups present in natural inhibitors enhance adsorption on the metal surface. The formation of a protective film, coupled with interaction with synergistic inhibitors, contributes to a more robust corrosion protection strategy.	Nik *et al.*, 2020; Ismail *et al.*, 2021
Heterocyclic inhibitors	Nitro-compounds, azoles, imidazole's, amines	The synergistic effect is attributed to the ability of the heterocyclic inhibitors to form complexes with the metal surface and the synergistic inhibitors, which enhances their adsorption and inhibitive properties.	Heterocyclic inhibitors, including nitro-compounds, azoles, imidazoles, and amines, exhibit synergy when combined. The ability of heterocyclic inhibitors to form complexes with the metal surface and synergistic inhibitors enhances their overall adsorption and inhibitive properties. This synergy is particularly effective in environments where complex interactions are required.	Youssif *et al*., 2023
Surfactant inhibitors	Anionic surfactants, cationic surfactants, nonionic surfactants	The synergistic effect is attributed to the ability of the surfactant inhibitors to enhance the solubility and adsorption of the synergistic inhibitors on the metal surface. The synergistic effect is also attributed to the formation of a protective film by the surfactant inhibitors and their interaction with the synergistic inhibitors.	Surfactant inhibitors, including anionic, cationic, and nonionic surfactants, demonstrate synergy by enhancing the solubility and adsorption of synergistic inhibitors. The ability to form a protective film and interact with synergistic inhibitors adds another layer of corrosion protection. This synergy is beneficial in conditions where solubility and film formation are crucial.	Yaagoob *et al*., 2023

Ionic liquid inhibitors	Imidazolium salts, pyridinium salts, phosphonium salts	The synergistic effect is attributed to the ability of the ionic liquid inhibitors to enhance the solubility and adsorption of the synergistic inhibitors on the metal surface. The synergistic effect is also attributed to the formation of a protective film by the ionic liquid inhibitors and their interaction with the synergistic inhibitors.	Ionic liquid inhibitors, including imidazolium salts, pyridinium salts, and phosphonium salts, exhibit synergy by enhancing the solubility and adsorption of synergistic inhibitors. The formation of a protective film and interaction with synergistic inhibitors enhance their overall inhibitive properties. This synergy is advantageous in environments where solubility and film formation play a crucial role.	Shadi *et al*., 2023 Yaagoob *et al*., 2023

the strengths of different inhibitors to enhance overall inhibitive properties. Polymeric inhibitors, natural inhibitors, heterocyclic inhibitors, surfactant inhibitors, and ionic liquid inhibitors exhibit unique mechanisms of synergy, providing diverse options for tailored corrosion protection strategies.

Green Inhibitors

Synergistic Green inhibitors are environmentally friendly inhibitors that are derived from natural sources. Green inhibitors are typically less toxic than traditional inhibitors and are biodegradable. Examples of green inhibitors include plant extracts, amino acids, and chitosan (El Mouaden *et al*., 2018). Table 5, compares the advantages and disadvantages of different types of green inhibitors.

The factors influencing the choice of inhibitor are:

(1) Application-specific Needs: The nature of the industry and the specific application will dictate the choice of inhibitor. For instance, inhibitors effective in an industrial setting might not be suitable for marine applications.

Table 5: Comparison of different types of green inhibitors in terms of their advantages and disadvantages properties

Type of Organic Inhibitor	Advantages as Green Inhibitor	Disadvantages as a Green Inhibitor	Discussion	References
Amino acids	Biodegradable, non-toxic	Limited corrosion inhibition efficiency	Amino acids, such as arginine and lysine, exhibit eco-friendly characteristics by being biodegradable and non-toxic. However, their limited efficiency in corrosion inhibition might be a drawback in scenarios where high levels of protection are required. The trade-off between environmental friendliness and corrosion inhibition efficiency should be considered.	Ikeuba *et al*., 2023

Carboxylic acids	Non-toxic, easily biodegradable	Limited stability at high temperatures and concentrations	Carboxylic acids, including citric acid and acetic acid, are advantageous as green inhibitors due to their non-toxic and biodegradable nature. However, their stability might be compromised at high temperatures and concentrations, limiting their applicability in certain industrial processes.	Li *et al*., 2023 Wang *et al*., 2023
Polysaccharides	Renewable, biodegradable, non-toxic	Limited efficiency, high cost	Polysaccharides like starch and chitosan offer green corrosion inhibition solutions with renewable, biodegradable, and non-toxic properties. However, their limited efficiency and relatively high cost might pose challenges, especially in large-scale industrial applications.	More *et al*., 2023
Essential oils	Biodegradable, renewable, non-toxic	Limited stability and efficiency	Essential oils (Eucalyptus oil, Lemongrass oil), derived from natural sources, are biodegradable and non-toxic. However, their limited stability and efficiency may restrict their use in environments with harsh corrosion conditions, necessitating frequent reapplication.	Nirmala *et al*., 2023
Plant extracts	Renewable, biodegradable, non-toxic	Limited stability, efficiency and reproducibility	Plant extracts (*aloe vera*, neem leaves, *Theobroma cacao* pod) offer a green alternative with renewable and non-toxic properties. However, challenges lie in their limited stability, efficiency, and reproducibility, requiring careful consideration in practical applications.	Ikhmal *et al*., 2019; Izionworu *et al, 2020*; Kamaruzzaman *et al*., 2022
Natural surfactants	Biodegradable, non-toxic, low cost	Limited efficiency, limited stability	Natural surfactants, like saponin and Tween 80, present green characteristics but may have limitations in terms of efficiency and stability, potentially impacting their suitability in prolonged or demanding corrosion scenarios	Jadhao *et al*., 2023

Green inhibitors mixtures	Synergistic effects, biodegradable, renewable	Difficult to optimize the composition	Green inhibitor mixtures (mixture of carboxylic acids and amino acids), while leveraging synergistic effects, pose challenges in optimising compositions. The difficulty in achieving an ideal balance may impact their effectiveness, emphasising the need for careful formulation.	Farhadian *et al*., 2023

(2) Corrosive Environment: Different inhibitors may excel in specific corrosive environments. The acidity or alkalinity of the surroundings, along with the presence of specific chemicals, will influence the inhibitor selection.

(3) Desired Level of Protection: The extent of protection required will vary. Some inhibitors might provide long-term protection with a trade-off in efficiency, while others may be highly effective but require frequent reapplication.

Researchers continue to explore new types of organic inhibitors. This pursuit is driven by the quest for more effective and environmentally friendly corrosion protection methods. The choice of an inhibitor is a nuanced decision, involving a careful balance between environmental concerns, efficiency, and practicality. While green inhibitors align with sustainability goals, their limitations in stability and efficiency necessitate a thorough understanding of the specific conditions they will encounter. The synergy of mixed and synergistic inhibitors shows promise but demands meticulous optimisation. This complexity implies a need for ongoing research to refine formulations for real-world applications. Film-forming inhibitors, despite providing a multilayer protective film, may face challenges in maintaining stability over extended periods, especially in harsh industrial settings. The need for ongoing research underscores the dynamic nature of corrosion protection. New inhibitors must not only be effective but also align with contemporary environmental standards.

The realm of organic inhibitors is diverse, offering a spectrum of choices with varying characteristics. The challenge lies in making informed decisions based on specific application needs, environmental considerations, and the evolving landscape of corrosion protection research. The journey toward more effective and sustainable inhibitors is a continuous one, emphasising the importance of ongoing exploration and development in this field.

Table 6 highlights the mechanisms of action employed by organic inhibitors for corrosion protection. Adsorption is a fundamental mechanism where the inhibitor molecules adsorb onto the metal surface, creating a protective layer. The surface coverage of the inhibitor affects the inhibition efficiency, with higher coverage providing better protection. Barrier formation involves the creation of a physical or chemical barrier on the metal surface to hinder corrosive species. Passivation involves the modification of the metal surface to form a stable passive layer, offering long-term protection against corrosion.

Mechanism of Action

Organic inhibitors function by adhering to the metal surface and establishing a protective layer, thereby impeding the corrosion process. The degree of inhibitor attachment to the metal surface is intricately influenced by several factors, including the concentration of the inhibitor, temperature, and pH levels (Resen *et al*., 2020; Hanoon *et al*., 2021). This phenomenon of adsorption is pivotal in the corrosion inhibition mechanism.

Table 6: Comparison of different types of green inhibitors in terms of their advantages and disadvantages properties

Mechanism	Description
Adsorption	Inhibitors adsorb onto the metal surface, forming a protective layer that hinders corrosive species from reaching the metal. Adsorption can occur through various interactions, such as electrostatic forces or chemical bonding. The adsorbed inhibitor molecules provide a physical barrier against corrosion.
Surface coverage	Surface coverage refers to the extent of the inhibitor's adsorption on the metal surface. It influences the efficiency of corrosion protection. High surface coverage ensures a more complete barrier against corrosive species and leads to improved inhibition efficiency.
Barrier formation	Inhibitors can form a barrier on the metal surface, preventing corrosive species from coming into contact with the metal. The barrier can be a physical layer or a chemical film formed through interactions between the inhibitor and the metal surface. Barrier formation is crucial for long-term corrosion protection.
Passivation	Passivation occurs when the inhibitor modifies the metal surface to form a passive layer, which is stable and protects the metal against corrosion. The passive layer can be an oxide or a complex film formed due to chemical reactions between the inhibitor and the metal. Passivation contributes to the inhibition efficiency.

Corrosion, characterised by the gradual deterioration of a metal surface due to chemical or electrochemical reactions with the environment, presents a significant challenge across various industries. Its consequences extend beyond material loss, encompassing structural damage and a decline in operational efficiency. The efficacy of organic inhibitors in mitigating corrosion hinges on their ability to form a protective shield through adsorption, with the extent of this process influenced by inhibitor concentration, temperature, and pH. Understanding and optimising these factors are crucial for tailoring corrosion protection strategies to diverse environments and applications. Figure 1 presents the corrosion inhibition mechanisms of organic inhibitors. It depicts the different stages involved in the inhibition process, including adsorption, surface coverage, barrier formation, and passivation. The figure provides a visual representation of how organic inhibitors interact with the metal surface and prevent corrosion. The diagram demonstrates that adsorption is the initial step

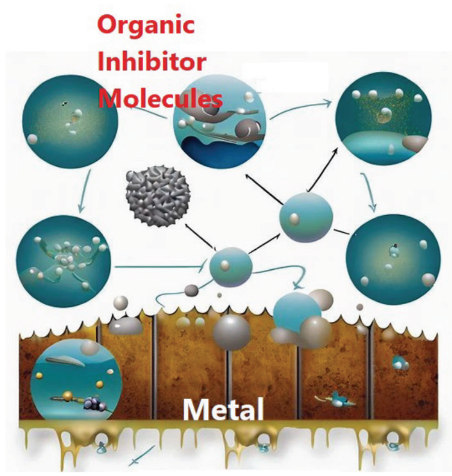

Figure 1: Corrosion inhibition mechanisms of organic inhibitors

where the inhibitor molecules attach to the metal surface. Subsequently, the surface coverage increases as more inhibitor molecules are adsorbed, leading to a higher level of corrosion protection. The inhibitors then form a barrier on the metal surface, impeding the access of corrosive species and preventing their interaction with the metal. Passivation is shown as the final stage, where the inhibitor modifies the metal surface to form a passive layer, offering long-term corrosion resistance. Figure 1 enhances the understanding of the mechanisms involved in organic corrosion inhibition. It emphasises the importance of inhibitor adsorption and the formation of protective layers or barriers on the metal surface. This visual representation aids researchers and practitioners in comprehending the complex processes and designing effective inhibitors targeting specific stages of corrosion.

Corrosion can be prevented or minimised by the use of inhibitors, which are chemical substances that are added to the corrosive environment to reduce or inhibit the corrosion rate. Organic inhibitors are one type of inhibitor commonly used in the industry (Al-Amiery *et al*., 2023). In general, the mechanism of action for organic inhibitors can be explained by the following steps:

Adsorption

The organic inhibitor molecules adsorb onto the metal surface through various types of interactions, such as Van der Waals forces, hydrogen bonding, and electrostatic interactions. The adsorption is influenced by the chemical structure and functional groups of the inhibitor molecules, as well as the surface properties of the metal (Lamghafri *et al*., 2023; Mandal *et al*., 2023).

Surface Coverage

The adsorbed inhibitor molecules form a monolayer on the metal surface, which reduces the availability of the metal surface for electrochemical reactions (Haque *et al*., 2023).

Barrier Formation

The adsorbed inhibitor molecules form a barrier between the metal surface and the corrosive environment, which prevents the diffusion of corrosive species, such as oxygen, chloride ions, or acid molecules, to the metal surface (Mubarak *et al*., 2023; Lipei *et al*., 2023).

Passivation

The adsorbed inhibitor molecules can promote the formation of a passive film on the metal surface, which is a protective layer that further inhibits the corrosion process (Anujay *et al*., 2023; Haque *et al*., 2023; Ghadeer *et al*., 2023).

The inhibitory efficiency can be evaluated by various electrochemical techniques, such as polarisation curves, electrochemical impedance spectroscopy, or electrochemical noise analysis. The mechanism of action involves adsorption, surface coverage, barrier formation, and passivation. The effectiveness of organic inhibitors depends on various factors, which can be evaluated by electrochemical techniques.

Application in Various Corrosive Environments

Corrosion poses a pervasive threat across diverse industries, leading to substantial damage to equipment and infrastructure. A highly effective strategy for corrosion prevention involves the deployment of organic inhibitors that creates a protective barrier that mitigates corrosion. Organic inhibitors have demonstrated success in countering corrosion in varied environments, including acidic and alkaline solutions, seawater, and industrial wastewater. Their effectiveness hinges on both their chemical properties and the corrosive characteristics of the environment (Khan *et al*., 2022). In acidic solutions, where corrosion affects metals like steel, aluminium, and copper, organic inhibitors play a crucial role. These acidic environments are encountered in industrial processes such as pickling, cleaning, and etching, as well as in natural settings like soil and water. Noteworthy organic inhibitors for acidic solutions encompass carboxylic acids, amines, and quinoline derivatives (Reza *et al*., 2021). Similarly, alkaline solutions, prevalent in electroplating, cleaning, and natural environments, pose a corrosion risk to metals like aluminium and magnesium. Organic inhibitors in alkaline solutions function by forming a protective film on the metal surface, impeding contact with the alkaline solution. Common examples include fatty acids, amines, and imidazolines (Kuznetsov & Redkina, 2022). Seawater, with its high salt content and corrosive ions, poses a formidable challenge to offshore structures, ships, and pipelines. Organic inhibitors, such as imidazolines, quinoline derivatives, and amino acids, prove instrumental in preventing corrosion by forming protective films on metal surfaces (Hossen *et al*., 2023). Industrial wastewater, characterised by varying chemical compositions and contaminants, is another corrosive environment affecting metals like steel, aluminium, and copper. Organic inhibitors in industrial wastewater, including amines, amino acids, and carboxylic acids, prevent corrosion by adsorbing onto metal surfaces and forming protective layers (Foorginezhad *et al*., 2021). In conclusion, the application of organic inhibitors in diverse corrosive environments emerges as a robust strategy for preventing metal corrosion. Their effectiveness is contingent on both their intrinsic chemical properties and the corrosive nature of the specific environment. Successful applications span acidic and alkaline solutions, seawater, and industrial wastewater, showcasing the versatility of organic inhibitors in corrosion prevention (Nik *et al*., 2011). However, continuous research is essential for developing novel and more potent organic inhibitors tailored to specific environmental challenges.

Corrosion Mitigation through Adsorption Inhibitors

Corrosion is a natural process that occurs when a metal reacts with its environment, leading to a degradation of the material's properties. To prevent this degradation, corrosion inhibitors are used to protect metal surfaces. Organic inhibitors are effective in various acidic solutions (Ahmed & Ganesh, 2022). Table 7 highlights recent inhibitors investigated for corrosion protection. Quinoline derivatives exhibit promising inhibitive properties and have shown

Table 7: Recent Published Inhibitors

Inhibitor	Description	References
Quinoline derivatives	Quinoline derivatives have been investigated as corrosion inhibitors due to their favourable inhibitive properties. They possess heterocyclic structures that facilitate adsorption onto the metal surface, forming protective layers. Quinoline derivatives exhibit promising corrosion inhibition in various corrosive solutions.	Fouda *et al.*, 2022
Schiff bases	Schiff bases are organic compounds formed by the condensation of primary amines with carbonyl compounds. They have been explored as corrosion inhibitors due to their ability to form protective films on metal surfaces. Schiff bases exhibit inhibitory properties and can be easily synthesised.	Hassan *et al.*, 2022; Al-Amiery *et al.*, 2023
Amino acids	Amino acids have shown potential as corrosion inhibitors due to their natural origin, low toxicity, and inhibitive properties. They can adsorb onto metal surfaces and form protective layers. Amino acids offer sustainable and environmentally friendly corrosion protection solutions.	Singh *et al.*, 2022
Polymers	Polymers have gained attention as corrosion inhibitors due to their film-forming properties. They can create protective films on metal surfaces, acting as barriers against corrosive species. Polymers offer versatility in terms of structure and functionality, allowing for tailored corrosion protection solutions.	Karthikaiselvi & Subhashini, 2014

effectiveness in various corrosive environments. Schiff bases offer a straightforward synthesis route and the ability to form protective films, making them attractive candidates as corrosion inhibitors. Amino acids provide a sustainable and eco-friendly option for corrosion inhibition, combining their natural origin with inhibitive properties. Polymers, with their film-forming properties, offer versatility and can be designed to meet specific corrosion protection requirements. These recent inhibitors contribute to the ongoing research and development of organic inhibitors for corrosion control.

Quinoline Derivatives

Quinoline derivatives are effective corrosion inhibitors for mild steel in acidic solutions. Studies have shown that the presence of nitrogen and oxygen in the quinoline ring contributes to its inhibitive properties. A recent study investigated the inhibitive properties of 2-(2-quinolyl) benzimidazole (QBI) and 2-(2-quinolyl) thiazole (QBT) on the corrosion of mild steel in hydrochloric acid solution. The study found that both QBI and QBT were effective inhibitors, with QBI being slightly more effective than QBT (Fouda *et al.*, 2022).

Schiff Bases

Schiff bases are organic compounds that contain an azomethine group (-C = N-) and have been shown to have inhibitive properties. A recent study investigated the inhibitive properties of two Schiff bases, N, N'-bis(2-hydroxy-5-methylphenyl)-1,4-phenylenediamine (BHMPD) and N, N'-bis(2-hydroxy-5-methoxyphenyl)-1,4-phenylenediamine (BHMPD-OCH3), on the corrosion of mild steel in hydrochloric acid solution. The study found that both BHMPD and BHMPD-OCH3 were effective inhibitors, with BHMPD-OCH3 being slightly more effective than BHMPD (Hassan *et al.*, 2022; Al-Amiery *et al.*, 2023).

Amino Acids

Amino acids are organic compounds that contain both an amino group (-NH2) and a carboxyl group (-COOH) and have been shown to have inhibitive properties. A recent study investigated the inhibitive properties of three amino acids, alanine, glycine, and histidine, on the corrosion of mild steel in a hydrochloric acid solution. The study found that all three amino acids were effective inhibitors, with histidine being the most effective (Singh *et al.*, 2022).

Polymers

Polymers are large molecules made up of repeating units and have been shown to have inhibitive properties. A recent study investigated the inhibitive properties of a water-soluble polymer, poly (vinyl alcohol) (PVA), on the corrosion of mild steel in hydrochloric acid solution. The study found that PVA was an effective inhibitor, with a higher concentration of PVA leading to a higher inhibition efficiency (Karthikaiselvi & Subhashini, 2014). Table 8, compares the concentration and inhibition efficiency of different types of recently published inhibitors.

The efficiencies of various organic corrosion inhibitors, as presented in Table 8, differ due to inhibitor type, concentration, and the specific metal surface under consideration.

1. ***Inhibitor Type:***
    - **DMAE (N, N-dimethylaminoethanol):** Being an amine, DMAE likely forms a protective layer through chemisorption, leading to high corrosion inhibition efficiency (CIE).
    - **AMMT (4-amino-3-mercapto-5-methyl-1,2,4-triazole):** As a triazole, AMMT might offer effective adsorption and inhibition due to the presence of nitrogen atoms, contributing to good CIE for carbon steel.
    - **AEAPTMS (N-(2-aminoethyl)-3-amino propyltrimethoxysilane):** As a silane, AEAPTMS could provide excellent surface coverage on mild steel, resulting in substantial corrosion inhibition.

Table 8: Comparison of different types of recently published inhibitors

Organic Corrosion Inhibitor	Type	Concentration	Surface	Corrosion Inhibition Efficiency (CIE)	References
N, N-dimethylaminoethanol (DMAE)	Amine	2 mM	Mild steel	99.4%	Subha *et al.*, 2015)
4-amino-3-mercapto-5-methyl-1,2,4-triazole (AMMT)	Triazole	0.1 mM	Carbon steel	98%	Alkadir *et al.*, 2021
N-(2-aminoethyl)-3-aminopropyltrimethoxysilane (AEAPTMS)	Silane	5 mM	Mild steel	95%	Zhang *et al.*, 2021
2-(2-methoxyphenyl)-1H-benzimidazole (MPBI)	Benzimidazole	1 mM	Copper	93.2%	Zhang & Li, 2020
2-mercaptobenzothiazole (MBT)	Thiazole	5 mM	Stainless steel	90.5%	Wu *et al.*, 2020
1,2,4-thiadiazole-5-carboxylic acid (TTCA)	Thiadiazole	0.1 mM	Mild steel	89%	Abed *et al.*, 2019

- **MPBI (2-(2-methoxyphenyl)-1H-benzi midazole):** The benzimidazole structure in MPBI likely contributes to its adsorption properties, influencing the inhibition efficiency of copper.
- **MBT (2-mercaptobenzothiazole):** MBT, a thiazole derivative, might interact effectively with the stainless-steel surface, forming a protective layer.
- **TTCA (1,2,4-thiadiazole-5-carboxylic acid):** The thiadiazole structure in TTCA may contribute to its inhibition efficiency on mild steel.

2. ***Concentration*:**
   - **Higher Concentration (e.g., DMAE and AEAPTMS):** Inhibitors with higher concentrations, like DMAE and AEAPTMS, may achieve greater adsorption and coverage on the metal surface, leading to higher CIE.
   - **Lower Concentration (e.g., TTCA and AMMT):** Even at lower concentrations, inhibitors like TTCA and AMMT demonstrate notable CIE, suggesting high effectiveness even at reduced dosages.
3. ***Metal Surface:***
   - **Variability in Metal Types (e.g., Mild steel, Copper, Stainless steel):** The nature of the metal surface significantly influences the adsorption mechanism and the resultant CIE. Different inhibitors may exhibit varied effectiveness based on the specific metal they are intended to protect.
4. ***Chemical Structure:***
   - **Differences in Functional Groups:** Variations in the chemical structures of the inhibitors lead to different mechanisms of adsorption and inhibition. For instance, the presence of amino groups, triazole rings, or triazole structures can influence the interaction with metal surfaces.
5. ***Research Conditions:***
   - **Methodological Differences:** Variability in experimental conditions, such as temperature, solution pH, and exposure time, across different studies can impact the reported efficiencies.

In conclusion, the observed differences in inhibition efficiencies among the inhibitors are multifaceted and stem from the interplay of inhibitor type, concentration, metal surface, and chemical structure. A comprehensive understanding of these factors is crucial for tailoring corrosion protection strategies to specific applications and metal types.

Comparison Studies

In this study, inhibitory efficiencies of several synthesised organic corrosion inhibitors that are available in the literature (Nik *et al.*, 2010; Aziz *et al.*, 2017; Nik *et al.*, 2017; Abed *et al.*, 2019; Al-Baghdadi *et al.*, 2021; Alamiery, 2021b, 2021a; Alamiery *et al.*, 2021a; Alamiery *et al.*, 2021b; Alamiery *et al.*, 2021c; Alamiery, 2021c; Alamiery *et al.*, 2021d; Alkadir *et al.*, 2021; Dawood *et al.*, 2021; Eltmimi *et al.*, 2021; Hanoon *et al.*, 2021; Al-Amiery *et al.*, 2022; Alamiery, 2022a; Alamiery *et al.*, 2022; Alamiery, 2022b; Mustafa *et al.*, 2022; Khalid Al-Azzawi *et al.*, 2023) were compared. By evaluating the inhibition efficiencies of these synthesised inhibitors, we aimed to gain insights into their performance and highlight potential candidates for effective corrosion inhibition. The summary presented in Figure 2 serves as a visual representation of the comparison of inhibition efficiencies among the synthesised organic corrosion inhibitors investigated in this study. The graph displays the inhibitors along the x-axis, likely labelled with their corresponding names or references, while the y-axis represents the inhibition efficiency percentage. The inhibition efficiencies are represented as percentages, where higher values indicate more effective inhibition against corrosion. The graph allows for a quick and easy comparison of the inhibitory performances of the synthesised inhibitors. By examining the plotted data points, it becomes evident which inhibitors exhibit higher inhibition efficiencies compared to others.

This information can aid researchers, engineers, and industrial professionals in selecting suitable inhibitors for specific applications and corrosive environments. The

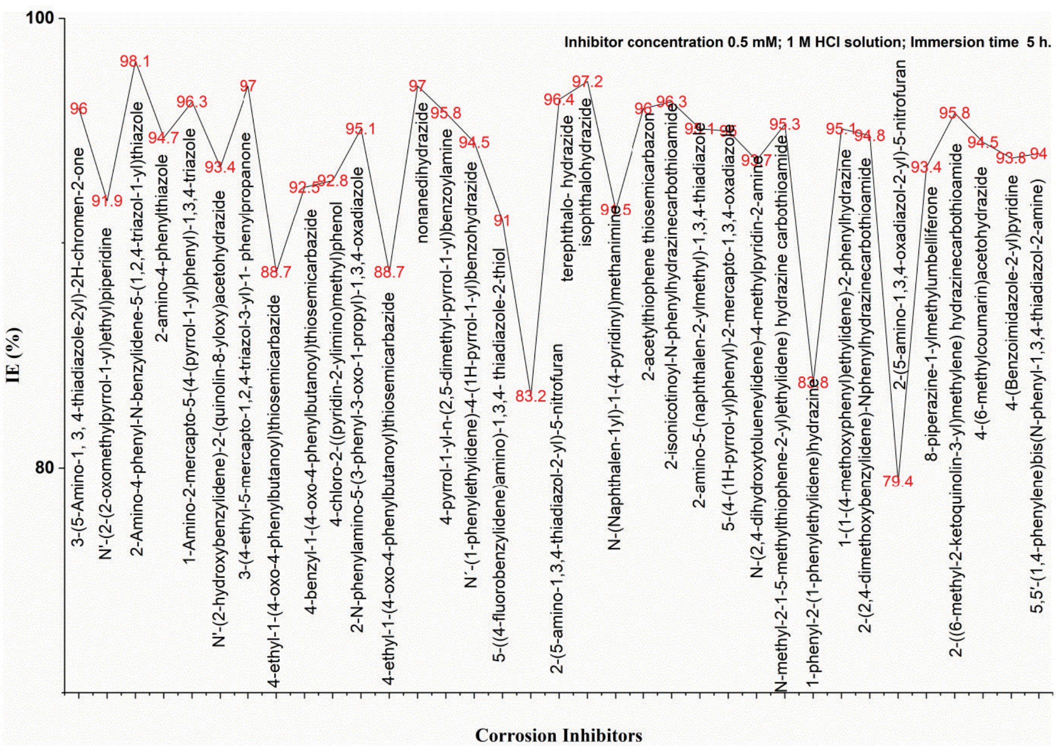

Figure 2: Comparison between several synthesised organic corrosion inhibitors

comparison of inhibition efficiencies presented in Figure 2 provides valuable insights into the relative effectiveness of the synthesised organic corrosion inhibitors. The graph enables a direct comparison of the inhibitors' performance, enabling the identification of inhibitors that offer high levels of corrosion protection. Furthermore, it allows for the identification of potential trends or patterns in inhibitor performance, such as inhibitors with consistently high or low inhibition efficiencies.

The variations in corrosion inhibition efficiency among the postulated inhibitors (Figure 2) can be attributed to several factors:

Chemical Structure:

- **Functional Groups:** The presence of different functional groups in inhibitors influences their interaction with the metal surface. For instance, amino, thiazole, hydrazide, and pyridine groups may contribute differently to the adsorption process (Ghazoui *et al.*, 2012).
- **Conjugation:** Molecules with extended conjugated systems, like 3-(5-Amino-1,3,4-thiadiazol-2yl)-2H-chromen-2-one, may exhibit higher efficiency due to enhanced electron delocalisation.

Steric Effects:

- **Substituent Groups:** The nature and position of substituent groups on the aromatic rings can affect the steric hindrance, influencing the accessibility of the inhibitor to the metal surface.

Electronic Effects:

- **Electron-withdrawing or Donating Group:** Electron-withdrawing or donating groups can influence the electron density of the inhibitor molecule, affecting its interaction with the metal surface.

Hydrophobicity and Hydrophilicity:

- **Balancing Hydrophobic and Hydrophilic Properties:** The balance between hydrophobic and hydrophilic characteristics in the inhibitor molecule can impact its solubility in the corrosive environment and, consequently, its effectiveness.

Concentration Dependency:

- **Optimal Concentration:** The efficiency of an inhibitor may vary with its concentration. Too low a concentration might be ineffective, while too high a concentration could lead to precipitation or reduced efficiency.

Molecular Size:

- **Size of the Inhibitor Molecule:** Bulky molecules may struggle with effective adsorption due to steric hindrance, whereas smaller molecules might adsorb more easily.

Experimental Conditions:

- **Solution Composition:** Differences in the corrosive media's composition (acidity, presence of other ions) during experimental setups can lead to variations in inhibition efficiency.
- **Temperature:** Corrosion rates can be temperature-dependent, and inhibitors may exhibit different efficiencies at varied temperatures.

Metal Specificity:

- **Metal Surface:** The nature of the metal being protected influences the adsorption mechanism. Different metals may have different affinities for specific inhibitors.

Adsorption Mechanism:

- **Chemisorption vs. Physisorption:** Inhibitors that chemisorb (form a chemical bond) might offer stronger and more stable protection compared to those relying on physisorption (physical interaction).

Hydrazide-Based Inhibitors:

- **Hydrazide Structure:** Inhibitors with hydrazide groups, like isophthalohydrazide and terephthalohydrazide, may form stable complexes with metal surfaces, enhancing their inhibition efficiency.

Several amine-based corrosion inhibitors are commonly used for multiple applications and can be used for industry. Among the best organic inhibitors is ethanolamine. Ethanolamine is effective in neutralising acidic components, forming a protective layer on metal surfaces, and is widely used in the oil and gas industry to prevent corrosion in systems such as pipelines and refineries. In conclusion, the complexities in inhibitor efficiency stem from a combination of structural, electronic, and environmental factors. It's crucial to consider the specific application conditions and metal surfaces when selecting or designing inhibitors for corrosion protection.

Conclusions

The use of organic inhibitors for mild steel protection in corrosive environments has been extensively studied and improved in recent years. The inhibitory efficiency of organic inhibitors is mainly dependent on the type of inhibitor, the corrosive medium, and the environmental conditions. The study of the mechanism of action of organic inhibitors has shown that these compounds mainly act by adsorption on the metal surface, which leads to a reduction in the corrosion rate. The types of organic inhibitors include adsorption inhibitors, film-forming inhibitors, mixed inhibitors, synergistic inhibitors, and green inhibitors. Each type of inhibitor has its advantages and limitations in various corrosive environments. Adsorption inhibitors have been shown to have good inhibitory performance in acidic media, while film-forming inhibitors are more effective in neutral to alkaline environments. Mixed inhibitors are efficient in a wide range of pH values and can provide better protection than single inhibitors. Synergistic inhibitors are an effective approach to improve the efficiency of inhibitors by combining two or more inhibitors that act through different mechanisms.

Recently published inhibitors such as quinoline derivatives, Schiff bases, amino acids, and polymers have shown great potential as organic inhibitors for mild steel in various corrosive environments. Quinoline derivatives have been found to have good inhibitory efficiency in acidic and neutral media, while Schiff bases and amino acids have shown high inhibitory performance in alkaline solutions. Polymers have also been shown to provide good protection for mild steel in different corrosive media due to their film-forming properties. Overall, the use of organic inhibitors has provided an effective and environmentally friendly approach to protect mild steel against corrosion. With continued research and development, organic inhibitors have the potential to become a widely used approach to mitigate corrosion in various industrial applications.

Acknowledgement

We would like to thank Universiti Malaysia Terengganu, Universiti Kebangsaan Malaysia and other collaborative institutions for the Corrosion UMT-UKM-RSU-AISSMS 1+3 matching grant (vot 53432).

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

Abed, T. K., Al-Azawi, K. F., Jaber, S. H., Al-Amiery, A. A., & Al-Baghdadi, S. B. (2019). Experimental study of 2-Amino-5-(4-nitrophenyl)-1, 3, 4-Thiadiazole for MS in HCl solution. *Engineering and Technology Journal*, *37*(2C), 214-218.

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

Abdulsahib, Y. M., Eltmimi, A. J. M., Alhabeeb, S. A., Hanoon, M. M., Al-Amiery, A. A., Allami, T., & Kadhum, A. A. H. (2021). Experimental and theoretical investigations on the inhibition efficiency of N-(2,4-Dihydroxytolueneylidene)-4-methyl pyridin-2-amine for the corrosion of mild steel in hydrochloric acid. *International Journal Corrosion and Scale Inhibition*, *10*, 885-899. https://doi.org/10.17675/2305-6894-2021-10-3-3

Ahmed, E. S. J., & Ganesh, G. M. (2022). A comprehensive overview of corrosion in RCC and its prevention using various green corrosion inhibitors. *Buildings*, *12*(10), 1682-1730.

Al-Amiery, A.A., Shaker, L.M., Kadhum, A.H., & Takriff, M.S. (2021). Exploration of Furan derivative for application as corrosion inhibitor for mild steel in hydrochloric acid solution: Effect of immersion time and temperature on efficiency. *Mater. Today Proc*, *42*, 2968-2973. https://doi.org/10.1016/j.matpr.2021.04.296

Al-Amiery, A. A., Betti, N., Isahak, W. N. R. W., Al-Azzawi, W. K., & Wan, W. M. N. (2023). Exploring the effectiveness of isatin-Schiff base as an environmentally friendly corrosion inhibitor for mild steel in hydrochloric acid. *Lubricants*, *11*(5), 211-235.

Al-Amiery, Ahmed A., Emad Y., Wan N. R. W. I., & Waleed K. A. (2023). A review of inorganic corrosion inhibitors: Types, mechanisms, and applications. *Tribology in Industry*, *44*(2), 313.

Al-Amiery, A. A., & Al-Azzawi, W. K. (2023). Organic synthesised inhibitors for corrosion protection of carbon steel: A comprehensive review. *Journal of Bio-and Tribo-Corrosion*, *9*(4), 74. https://doi.org/10.1007/s40735-023-00791-4

Al-Amiery, A. A., Isahak, W. N. R. W., & Al-Azzawi, W. K. (2023). Corrosion inhibitors: Natural and synthetic organic inhibitors. *Lubricants*, *11*(4), 174. https://doi.org/10.3390/lubricants11040174

Al-Baghdadi, S. B., Al-Amiery, A. A., Gaaz, T. S., & Kadhum, A. A. H. (2021). Terephthalohydrazide and isophthalohydrazide as new corrosion inhibitors for mild steel in hydrochloric acid: Experimental and theoretical approaches. *KOM–Corrosion and Material Protection Journal*, *65*(1), 12-22.

Alkadir, A. I. A., Annon, I. A., Abdulkareem, M. H., Hanoon, M. M., Alkaabi, M. H., Shaker, L. M., & Takriff, M. S. (2021). Insights into corrosion inhibition behaviour of a 5-mercapto-1, 2, 4-triazole derivative for mild steel in hydrochloric acid solution: experimental and DFT studies. *Lubricants*, *9*(12), 122-136.

Aziz, N. A. M., Ghazali, M. S. M., Abdullah, W. R. W., Nik, W. M. N. W., Huda, N., Abd Kadir, N. A. A. R. A., & Othman, A. (2017). Cytotoxicity of TiO_2 nanoparticles and effect of incorporation of nanoTiO_2-PEDOT: PSS composite in PVAc coating on anti-corrosive performance. *Measurement*, *316*, 80-85.

Belghiti, M. E. Karzazi, Y. Dafali, A., Obot, I. B., Ebenso, E. E., Emran, K. M., Bahadur, I., Hammouti, B. & Bentiss, F. (2016). Anti-corrosive properties of 4-amino-3,5-bis(disubstituted)-1,2,4-triazole derivatives on mild steel corrosion in 2M H3PO4 solution: Experimental and theoretical studies. *Journal of Molecular Liquids, 218*(6), 874-886. https://doi.org/10.1016/j.molliq.2015.12.093

Chraka, A., Nordin, B.S., Ihssane R., Jalal K., Mohamed C., Mustapha E., & Oulya Z. (2023). Electrochemical explorations, SEM/EDX analysis, and quantum mechanics/molecular simulations studies of sustainable corrosion inhibitors on the Cu-Zn Alloy in 3% NaCl solution. *Journal of Molecular Liquids*, 387, 122715.

Dawood, M., Alasady, Z., Abdulazeez, M., Ahmed, D., Sulaiman, G., Kadhum, A., . . . Alamiery, A. (2021). 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*, *10*(4), 1766-1782.

El-Rehim, S. A., Refaey, S., Taha, F., Saleh, M., & Ahmed, R. (2001). Corrosion inhibition of mild steel in acidic medium using 2-amino thiophenol and 2-cyanomethyl benzothiazole. *Journal of Applied Electro chemistry*, *31*, 429-435.

El-Haitout, B., Ilhem S., Hassane L., Mustafa R. A., Han-Seung L., Abdelkarim C., Young, G. K., Ismat H. A., & Rachid, S. (2023). Exploring the feasibility of new eco-friendly heterocyclic compounds for establishing efficient corrosion protection for N80 steel in a simulated oil well acidising environment: From molecular-level prediction to experimental validation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *656*, 130372.

El-Mouaden, K., El-Ibrahimi, B., Oukhrib, R., Bazzi, L., Hammouti, B., Jbara, O., Tara, A., Chauhan, D. S. & Quraishi, M.A. (2018). Chitosan polymer as a green corrosion inhibitor for copper in sulfide-containing synthetic seawater. *International Journal of Biological Macromolecules, 119*, 1311-1323.

Eltmimi, A. J. M., Alamiery, A., Allami, A. J., Yusop, R. M., Kadhum, A. H., & Allami, T. (2021). Inhibitive effects of a novel efficient Schiff base on mild steel in a hydrochloric acid environment. *International Journal of Corrosion and Scale Inhibition*, *10*(2), 634-648.

Farhadian, A., Azam S., Xin Z., Roman S. P., Kiana P., Zhengsong Q., & Mikhail A. V. (2023). Challenges and advantages of using environmentally friendly kinetic gas hydrate inhibitors for flow assurance application: A comprehensive review. *Fuel*, *336*, 127055.

Foorginezhad, S., Mohseni-Dargah, M., Firoozirad, K., Aryai, V., Razmjou, A., Abbassi, R., Garaniya, V., Beheshti, A., & Asadnia, M. (2021). Recent advances in sensing and assessment of corrosion in sewage pipelines. *Process Safety and Environmental Protection*, *147*, 192-213.

Fouda, A. S., Ismail, M. A., Khaled, M. A., & El-Hossiany, A. A. (2022). Experimental and computational chemical studies on the corrosion inhibition of new pyrimidinone derivatives for copper in nitric acid. *Scientific Reports*, *12*(1), 16089-16108.

Fu, L., Tianyu, S., Minglu, S., Ziqiang, X, Kaili, L., Heng, Z., Junnan, A., Lujun, J., & Feng, G. (2023). Application of modified graphene oxide in corrosion protection. *ChemistrySelect, 8*(28), e2023 01364. https://doi.org/10.1002/slct.202301 364

Gabsi, M., Hana, F., Amel, D., Abir, B., Chérifa, B., Abdesalem, K., Ahmad, S. D., Tarek, L., & Yacine, B. (2023). The curious case of polyphenols as green corrosion inhibitors: A review on their extraction, design, and applications. *Environmental Science and Pollution Research*, *30*(21), 59081-59105.

Ghazoui, A., Saddik, R., Benchat, N., Guenbour, M., Hammouti, B., Al-Deyab, S. S. & Zarrouk, A. (2012). Comparative study of pyridine and pyrimidine derivatives as corrosion inhibitors of C38 steel in molar HCl. *International Journal of Electrochemistry* Science, *7*(8), 7080-7097.

Guo, L., Yue, H., Alessandra, G. R., Kai, W., Ida, R., Yan, T., Yujie, Q., Nabil, A., Wei, S., & Xingwen, Z. (2023). Effect of Indole-2-carboxylic acid on the self-corrosion and discharge activity of aluminium alloy anode in alkaline Al-air battery. *Molecules*, *28*(10), 4193.

Hajar, H., Zulkifli, F., Suriani, M., Sabri, M. M., & Nik, W. W. (2016). *Lawsonia lnermis* extract enhances the performance of corrosion protection of coated mild steel in seawater. *MATEC Web of Conferences*, *78*(1), 01091. https://doi.org/10.1051/matec conf/20167801091

Hanoon, M. M., Resen, A. M., Shaker, L. M., Kadhum, A. A. H., & Al-Amiery, A. A. (2021). Corrosion investigation of mild steel in an aqueous hydrochloric acid environment using n-(Naphthalen-1yl)-1-(4-pyridinyl) methenamine complemented with antibacterial studies. *Biointerface Research in Applied Chemistry*, *11*(2), 9735-9743.

Hanoon, M. M., Resen, A. M., Al-Amiery, A. A., Kadhum, A. A. H., Takriff, M. S. (2021). 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 Colour Colorants and Coatings*, *15*(1), 21-33. https://doi.org/10.3390/pccc15010003

Haque, J., Mohammad, F. R. Z., Nabilah, I., Mumtaz, A. Q., Mohd, S. M. G., Elyor, B., & Wan M. N. W. Nik. (2023). Environmentally benign water-soluble sodium L-2-(1-Imidazolyl) alkanoic acids as new corrosion inhibitors for mild steel in artificial seawater. *ACS Omega, 8*(28), 24797-24812. https://doi.org/10.1021/acsomega.3c00366

Hassan, H. H., Hussein, H. M., & Elhusseiny, A. F. (2022). Green synthesis of nanosised N, N'-bis (1-naphthylidene)-4, 4'-diaminodiphenylmethane and its metal (II) complexes and evaluation of their biological activity. *Scientific Reports*, *12*(1), 21142-21161.

Hashim, F. G., Salman, T. A., Al-Baghdadi, S. B., Gaaz, T., Al-Amiery, A. A. (2020). Inhibition effect of hydrazine-derived coumarin on a mild steel surface in hydrochloric acid. *Tribologia*, *37*, 45-53.

Hossen, A., Mahmud, R., & Islam, A. (2023). Minimisation of corrosion in the aquatic environment – A review. *International Journal of Hydrology*, *7*(1), 9-16.

Hu, J., & Wei, L. (2023). Chitosan/tannic acid phenamine networks-hollow mesoporous silica capsules with reversible pH response: Controlled-releasing amino acid derivatives as "green" corrosion inhibitor. *Carbohydrate Polymers*, 121244.

Ikhmal, W., Yasmin, M., Fazira, M., Rafizah, W., Nik, W. W., & Sabri, M. (2018). Anticorrosion coating using *Olea* sp. leaves extract. *IOP Conference Series: Materials Science and Engineering, 344*, 012028. https://doi.org/10.1088/1757-899X/344/1/012028

Ikhmal, W., Maria, M., Rafizah, W., Norsani, W., & Sabri, M. (2019). Corrosion inhibition of mild steel in seawater through a green approach using *Leucaena leucocephala* leaves extract. *International Journal of Corrosion and Scale Inhibition*, *8*(3), 628-643.

Ikeuba, A. I., Christopher, U. S, Ifeatu, E. C., Remigius, C. A., Benedict, U. U., Benedict, O., Okpo, O. E., & Wilfred, E. (2023). Electrochemical evaluation of the anti-corrosion potential of selected amino acids on magnesium in aqueous sodium chloride solutions. *Anti-Corrosion Methods and Materials, 70*(5), 252-258. https://doi.org/10.1108/ACMM-04-2023-2796

Ismail, N., Ghazali, M. S. M., Fakhratul, M., Zulkifli, R., Umoren, S. A., Kamal, C., Nik, W. M. N. W. (2021). Employing *Cymbopogon citratus* (Lemongrass) as an eco-friendly corrosion inhibitor for mild steel in seawater. *Journal of Sustainability Science and Management*, *16*(3), 71-82.

Ismail, N., Mujad, S. M., Zulkifli, M. F. R., Izionworu, V. O., Ghazali, M. J., & Nik, W. M. N. W. (2022). A review on application of marine algae as green corrosion inhibitors in acid medium. *Vietnam Journal of Chemistry*, *60*(4), 409-416.

Izionworu, V. O., Puyate, Y. T., & Wan-Nik, W. B. (2021). A Study of wire croton as an inhibitor of mild steel in HCl using electrochemical – SEM – Gas Chromatography-Mass Spectrometry and FTIR measurements. *Journal of Newviews* *in Engineering and Technologies. 3(1), 1-11.*

Izionworu, V. O., Ukpaka, C. P., & Oguzie, E. E. (2020). Inhibition of mild steel corrosion in acidic medium using theobroma cacao pod. *International Journal of Scientific & Engineering Research. 11*(3)*,* 255, 265.

Jadhao, P., Ankur, K., Mahendra, P., & Asirvatham, R. K. (2023). Roles of surfactant, oxidant and activator on enhanced electrokinetic-persulfate technique for the removal of hydrophobic organic compounds in soil: A review. *Journal of Environmental Chemical Engineering*, 109525.

Kamaruzzaman, W. M. I. W. M., Fekeri, M. F. M., Nasir, N. A. M., Hamidi, N. A. S. M., Baharom, M. Z., Adnan, A., . . . Suhailin, F. H. (2021). Anticorrosive and microbial inhibition performance of a coating loaded with *Andrographis paniculata* on stainless steel in seawater. *Molecules*, *26*(11), 1-18.

Kamaruzzaman, W. M. I. W. M., Nasir, N. A. M., Hamidi, N. A. S. M., Yusof, N., Shaifudin, M. S., Suhaimi, A. M. A. A. M., . . . Ghazali, M. S. M. (2022). 25 years of progress on plants as corrosion inhibitors through a bibliometric analysis using the Scopus database (1995-2020). *Arabian Journal of Chemistry*, *15*(4), 1-13.

Karthikaiselvi, R., & Subhashini, S. (2014). Study of adsorption properties and inhibition of mild steel corrosion in hydrochloric acid media by water-soluble composite poly (vinyl alcohol-omethoxy aniline). *Journal of the Association of Arab Universities for Basic and Applied Sciences*, *16*(1), 74-82.

Kaseem, M., Burak, D., Ali, D., & Arash, F. (2023). Self-assembly of coumarin molecules on plasma electrolysed layer for optimising the electrochemical performance of AZ31 Mg alloy. *Journal of Magnesium and Alloys, 11*(5), 1618-1628.

Kaya, F., Ramazan, S., & Ibrahim, H. G. (2023). Adsorption and corrosion inhibition capability of Rheum ribes root extract (Işgın) for mild steel protection in acidic medium: A comprehensive electrochemical, surface characterisation, synergistic inhibition effect, and stability study. *Journal of Molecular Liquids*, *372*, 121219.

Khalid, A. W., Hussein, S. S., Salih, S. M., Zinad, D., Al-Azzawi, R., Hanoon, M., . . . Wan, I, W. (2023). Efficient protection of mild steel corrosion in hydrochloric acid using 3-(5-amino-1, 3, 4-thiadiazole-2yl)-2H-chromen-2-one, a coumarin derivative bearing a 1, 3, 4-thiadiazole moiety: Gravimetrical techniques, computational and thermodynamic investigations. *Progress in Color, Colorants and Coatings*, *16*(1), 97-111.

Khan, M. A. A., Irfan, O. M., Djavanroodi, F., & Asad, M. (2022). Development of sustainable inhibitors for corrosion control. *Sustainability*, *14*(15), 9502-9519.

Khudhair, A. K., Mustafa, A. M., Hanoon, M. M., Al-Amiery, A., Shaker, L. M., Gazz, T., Mohamad, A. B., Kadhum, A. H., & Takriff, M. S. (2021). Experimental and theoretical investigation on the corrosion inhibitor potential of N-MEH for mild steel in HCl. *Progress in Color, Colorants and Coatings*, *15*, 111-122. https://doi.org/10.30509/PCCC.2021.166815.1111

Kuznetsov, Y. I., & Redkina, G. V. (2022). Thin protective coatings on metals formed by organic corrosion inhibitors in neutral media. *Coatings*, *12*(2), 149-228.

Lamghafri, S., Walid, D., Abdelmalik E., Omar, D., Avni, B., Asma, B., Wan W. B., Abdelkader, Z., & Abdellatif, L. (2023). Comparative study of the performance and inhibitory efficiency of two new organic heterocyclics in the chemical industry. *Materials Science and Engineering: B*, *297*, 116779.

Li, E., Songling, L., Fang, L., & Pei, Y. (2023). Amino acid imidazole ionic liquids as green corrosion inhibitors for mild steel in neutral media: synthesis, electrochemistry, surface analysis and theoretical calculations.

Journal of Electroanalytical Chemistry, *944*, 117650.

Li, N., Yanan, H., Gang, X., Pingli, L., Yin, X., Zhifeng, L., Qian, Z., Yue, L., Shijie, Z., & Wentao, F. (2023). Research and application of eco-friendly chelating agents in plugging removal systems: A review. *Geoenergy Science and Engineering*, *229*, 212135.

Liu, Z., Fengrui, Z., Xuan, L., & Danqian, W. (2023). Improved corrosion inhibition of calcium disodium EDTA for mild steel in chloride-contaminated concrete pore solution. *Cement and Concrete Composites*, *140,* 105075.

Mandal, S., Sourav, B., & Priyabrata, B. (2023). Insights into the uses of two azine decorated d10-MOFs for corrosion inhibition application on mild steel surface in saline medium: Experimental as well as theoretical investigation. *Journal of Molecular Liquids*, *381*, 121789.

More, P., Kundan J., Sailee G., Rajeshwari A., Fatima C., & Ramesh Y. (2023). Sustainable grafted biopolymer - Grafted biopolymers as corrosion inhibitors: Safety, sustainability, and efficiency, 7, 89-120.

Mubarak, G., Chandrabhan, V., Imad, B., Akram, A., & Kyong, Y. R. (2023). Internal corrosion in oil and gas wells during casings and tubing: Challenges and opportunities of corrosion inhibitors. *Journal of the Taiwan Institute of Chemical Engineers, 150*, 105027.

Mustafa, A. M., Sayyid, F. F., Betti, N., Hanoon, M. M., Al-Amiery, A. A., Kadhum, A. A. H., Takriff, M. S. (2021). Inhibition evaluation of 5-(4-(1H-Pyrrol-1-yl) phenyl)-2-mercapto-1,3,4-oxadiazole for the corrosion of mild steel in an acidic environment: Thermodynamic and DFT aspects. *Tribologia, 38*, 39-47. https://doi.org/10.30678/fjt.105330

Mustafa, A., Sayyid, F., Betti, N., Shaker, L., Hanoon, M., Alamiery, A., . . .& Takriff, M. (2022). Inhibition of mild steel corrosion in the hydrochloric acid environment by 1-amino-2-mercapto-5-(4-(pyrrole-1-yl) phenyl)-1, 3, 4-triazole. *South African Journal of Chemical Engineering*, *39*(1), 42-51.

Nik, W. B. W., Hajar, H. M., Suriani, M. J., Sabri, M. G. M., & Ghazali, M. J. (2017). Development of anti-corrosive paint incorporated with henna extract as a natural inhibitor. *Journal of Mechanical Engineering and Sciences*, *11*(4), 3179-3189.

Nik, W. B. W., Sulaiman, O., Giap, S. G. E., & Rosliza, R. (2010). Evaluation of inhibitive action of sodium benzoate on corrosion behaviour of AA6063 in seawater. *International Journal of Technology*, *1*(1), 20-28.

Nik, W. N. W., Hui, S. Y., Nazri, N. K., Tarmizi, N., Ismail, N., & Diah, S. A. M. (2020). Utilisation of *Dendrobium crumenatum* as an anti-corrosion additive for mild steel in different seawater velocities. *Journal of Sustainability Science and Management*, *15*(5), 19-28.

Nik, W. W., Zulkifli, M., Rosliza, R., Ghazali, M., & Khaled, K. (2011). Potential of honey as corrosion inhibitor for aluminium alloy in seawater. *World Applied Sciences Journal*, *14*(2), 215-220.

Nirmala, M. Joyce, P. Chandra, S., Athira, J., Uma, K., Shasmeen, S., & Nagarajan, R. (2023). A comprehensive review of nano additives in plant-based biodiesels with a special emphasis on essential oils. *Fuel, 351*, 128934.

Peter, A., & Sharma, S. (2017). Use of *Azadirachta indica* (AZI) as a green corrosion inhibitor against mild steel in acidic medium: Anti-corrosive efficacy and adsorptive behaviour. *International Journal of Corrosion and Scale Inhibition*, *6*(2), 112-131.

Pour, A., Sadegh, R. T., & Seyedsina, H. (2023). Comprehensive assessment of some l-amino acids as eco-friendly corrosion inhibitors for mild steel in HCl: Insights from experimental and theoretical studies. *Journal of Physics and Chemistry of Solids*, 111550.

Punitha, N., Sundaram, R. G., Vengatesh, G., Rengasamy, R. & Elangovan, J. (2023). Bis-1, 2, 3-triazole derivative as an efficient corrosion inhibitor for mild steel in hydrochloric acid environment: Insights from experimental and computational analysis. *Inorganic Chemistry Communications, 153*, 110732.

Qi, W., Yu, H., Yuting, M., Zizhou, Y., & Xinbao, Z. (2023). Developing novel imidazoline-modified glucose derivatives as eco-friendly corrosion inhibitors for Q235 steel. *RSC Advances*, *13*(20), 13516-13525.

Rawat, A., Karade, S. R. & Thapliyal, P. C. (2023). Mechanism of inhibitors in control of corrosion of steel in concrete. *Materials Today: Proceedings*, 1-7. https://doi.org/10.1016/j.matpr.2023.06.210

Resen, A. M., Hanoon, M., Salim, R. D., Al-Amiery, A. A., Shaker, L. M. & Kadhum, A. A. H. (2020). 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 Materialu, 64*, 122-130. https://doi.org/10.2478/kom-2020-0018

Resen, A. M., Hanoon, M. M., Alani, W. K., Kadhim, A., Mohammed, A. A., Gaaz, T. S., Kadhum, A. A. H., Al-Amiery, A. A. & Takriff, M. S. (2021). 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, 10*, 368-387. https://doi.org/10.17675/2305-6894-2021-10-1-21

Reza, N. A., Akhmal, N. H., Fadil, N. A., & Taib, M. F. M. (2021). A review on plants and biomass wastes as organic green corrosion inhibitors for mild steel in an acidic environment. *Metals*, *11*(7), 1062-1087.

Salhi, A., Abdellah, E., Issam, A., Abdelmalek, E., Hassan, A., Mohamed, E., Abdelhamid, B., & Smaail, R. (2023). A correlated theoretical and electrochemical investigation of the corrosion inhibition performance of phenolic Schiff bases on mild steel in HCl solution (Part B). *Inorganic Chemistry Communications*, *152*, 110684. https://doi.org/10.1016/j.inoche.2023.110684

Salim, R. D., Betti, N., Hanoon, M. & Al-Amiery, A. A. (2021). 2-(2,4-Dimethoxybenzylidene)-N-Phenylhydrazinecarbothioamide as an efficient corrosion inhibitor for mild steel in an acidic environment. *Progress in Colour Colorants and Coatings, 15*, 45-52. https://doi.org/10.3390/pccc15010006

Salman, A. Z., Jawad, Q. A., Ridah, K. S., Shaker, L. M., & Al-Amiery, A. A. (2020). Selected BIS-Thiadiazole: Synthesis and corrosion inhibition studies on mild steel in HCL environment. *Surface Review and Letters* (SRL), *27*, 2050014.

Satpati, S., Aditya, S., Subhas, G., Sukalpa, D., & Dipankar, S. (2023). Interaction of newly synthesised dipeptide Schiff bases with mild steel surface in aqueous HCl: Experimental and theoretical study on thermodynamics, adsorption and anti-corrosion characteristics. *Materials Chemistry and Physics, 296*, 127200.

Shadi, S., Ghasem, B., Bahram, R. & Amir, H. J. M. (2023). Experimental and computational exploration of the synergistic effect of Laurus Nobilis extract: Zinc cation on mild steel corrosion inhibition in saline solution. *Journal of Molecular Liquids*, *385*, 122424. https://doi.org/10.1016/j.molliq.2023.122424

Singh, R. A. P., Muhammad, A. A., Singh, H., Singh, T., Mkhize, Z., Jain, P., . . . Singh, P. (2022). A review of interactions between amino acids and surfactants as well as their impact on corrosion inhibition. *ACS Omega*, *7*(51), 47471-47489.

Subha, R., Sudha, D., & Murugan, K. (2015). 2-Dimethyl amino ethanol as a non-toxic corrosion inhibitor for austenitic stainless steel 304 in 1 M HCl solution. *International Conference on Systems, Science, Control, Communication, Engineering and Technology, Vol. 4, Issue 11, November 2015.*

Talat, N. T., Dahadha, A. Al Rabadi, A. S. Abunuwar, J. M. Hussien, A. A. Al-Dhoun, M., Al-Abrouni, K. F., Mfarej, T., Issa, R. B., & Al-qderat. M. (2023). Corrosion inhibition of aluminium in HBr solutions by nonionic surfactants at different temperatures. *International Journal Corrossion Scale Inhibition, 12*(2), 741-770.

Tebbji, K., Bouabdellah, I., Aouniti, A., Hammouti, B., Oudda, H., Benkaddour, M., & Ramdani, A. (2007), N-benzyl-N, N-bis[(3,5-dimethyl-1H-pyrazol-1-yl) methyl] amine as corrosion inhibitor of steel in 1 M HCl. *Material Letters*, *61*(3), 799-804.

Verma, D. K., Sahu, R., Berdimurodov, E., Verma, C., Quraishi, M. A., Jain, V.K. & Berdimuradov, K. (2023). Isatin is a new core in the developing of corrosion inhibitors: A comprehensive review. *Journal of Molecular Structure*, *1294* (Part 1), 136313. https://doi.org/10. 1016/j. molstruc.2023.136313

Verma, C., Goni, L. K. M. O., Yaagoob, I. Y., Vashisht, H., Mazumder, M. A. J., & Alfantazi, A. (2023). Polymeric surfactants as ideal substitutes for sustainable corrosion protection: A perspective on colloidal and interface properties. *Advances in Colloid and Interface Science*, *318*, 102966.

Wang, Y., Hongbin L., Xingxiang J., Qiang W., Zhongjian T. & Pedram F., (2023). Production of nanocellulose using acidic deep eutectic solvents based on choline chloride and carboxylic acids: A review. *International Journal of Biological Macro molecules*, *245*, 125227.

Wen, J., Xin Z., Yunxia L., Bo S., Jianxin H. & Lingjie L., (2023). Exploration of Imidazol-4-Methylimine thiourea as effective corrosion inhibitor for mild steel in hydrochloric medium: Experimental and theoretical studies. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *674*, 131895. https://doi.org/10.1016/j.col surfa.2023.131895

Wu, X., Wiame, F., Maurice, V., & Marcus, P. (2020). 2-Mercaptobenzothiazole corrosion inhibitor deposited at ultra-low pressure on model copper surfaces. *Corrosion Science*, *166*, 1-23.

Yaagoob, I.Y., Lipiar K.G., Mohammad A.M., Shaikh A., Ali, A.A. & Chandrabhan V., (2023). Surface and interfacial properties of poly (methyldiallylammonium chloride): Effect of hydrophobic pendant and synergism (KI) on corrosion of C1018CS in 15% HCl. *Journal of the Taiwan Institute of Chemical Engineers, 149*, 105000.

Yadav, M., Kumar, S., Kumari, N., Bahadur, I., & Ebenso, E. E. (2015). Experimental and theoretical studies on corrosion inhibition effect of synthesised benzothiazole derivatives on mild steel in 15% HCl solution. *International Journal of Electro chemical Science*, *10*(1), 602-624.

Youssif, M. M., El-Nahass, M. N., Fayed, T. A., El-Daly, H. A., El-Gamil, M. M., & Eldesoky, A. M. (2023). Tunable anticorrosive effects of newly synthesised benzothiazole azo dyes by potassium iodide synergism for carbon steel in 1 M HCl: Combined experimental and theoretical studies. *ACS Omega, 8*(31), 28314-28332. https://doi.org/10.1021/acsomega.3c02105

Yuyang, D., Yilei L., Xianliang L., Zhihao C., & Wenzhong Y. (2023). Fluorocarbon chain-based imidazoline derivatives as highly efficient corrosion inhibitors at elevated temperatures. *Journal of Molecular Structure*, *1282*, 135266. https://doi.org/10. 1016/j.molstruc.2023.135266

Zhang, H., Qi, Y., Zhang, Z., & Yang, Q. (2021). Effect of N-(2-aminoethyl)-3-aminopropyltrimethoxysilane on the adhesion of the modified silicone tie-coating to epoxy primer. *Coatings*, *11*(1), 71-83.

Zhang, J., & Li, H. (2020). 2-(2-chlorophenyl)-1H-benzimidazole as a new corrosion inhibitor for copper in sulfuric acid. *International Journal of Electrochemical Science*, *15*(6), 5362-5372.

Zhang, J., Fang Z., & Nobli A. (2023). Corrosion inhibition performance of Punica granatum L extract on Q235 steel in H2SO4 environment: Electrochemical, morphological, and quantum chemical studies. *International Journal of Electro chemical Science*, *18*(10), 100267.

Zhang, W., Yuxia Z., Benzhe L., Hanyu G., Xiangyu D., Ke L., & Yuanyuan F. (2023). The high-performance corrosion resistance of chemically-reinforced chitosan as an eco-friendly inhibitor for mild steel. *Bioelectrochemistry, 150*, 108330.

Zhang, P., Lida W., Wen S., Zhengqing Y., Wei G., & Guichang L. (2023). Anti-scale performance degradation of carboxylic acid scale inhibitors under corrosion conditions. *Corrosion Science*, 222, 111423. https://doi.org/10.1016/j.corsci.2023.111423

Zheng, H., Bingru Z., Xinyu W., Yufei L., Fengting L., & Chunjiang L. (2023). Improved corrosion resistance of carbon steel in soft water with dendritic-polymer corrosion inhibitors. *Chemical Engineering Journal, 452*, 139043.

Zinad, D.S., Salim, R.D., Betti, N., Shaker, L.M., & AL-Amiery, A.A. (2021). Comparative investigations of the corrosion inhibition efficiency of a 1-phenyl-2-(1-phenylethylidene) hydrazine and its analogue against mild steel corrosion in hydrochloric acid solution. *Progress in Colour Colorants and Coatings, 15*, 53-63. https://doi.org/10.3390/pccc15010007

Zulkifli, M. F. R., Bahrin, S. N. S., Abdullah, S., Ghazali, M. S. M., & Nik, W. M. N. (2021). *Citrus aurantifolia* leaf extract as a potential anti-corrosion additive in alkyd paint for mild steel. *Journal of Sustainability Science and Management*, *16*(3), 10-20.