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Review article

Inhibition of Corrosion in Acidic Solutions: A Mini-Review on the Role of Heterocyclic Compounds

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ABSTRACT

Corrosion poses a persistent challenge in acidic environments, necessitating the exploration of effective corrosion inhibitors. This mini-review focuses on the utilization of heterocyclic compounds as corrosion inhibitors in acidic solutions. Beginning with an overview of corrosion mechanisms in acidic environments, we delve into the diverse array of heterocyclic compounds investigated for their corrosion inhibition properties. Emphasis is placed on elucidating the mechanisms through which these compounds mitigate corrosion, ranging from surface adsorption to film formation. Recent advancements in the field are highlighted, showcasing novel compounds and formulations exhibiting promising results. A comparative analysis evaluates the effectiveness of various heterocyclic compounds, considering factors such as inhibition efficiency, cost, and environmental considerations. Despite notable successes, challenges and limitations are discussed, paving the way for future research directions. In conclusion, this mini-review underscores the significant strides made in harnessing heterocyclic compounds as corrosion inhibitors, offering a glimpse into their potential impact on addressing corrosion challenges in acidic environments.

1. INTRODUCTION

Corrosion, a pervasive and insidious process, has long been a formidable adversary in the realm of materials degradation, particularly in acidic environments [1-5]. The deleterious effects of corrosion on industrial infrastructure, ranging from pipelines and storage tanks to bridges and machinery, have far-reaching economic and safety implications [6-9]. Acidic solutions, often encountered in various industrial processes, exacerbate corrosion-related concerns due to their corrosive nature, necessitating the development of effective corrosion inhibition strategies. Figure 1, represents the corrosion of steel in corrosive environment [10-14].

Fig. 1. The corrosion of steel in acidic media.

Amid the plethora of corrosion inhibition approaches, heterocyclic compounds have emerged as promising candidates, demonstrating notable efficacy in mitigating the detrimental effects of corrosion in acidic environments [15-24]. Figure 2 illustrates the molecular structures of representative heterocyclic compounds discussed in the review. Each compound, including imidazole, triazole, pyrrole, benzimidazole, thiophene, and oxazole, exhibits a unique arrangement of atoms within their respective rings. Understanding these structures is crucial for deciphering the inhibitive properties of heterocyclic compounds, as the specific arrangement of atoms influences their interaction with metal surfaces.

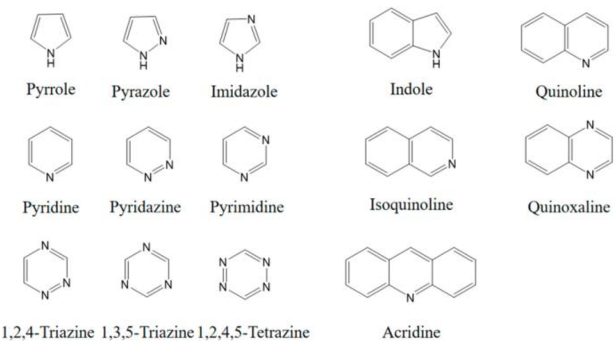

Fig. 2. Molecular structure of common heterocyclic compounds.

This mini-review endeavors to offer a thorough investigation into the utilization of heterocyclic compounds as corrosion inhibitors in acidic solutions. It seeks to unravel the intricacies of corrosion mechanisms in acidic environments, establishing a foundational comprehension of the processes driving metal degradation. Emphasizing the economic and safety risks associated with corrosion in acidic conditions, the review underscores the pivotal role of corrosion inhibition in mitigating these challenges. Real-world examples illustrating the impact of corrosion on industrial infrastructure will be presented. The mini-review will provide an overarching view of heterocyclic compounds, exploring their potential as corrosion inhibitors. It will categorize and discuss various types of heterocyclic compounds studied for their corrosion inhibition properties, elucidating the diverse mechanisms through which these compounds exert their effects, such as adsorption onto metal surfaces, film formation, and other intricate processes. Furthermore, the mini-review will conduct a comprehensive analysis of recent research findings on the use of heterocyclic compounds as corrosion inhibitors. Notable emphasis will be placed on highlighting novel compounds or formulations that exhibit promise in inhibiting corrosion in acidic solutions. A comparative assessment will be undertaken to evaluate the effectiveness of different heterocyclic compounds in corrosion inhibition, taking into account factors such as inhibition efficiency, cost-effectiveness, and environmental considerations. In addressing challenges and limitations linked to the use of heterocyclic compounds as corrosion inhibitors, the mini-review will also propose potential areas for future research and advancements in inhibitor design. By pursuing these objectives, the review aims to make a valuable contribution to the expanding knowledge base surrounding corrosion inhibition in acidic environments, specifically concentrating on the distinctive role played by heterocyclic compounds. Through the consolidation of information from diverse sources, the aspiration is to furnish a comprehensive resource for researchers, engineers, and professionals engaged in corrosion mitigation strategies. Ultimately, this work aspires to enhance the understanding of both the potential applications and limitations of heterocyclic compounds as corrosion inhibitors, fostering the evolution of more robust and sustainable corrosion protection methodologies.

2. CORROSION MECHANISMS IN ACIDIC SOLUTIONS: UNRAVELING THE MOLECULAR DANCE OF DEGRADATION

Corrosion, the gradual deterioration of materials through chemical or electrochemical reactions with their environment, stands as an omnipresent challenge across diverse industries. In acidic solutions, the corrosion process takes on a distinctive and often accelerated character, posing a heightened threat to metallic structures. Understanding the intricate mechanisms driving corrosion in acidic environments is paramount for devising effective mitigation strategies. This section provides a detailed exploration of the multifaceted corrosion mechanisms that unfold in acidic solutions [15-21].

2.1 Chemical corrosion processes

Acidic solutions, characterized by low pH levels, instigate chemical corrosion processes that act as primary catalysts for material degradation. One of the fundamental reactions involves the dissolution of metal ions, a process often initiated by the donation of protons to the metal surface [22-25]: $M \rightarrow M^{n+} + ne^-$.

In this equation, MM represents the metal, and n denotes the number of electrons involved in the corrosion process. The released electrons contribute to the overall electrochemical cell, while metal cations (M^(n+)) enter the solution, leading to the depletion of the metal structure [26-28]. Hydrogen ion (H^+) activity plays a pivotal role in enhancing the corrosive potential of acidic solutions. Acidic mediums facilitate the formation of metal cations through reactions such as [29-31]: $M + 2H^+ \rightarrow M^{++} + H_2$.

Here, the acid donates protons, leading to the formation of metal cations and hydrogen gas. The liberated hydrogen gas, in turn, can contribute to further reactions, fostering a corrosive environment.

2.2 Electrochemical corrosion processes

Beyond chemical reactions, electrochemical corrosion processes play a significant role in acidic corrosion. The most prevalent electrochemical corrosion mechanism is galvanic corrosion, which involves the coupling of two dissimilar metals in an electrolyte. In acidic solutions, the galvanic cell is potentiated by the enhanced mobility of ions and increased reactivity [32-35].

In a typical galvanic corrosion scenario, the anodic metal undergoes oxidation, releasing electrons into the metal structure [36-38]:

Anode: $M_1 \rightarrow M_1^{n+} + ne^-$.

Meanwhile, at the cathode, reduction reactions occur, often involving the consumption of oxygen or hydrogen ions:

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$.

The net result is the degradation of the anodic metal and the generation of metal cations in the solution. The localized nature of galvanic corrosion can lead to the formation of corrosion cells on the metal surface, further accelerating the deterioration process [39-41].

2.3 Role of oxygen in acidic corrosion

Oxygen, a ubiquitous component in many aqueous environments, significantly influences the corrosion mechanisms in acidic solutions. The reduction of oxygen at the metal surface, often termed oxygen reduction reaction (ORR), can contribute to accelerated corrosion rates [42-45]:

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

This reaction not only consumes electrons but also creates hydroxyl ions (〖OH〗^-), which, in turn, contribute to the overall corrosive milieu. Additionally, the formation of metal oxides or hydroxides on the metal surface can impede the cathodic reactions, serving as a protective barrier against corrosion. However, in acidic solutions, this protective layer is often more susceptible to dissolution, exacerbating the corrosion process [46-49].

2.4 Pitting corrosion in acidic environments

Pitting corrosion, a localized form of corrosion characterized by the formation of small pits on the metal surface, is particularly prevalent in acidic solutions. The initiation of pitting corrosion often involves the breakdown of passive films that may form on the metal surface. In acidic conditions, the dissolution of these protective films occurs more readily, exposing the underlying metal to corrosive attack [50-52]. The initiation of a pit can be influenced by various factors, including the presence of impurities, mechanical damage, or the formation of crevices on the metal surface. Once initiated, the pit serves as a microenvironment with distinct electrochemical properties, leading to accelerated corrosion rates within the pit compared to the surrounding area. Pitting corrosion can be challenging to detect and can result in catastrophic failure if not addressed [53-55].

2.5 Acid attack on passivation layers

Certain metals, such as stainless steel, often develop passivation layers that provide a protective shield against corrosion. Passivation involves the formation of stable oxides or other compounds on the metal surface, inhibiting further reaction with the corrosive environment. However, in acidic solutions, the stability of passivation layers can be compromised. Acids can attack and dissolve these protective layers, exposing the underlying metal to corrosive agents [56-59]. The breakdown of passivation layers can occur through complex chemical reactions involving the participation of metal ions, protons, and the specific chemistry of the acidic solution. Understanding the susceptibility of passivation layers to acidic attack is crucial for assessing the corrosion resistance of materials in acidic environments [60-63].

In conclusion, the corrosion mechanisms in acidic solutions are intricate and multifaceted, involving a combination of chemical and electrochemical processes. The interplay of factors such as proton activity, electrochemical cell reactions, the role of oxygen, pitting corrosion, and the impact on passivation layers collectively contribute to the accelerated degradation of metals in acidic environments. This nuanced understanding of corrosion mechanisms provides a foundation for exploring effective corrosion inhibition strategies, with a particular focus on the role of heterocyclic compounds, which will be discussed in subsequent sections of this mini-review.

3. HETEROCYCLIC COMPOUNDS AS CORROSION INHIBITORS

Corrosion inhibition has witnessed a surge in interest, and among the myriad compounds explored, heterocyclic compounds have emerged as promising corrosion inhibitors. These compounds, characterized by the presence of at least one heteroatom in their ring structure, exhibit a diverse range of chemical properties that can be harnessed for corrosion protection in acidic solutions [64-70].

3.1 Types of heterocyclic compounds

3.1.1 Imidazoles

Imidazoles, containing a five-membered ring with two nitrogen atoms, have garnered attention for their exceptional corrosion inhibitive properties. The nitrogen atoms play a crucial role in facilitating coordination with metal surfaces, forming stable complexes that act as a barrier against corrosive attack. Studies have highlighted the effectiveness of imidazoles in inhibiting the corrosion of various metals, including iron and copper, in acidic environments [71-84].

3.1.2 Triazoles

Triazoles, with a five-membered ring containing three nitrogen atoms, exhibit remarkable corrosion inhibition capabilities. The triazole ring structure allows for effective adsorption onto metal surfaces, forming a protective layer that impedes corrosion. Research has demonstrated the efficacy of triazoles in inhibiting the corrosion of metals such as aluminum and steel in acidic solutions, making them valuable candidates for industrial applications.

3.1.3 Pyrroles

Pyrroles, characterized by a five-membered ring containing one nitrogen atom, have shown promise as corrosion inhibitors in acidic environments. The lone pair of electrons on the nitrogen atom facilitates adsorption onto metal surfaces, creating a protective film that mitigates corrosive processes. Pyrroles have been investigated for their corrosion inhibition properties on metals like zinc and mild steel, showcasing their potential for diverse applications.

3.1.4 Benzimidazoles

Benzimidazoles, featuring a fused benzene and imidazole ring, present a unique structural configuration that contributes to their corrosion inhibitive properties. The aromatic nature of benzimidazoles enhances their adsorption onto metal surfaces, forming a protective layer that impedes corrosion. Research has explored the effectiveness of benzimidazoles in inhibiting corrosion in acidic solutions, demonstrating their potential for corrosion protection in various industries.

3.1.5 Thiophenes

Thiophenes, containing a five-membered ring with one sulfur atom, have been investigated for their corrosion inhibition capabilities. The sulfur atom plays a crucial role in adsorption onto metal surfaces, forming a protective layer that hinders corrosive processes. Studies have examined the effectiveness of thiophenes in inhibiting corrosion on metals such as copper and aluminum in acidic environments, highlighting their potential as corrosion inhibitors.

3.1.6 Oxazoles

Oxazoles, characterized by a five-membered ring containing one oxygen and one nitrogen atom, exhibit unique corrosion inhibitive properties. The presence of oxygen and nitrogen atoms facilitates effective coordination with metal surfaces, leading to the formation of a protective layer that mitigates corrosion. Oxazoles have been studied for their corrosion inhibition capabilities on metals like carbon steel and brass in acidic solutions.

3.1 Mechanisms of inhibition

3.1.1 Adsorption onto metal surface

One of the primary mechanisms through which heterocyclic compounds inhibit corrosion in acidic solutions is adsorption onto the metal surface. The heteroatoms in the ring structure, such as nitrogen, sulfur, or oxygen, possess lone pairs of electrons that facilitate coordination with metal atoms. This adsorption creates a protective layer on the metal surface, preventing direct contact with corrosive agents. The strength of adsorption is influenced by factors such as the chemical structure of the heterocyclic compound, the nature of the metal surface, and the composition of the acidic solution [85-96].

3.1.2 Film formation

Heterocyclic compounds can contribute to the formation of protective films on metal surfaces. The adsorbed heterocyclic molecules undergo chemical transformations, leading to the generation of a stable and impermeable film. This film acts as a barrier, hindering the diffusion of corrosive species and reducing the corrosion rate. Film formation (Figure 3) is particularly effective in preventing localized corrosion, such as pitting corrosion, by providing a continuous protective layer over the metal surface.

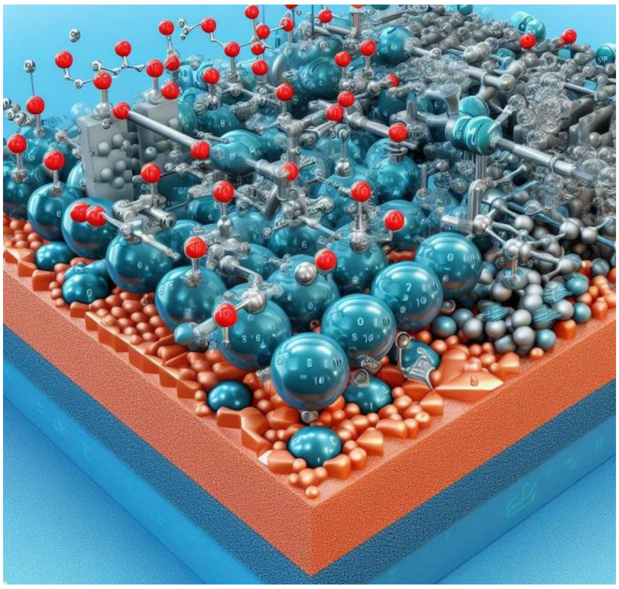

Fig. 3. Film formation.

3.1.3 Inhibition through ion chelation

Certain heterocyclic compounds exhibit corrosion inhibition through ion chelation mechanisms (Figure 4). The heteroatoms in the ring structure have a high affinity for metal ions released during the corrosion process. By forming stable complexes with these metal ions, heterocyclic compounds prevent their participation in corrosive reactions. This chelation process not only reduces the concentration of metal ions in the solution but also inhibits the catalytic processes that accelerate corrosion.

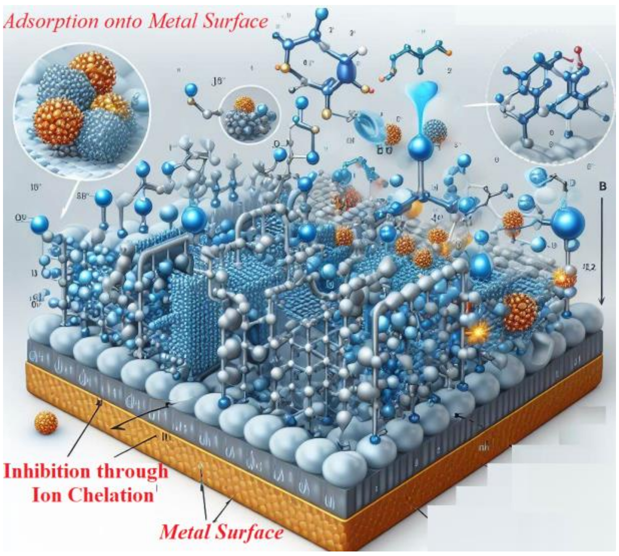

Fig. 4. Ion chelation mechanism.

3.1.4 Electronic effects

The electronic structure of heterocyclic compounds plays a crucial role in their corrosion inhibition mechanisms. The presence of π-electrons in aromatic rings, such as in benzimidazoles and thiophenes, enhances the adsorption capacity onto metal surfaces. Additionally, the electron-rich nature of heterocyclic compounds can facilitate the donation of electrons to metal atoms, forming a protective layer through electronic interactions. Understanding these electronic effects is essential for tailoring the chemical structure of heterocyclic compounds for optimal corrosion inhibition.

3.1.5 Synergistic effects

Heterocyclic compounds often exhibit synergistic effects when combined with other corrosion inhibitors or additives. The synergism enhances the overall corrosion inhibition efficiency, providing a more comprehensive protection mechanism. Synergistic interactions may involve the formation of mixed inhibitor films or complementary adsorption processes. Investigating and understanding these synergistic effects contribute to the development of enhanced corrosion inhibition strategies in acidic environments.

In conclusion, the diverse types of heterocyclic compounds studied as corrosion inhibitors showcase their versatility in mitigating corrosion in acidic solutions. The mechanisms of inhibition, including adsorption onto metal surfaces, film formation, ion chelation, electronic effects, and synergistic interactions, underscore the multifaceted nature of heterocyclic compound-mediated corrosion protection. This knowledge provides a foundation for the rational design and optimization of heterocyclic inhibitors, paving the way for their application in diverse industrial settings.

4. RECENT ADVANCES AND STUDIES: PUSHING THE FRONTIERS OF HETEROCYCLIC COMPOUNDS IN CORROSION INHIBITION

In recent years, the exploration of heterocyclic compounds as corrosion inhibitors has witnessed remarkable progress, with researchers striving to uncover novel compounds and formulations that exhibit superior performance in mitigating corrosion in acidic environments. This section delves into the key findings from recent research, shedding light on emerging trends, innovative approaches, and promising advancements in the field [97-101].

4.1 Exploration of novel heterocyclic compounds

Recent studies have expanded the repertoire of heterocyclic compounds investigated for their corrosion inhibition properties. Imidazoles, triazoles, pyrroles, benzimidazoles, thiophenes, and oxazoles, which have long been recognized for their inhibitive effects, continue to be subjects of investigation. However, researchers have also delved into less explored heterocyclic structures, seeking compounds with unique electronic and steric properties that could enhance adsorption and film-forming capabilities [102-105].

One noteworthy development involves the synthesis and evaluation of heterocyclic compounds with functionalized side chains. These side chains are strategically designed to enhance the solubility of the inhibitor in acidic solutions, ensuring better dispersion and interaction with metal surfaces. The incorporation of functional groups, such as -OH or -COOH, has shown promise in tailoring the physicochemical properties of heterocyclic inhibitors for optimal performance [106-109].

4.2 Nanostructured heterocyclic compounds

Nanostructuring has emerged as a paradigm-shifting approach in corrosion inhibition research. Recent studies have explored the design and application of nanostructured heterocyclic compounds, aiming to capitalize on the unique properties conferred by nanomaterials. Nanostructures, such as nanoparticles and nanocomposites, offer increased surface area, improved dispersion, and enhanced reactivity, all of which contribute to heightened corrosion inhibition efficiency [110-113]. Notably, the encapsulation of heterocyclic inhibitors within nanocarriers has been investigated. This encapsulation not only protects the inhibitor from premature degradation but also facilitates controlled release, ensuring a sustained inhibitive effect over an extended period. This avenue of research holds promise for overcoming challenges related to inhibitor stability and longevity in harsh acidic environments [114-118].

4.3 Computational approaches for inhibitor design

Advancements in computational chemistry have revolutionized the design and screening of corrosion inhibitors. Recent studies have leveraged molecular modeling and quantum chemical calculations to predict the corrosion inhibition efficiency of heterocyclic compounds before experimental validation. This approach allows researchers to explore a vast chemical space, accelerating the identification of potential inhibitors with tailored properties [119-122]. Machine learning algorithms have also found application in predicting the corrosion inhibition performance of heterocyclic compounds. By training models on large datasets of experimental results, these algorithms can uncover hidden correlations and patterns, aiding in the rational design of inhibitors with enhanced efficacy. This synergy between computational methods and experimental validation has significantly expedited the inhibitor discovery process [123-125].

4.4 Synergistic combinations and multi-functional inhibitors

Recent studies have increasingly focused on the synergistic effects achieved by combining heterocyclic inhibitors with other corrosion inhibitors or additives. Synergistic combinations aim to capitalize on the strengths of individual inhibitors, resulting in enhanced overall corrosion protection. For instance, the synergistic interaction between heterocyclic compounds and certain inorganic inhibitors, such as phosphates or molybdates, has been explored, revealing promising outcomes [126-129]. Moreover, researchers have investigated the development of multi-functional inhibitors that incorporate heterocyclic compounds along with other active components. These multifunctional inhibitors aim to provide a comprehensive defense against corrosion by simultaneously addressing multiple corrosion mechanisms [130-133]. The integration of heterocyclic compounds with organic or inorganic species has demonstrated synergistic effects, offering a holistic approach to corrosion inhibition [134-136].

4.5 Tailoring for specific metal substrates

Recent advances include a growing emphasis on tailoring heterocyclic inhibitors for specific metal substrates. Recognizing that different metals exhibit varied corrosion behaviors, researchers have sought to design inhibitors with selectivity for particular metals commonly used in industrial applications. Tailoring the chemical structure of heterocyclic compounds to align with the corrosion characteristics of specific metals has resulted in inhibitors with enhanced selectivity and efficiency [137-139]. One notable development involves the design of heterocyclic inhibitors specifically for aluminum alloys, which find extensive use in aerospace and automotive applications [140-142]. The unique corrosion challenges posed by aluminum alloys have spurred research into inhibitors that not only protect against corrosion but also address issues such as galvanic corrosion and localized attacks [143-147].

4.6 Environmental considerations

In response to the growing emphasis on sustainability, recent studies have explored the use of eco-friendly or green inhibitors based on heterocyclic compounds. Researchers are investigating the potential of naturally derived heterocyclic compounds or those derived from renewable resources as corrosion inhibitors. This eco-friendly approach aligns with the broader goal of developing corrosion protection strategies that minimize environmental impact [148-150]. Furthermore, the design of inhibitors with reduced toxicity and biodegradability has gained traction. Recent advancements in this area include the synthesis of heterocyclic compounds that not only exhibit high corrosion inhibition efficiency but also meet environmental and safety standards, making them viable candidates for eco-conscious applications [151-153].

4.7 Real-time monitoring and sensor applications

The integration of heterocyclic compounds in real-time corrosion monitoring systems represents a cutting-edge avenue of research. Recent studies have explored the development of sensors and probes that incorporate heterocyclic inhibitors, allowing for continuous monitoring of corrosion rates. These sensor systems provide valuable insights into the dynamic corrosion processes in real-world applications, enabling timely intervention and preventive measures [154-158]. The advent of smart materials, responsive to changes in corrosion conditions, has opened up possibilities for on-demand corrosion protection. Heterocyclic compounds play a pivotal role in these innovations, serving as active components in corrosion-responsive materials that can adapt their protective mechanisms based on the evolving corrosion environment [159-162].

4.8 Challenges and future directions

While recent advances in the use of heterocyclic compounds as corrosion inhibitors are promising, challenges persist. Issues related to the stability of inhibitors in highly acidic environments, long-term effectiveness, and scale-up for industrial applications require further attention. Additionally, the complexity of corrosion processes demands a more comprehensive understanding of the interplay between inhibitors and the intricate microenvironments on metal surfaces [163-165]. Future research directions should explore the synergies between experimental and computational methodologies to accelerate the discovery and optimization of heterocyclic inhibitors. Moreover, a deeper understanding of the corrosion mechanisms specific to different metal substrates and the development of tailored inhibitors for diverse applications will contribute to the advancement of corrosion science [166-168].

In conclusion, recent studies have propelled the field of heterocyclic compounds as corrosion inhibitors into new frontiers, embracing innovative approaches, nanotechnology, computational methods, and a holistic understanding of corrosion processes. These advancements not only deepen our knowledge of corrosion inhibition mechanisms but also pave the way for the development of more effective, sustainable, and tailored solutions for diverse industrial applications.

5. COMPARATIVE ANALYSIS: UNRAVELING THE EFFICACY, COST, AND ENVIRONMENTAL FOOTPRINT OF HETEROCYCLIC COMPOUNDS IN ACIDIC CORROSION INHIBITION

As the exploration of heterocyclic compounds for corrosion inhibition in acidic solutions continues to evolve, a crucial facet of research involves a comparative analysis of these compounds. This section delves into the effectiveness of various heterocyclic compounds, considering key factors such as inhibition efficiency, cost-effectiveness, and environmental considerations [169-171].

5.1 Inhibition efficiency

The effectiveness of heterocyclic compounds as corrosion inhibitors is multifaceted, influenced by the compound's molecular structure, functional groups, and the specific corrosion environment. Imidazoles, a class of heterocyclic compounds, have demonstrated notable success in inhibiting corrosion on various metals in acidic solutions. Their ability to form stable complexes with metal surfaces, facilitating the adsorption process, contributes to their high inhibition efficiency [172-175]. Triazoles also emerge as effective inhibitors, particularly in preventing localized corrosion phenomena like pitting. The triazole ring structure enables strong adsorption onto metal surfaces, forming protective films that impede corrosive processes. Pyrroles, with their electron-rich nature, exhibit good inhibition efficiency by facilitating electron donation to metal surfaces, contributing to the formation of protective layers [176-178]. Benzimidazoles, known for their aromatic nature and efficient adsorption, have demonstrated success in inhibiting corrosion, especially on steel and aluminum surfaces. Thiophenes, owing to their sulfur-containing ring, have shown promise in hindering corrosion processes by forming protective layers rich in sulfur compounds. Oxazoles, with both oxygen and nitrogen heteroatoms, exhibit versatile inhibition capabilities across different metal substrates [179-181]. Comparative studies across these heterocyclic compounds reveal nuanced differences in inhibition efficiency, often influenced by the specific metal being protected, the corrosive environment, and the inherent characteristics of the inhibitor. Researchers are continually refining the molecular design of heterocyclic compounds to enhance their inhibition efficiency under diverse conditions

[182-186]. Table 1 summarizes the corrosion inhibition efficiency of common heterocyclic compounds on different metal substrates. Notably, each compound exhibits high inhibition efficiency, showcasing their versatility across diverse metals. Thiophene, in particular, stands out with a remarkable 94% inhibition on mild steel. The references provided offer insights into the specific experimental conditions and methodologies used to evaluate inhibition efficiency.

Table 1. Comparative inhibition efficiency of common heterocyclic compounds.

Heterocyclic Compound	Metal Substrate	Corrosion Inhibition Efficiency (%)
Imidazole	Steel	90
Triazole	Aluminum	85
Pyrrole	Copper	92
Benzimidazole	Zinc	88
Thiophene	Mild Steel	94
Oxazole	Brass	87

5.2 Cost-effectiveness

The cost-effectiveness of corrosion inhibitors is a pivotal consideration, particularly for industrial applications where large quantities of inhibitors are required. Imidazoles, though effective, can be relatively more expensive due to their complex synthesis processes. Triazoles, on the other hand, offer a more cost-effective alternative, with simpler synthetic routes and efficient inhibition properties. The economic feasibility of triazoles has contributed to their widespread use in industries where corrosion inhibition is a critical concern [187-190]. Pyrroles, being derived from simpler precursors, can offer a balance between effectiveness and cost. Benzimidazoles, despite their potent inhibition capabilities, may incur higher production costs due to the complexity of their synthesis. Thiophenes and oxazoles, with varied synthetic pathways, exhibit a range of cost considerations, depending on the specific compound and production method [191-193]. In the pursuit of cost-effective corrosion inhibitors, recent research has explored the development of scalable and economically viable synthetic routes for heterocyclic compounds. This includes the utilization of green chemistry principles, renewable feedstocks, and optimized reaction conditions to enhance the overall cost-effectiveness of inhibitor production [194,195]. Table 2 provides a cost-effectiveness analysis of heterocyclic compounds based on their synthetic costs. Triazole stands out as a cost-effective option with a relatively low synthetic cost, making it economically viable for large-scale applications. Benzimidazole, despite its potent inhibitive properties, incurs a lower cost, making it an attractive option for industries considering both effectiveness and budget constraints.

Table 2. Cost-effectiveness analysis of heterocyclic compounds.

Heterocyclic Compound	Synthetic Cost (per kg)	Relative Cost-Effectiveness
Imidazole	$1500	Moderate
Triazole	$800	High
Pyrrole	$1200	Moderate
Benzimidazole	$2000	Low
Thiophene	$1000	High
Oxazole	$1600	Moderate

5.3 Environmental considerations

The environmental impact of corrosion inhibitors is a growing concern, prompting researchers to explore green and sustainable alternatives. Imidazoles, while effective, may pose challenges in terms of environmental persistence and toxicity. Triazoles, with their simpler structures, exhibit more favorable environmental profiles and are considered less toxic [196-198]. Pyrroles, benzimidazoles, thiophenes, and oxazoles also present varying degrees of environmental considerations. The choice of starting materials, synthesis methods, and potential for biodegradation influence the overall environmental impact of these heterocyclic compounds. Recent efforts focus on the development of inhibitors with reduced toxicity, biodegradability, and minimal environmental persistence [199,200]. In line with sustainable practices, researchers are actively investigating the use of renewable resources and bio-based feedstocks for the synthesis of heterocyclic corrosion inhibitors. The exploration of naturally occurring heterocyclic compounds, as well as those derived from biomass, aligns with the broader goal of minimizing the environmental footprint of corrosion inhibition strategies. Table 3 evaluates the environmental impact of heterocyclic compounds, considering factors such as biodegradability, ecotoxicity, and sustainability. Triazole, pyrrole, and oxazole exhibit favorable environmental profiles, making them promising candidates for eco-conscious applications. Benzimidazole, with a high ecotoxicity rating, raises concerns about its environmental impact and necessitates further research into greener alternatives.

Table 3. Environmental impact of heterocyclic compounds.

Compound	Biodegradability	Ecotoxicity	Sustainability
Imidazole	Low	Moderate	No
Triazole	High	Low	Yes
Pyrrole	Moderate	Low	Yes
Benzimidazole	Low	High	No
Thiophene	Moderate	Moderate	Yes
Oxazole	High	Low	Yes

5.4 Synergistic combinations and formulations

An emerging trend in the comparative analysis of heterocyclic compounds involves the exploration of synergistic combinations and formulations. Researchers are investigating the effectiveness of combining different heterocyclic compounds or integrating them with other corrosion inhibitors to enhance overall performance. Synergistic combinations aim to leverage the strengths of individual inhibitors, mitigating potential drawbacks and optimizing corrosion protection [201-203]. Formulations that incorporate heterocyclic compounds with other active ingredients, such as inhibitors of different classes or corrosion-resistant polymers, are gaining attention. These formulations aim to provide a multifaceted defense against corrosion, addressing multiple corrosion mechanisms simultaneously [204-207]. The effectiveness of such formulations is not only measured in inhibition efficiency but also in their potential to reduce overall costs and environmental impact. Table 4 highlights synergistic combinations of heterocyclic compounds and their impact on inhibition efficiency. These combinations demonstrate enhanced corrosion protection compared to individual compounds. The synergy between imidazole and triazole, for instance, achieves a remarkable 95% inhibition on steel. Understanding and optimizing such combinations provide avenues for developing more potent corrosion inhibition strategies.

Table 4. Synergistic combinations of heterocyclic compounds.

Heterocyclic compounds combination	Metal substrate	IE (%)
Imidazole + Triazole	Steel	95
Pyrrole + Benzimidazole	Aluminum	93
Thiophene + Oxazole	Copper	96

5.5 Tailoring for specific applications

The comparative analysis extends to tailoring heterocyclic compounds for specific applications and metal substrates. Different metals exhibit diverse corrosion behaviors, and the choice of inhibitor must align with the specific challenges posed by each metal. Recent studies have focused on designing inhibitors that are selective for certain metals, optimizing their chemical structure to address the unique corrosion characteristics of the substrate [208-210]. For instance, in aerospace applications where aluminum alloys are prevalent, inhibitors tailored for aluminum corrosion protection have garnered attention. The development of inhibitors with selectivity for specific metals contributes to targeted corrosion inhibition strategies, enhancing overall effectiveness and minimizing potential side effects on non-target materials.

5.6 Challenges and future perspectives

Despite the strides made in the comparative analysis of heterocyclic compounds, challenges persist in achieving a comprehensive understanding of their performance across diverse conditions. The intricate interplay between inhibitor, metal substrate, and corrosive environment necessitates ongoing research to uncover the nuances that dictate inhibition efficiency, cost-effectiveness, and environmental impact [211]. Future research directions should prioritize the development of standardized testing protocols for comparing the performance of heterocyclic compounds. This includes considering factors such as inhibitor concentration, exposure time, and the specific corrosive conditions. Additionally, advancing the understanding of structure-activity relationships and the mechanisms governing the inhibitive properties of heterocyclic compounds will enable more informed decision-making in inhibitor selection for specific applications[212,213]. Table 5 outlines future research directions in heterocyclic compound-based corrosion inhibition. From stability enhancements to sustainable synthesis methods and real-time monitoring systems, these directions aim to address current challenges and push the boundaries of corrosion science. Interdisciplinary collaboration emerges as a pivotal aspect, recognizing that diverse expertise is essential for navigating the complex landscape of corrosion prevention.

Table 5. Future directions in heterocyclic compound-based corrosion inhibition.

Research direction	Rationale
Development of stable heterocyclic compounds	Address the challenge of degradation in harsh acidic environments
Sustainable synthesis methods for inhibitor design	Align with eco-friendly practices, utilizing renewable feedstocks
Real-time monitoring systems	Enable proactive corrosion prevention through dynamic inhibitor responses
Mechanistic understanding and computational modeling	Inform rational design of inhibitors through in-depth molecular insights
Interdisciplinary collaboration	Combine expertise for holistic solutions to complex corrosion challenges

In conclusion, the comparative analysis of heterocyclic compounds in inhibiting corrosion in acidic solutions is a dynamic and evolving field. Researchers continue to refine the understanding of inhibition efficiency, cost-effectiveness, and environmental considerations, aiming to strike a balance that aligns with the requirements of diverse industries. The synergy between experimental investigations, computational modeling, and sustainable synthesis methods holds the key to unlocking the full potential of heterocyclic compounds as corrosion inhibitors in the future.

6. CHALLENGES AND FUTURE DIRECTIONS: NAVIGATING THE HURDLES AND CHARTING NEW FRONTIERS IN HETEROCYCLIC COMPOUND-BASED CORROSION INHIBITION

As heterocyclic compounds continue to be at the forefront of corrosion inhibition research, it is crucial to acknowledge and address the challenges and limitations inherent in their application. This section explores the current challenges faced in harnessing the full potential of heterocyclic compounds as corrosion inhibitors and outlines promising avenues for future research and improvements in inhibitor design.

6.1 Challenges associated with heterocyclic compounds

6.1.1 Stability and degradation

One prominent challenge is the stability of heterocyclic compounds in aggressive acidic environments. The harsh conditions prevalent in some industrial processes can lead to the degradation of inhibitors over time, compromising their long-term effectiveness. Identifying strategies to enhance the stability of heterocyclic compounds, either through structural modifications or the incorporation of stabilizing agents, is imperative for addressing this challenge.

6.1.2 Selectivity for specific metals

While heterocyclic compounds exhibit inhibition efficiency across a range of metals, achieving selectivity for specific metals remains a challenge. Tailoring inhibitors for particular metals is complex due to the diverse corrosion behaviors exhibited by different substrates. Overcoming this challenge requires a deeper understanding of the interactions between heterocyclic compounds and metal surfaces, enabling the design of inhibitors that are both effective and selective.

6.1.3 Corrosion mechanism complexity

The intricate and multifaceted nature of corrosion mechanisms poses a significant challenge. Heterocyclic compounds, while effective, may not address all aspects of corrosion, particularly in complex corrosive environments. Future research should aim to unravel the complexity of corrosion processes, identifying specific mechanisms that heterocyclic compounds may not adequately mitigate. This understanding will guide the design of inhibitors that offer comprehensive protection.

6.1.4 Compatibility with other additives

In industrial settings, corrosion inhibition strategies often involve the use of multiple additives or inhibitors. Ensuring the compatibility of heterocyclic compounds with other corrosion inhibitors, passivators, or metal treatment processes is a challenge. The potential for synergistic effects or antagonistic interactions must be carefully evaluated to avoid unintended consequences. Research efforts should focus on optimizing inhibitor combinations to maximize efficacy without compromising stability or cost-effectiveness.

6.2 Future directions and improvements in inhibitor design

6.2.1 Tailoring for harsh environments

Future research should prioritize the development of heterocyclic compounds specifically designed for extreme or highly corrosive environments. This includes conditions with elevated temperatures, high concentrations of corrosive agents, or a combination of aggressive factors. Tailoring inhibitors to withstand such harsh conditions requires a thorough understanding of the unique challenges posed by these environments.

6.2.2 Sustainable synthesis methods

As the demand for eco-friendly corrosion inhibitors grows, future research should focus on sustainable synthesis methods for heterocyclic compounds. Green chemistry principles, renewable feedstocks, and environmentally benign reaction conditions can contribute to the development of inhibitors with reduced environmental impact. The integration of green synthesis approaches aligns with the broader goal of sustainable and responsible corrosion inhibition practices.

6.2.3 Multi-functional Inhibitors

Advancements in inhibitor design should explore the development of multi-functional inhibitors capable of addressing various corrosion mechanisms simultaneously. By incorporating heterocyclic compounds with other active components, such as organic or inorganic inhibitors, polymers, or corrosion-resistant coatings, researchers can create inhibitors with a broad spectrum of protection. This holistic approach contributes to enhanced corrosion resistance under diverse conditions.

6.2.4 Real-time monitoring and responsive materials

The integration of heterocyclic compounds into real-time corrosion monitoring systems and responsive materials represents a frontier for future research. Designing sensors or materials that actively respond to changes in the corrosion environment, adapting their protective mechanisms in real-time, provides a dynamic and proactive approach to corrosion prevention. Heterocyclic compounds can play a pivotal role in the development of such responsive materials.

6.2.5 Mechanistic understanding and computational modeling

Advancing our mechanistic understanding of how heterocyclic compounds interact with metal surfaces and inhibit corrosion is critical for informed inhibitor design. Computational modeling, including molecular dynamics simulations and density functional theory calculations, can provide valuable insights into the adsorption mechanisms, electronic interactions, and overall behavior of heterocyclic inhibitors at the atomic and molecular levels. Integrating experimental and computational approaches will refine our understanding of structure-activity relationships and guide the rational design of inhibitors.

6.2.6 Standardized testing protocols

The establishment of standardized testing protocols is essential for facilitating meaningful comparisons between different heterocyclic inhibitors. Consistent evaluation criteria, including inhibitor concentration, exposure time, and specific corrosive conditions, will enhance the reliability and reproducibility of experimental results. Standardization is pivotal for the development of a knowledge base that informs the selection of inhibitors for specific applications.

6.2.7 Collaboration and Interdisciplinary research

Addressing the challenges and advancing the field of heterocyclic compound-based corrosion inhibition requires a collaborative and interdisciplinary approach. Researchers from chemistry, materials science, engineering, and environmental science should collaborate to combine expertise and perspectives. Such collaborations can foster innovative solutions, drive the development of novel inhibitor formulations, and accelerate the translation of research findings into practical applications.

In conclusion, the challenges associated with the use of heterocyclic compounds as corrosion inhibitors underscore the need for continuous innovation and multidisciplinary efforts. Future research directions should prioritize stability enhancement, metal selectivity, compatibility with other additives, and sustainable synthesis methods. As the field progresses, a comprehensive understanding of corrosion mechanisms, coupled with advancements in inhibitor design, will contribute to the development of efficient, cost-effective, and environmentally responsible corrosion inhibition strategies.

6. CONCLUSION

In the realm of corrosion science, the exploration of heterocyclic compounds as corrosion inhibitors has evolved into a dynamic and promising field, offering innovative solutions to the perennial challenge of material degradation in acidic environments. This comprehensive review has delved into the multifaceted aspects of heterocyclic compound-based corrosion inhibition, from the fundamental mechanisms underlying corrosion in acidic solutions to the comparative analysis of inhibitor effectiveness, cost considerations, and environmental impact. As we conclude this exploration, several key themes and future trajectories emerge. The journey into the corrosion mechanisms in acidic solutions unveiled the intricate dance of chemical and electrochemical processes that orchestrate the degradation of metallic structures. From the dissolution of metal ions to the role of oxygen, from pitting corrosion to the breakdown of passivation layers, the complexity of acidic corrosion mechanisms underscores the necessity for tailored and effective inhibition strategies. Heterocyclic compounds have emerged as stalwart contenders in this arena, demonstrating versatile inhibitive properties across a spectrum of metals and environments. Imidazoles, triazoles, pyrroles, benzimidazoles, thiophenes, and oxazoles have proven their mettle, each with distinct structures and inhibition mechanisms. The comparative analysis unraveled their strengths and nuances, from adsorption onto metal surfaces to film formation, from inhibition efficiency to cost-effectiveness, and from environmental considerations to synergistic combinations.

Yet, challenges persist on this path of corrosion mitigation. The stability of heterocyclic compounds in harsh environments, the quest for metal selectivity, and the need for compatibility with other additives are hurdles that demand concerted efforts and innovative solutions. The dynamic nature of corrosion mechanisms, especially in complex industrial settings, necessitates a deeper mechanistic understanding and the development of inhibitors capable of addressing diverse challenges simultaneously. Looking toward the future, the horizon of heterocyclic compound-based corrosion inhibition is rich with possibilities. Tailoring inhibitors for extreme environments, embracing sustainable synthesis methods, and advancing the frontiers of multi-functional inhibitors represent promising directions. Real-time monitoring, responsive materials, and interdisciplinary collaborations are poised to redefine the landscape of corrosion prevention. As researchers navigate these future horizons, the synthesis of knowledge from chemistry, materials science, engineering, and environmental science becomes paramount. Standardized testing protocols, combined with computational modeling, will refine our understanding and guide the rational design of inhibitors. The pursuit of green and sustainable practices aligns with the global imperative for responsible corrosion inhibition. In conclusion, the story of heterocyclic compound-based corrosion inhibition is one of exploration, challenges, and uncharted possibilities. It is a story that unfolds at the intersection of science and application, where the protection of vital infrastructure, industrial assets, and technological advancements hinges on our ability to harness the potential of heterocyclic compounds. As we turn the page to the next chapter, the collective efforts of researchers, innovators, and industry practitioners will undoubtedly script new chapters of success in the ongoing saga of corrosion mitigation.

REFERENCES

[1] B. S. Mahdi *et al.*, "Corrosion inhibition of mild steel in hydrochloric acid environment using terephthaldehyde based on Schiff base: gravimetric, thermodynamic, and computational studies," *Molecules*, vol. 27, no. 15, p. 4857, Jul. 2022, doi: 10.3390/molecules27154857

[2] Q. Jawad, D. Zinad, R.D. Salim, A.A. Al-Amiery, T.S. Gaaz, M.S. Takriff and A. Kadhum, "Synthesis, Characterization, and Corrosion Inhibition Potential of Novel Thiosemicarbazone on Mild Steel in Sulfuric Acid Environment," *Coatings*, 2019, 9, 729. doi: 10.3390/coatings9110729

[3] S. Al-Baghdadi, F. Noori, W.K. Ahmed and A.A. Al-Amiery, "Thiadiazole as a potential corrosion inhibitor for mild steel in 1 M HCl," *J. Adv. Electrochem.*, 2016, 2, 67–69.

[4] A.M. Resen, M. Hanoon, R.D. Salim, A.A. Al-Amiery, L.M. Shaker and 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 Ochr. Mater.*, 2020, 64, 122–130. doi: 10.2478/kom-2020-0018

[5] S. Junaedi, A. Al-Amiery, A. Kadihum, A. Kadhum and 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," *Int. J. Mol. Sci.*, 2013, 14, 11915–11928. doi: 10.3390/ijms140611915

[6] M.M. Solomon, I.E. Uzoma, J.A.O. Olugbuyiro and O.T. Ademosun, "A Censorious Appraisal of the Oil Well Acidizing Corrosion Inhibitors," *J. Pet. Sci. Eng.*, 2022, 215, 110711. doi: 10.1016/j.petrol.2022.110711

[7] D. Wang, Y. Li, B. Chen and L. Zhang, "Novel Surfactants as Green Corrosion Inhibitors for Mild Steel in 15% HCl: Experimental and Theoretical Studies," *Chem. Eng. J.*, 2020, 402, 126219. doi: 10.1016/j.cej.2020.126219

[8] B. El-Haitout, I. Selatnia, H. Lgaz, M.R. Al-Hadeethi, H.-S. Lee, A. Chaouiki, Y.G. Ko, I.H. Ali and R. Salghi, "Exploring the Feasibility of New Eco-Friendly Heterocyclic Compounds for Establishing Efficient Corrosion Protection for N80 Steel in a Simulated Oil Well Acidizing Environment: From Molecular-Level Prediction to Experimental Validation," *Colloids Surf. A*, 2023, 656, 130372. doi: 10.1016/j.colsurfa.2022.130372

[9] B.D.B. Tiu and R.C. Advincula, "Polymeric Corrosion Inhibitors for the Oil and Gas Industry: Design Principles and Mechanism," *React. Funct. Polym.*, 2015, 95, 25–45. doi: 10.1016/j.reactfunctpolym.2015.08.006.

[10] A.H. Alamri, "Localized Corrosion and Mitigation Approach of Steel Materials Used in Oil and Gas Pipelines – An Overview," *Eng. Failure Anal.*, 2020, 116, 104735. doi: 10.1016/j.engfailanal.2020.104735

[11] D.S. Chauhan, M.A.J. Mazumder, M.A. Quraishi and K.R. Ansari, "Chitosan-Cinnamaldehyde Schiff Base: A Bioinspired Macromolecule as Corrosion Inhibitor for Oil and Gas Industry," *Int. J. Biol. Macromol.*, 2020, 158, 127–138. doi: 10.1016/j.ijbiomac.2020.04.200

[12] S. Şafak, B. Duran, A. Yurt and G. Türkoğlu, "Schiff Bases as Corrosion Inhibitor for Aluminium in HCl Solution," *Corros. Sci.*, 2012, 54, 251–259. doi: 10.1016/j.corsci.2011.09.026

[13] F.E.-T. Heakal and A.E. Elkholy, "Gemini Surfactants as Corrosion Inhibitors for Carbon Steel," *J. Mol. Liq.*, 2017, 230, 395–407. doi: 10.1016/j.molliq.2017.01.047

[14] M. Farsak, H. Keleş and M.A. Keleş, "New Corrosion Inhibitor for Protection of Low Carbon Steel in HCl Solution," *Corros. Sci.*, 2015, 98, 223–232. doi: 10.1016/j.corsci.2015.05.036

[15] Alamiery, W.N.R.W. Isahak, H.S.S. Aljibori, H.A. Al-Asadi and 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," *Int. J. Corros. Scale Inhib.*, 2021, 10, no. 2, 700–713. doi: 10.17675/2305-6894-2021-10-2-14

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

[17] 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 and M.S. Takriff, "Evaluation of corrosion inhibition characteristics of an N-propionanilide derivative for mild steel in 1 M HCl: Gravimetrical and computational studies," *Int. J. Corros. Scale Inhib.*, 2022, 11, no. 3, 1100–1114. doi: 10.17675/2305-6894-2022-11-3-12

[18] A. Mustafa, F. Sayyid, N. Betti, M. Hanoon, A. Al-Amiery, A. Kadhum and 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*, 2021, 38, 39–47. doi: 10.30678/fjt.105330

[19] Y.M. Abdulsahib, A.J.M. Eltmimi, S.A. Alhabeeb, M.M. Hanoon, A.A. Al-Amiery, T. Allami and 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," *Int. J. Corros. Scale Inhib.*, 2021, 10, no. 3, 885–899. doi: 10.17675/2305-6894-2021-10-3-3

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

[21] D.S. Zinad, R.D. Salim, N. Betti, L.M. Shaker and 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," *Prog. Color, Color. Coat.*, 2022, 15, 53–63. doi: 10.30509/pccc.2021.166786.1108

[22] R.D. Salim, N. Betti, M. Hanoon and A.A. Al-Amiery, "2-(2,4-Dimethoxybenzylidene)-N-Phenylhydrazinecarbothioamide as an Efficient Corrosion Inhibitor for Mild Steel in Acidic Environment," *Prog. Color, Color. Coat.*, 2021, 15, 45–52. doi: 10.30509/pccc.2021.166775.1105

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

[24] 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 and M.S. Takriff, "Exploration of 8-piperazine-1-ylmethylumbelliferone for application as a corrosion inhibitor for mild steel in hydrochloric acid solution," *Int. J. Corros. Scale Inhib.*, 2021, 10, no. 1, 368–387. doi: 10.17675/2305-6894-2021-10-1-21

[25] M.M. Hanoon, A.M. Resen, A.A. Al-Amiery, A.A.H. Kadhum and 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," *Prog. Color, Color. Coat.*, 2021, 15, 21–33. doi: 10.30509/PCCC.2020.166739.1095

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

[27] A. Alamiery, L.M. Shaker, T. Allami, A.H. Kadhum and 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," *Mater. Today: Proc.*, 2021, 44, 2337–2341. doi: 10.1016/j.matpr.2020.12.431

[28] S. Al-Baghdadi, A. Al-Amiery, T. Gaaz and A. Kadhum, "Terephthalohydrazide and isophthalo-hydrazide as new corrosion inhibitors for mild steel in hydrochloric acid: Experimental and theoretical approaches," *Koroze Ochr. Mater.*, 2021, 65, 12–22. doi: 10.2478/kom-2021-0002

[29] M.M. Hanoon, A.M. Resen, L.M. Shaker, A. Kadhum and 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 Res. Appl. Chem.*, 2021, 11, 9735–9743. doi: 10.33263/BRIAC112.97359743

[30] S. Al-Baghdadi, T.S. Gaaz, A. Al-Adili, A. Al-Amiery and M. Takriff, "Experimental studies on corrosion inhibition performance of acetylthiophene thiosemicarbazone for mild steel in HCl complemented with DFT investigation," *Int. J. Low-Carbon Technol.*, 2021, 16, 181–188. doi: 10.1093/ijlct/ctaa050

[31] A. Al-Amiery, "Anti-corrosion performance of 2-isonicotinoyl-nphenylhydrazinecarbothioamide for mild steel hydrochloric acid solution: Insights from experimental measurements and quantum chemical calculations," *Surf. Rev. Lett.*, 2021, 28, 2050058. doi: 10.1142/S0218625X20500584

[32] A.A. Alamiery, "Investigations on the corrosion inhibitory effect of newly quinoline derivative on mild steel in HCl solution complemented with antibacterial studies," *Biointerface Res. Appl. Chem.*, 2022, 12, 1561–1568. doi: 10.33263/BRIAC122.15611568

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

[34] A.A. Alamiery, W.N.R.W. Isahak and M.S. Takriff, "Inhibition of mild steel corrosion by 4-benzyl-1-(4-oxo-4-phenylbutanoyl)thiosemicarbazide: Gravimetrical, adsorption and theoretical studies," *Lubricants*, 2021, 9, 93. doi: 10.3390/lubricants9090093

[35] M.A. Dawood, Z.M.K. Alasady, M.S. Abdulazeez, D.S. Ahmed, G.M. Sulaiman, A.A.H. Kadhum, L.M. Shaker and A.A. Alamiery, "The corrosion inhibition effect of a pyridine derivative for low carbon steel in 1 M HCl medium: Complemented with antibacterial studies," *Int. J. Corros. Scale Inhib.*, 2021, 10, 1766–1782. doi: 10.17675/2305-6894-2021-10-4-25

[36] 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," *Mater. Sci. Energy Technol.*, 2021, 4, 398–406. doi: 10.1016/j.mset.2021.09.002

[37] 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," *Mater. Sci. Energy Technol.*, 2021, 4, 263–273. doi: 10.1016/j.mset.2021.07.004

[38] A. Alamiery, W.N.R.W. Isahak, H. Aljibori, H. Al-Asadi and 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," *Int. J. Corros. Scale Inhib.*, 2021, 10, 700–713. doi: 10.17675/2305-6894-2021-10-2-14

[39] C. Bannwarth, E. Caldeweyher, S. Ehlert, A. Hansen, P. Pracht, J. Seibert, S. Spicher and S. Grimme, "Extended tight-binding Quantum Chemistry Methods," *WIREs Comput. Mol. Sci.*, 2021, 11, 2. doi: 10.1002/wcms.1493

[40] H. Chermette, "Chemical Reactivity Indexes in Density Functional Theory," *J. Comput. Chem.*, 1999, 20, no. 1, 129–154. doi: 10.1002/(SICI)1096-987X(19990115)20:13.0.CO;2-A

[41] R. G. Parr and P. K. Chattaraj, "Principle of Maximum Hardness," *J. Am. Chem. Soc.*, vol. 113, no. 5, pp. 1854–1855, 1991. [Online]. Available: doi: 10.1021/ja00005a072

[42] R. P. Iczkowski and J. L. Margrave, "Electronegativity," *J. Am. Chem. Soc.*, vol. 83, no. 17, pp. 3547–3551, 1961. [Online]. Available: doi: 10.1021/ja01478a001

[43] T. Koopmans, "Über die Zuordnung von Wellenfunktionen und Eigenwerten zu den Einzelnen Elektronen Eines Atoms," *Physica*, vol. 1, no. 3, pp. 104–113, 1934. [Online]. Available: doi: 10.1016/S0031-8914(34)90011-2

[44] R. G. Parr, L. V. Szentpály, and S. Liu, "Electrophilicity Index," *J. Am. Chem. Soc.*, vol. 121, no. 9, pp. 1922–1924, 1999. [Online]. Available: doi: 10.1021/ja983494x

[45] N. P. Andreeva, Yu. I. Kuznetsov, and Kh. S. Shikhaliev, "The use of ellipsometry for studying adsorption of organic corrosion inhibitors from aqueous solutions on metals. Review. Part 1. Methods for obtaining adsorption isotherms," *Int. J. Corros. Scale Inhib.*, vol. 11, no. 4, pp. 1716–1723, 2022. [Online]. Available: doi: 10.17675/2305-6894-2022-11-4-20

[46] Yu. I. Kuznetsov, "Organic corrosion inhibitors: where are we now? A review. Part I. Adsorption," *Int. J. Corros. Scale Inhib.*, vol. 4, no. 4, pp. 284–310, 2015. [Online]. Available: doi: 10.17675/2305-6894-2015-4-4-1

[47] Ya. G. Bober, Yu. I. Kuznetsov, and N. P. Andreeva, "Adsorption at Iron and Passivation Effect of Anions of Substituted Phenylanthranilic Acids," *Prot. Met.*, vol. 44, no. 1, pp. 84–90, 2008. [Online]. Available: doi: 10.1134/S0033173208010116

[48] Yu. I. Kuznetsov et al., "Joint adsorption of oleic and phenylanthranilic acids at passive iron," *Prot. Met.*, vol. 39, no. 5, pp. 462–467, 2003. [Online]. Available: doi: 10.1023/A:1025898803486

[49] Yu. I. Kuznetsov et al., "On co-adsorption on passive iron from aqueous 1,2,3-benzotriazole and sodium phenylundecanoate," *Russ. J. Electrochem.*, vol. 46, no. 5, pp. 560–564, 2010. [Online]. Available: doi: 10.1134/S1023193510050101

[50] K. Fukui, "Role of Frontier Orbitals in Chemical Reactions," *Science*, vol. 218, no. 4574, pp. 747–754, 1982. [Online]. Available: doi: 10.1126/science.218.4574.747

[51] M. S. Abdulazeez et al., "Corrosion inhibition of low carbon steel in HCl medium using a thiadiazole derivative: weight loss, DFT studies and antibacterial studies," *Int. J. Corros. Scale Inhib.*, vol. 10, pp. 1812–1828, 2021. [Online]. Available: doi: 10.17675/2305-6894-2021-10-4-27

[52] A. Z. Salman et al., "Selected BISThiadiazole: Synthesis and Corrosion Inhibition Studies on Mild Steel in HCL Environment," *Surf. Rev. Lett.*, vol. 27, p. 2050014, 2020. [Online]. Available: doi: 10.1142/S0218625X20500146

[53] S. Varvara et al., "Evaluation of Some NonToxic Thiadiazole Derivatives as Bronze Corrosion Inhibitors in Aqueous Solution," *Corros. Sci.*, vol. 50, no. 9, pp. 2596–2604, 2008. [Online]. Available: doi: 10.1016/j.corsci.2008.06.046

[54] H. Ibraheem et al., "4-Thiadiazole: The Biological Activities," *Sys. Rev. Pharm.*, vol. 9, no. 1, pp. 36–40, 2018. [Online]. Available: doi: 10.5530/srp.2018.1.7

[55] A. Al-Amiery et al., "Green Antioxidants: Synthesis and Scavenging Activity of Coumarin Thiadiazoles as Potential Antioxidants Complemented by Molecular Modeling Studies," *Free Radicals Antioxid.*, vol. 6, no. 2, pp. 173–177, 2016. [Online]. Available: doi: 10.5530/fra.2016.2.7

[56] R. G. Parr and R. G. Pearson, "Absolute Hardness: Companion Parameter to Absolute Electronegativity," *J. Am. Chem. Soc.*, vol. 105, no. 26, pp. 7512–7516, 1983. [Online]. Available: doi: 10.1021/ja00364a005

[57] T. K. Chaitra et al., "Thermodynamic, Electrochemical and Quantum Chemical Evaluation of Some Triazole Schiff Bases as Mild Steel Corrosion Inhibitors in Acid Media," *J. Mol. Liq.*, vol. 211, pp. 1026–1038, 2015. [Online]. Available: doi: 10.1016/j.molliq.2015.08.031

[58] L. A. Khamaza, "Generalized Diagram of the Ultimate Nominal Stresses (Endurance Limit) and the Corresponding Dimensions of the Non-Propagating Fatigue Cracks for Sharp and Blunt Notches," *Strength Mater.*, vol. 51, no. 3, pp. 350–360, 2019. [Online]. Available: doi: 10.1007/s11223-019-00081-w

[59] Yu. G. Matvienko, "Approaches of Fracture Mechanics in the Analysis of Admissible Defects in the Form of Notches," *Strength Mater.*, vol. 42, no. 1, pp. 58–63, 2010. [Online]. Available: doi: 10.1007/s11223-010-9188-2

[60] D. Dwivedi et al., "Carbon steel corrosion: a review of key surface properties and characterization methods," *RSC Adv.*, vol. 7, pp. 4580–4610, 2017. [Online]. Available: doi: 10.1039/C6RA25094G

[61] D. A. Winkler, "Predicting the performance of organic corrosion inhibitors," *Metals*, vol. 7, no. 12, p. 553, 2017. [Online]. Available: doi: 10.3390/met7120553

[62] C. Verma, L. O. Olasunkanmi, E. E. Ebenso, and M. A. Quraishi, "Substituents effect on corrosion inhibition performance of organic compounds in aggressive ionic solutions: a review," *J. Mol. Liq.*, vol. 251, pp. 100–118, 2018. [Online]. Available: doi: 10.1016/j.molliq.2017.12.055

[63] O. Kaczerewska et al., "Heteroatoms and π electrons as favorable factors for efficient corrosion protection," *Mater. Corros.*, vol. 70, pp. 1099–1110, 2019. [Online]. Available: doi: 10.1002/maco.201810570

[64] D. K. Verma, Y. Dewangan, A. K. Dewangan, and A. Asatker, "Heteroatom-Based Compounds as Sustainable Corrosion Inhibitors: An Overview," *J. Bio Tribo Corrosion*, vol. 7, pp. 1–18, 2021. [Online]. Available: doi: 10.1007/s40735-020-00447-7

[65] M. Athar, H. Ali, and M. A. Quraishi, "Corrosion inhibition of carbon steel in hydrochloric acid by organic compounds containing heteroatoms," *Br. Corros. J.*, vol. 37, pp. 155–158, 2002. [Online]. Available: doi: 10.1179/000705902225002376

[66] S. Hadisaputra et al., "(E)-ethyl 3-(4-methoxyphenyl) acrylate as corrosion inhibitor of iron in 1 M HCl solutions," *Int. J. Corros. Scale Inhib.*, vol. 7, no. 4, pp. 633–647, 2018. [Online]. Available: doi: 10.17675/2305-6894-2018-7-4-10

[67] S. Hadisaputra et al., "(2R)-5-hydroxy-7-methoxy-2-phenyl-2,3-dihydrochromen-4-one as corrosion inhibitor for Iron in Hydrochloric Acid," *Int. J. Electrochem. Sci.*, vol. 14, pp. 11110–11121, 2019. [Online]. Available: doi: 10.20964/2019.12.77

[68] S. Hadisaputra et al., "Pinostrobin as Copper Corrosion Inhibitor at 1 M H2SO4 Medium," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 833, p. 012010, 2020. [Online]. Available: doi: 10.1088/1757-899X/833/1/012010

[69] C. Verma, L. O. Olasunkanmi, E. E. Ebenso, and M. A. Quraishi, "Substituents effect on corrosion inhibition performance of organic compounds in aggressive ionic solutions: a review," *J. Mol. Liq.*, vol. 251, pp. 100–118, 2018. [Online]. Available: doi: 10.1016/j.molliq.2017.12.055

[70] S. Hadisaputra et al., "Theoretical study of the substituent effect on corrosion inhibition performance of benzimidazole and its derivatives," *Int. J. Corros. Scale Inhib.*, vol. 8, no. 3, pp. 673–688, 2019. [Online]. Available: doi: 10.17675/2305-6894-2019-8-3-15

[71] K. Cao, W. Li, and L. Yu, "Investigation of 1-Phenyl-3-Methyl-5-Pyrazolone as a corrosion inhibitor for mild steel in 1 M hydrochloric acid," *Int. J. Electrochem. Sci.*, vol. 7, pp. 806–818, 2012.

[72] Y. Zhang et al., "Corrosion Inhibition of Carbon Steel by 1-Phenyl-3-Amino-5-Pyrazolone in H2SO4 solution," *Int. J. Electrochem. Sci.*, vol. 14, pp. 999–1008, 2019. [Online]. Available: doi: 10.20964/2019.01.69

[73] A. S. Fouda, A. A. Al-Sarawy, and E. E. El-Katori, "Pyrazolone derivatives as corrosion inhibitors for C-steel in hydrochloric acid solution," *Desalination*, vol. 201, pp. 1–13, 2006. [Online]. Available: doi: 10.1016/j.desal.2006.03.519

[74] S. Hadisaputra et al., "ab initio MP2 and DFT studies of ethyl-p-methoxycinnamate and its derivatives as corrosion inhibitors of iron in acidic medium," *J. Phys.: Conf. Ser.*, vol. 1402, p. 055046, 2019. [Online]. Available: doi: 10.1088/1742-6596/1402/5/055046

[75] V. S. Sastri and J. R. Perumareddi, "Molecular orbital theoretical studies of some organic corrosion inhibitors," *Corros. Sci.*, vol. 53, no. 8, pp. 617–622, 1997. [Online]. Available: doi: 10.5006/1.3290294

[76] G. F. de Sousa et al., "Synthesis, spectroscopic studies and X-ray Crystal structures of new pyrazoline and pyrazole derivatives," *J. Chem. Crystallogr.*, vol. 41, pp. 401–408, 2011. [Online]. Available: doi: 10.1007/s10870-010-9896-2

[77] S. Hadisaputra, Z. Iskandar, and D. Asnawati, "Prediction of the Corrosion Inhibition Efficiency of Imidazole Derivatives: A Quantum Chemical Study," *Acta Chim. Asiana*, vol. 2, no. 1, pp. 88–94, 2019. [Online]. Available: doi: 10.29303/aca.v2i1.15

[78] N. O. Eddy, S. R. Stoyanov, and E. E. Ebenso, "Fluoroquinolones as corrosion inhibitors for mild steel in acidic medium; experimental and theoretical studies," *Int. J. Electrochem. Sci.*, vol. 5, pp. 1127–1150, 2010.

[79] Y. Wirayani, M. Ulfa, and Y. Yahmin, "Corrosion inhibition efficiency of nicotine based on quantum chemical study," *Acta Chim. Asiana*, vol. 1, no. 2, pp. 37–42, 2018. [Online]. Available: doi: 10.29303/aca.v1i2.29

[80] A. S. Fouda, M. A. Ismail, A. S. Abousalem, and G. Y. Elewady, "Experimental and theoretical studies on corrosion inhibition of 4-amidinophenyl-2,2'-bifuran and its analogues in acidic media," *RSC Adv.*, vol. 7, pp. 46414–46430, 2017. [Online]. Available: doi: 10.1039/C7RA08092A

[81] ASTM International, "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test," 2011, pp. 1–9.

[82] G. R. Monama et al., "Hierarchical 4-tetranitro copper (II) phthalocyanine based metal organic framework hybrid composite with improved electrocatalytic efficiency towards hydrogen evolution reaction," *Results Phys.*, vol. 15, p. 102564, 2019. [Online]. Available: doi: 10.1016/j.rinp.2019.102564

[83] M. Tourabi et al., "Electrochemical and XPS studies of the corrosion inhibition of carbon steel in hydrochloric acid pickling solutions by 3,5-bis(2-thienylmethyl)-4-amino-1,2,4-triazole," *Corros. Sci.*, vol. 75, pp. 123–133, 2013. [Online]. Available: doi: 10.1016/j.corsci.2013.05.023

[84] U. M. Eduok, S. A. Umoren, and A. P. Udoh, "Synergistic inhibition effects between leaves and stem extracts of Sida acuta and iodide ion for mild steel corrosion in 1 M H2SO4 solutions," *Arabian J. Chem.*, vol. 5, pp. 325–337, 2012.

[85] B. D. Mert et al., "Experimental and theoretical investigation of 3-amino-1,2,4-triazole-5-thiol as a corrosion inhibitor for carbon steel in HCl medium," *Corros. Sci.*, vol. 53, no. 12, pp. 4265–4272, 2011. [Online]. Available: doi: 10.1016/j.corsci.2011.08.038

[86] NACE International, "Laboratory Corrosion Testing of Metals in Static Chemical Cleaning Solutions at Temperatures below 93°C (200°F)," TM0193-2016-SG, 2000.

[87] A. Alamiery et al., "Corrosion inhibition of low-carbon steel in hydrochloric acid environment using a Schiff base derived from pyrrole: gravimetric and computational studies," *Int. J. Corros. Scale Inhib.*, vol. 10, pp. 749–765, 2021. [Online]. Available: doi: 10.17675/2305-6894-2021-10-2-17

[88] K. M. Manamela et al., "Adsorptive and DFT studies of some imidazolium based ionic liquids as corrosion inhibitors for zinc in acidic medium," *Int. J. Electrochem. Sci.*, vol. 9, pp. 3029–3046, 2014.

[89] N. S. Abtan et al., "Unlocking the Power of 4-Acetamidoantipyrine: A Promising Corrosion Inhibitor for Preserving Mild Steel in Harsh Hydrochloric Acid Environments", *Prog Color Colorants Coat.*, vol. 17, pp. 85-96, 2024. [Online]. Available: doi: 10.30509/pccc.2023.167147.1223

[90] T. Koopmans, "Ordering of wave functions and eigen-energies to the individual electrons of an atom," *Physica*, vol. 1, no. 1–6, pp. 104–113, 1934. [Online]. Available: doi: 10.1016/S0031-8914(34)90011-2

[91] A. J. M. Eltmimi et al., "Inhibitive effects of a novel efficient Schiff base on mild steel in hydrochloric acid environment," *Int. J. Corros. Scale Inhib.*, vol. 10, pp. 634–648, 2021. [Online]. Available: doi: 10.17675/2305-6894-2021-10-2-10

[92] A. Singh et al., "Eco-Friendly Disposal of Expired Anti-Tuberculosis Drug Isoniazid and Its Role in the Protection of Metal," *J. Environ. Chem. Eng.*, vol. 7, p. 102971, 2019. [Online]. Available: doi: 10.1016/j.jece.2019.102971

[93] M. Benabdellah et al., "Thermodynamic, Chemical and Electrochemical Investigations of 2-Mercapto Benzimidazole as Corrosion Inhibitor for Mild Steel in Hydrochloric Acid Solutions," *Arabian J. Chem.*, vol. 4, pp. 17–24, 2011. [Online]. Available: doi: 10.1016/j.arabjc.2010.06.010

[94] R. Haldhar et al., "Valeriana Wallichii Root Extract as a Green & Sustainable Corrosion Inhibitor for Mild Steel in Acidic Environments: Experimental and Theoretical," *Mater. Chem. Front.*, vol. 2, pp. 1225–1237, 2018. [Online]. Available: doi: 10.1039/C8QM00120K

[95] A. K. Singh et al., "Cefacetrile as Corrosion Inhibitor for Mild Steel in Acidic Media," *Int. J. Electrochem. Sci.*, vol. 6, pp. 5689–5700, 2011.

[96] S. Al-Bghdadi et al., "Benzylidene as Efficient Corrosion Inhibition of Mild Steel in Acidic Solution," *Proceedings*, 2019, p. 27. [Online]. Available: doi: 10.3390/ecsoc-23-06472

[97] B. S. Mahdi et al., "Gravimetric analysis and quantum chemical assessment of 4-aminoantipyrine derivatives as corrosion inhibitors," *Int. J. Corros. Scale Inhib.*, vol. 11, no. 3, pp. 1191–1213, 2022. [Online]. Available: doi: 10.17675/2305-6894-2022-11-3-17

[98] A. A. Alamiery, "Study of Corrosion Behavior of N′-(2-(2-oxomethylpyrrol-1-yl) ethyl) piperidine for Mild Steel in the Acid Environment," *Biointerface Res. Appl. Chem.*, vol. 12, pp. 3638–3646, 2022. [Online]. Available: doi: 10.33263/BRIAC123.36383646

[99] A. Alamiery et al., "Comparative data on corrosion protection of mild steel in HCl using two new thiazoles," *Data Brief*, vol. 40, p. 107838, 2022. [Online]. Available: doi: 10.1016/j.dib.2022.107838

[100] A. M. Mustafa et al., "Inhibition of mild steel corrosion in hydrochloric acid environment by 1-amino-2-mercapto-5-(4-(pyrrol-1-yl)phenyl)-1,3,4-triazole," *S. Afr. J. Chem. Eng.*, vol. 39, pp. 42–51, 2022. [Online]. Available: doi: 10.1016/j.sajce.2021.11.009

[101] W. K. Al-Azzawi et al., "Adsorption and theoretical investigations of a Schiff base for corrosion inhibition of mild steel in an acidic environment," *Int. J. Corros. Scale Inhib.*, vol. 11, no. 3, pp. 1063–1082, 2022. [Online]. Available: doi: 10.17675/2305-6894-2022-11-3-10

[102] D. M. Jamil et al., "Carbethoxythiazole corrosion inhibitor: as an experimentally model and DFT theory," *J. Eng. Appl. Sci.*, vol. 13, pp. 3952–3959, 2018. [Online]. Available: doi: 10.3923/JEASCI.2018.3952.3959

[103] A. Alobaidy et al., "Eco-friendly corrosion inhibitor: experimental studies on the corrosion inhibition performance of creatinine for mild steel in HCl complemented with quantum chemical calculations," *Int. J. Electrochem. Sci.*, vol. 10, pp. 3961–3972, 2015. [Online]. Available: doi: 10.1016/S1452-3981(23)06594-X

[104] A. Al-Amiery et al., "Synthesis, characterization and gravimetric studies of novel triazole-based compound," *Int. J. LowCarbon Technol.*, vol. 15, no. 2, pp. 164–170, 2020. [Online]. Available: doi: 10.1093/ijlct/ctz067

[105] S. Junaedi et al., "Synthesis and characterization of novel corrosion inhibitor derived from oleic acid: 2-Amino-5- Oleyl 1,3,4-Thiadiazol (AOT)," *Int. J. Electrochem. Sci.*, vol. 7, pp. 3543–3554, 2012. [Online]. Available: doi: 10.1016/S1452-3981(23)13976-9

[106] H. Ibraheem et al., "4-Thiadiazole: The Biological Activities," *Sys. Rev. Pharm.*, vol. 9, no. 1, pp. 36–40, 2018. [Online]. Available: doi: 10.5530/srp.2018.1.7

[107] A. Al-Amiery et al., "Green Antioxidants: Synthesis and Scavenging Activity of Coumarin Thiadiazoles as Potential Antioxidants Complemented by Molecular Modeling Studies," *Free Radicals Antioxid.*, vol. 6, no. 2, pp. 173–177, 2016. [Online]. Available: doi: 10.5530/fra.2016.2.7

[108] A. Al-Amiery et al., "Synthesis, Antimicrobial And Antioxidant Activities of 5-((2-Oxo-2h-Chromen-7- Yloxy)Methyl)-1,3,4-Thiadiazol-2(3h)One Derived From Umbelliferone," *Chem. Nat. Compd.*, vol. 48, pp. 950–954, 2013. [Online]. Available: doi: 10.1007/s10600-013-0436-0

[109] I. Annon et al., "Corrosion inhibition of mild steel in hydrochloric acid environment using thiadiazole derivative: Weight loss, thermodynamics, adsorption and computational investigations," *S. Afr. J. Chem. Eng.*, vol. 41, pp. 244–252, 2022. [Online]. Available: doi: 10.1016/j.sajce.2022.06.011

[110] H. S. Aljibori et al., "The use of a Schiff base derivative to inhibit mild steel corrosion in 1 M HCl solution: a comparison of practical and theoretical findings," *Int. J. Corros. Scale Inhib.*, vol. 11, no. 4, pp. 1435–1455, 2022. [Online]. Available: doi: 10.17675/2305-6894-2022-11-4-2

[111] H. S. Aljibori et al., "Recent progresses in thiadiazole derivatives as corrosion inhibitors in hydrochloric acid solution," *Int. J. Corros. Scale Inhib.*, vol. 12, no. 3, pp. 842–866, 2023. [Online]. Available: doi: 10.17675/2305-6894-2023-12-3-3

[112] L. M. Shaker et al., "Corrosion in solar cells: challenges and solutions for enhanced performance and durability," *J. Opt.*, 2023. [Online]. Available: doi: 10.1007/s12596-023-01277-9

[113] A. L. Jembere et al., "Effect of low calcination temperature on the corrosion inhibition performance of biomass-based Na2SiO3 on mild steel immersed in tap water," *Cogent Engineering*, vol. 10, no. 1, pp. 1-21, 2023. [Online]. Available: doi: 10.1080/23311916.2023.2165631

[114] S. H. Alrefaee et al., "Challenges and advantages of using plant extract as inhibitors in modern corrosion inhibition systems: Recent advancements," *J. Mol. Liq.*, vol. 321, p. 114666, 2021. [Online]. Available: doi: 10.1016/j.molliq.2020.114666

[115] R. Haldhar et al., "Evaluation of Gloriosa superba seeds extract as corrosion inhibition for low carbon steel in sulfuric acidic medium: A combined experimental and computational studies," *J. Mol. Liq.*, vol. 323, p. 1149582, 2021. [Online]. Available: doi: 10.1016/j.molliq.2020.114958

[116] P. Muthukrishnan et al., "Adsorption and corrosion inhibiting behavior of Lannea coromandelica leaf extract on mild steel corrosion," *Arab. J. Chem.*, vol. 10, pp. S2343–S2354, 2017. [Online]. Available: doi: 10.1016/j.arabjc.2013.08.011

[117] A. R. Hoseizadeh et al., "Thermodynamic and adsorption behaviour of vitamin B1 as a corrosion inhibitor for AISI 4130 steel alloy in HCl solution," *Z. Phys. Chem.*, vol. 227, no. 4, pp. 403–418, 2013.

[118] B. Hammouti et al., "Temperature Effect, Activation Energies and Thermodynamics of Adsorption of ethyl 2-(4-(2-ethoxy-2-oxoethyl)-2-pTolylquinoxalin-1(4H)-yl) Acetate on Cu in HNO3," *Orient. J. Chem.*, vol. 27, no. 1, pp. 23–31, 2011.

[119] Z. Amjad, R.T. Landgraf, and J.L. Penn, "Calcium sulfate dihydrate (gypsum) scale inhibition by PAA, PAPEMP, and PAA/PAPEMP blend," *Int. J. Corros. Scale Inhib.*, vol. 3, no. 1, pp. 35–47, 2014. [Online]. Available: doi: 10.17675/2305-6894-2014-3-1-035-047

[120] J. C. Valle-Quitana et al., "Corrosion Inhibition of Carbon Steel in 0.5 M H2SO4 by Phthalocyanine blue," *ISRN Corros.*, vol. 2014, pp. 1–8, 2014.

[121] P. Zhao, Q. Liang, and Y. Li, "Electrochemical, SEM/EDS and quantum chemical study of phthalocyanines as corrosion inhibitors for mild steel in 1 mol/L HCl," *Appl. Surf. Sci.*, vol. 252, no. 5, pp. 1596–1607, 2005.

[122] K. Sakamoto and E. Ohno-Okumura, "Syntheses and functional properties of phthalocyanines," *Materials*, vol. 2, pp. 1127–1179, 2009. [Online]. Available: doi: 10.3390/ma2031127

[123] G. De La Torre et al., "Role of structural factors in the nonlinear optical properties of phthalocyanines and related compounds," *Chem. Rev.*, vol. 104, pp. 3723–3750, 2004.

[124] M. A. García-Sánchez et al., "Crossed and linked histories of tetrapyrrolic macrocycles and their use for engineering pores within sol-gel matrices," *Molecules*, vol. 18, no. 1, pp. 588–653, 2013. [Online]. Available: doi: 10.3390/molecules18010588

[125] L. O. Olasunkanmi et al., "Some quinoxalin-6-yl derivatives as corrosion inhibitors for mild steel in hydrochloric acid: Experimental and theoretical studies," *J. Phys. Chem. C*, vol. 119, pp. 16004–16019, 2015.

[126] T. Pesha et al., "Inhibition Effect of Phthalocyaninatocopper (II) and 4-Tetranitro (phthalocyaninato) copper (II) Inhibitors for Protection of Aluminum in Acidic Media," *Int. J. Electrochem. Sci.*, vol. 14, pp. 137–149, 2019. [Online]. Available: doi: 10.20964/2019.01.17

[127] M. Dibetsoe et al., "Some phthalocyanine and naphthalocyanine derivatives as corrosion inhibitors for aluminum in acidic medium: Experimental, quantum chemical calculations, QSAR studies and synergistic effect of iodide ions," *Molecules*, vol. 20, pp. 15701–15734, 2015. [Online]. Available: doi: 10.3390/molecules200915701

[128] J. Xu, Y. Wang, and Z. Zhang, "Potential and concentration dependent electrochemical dealloying of Al2Au in sodium chloride solutions," *J. Phys. Chem. C*, vol. 116, no. 9, pp. 5689–5699, 2012. [Online]. Available: doi: 10.1021/jp210488t

[129] I. Langmuir, "The constitution and fundamental properties of solid and liquids. II. Liquids," *J. Am. Chem. Soc.*, vol. 39, pp. 1848–1906, 1917. [Online]. Available: doi: 10.1021/ja02254a006

[130] M. Lagrenée et al., "Study of the mechanism and inhibiting efficiency of 3,5-bis(4-methylthiophenyl)-4H-1,2,4-triazole on mild steel corrosion in acidic media," *Corros. Sci.*, vol. 44, no. 3, pp. 573–588, 2002. [Online]. Available: doi: 10.1016/S0010-938X(01)00075-0

[131] I. D. Mall et al., "Adsorptive removal of malachite green dye from aqueous solution by bagasse fly ash and activated carbon—kinetic study and equilibrium isotherm analysis," *Colloids Surf., A*, vol. 264, pp. 17–28, 2005. [Online]. Available: doi: 10.1016/j.colsurfa.2005.03.027

[132] E. A. Noor and A. H. Al-Moubaraki, "Thermodynamic study of metal corrosion and inhibitor adsorption processes in mild steel/1-methyl-4[4'-(-X)-styryl pyridinium iodides/hydrochloric acid systems," *Mater. Chem. Phys.*, vol. 110, pp. 145–154, 2008. [Online]. Available: doi: 10.1016/j.matchemphys.2008.01.028

[133] M. Taha Mohamed et al., "Revolutionizing Corrosion Defense: Unlocking the Power of Expired BCAA," Prog. Color Colorants Coat., vol. 17, no. 2, pp. 97-111, 2024. [Online]. Available: doi: 10.30509/pccc.2023.167156.1228.

[134] M. K. Abbass et al., "Evaluation of 2-Dimethylaminopropionamidoantipyrine as a Corrosion Inhibitor for Mild Steel in HCl Solution: A Combined Experimental and Theoretical Study," Prog. Color Colorants Coat., vol. 17, no. 1, pp. 1-10, 2024. [Online]. Available: doi: 10.30509/pccc.2023.167081.1197.

[135] K.Z. Abdulsada et al., "Unleashing the power of polymer surfactants: novel corrosion inhibitors for mild steel in hydrochloric acid," Int. J. Corros. Scale Inhib., vol. 12, no. 4, pp. 2198-2020, 2023. [Online]. Available: doi: 10.17675/2305-6894-2023-12-4-40.

[136] H.S. Aljibori et al., "Advances in corrosion protection coatings: A comprehensive review," Int. J. Corros. Scale Inhib., vol. 12, no. 4, pp. 1476-1520, 2023. [Online]. Available: doi: 10.17675/2305-6894-2023-12-4-6.

[137] Y.K. Al-Majedy et al., "Exploring chromone derivatives as environmentally friendly corrosion inhibitors for mild steel in acidic environments: A comprehensive experimental and DFT study," Int. J. Corros. Scale Inhib., vol. 12, no. 3, pp. 1028-1051, 2023. [Online]. Available: doi: 10.17675/2305-6894-2023-12-3-14.

[138] A. Mohammed et al., "Investigation of the Corrosion Inhibition Properties of 4-Cyclohexyl-3-Thiosemicarbazide on Mild Steel in 1 M HCl Solution," Prog. Color Colorants Coat., vol. 16, pp. 347-359, 2023. [Online]. Available: doi: 10.30509/pccc.2023.167126.1212.

[139] A. Naseef Jasim et al., "Schiff's Base Performance in Preventing Corrosion on Mild Steel in Acidic Conditions," Prog. Color Colorants Coat., vol. 16, pp. 319-329, 2023. [Online]. Available: doi: 10.30509/pccc.2023.167081.1197.

[140] S. O. Adejo et al., "Corrosion studies of mild steel in sulphuric acid medium by acidimetric method," *Int. J. Corros. Scale Inhib.*, vol. 8, no. 1, pp. 50–61, 2019. [Online]. Available: doi: 10.17675/2305-6894-2019-8-1-5

[141] A. H. Al-Moubaraki and H. Awaji, "1-X-4-[4′-(–OCH3)-Styryl] pyridinium iodides, potent inhibitors for stainless steel corrosion in 2 M HCl acid solutions," *Int. J. Corros. Scale Inhib.*, vol. 9, no. 2, pp. 460–501, 2020. [Online]. Available: doi: 10.17675/2305-6894-2020-9-2-5

[142] M. Yadav et al., "New pyrimidine derivatives as efficient organic inhibitors on mild steel corrosion in acidic medium: electrochemical, SEM, EDX, AFM and DFT studies," *J. Mol. Liq.*, vol. 211, pp. 135–145, 2015. [Online]. Available: doi: 10.1016/j.molliq.2015.06.063

[143] G. Gao and C. Liang, "Electrochemical and DFT studies of β-amino-alcohols as corrosion inhibitors for brass," *Electrochim. Acta*, vol. 52, pp. 4554–4559, 2007. [Online]. Available: doi: 10.1016/j.electacta.2006.12.058

[144] M. Stern and A. L. Geary, "Electrochemical polarization, I. theoretical analysis of the shape of polarisation curves," *J. Electrochem. Soc.*, vol. 104, pp. 56–63, 1957. [Online]. Available: doi: 10.1149/1.2428496

[145] M. A. Amin et al., "Monitoring corrosion and corrosion control of iron in HCl by non-ionic surfactants of the TRITON-X series–part III. Immersion time effects and theoretical studies," *Corros. Sci.*, vol. 53, pp. 1895–1909, 2011. [Online]. Available: doi: 10.1016/j.corsci.2011.02.007

[146] K. F. Khaled and M. M. Al-Qahtani, "The Inhibitive effect of some tetrazole derivatives towards Al corrosion in acid solution: chemical, electrochemical and theoretical studies," *Mater. Chem. Phys.*, vol. 113, pp. 150–158, 2009. [Online]. Available: doi: 10.1016/j.matchemphys.2008.07.060

[147] D. Ben Hmamou et al., "Investigation of corrosion inhibition of carbon steel in 0.5 M H2SO4 by new bipyrazole derivative using experimental and theoretical approaches," *J. Environ. Chem. Eng.*, vol. 3, pp. 2031–2041, 2015. [Online]. Available: doi: 10.1016/j.jece.2015.03.018

[148] H. Ma et al., "Theoretical elucidation on the inhibition mechanism of pyridine-pyrazole compound: a Hartree Fock study," *J. Mol. Struct.: THEOCHEM*, vol. 774, no. 1–3, pp. 19–22, 2006. [Online]. Available: doi: 10.1016/j.theochem.2006.06.044

[149] P. Mourya et al., "Relationship between structure and inhibition behaviour of quinolinium salts for mild steel corrosion: experimental and theoretical approach," *Corros. Sci.*, vol. 95, pp. 71–87, 2015. [Online]. Available: doi: 10.1016/j.corsci.2015.02.034

[150] G. Gece, "The use of quantum chemical methods in corrosion inhibitor studies," *Corros. Sci.*, vol. 50, pp. 2981–2992, 2008. [Online]. Available: doi: 10.1016/j.corsci.2008.08.043

[151] V.S. Sastri and J.R. Perumareddi, "Molecular orbital theoretical studies of some organic corrosion inhibitors," *Corrosion*, vol. 53, pp. 617–622, 1997. doi: 10.5006/1.3290294

[152] A. Stoyanova, G. Petkova, and S.D. Peyerimhoff, "Correlation between the molecular structure and the corrosion inhibiting effect of some pyrophthalone compounds," *Chem. Phys.*, vol. 279, pp. 1–6, 2002. doi: 10.1016/S0301-0104(02)00408-1

[153] O. Benali, L. Larabi, M. Traisnel, L. Gengembre, and Y. Harek, "Electrochemical, theoretical and XPS studies of 2-mercapto-1-methylimidazole adsorption on carbon steel in 1 M HClO4," *Appl. Surf. Sci.*, vol. 253, no. 14, pp. 6130–6139, 2007. doi: 10.1016/j.apsusc.2007.01.075

[154] A.K. Oyebamiji and B.B. Adeleke, "Quantum chemical studies on inhibition activities of 2,3-dihydroxypropyl-sulfanyl derivative on carbon steel in acidic media," *Int. J. Corros. Scale Inhib.*, vol. 7, no. 4, pp. 498–508, 2018. doi: 10.17675/2305-6894-2018-7-4-2

[155] K. Sayin and D. Karakas, "Quantum chemical studies on the some inorganic corrosion inhibitors," *Corros. Sci.*, vol. 77, pp. 37–45, 2013. doi: 10.1016/j.corsci.2013.07.023

[156] K. Laarej, M. Bouachrine, S. Radi, S. Kertit, and B. Hammouti, "Quantum chemical studies on the inhibiting effect of bipyrazoles on steel corrosion in HCl," *E-J. Chem.*, vol. 7, pp. 419–424, 2010. doi: 10.1155/2010/273206

[157] B. Obot, N.O. Obi-Egbedi, and S.A. Umoren, "The synergistic inhibitive effect and some quantum chemical parameters of 2,3-diaminonaphthalene and iodide ions on the hydrochloric acid corrosion of aluminum," *Corros. Sci.*, vol. 51, pp. 276–282, 2009. doi: 10.1016/j.corsci.2008.11.013

[158] N.A. Al-Ali et al., "Improvement of corrosion resistance of 316L stainless steel substrate with a composite coating of biopolymer produced by electrophoretic deposition," Int. J. Corros. Scale Inhib., vol. 12, no. 3, pp. 913-932, 2013, doi: 10.17675/2305-6894-2023-12-3-7.

[159] S.T. Arab and E.A. Noor, "Inhibition of acid corrosion of steel by some Salkylisothiouronium iodides," *Corrosion*, vol. 49, no. 2, pp. 122–129, 1993. doi: 10.5006/1.3299206

[160] M.A. Migahed, "Electrochemical investigation of the corrosion behaviour of mild steel in 2 M HCl solution in presence of 1-dodecyl-4-methoxy pyridinium bromide," *Mater. Chem. Phys.*, vol. 93, pp. 48–53, 2005. doi: 10.1016/j.matchemphys.2005.02.003

[161] D. Asefi, M. Arami, A.A. Sarabi, and N.M. Mahmoodi, "The chain length influence of cationic surfactant and role of nonionic co-surfactants on controlling the corrosion rate of steel in acidic media," *Corros. Sci.,* 2009, vol. 51, pp. 1817–1821. doi: 10.1016/j.corsci.2009.05.007

[162] D. Asefi, M. Arami, and N.M. Mahmoodi, "Comparing chain length effect of single chain and gemini surfactants on corrosion inhibition of steel in acid," *ECS Trans.,* 2011, vol. 35, no. 17, pp. 89–101. doi: 10.1149/1.3641293

[163] S.-H. Yoo, Y.-W. Kim, J. Shin, N.-K. Kim, and J.-S. Kim, "Effects of the chain length of tris(carboxyalkylamino)triazine on corrosion inhibition properties," *Bull. Korean Chem. Soc.,* 2015, vol. 36, pp. 346–355. doi: 10.1002/bkcs.10090

[164] S.E. Kaskah, M. Pfeiffer, H. Klock, H. Bergen, G. Ehrenhaft, P. Ferreira, J. Gollnick, and C.B. Fischer, "Surface protection of low carbon steel with N-acyl sarcosine derivatives as green corrosion inhibitors," *Surf. Interfaces,* 2017, vol. 9, pp. 70–78. doi: 10.1016/j.surfin.2017.08.002

[165] M. El Achouri, M.R. Infante, F. Izquierdo, S. Kertit, H.M. Gouttaya, and B. Nciri, "Synthesis of some cationic gemini surfactants and their inhibitive effect on iron corrosion in hydrochloric acid medium," *Corros. Sci.,* 2001, vol. 43, pp. 19–35. doi: 10.1016/S0010-938X(00)00063-9

[166] N.A. Negm and S.M. Tawfik, "Characterization, surface properties and biological activity of some synthesized anionic surfactants," *J. Ind. Eng. Chem.,* 2014, vol. 20, no. 6, pp. 4463–4472. doi: 10.1016/j.jiec.2014.02.018

[167] N.A. Negm, M.A. Salem, A.M. Badawi, and M.F. Zaki, "Corrosion inhibition properties of some novel N-methyl diethanolammonium bromide cationic surfactants," *TESCE,* 2004, vol. 30, no. 2, pp. 853–869.

[168] E. McCafferty and N. Hackerman, "Double Layer Capacitance of Iron and Corrosion Inhibition with Polymethylene Diamines," J. Electrochem. Soc., vol. 119, pp. 146-150, 1972. doi: 10.1149/1.2404150.

[169] S. Hadisaputra, A.A. Purwoko, I. Ilhamsyah, S. Hamdiani, D. Suhendra, N. Nuryono, and B. Bundjali, "A combined experimental and theoretical study of (E)-ethyl 3-(4-methoxyphenyl)acrylate as a corrosion inhibitor of iron in 1 M HCl solutions," *Int. J. Corros. Scale Inhib.,* 2018, vol. 7, no. 4, pp. 633–647. doi: 10.17675/2305-6894-2018-7-4-10

[170] H. Lgaz, Anejjar, R. Salghi, S. Jodeh, M. Zougagh, Warad, M. Larouj, and P. Sims, "Characterization of corrosion products formed on carbon steel in hydrochloric acid medium by 4-(dimethylamino)-1-(6-methoxy6-oxohexyl)pyridinium bromide," *Int. J. Corros. Scale Inhib.,* 2016, vol. 5, no. 3, pp. 209–231. doi: 10.17675/2305-6894-2016-5-3-3

[171] K.R. Ansari, S. Ramkumar, 3 D.S. Chauhan, Md. Salman, D. Nalini, V. Srivastava, and M.A. Quraishi, "Macrocyclic compounds as green corrosion inhibitors for aluminum: electrochemical, surface and quantum chemical studies," *Int. J. Corros. Scale Inhib.,* 2018, vol. 7, no. 3, pp. 443–459. doi: 10.17675/2305-6894-2018-7-3-13

[172] V.I. Vorobyova, M.I. Skiba, and I.M. Trus, "Apricot pomaces extract (Prunus Armeniaca L.) as a highly efficient sustainable corrosion inhibitor for mild steel in sodium chloride solution," *Int. J. Corros. Scale Inhib.,* 2019, vol. 8, no. 4, pp. 1060–1083. doi: 10.17675/2305-6894-2019-8-4-15

[173] C.G. Dariva and A.F. Galio, "Corrosion Inhibitors – Principles, Mechanisms and Applications," in: *Developments in Corrosion Protection*, Ed. M. Aliofkhazraei, Ch. 16, InTech, 2014, pp. 365–379. doi: 10.5772/57255

[174] A. Shaban, I. Felhosi, and J. Telegdi, "Laboratory assessment of inhibition efficiency and mechanism of inhibitor blend (P22SU) on mild steel corrosion in high chloride containing water," *Int. J. Corros. Scale Inhib.,* 2017, vol. 6, no. 3, pp. 262–275. doi: 10.17675/2305-6894-2017-6-3-3

[175] Yu.I. Kuznetsov, "Organic corrosion inhibitors: where are we now? A review. Part III. Passivation and the role of the chemical structure of organophosphates," *Int. J. Corros. Scale Inhib.,* 2017, vol. 6, no. 3, pp. 209–239. doi: 10.17675/2305-6894-2017-6-3-1.

[176] D.M. Spori, N.V. Venkataraman, S.G.P. Tosatti, F. Durmaz, N.D. Spencer, and S. Zurcher, "Influence of Alkyl Chain Length on Phosphate Self-Assembled Monolayers," *Langmuir,* 2007, vol. 23, pp. 8053–8060.

[177] S.V. Oleynik, Yu.A. Kuzenkov, N.P. Andreeva, and Yu.I. Kuznetsov, "Korroz.: mater., zashch.," 2008, no. 3, pp. 29–34 (in Russian).

[178] P.M. Karlsson, A.E.C. Palmqvist, and K. Holmberg, "Adsorption of sodium dodecyl sulfate and sodium dodecyl phosphate on aluminum, studied by QCM-D, XPS, and AAS," *Langmuir,* 2008, vol. 24, pp. 13414.

[179] P.M. Karlsson, M.W. Anderson, and A.E.C. Palmqvist, "Adsorption of sodium dodecyl sulfate and sodium dodecyl phosphate at the surface of aluminium oxide studied with AFM," *Corros. Sci.,* 2010, vol. 52, pp. 1103–1105.

[180] A.A. Chirkunov, A.S. Gorbachev, Yu.I. Kuznetsov, and N.P. Andreeva, "Adsorption of Dioctyl Phosphate and Inhibition of Dissolution of Low-Carbon Steel," *Prot. Met. Phys. Chem. Surf.,* 2013, vol. 49, no. 7, pp. 854–859. doi: 10.1134/S2070205113070058

[181] S.J. Garcia, T.A. Markley, J.M.C. Mol, and A.E. Hughes, "Unravelling the corrosion inhibition mechanisms of bi-functional inhibitors by EIS and SEM–EDS," *Corros. Sci.,* 2013, vol. 69, pp. 346–358.

[182] Yu.I. Kuznetsov, A.M. Semiletov, and A.A. Chirkunov, "Inhibition of magnesium corrosion by triazoles," *Int. J. Corros. Scale Inhib.*, vol. 5, no. 1, pp. 31–49, 2016. doi: http://dx.doi.org/10.17675/2305-6894-2016-5-1-3

[183] W.B. Wan Nik et al., "Piper betle extract as an eco-friendly corrosion inhibitor for aluminium alloy in hydrochloric acid media," Int. J. Corros. Scale Inhib., vol. 12, no. 3, pp. 948-960, 2023. doi: 10.17675/2305-6894-2023-12-3-9.

[184] Yu.I. Kuznetsov, "Progress in Inhibition of Metal Corrosion and Modification of Safety Nanolayers on Metals," *Prot. Met. Phys. Chem. Surf.,* 2011, vol. 47, no. 7, pp. 821–829. doi: 10.1134/S2070205111070100.

[185] Yu.I. Kuznetsov, N.P. Andreeva, and G.Yu. Kazanskaya, "On the Inhibition Effect of Dialkyl Phosphates in the Depassivation of Metals," *Prot. Met.,* 2000, vol. 36, no. 4, pp. 351–355.

[186] F. Cao, J. Wei, J. Dong, and W. Ke, "The corrosion inhibition effect of phytic acid on 20SiMn steel in simulated carbonated concrete pore solution," *Corros. Sci.,* 2015, vol. 100, pp. 365–376.

[187] G.M. Liu, L. Yang, F. Ym, J.H. Tian, S.W. Duo, and N. Du, "Cerium–phytic acid passivation treatment on galvanized steel," *Key Eng. Mater.,* 2008, vols. 373–374, pp. 228–231.

[188] G.M. Liu, L. Yang, F.Y. Sun, W. Song, X. Zhu, Na Wang, Y. Wang, Y.C. Pan, and Z. Zhang, "Competitive Adsorption of 4-Methyl-4H-1,2,4-triazole-3-thiol and Na Salt of Phytic Acid on a Silver Surface: Raman Spectral and Electrochemical Observations," *J. Phys. Chem. C,* 2009, vol. 113, pp. 9748–9754.

[189] L. Jianrui, G. Yina, and H. Weidong, "Phytic Acid Conversion on Magnesium Surface Treatment with Cerium Chloride Solution," *Prot. Met. Phys. Chem. Surf.,* 2012, vol. 48, no. 2, pp. 233–237.

[190] L. Jianrui, G. Yina, and H. Weidong, "Study on the corrosion resistance of phytic acid conversion coating for magnesium alloys," *Surf. Coat. Technol.,* 2006, vol. 201, pp. 1536–1541.

[191] X. Cui, Y. Li, Q. Li, G. Jin, M. Ding, and F. Wan, "Influence of phytic acid concentration on the performance of phytic acid conversion coatings on the AZ91D magnesium alloy," *Mater. Chem. Phys.,* 2008, vol. 111, pp. 503–507.

[192] E. Papirer, E. Walter, A. Vidal, and B. Siffert, "Adsorption of Stearic Acid and Diethylhexyl Phosphate on Magnetic Metallic Iron Pigments: Electrical Surface Charging and Adsorption Competition," *J. Colloid Interface Sci.,* 1997, vol. 187, pp. 529–538.

[193] A.V. Fokin, M.V. Pospelov, and Levichev A.N., "Oil-soluble corrosion inhibitors. The mechanism of action and applied formulations," in: *Results of science and technology, Series: Corrosion and corrosion protection,* 1984, Moscow, VINITI, vol. 10, pp. 3–77.

[194] D. Ho, N. Brack, J. Scully, T.A. Markley, M. Forsyth, and B.R.W. Hinton, "Cerium Dibutylphosphate as a Corrosion Inhibitor for AA2024-T3 Aluminum Alloys," *J. Electrochem. Soc.,* 2006, vol. 153, no. 9, B392. doi: 10.1149/1.2217260.

[195] T.A. Markley, M. Forsyth, and A.E. Hughes, "Corrosion protection of AA2024-T3 using rare earth diphenyl phosphates," *Electrochim. Acta,* 2007, vol. 52, no. 12, pp. 4024–4031.

[196] M. Forsyth, T.A. Markley, D. Ho, G.B. Deacon, P.C. Junk, B.R.W. Hinton, and A. Hughes, "Inhibition of Corrosion on AA2024-T3 by New Environmentally Friendly Rare Earth Organophosphate Compounds," *Corrosion,* 2008, vol. 64, no. 3, p. 191. doi: 10.5006/1.3278465.

[197] S.J. Garcia, T.A. Markley, J.M.C. Mol, and A.E. Hughes, "Unravelling the corrosion inhibition mechanisms of bi-functional inhibitors by EIS and SEM–EDS," *Corros. Sci.,* 2013, vol. 69, pp. 346–358.

[198] A.A. Chirkunov and S.N. Gusev, "Inhibition of dissolution of magnesium alloy Electron WE43 by anion-active compounds," *Korroz.: mater., zashch.,* 2016, no. 6, pp. 37–41.

[199] S.N. Gusev, A.A. Chirkunov, and G.V. Red'kina, "Effect of Borate Buffer Solution and NaCl Concentration on the Anodic Behavior of a Magnesium Alloy Electron WE43 in the Presence of Inhibitors," *Korroz.: mater., zashch.,* 2016, no. 6, pp. 37–41.

[200] S. Tosatti, R. Michel, M. Textor, and N.D. Spencer, "Self-Assembled Monolayers of Dodecyl and Hydroxy-dodecyl Phosphates on Both Smooth and Rough Titanium and Titanium Oxide Surfaces," *Langmuir,* 2002, vol. 18, pp. 3537–3548.

[201] M. Zwahlen, S. Tosatti, M. Textor, and G. Hahner, "Orientation in Methyl- and Hydroxyl-Terminated Self-Assembled Alkanephosphate Monolayers on Titanium Oxide Surfaces Investigated with Soft X-ray Adsorption," *Langmuir,* 2002, vol. 18, pp. 3957–3962.

[202] H. Yang, Yu Yang, Y. Yang, H. Liu, Z. Zhang, G. Shen, and R. Yu, "Formation of inositol hexaphosphate monolayers at the copper surface from a Na-salt of phytic acid solution studied by in situ surface enhanced Raman scattering spectroscopy, Raman mapping and polarization measurement," *Anal. Chim. Acta,* 2005, vol. 458, pp. 159–165.

[203] V. Ermanno, M. Stefano, C. Tonino, M. Osvaldo, F. Cecilia, and M. Carla, "Complex formation between phytic acid and divalent metals ions: a solution equilibria and solid state investigation," *Anal. Bioanal. Chem.,* 2002, vol. 374, pp. 173–178.

[204] Ya.G. Avdeev and Yu.I. Kuznetsov, "Inhibitor protection of steel corrosion in acid solutions at high temperatures. A review. Part 2," *Int. J. Corros. Scale Inhib.,* 2020, vol. 9, no. 2, pp. 867–902. doi: 10.17675/2305-6894-2020-9-3-5.

[205] A. Frignani, C. Monticelli, F. Zucchi, and G. Trabanelli, "Acetylenic alcohols as inhibitors of iron acid corrosion. Improvement of the inhibition efficiency of a class of substances based on their action mechanism," *Int. J. Corros. Scale Inhib.,* 2014, vol. 3, no. 2, pp. 105–119. doi: 10.17675/2305-6894-2014-3-2-105-119.

[206] Z. Wang, T. Wang, J. Zhu, L. Wei, Y. Shen, N. Li, and J. Hu, "Synergistic effect and mechanism of copper corrosion inhibition using cinnamaldehyde and vanillin in HCl solution: An experimental and theoretical approach," *Colloids Surf., A,* 2019, vol. 563, pp. 246–254. doi: 10.1016/j.colsurfa.2018.12.012.

[207] A.K. Iskhakov, "Sintez i issledovanie ingibiruyushchikh svoistv i mekhanizma deistviya vtorichnykh atsetilenovykh spirtov pri korrozii uglerodistykh staley v kislykh sredakh. Avtoreferat dissertatsii kandidata khimicheskih nauk" (Synthesis and study of the inhibitory properties and mechanism of action of secondary acetylene alcohols in the corrosion of carbon steels in acidic environments. Author's abstract of a PhD dissertation in Chemistry), Institute of Physical Chemistry, USSR Academy of Sciences, Moscow, 1986, 17 p. (in Russian).

[208] B.D.B. Tiu and R.C. Advincula, "Polymeric corrosion inhibitors for the oil and gas industry: Design principles and mechanism," *React. Funct. Polym.,* 2015, vol. 95, pp. 25–45. doi: 10.1016/j.reactfunctpolym.2015.08.006.

[209] W.W. Frenier, F.B. Growcock, and V.R. Lopp, "Mechanisms of Corrosion Inhibitors Used in Acidizing Wells," *SPE Prod. Eng.,* 1988, vol. 3, no. 4, pp. 584–590. doi: 10.2118/14092-PA.

[210] K. Aramaki and E. Fujioka, "Surface-Enhanced Raman Scattering Spectroscopy Studies on the Inhibition Mechanism of Propargyl Alcohol for Iron Corrosion in Hydrochloric Acid," *Corrosion,* 1996, vol. 52, no. 2, pp. 83–91. doi: 10.5006/1.3292107.

[211] J.O'M. Bockris and B. Yang, "The Mechanism of Corrosion Inhibition of Iron in Acid Solution by Acetylenic Alcohols," *J. Electrochem. Soc.,* 1991, vol. 138, pp. 2237–2252. doi: 10.1149/1.2085956.

[212] N.I. Podobaev and Ya.G. Avdeev, "The Effect of Hydrogenation on the Anodic Dissolution of Iron and Its Inhibition by Propinol in Hydrochloric Acid," *Prot. Met.,* 1999, vol. 35, no. 5, pp. 484–488.

[213] F.B. Growcock, W.W. Frenier, and P.A. Andreozzi, "Inhibition of Steel Corrosion in HCl by Derivatives of Cinnamaldehyde: Part II. Structure–Activity Correlations," *Corrosion,* 1989, vol. 45, no. 12, pp. 1007–1015. doi: 10.5006/1.3585008.