Vol. 02, Iss. 4 (2024) 235-249, DOI: 10.61552/JME.2024.04.001

JME

Journal of Materials and Engineering

www.jme.aspur.rs

Review article

Synthesized Heterocyclic Compounds as Corrosion Inhibitors for Steel in Acidic Environments: A Mini-Review

Ahmed A. Alamiery[a,b,*]

[a]*Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), Bangi 43000, Malaysia,*
[b]*Energy and Renewable Energies Technology Center, University of Technology, Iraq, 10001, Iraq.*

Keywords:

Heterocyclic compounds
Corrosion inhibitors
Steel
Acidic solution
Synthesis

* Corresponding author:

Ahmed A. Alamiery
E-mail: dr.ahmed1975@gmail.com

Received: 21 January 2024
Revised: 27 February 2024
Accepted: 25 March 2024

ABSTRACT

Corrosion is a significant problem in various industries, leading to the degradation of steel structures and causing significant economic losses. Heterocyclic compounds, which contain heteroatoms such as nitrogen, sulfur, and oxygen, have been found to be effective corrosion inhibitors for steel in acidic environments. This mini-review discusses the synthesis and use of heterocyclic compounds as corrosion inhibitors for steel in acidic solutions. The review highlights the potential of these compounds as effective and low-cost corrosion inhibitors for various industries.

1. INTRODUCTION

Corrosion poses a substantial challenge across diverse industries, instigating the deterioration of steel structures and inflicting consequential economic losses. This intricate phenomenon involves the material's degradation due to chemical or electrochemical reactions with its surrounding environment [1-3]. A spectrum of corrosion types, including uniform corrosion, pitting corrosion, crevice corrosion, and galvanic corrosion, underscores the complexity of this issue [4-7]. In industrial settings, acidic solutions find widespread use in activities such as cleaning, pickling, and etching. Paradoxically, the ubiquity of acidic solutions exacerbates the corrosion of steel, leading to substantial financial repercussions [8-11]. To counteract the pervasive impact of corrosion, diverse methodologies have been devised, among which corrosion inhibitors stand out prominently. These inhibitors, characterized by their ability to curtail the corrosion rate by forming protective layers on metal surfaces, have emerged as pivotal agents in corrosion control [12-15]. Within the realm of organic inhibitors, heterocyclic compounds have garnered attention for their promising corrosion inhibiting properties, particularly in acidic environments [16-18]. Heterocyclic compounds, organic molecules featuring one or more heteroatoms like nitrogen, sulfur, and oxygen in their ring structure, represent a focal point in contemporary research efforts [19,20]. Notably, these compounds exhibit a unique capability to form protective layers on metal surfaces, offering a tangible reduction in the corrosion rate of steel within acidic solutions.

The imperative to develop corrosion inhibitors, effective and efficient, becomes paramount in ensuring the durability and reliability of infrastructure constructed with steel [21-24]. Figure 1 serves as a visual guide, illustrating various corrosion types, ranging from the common uniform corrosion to the more destructive pitting corrosion and erosion-corrosion observed in high-velocity environments. The multifaceted nature of corrosion manifests through distinct forms, encompassing uniform corrosion, galvanic corrosion, crevice corrosion, pitting corrosion, intergranular corrosion, selective leaching, erosion-corrosion, and stress-corrosion cracking [25-29]. Figure 1 provides a schematic representation, elucidating each type's characteristics and mechanisms, offering a comprehensive understanding of this intricate phenomenon.

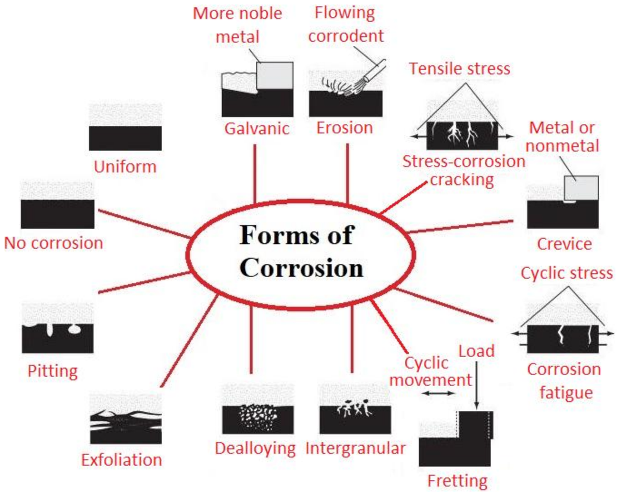

Fig. 1. Types of corrosion.

The primary objective of this mini-review is to furnish a thorough overview of the synthesis, characterization, and performance of heterocyclic compounds as corrosion inhibitors for steel in acidic environments. By delving into the latest research findings and insights in this field, the review aspires to enrich the comprehension of the potential applications of these compounds in industrial corrosion protection. The synthesis of heterocyclic compounds involves intricate chemical reactions such as cyclization, condensation, and oxidation. Subsequently, the application of these compounds as corrosion inhibitors entails the adsorption of inhibitor molecules on the metal surface, orchestrating the formation of a protective layer that significantly diminishes the corrosion rate of steel in acidic solutions.

2. HETEROCYCLIC COMPOUNDS AS CORROSION INHIBITORS

Heterocyclic compounds are organic molecules characterized by the presence of at least one ring structure composed of carbon atoms and other non-carbon atoms, known as heteroatoms. The term "heterocyclic" indicates the diverse nature of these compounds, where the heteroatoms can include nitrogen, sulfur, oxygen, and other elements [30,31]. The cyclic nature of these compounds imparts unique properties that make them particularly valuable in the field of corrosion inhibition. The heteroatoms within the ring structure of heterocyclic compounds play a crucial role in their corrosion inhibition properties. Nitrogen, sulfur, and oxygen, being more electronegative than carbon, introduce polar characteristics to the molecule. This property facilitates the formation of coordinate bonds with metal surfaces, leading to the creation of protective layers [32-33]. The presence of heteroatoms also enhances the electron density around the ring, influencing the adsorption process on the metal surface and ultimately contributing to the corrosion inhibition effect.

2.1 Mechanisms of corrosion inhibition by heterocyclic compounds

The corrosion inhibition mechanisms employed by heterocyclic compounds are diverse and multifaceted. These mechanisms can be broadly categorized into three main processes:

2.1.1. Adsorption onto metal surface

Heterocyclic compounds adsorb onto the metal surface, forming a protective layer that acts as a barrier against corrosive substances. The adsorption process is influenced by factors such as the nature of the heterocyclic compound, the type of metal, and the characteristics of the corrosive environment. Figure 2 could illustrate the different adsorption mechanisms, such as chemisorption, physisorption, and mixed-mode adsorption, through schematic diagrams. Arrows and labels would indicate the interactions between heterocyclic compounds and metal surfaces [34-36]. Figure 2 visually explains the diverse adsorption mechanisms employed by heterocyclic compounds, aiding in the understanding of how these compounds form protective layers on metal surfaces, influencing corrosion inhibition.

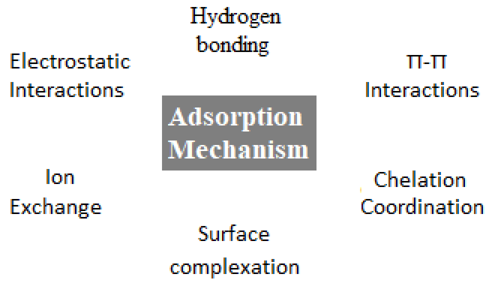

Fig. 2. Adsorption mechanisms of heterocyclic compounds on metal surfaces.

2.1.2 Formation of protective film

Heterocyclic compounds have the ability to undergo chemical reactions with metal surfaces, leading to the formation of protective films. These films act as a shield, preventing the penetration of corrosive agents and hindering the electrochemical reactions that cause corrosion [37,38].

2.1.3 Electron density modification

The presence of heteroatoms alters the electron density distribution within the heterocyclic ring. This modification influences the electrochemical reactions occurring on the metal surface, thereby reducing the corrosion rate [39,40]. The heterocyclic compounds act as electron donors or acceptors, depending on the specific heteroatom involved. Table 1 outlines key factors influencing the effectiveness of corrosion inhibition by heterocyclic compounds. Understanding these factors is crucial for optimizing conditions in industrial applications.

Table 1. Key factors influencing corrosion inhibition effectiveness.

Factor	Influence on Inhibition Effectiveness
Concentration of Inhibitor	Higher concentrations often lead to increased efficiency.
Temperature and Pressure	Optimal conditions are essential for efficient adsorption.
Nature of Corrosive Environment	pH, composition, and aggressiveness significantly impact effectiveness.

2.2. Advantages of using heterocyclic compounds as corrosion inhibitors

The use of heterocyclic compounds as corrosion inhibitors presents several advantages [41-47]:

- **Versatility:** Heterocyclic compounds exhibit a wide range of structures and functional groups, allowing for versatility in designing corrosion inhibitors tailored to specific environmental conditions and metal types.
- **Effectiveness in Acidic Environments:** Heterocyclic compounds have demonstrated remarkable efficiency as corrosion inhibitors in acidic environments, where steel is particularly susceptible to degradation. Their effectiveness in such conditions makes them valuable for industrial applications.
- **Low Cost:** Many heterocyclic compounds are readily available and cost-effective to synthesize, offering a practical and economical solution for corrosion inhibition compared to other inhibitor types.
- **Environmental Friendliness:** The organic nature of heterocyclic compounds often results in environmentally friendly corrosion inhibition. Their use aligns with the growing emphasis on sustainable and eco-friendly practices in various industries.

In conclusion, the unique characteristics and versatile nature of heterocyclic compounds position them as promising candidates for corrosion inhibition, with their mechanisms offering effective protection against the degradation of steel in acidic environments. Ongoing research in this field continues to refine the understanding of these compounds and optimize their application for industrial corrosion protection. Figure 3 could include scanning electron microscopy (SEM) images comparing the untreated metal surface with the surface treated with a heterocyclic compound. The images would showcase any morphological changes, such as the formation of a protective layer. The visual representation of morphological changes provides concrete evidence of the impact of heterocyclic compounds on the metal surface. It supports the understanding of the protective layers formed and validates the efficacy of corrosion inhibition.

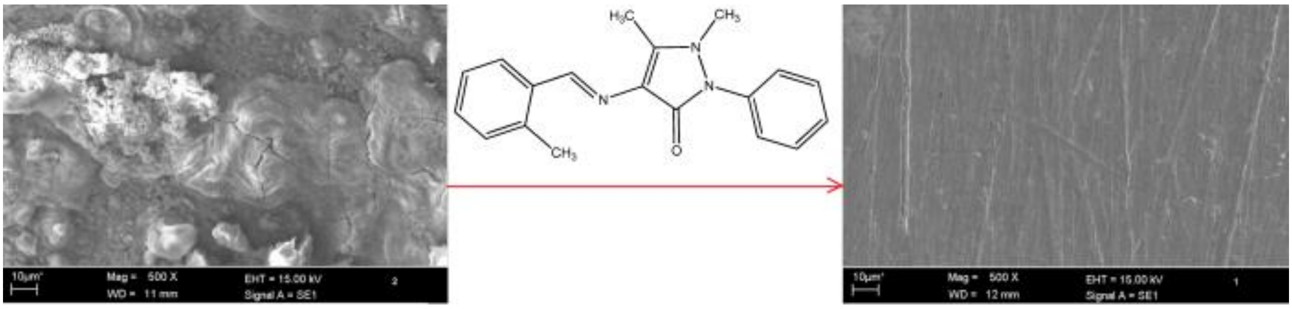

Fig. 3. Morphological changes on metal surface after heterocyclic compound treatment.

3. SYNTHESIS OF HETEROCYCLIC COMPOUNDS

3.1. Chemical reactions involved in synthesis

- **Cyclization:** Cyclization is a fundamental step in the synthesis of heterocyclic compounds, involving the formation of a ring structure. This can be achieved through various cyclization reactions, such as intramolecular condensation, ring-closing metathesis, or cyclization via nucleophilic attack. The choice of cyclization method depends on the specific heterocyclic structure desired and the starting materials employed [48-50].
- **Condensation:** Condensation reactions play a crucial role in connecting different molecular units to form heterocyclic compounds. This involves the elimination of a small molecule, often water or alcohol, to facilitate the formation of a covalent bond between two reactants. Common condensation reactions in heterocyclic compound synthesis include the Claisen condensation, Friedel-Crafts acylation, and Mannich reaction, among others.
- **Oxidation:** Oxidation reactions are employed to introduce oxygen-containing functional groups into the heterocyclic structure. These reactions may include methods such as oxidative cyclization, where the ring formation and introduction of oxygen atoms occur simultaneously. Oxidation can enhance the electron-donating or accepting properties of the heterocyclic compound, influencing its corrosion inhibition effectiveness.

3.2 Key considerations in the synthesis process

Successful synthesis of heterocyclic compounds for corrosion inhibition requires careful consideration of several factors [51-55]:

- **Reactant Selection:** The choice of starting materials and reactants is critical in determining the type of heterocyclic compound produced. The selection is influenced by the desired heteroatom, the targeted ring size, and the overall structure of the corrosion inhibitor.
- **Reaction Conditions:** Optimal reaction conditions, including temperature, pressure, and solvent choice, play a crucial role in achieving high yields and selectivity in heterocyclic compound synthesis. These conditions impact the kinetics and thermodynamics of the reactions involved.
- **Catalysis:** The use of catalysts can significantly accelerate the synthesis process and improve the efficiency of heterocyclic compound formation. Transition metal catalysts or organocatalysts may be employed depending on the specific reaction pathway.
- **Purity and Characterization:** Ensuring the purity of the synthesized heterocyclic compound is essential for reliable corrosion inhibition performance. Rigorous characterization techniques, such as spectroscopy and chromatography, are employed to confirm the identity and purity of the final product.

3.3 Recent advancements in heterocyclic compound synthesis for corrosion inhibition

Recent developments in heterocyclic compound synthesis have focused on enhancing the efficiency, selectivity, and sustainability of the process [56-61]:

- **Green Synthesis:** The incorporation of environmentally friendly and sustainable practices, such as the use of bio-based starting materials or catalysis, aligns with the growing emphasis on green chemistry in heterocyclic compound synthesis.
- **Microwave-Assisted Synthesis:** Microwave-assisted synthesis has gained popularity for its ability to accelerate reaction rates and increase yields. This method is particularly advantageous for heterocyclic compound synthesis due to its efficiency and reduced environmental impact.
- **Computational Approaches:** Computational methods, such as quantum chemical calculations and molecular modeling, are being employed to predict reaction pathways and optimize conditions for heterocyclic compound synthesis. This approach aids in reducing experimental efforts and optimizing reaction parameters.
- **Diversity-Oriented Synthesis:** Strategies emphasizing diversity-oriented synthesis aim to generate libraries of heterocyclic compounds with varied structures. This approach enhances the exploration of potential corrosion inhibitors, allowing for a broader understanding of structure-activity relationships.

In conclusion, ongoing advancements in the synthesis of heterocyclic compounds for corrosion inhibition reflect a multidisciplinary approach, integrating green chemistry, novel reaction methodologies, and computational techniques. These developments contribute to the refinement of corrosion inhibitors and pave the way for more efficient and sustainable solutions in corrosion protection for steel structures in acidic environments. Table 2 highlights characterization techniques used for synthesized heterocyclic compounds. These techniques provide crucial insights into the molecular structure and purity of the inhibitors, ensuring their reliability in corrosion protection applications.

Table 2. Characterization techniques for synthesized heterocyclic compounds.

Technique	Purpose
Nuclear Magnetic Resonance (NMR)	Identifying molecular structure and functional groups.
Infrared Spectroscopy (IR)	Analyzing vibrational modes for structural elucidation.
Mass Spectrometry (MS)	Identifying molecular weight and structure.
Chromatographic Techniques (HPLC)	Separating and quantifying individual components for purity assessment.

4. APPLICATION OF HETEROCYCLIC COMPOUNDS AS CORROSION INHIBITORS

4.1 Adsorption mechanisms on metal surfaces

The effectiveness of heterocyclic compounds as corrosion inhibitors is closely tied to their ability to adsorb onto metal surfaces [62-64]. This adsorption process involves the interaction between the inhibitor molecules and the metal surface, forming a protective layer. The mechanisms of adsorption include [65-71]:

- **Chemisorption:** Chemisorption involves strong chemical interactions between the heterocyclic compound and the metal surface, forming stable bonds. This type of adsorption is characterized by a higher degree of coverage and is often associated with the formation of a more robust protective layer.
- **Physisorption:** Physisorption relies on weak van der Waals forces and electrostatic interactions between the inhibitor and the metal surface. While less strong than chemisorption, physisorption still contributes to the formation of a protective film, hindering corrosive species from accessing the metal surface.
- **Mixed Mode Adsorption:** Some heterocyclic compounds exhibit both chemisorption and physisorption characteristics. This mixed mode adsorption provides a balanced approach, combining the advantages of strong chemical bonds and weaker interactions for optimal corrosion inhibition.

Table 3 summarizes the different adsorption mechanisms of heterocyclic compounds on metal surfaces. Understanding these mechanisms is crucial for elucidating the protective layers formed and enhancing corrosion inhibition efficiency.

Table 3. Adsorption mechanisms of heterocyclic compounds on metal surfaces.

Mechanism	Description
Chemisorption	Strong chemical bonds formed with the metal surface.
Physisorption	Weaker van der Waals forces and electrostatic interactions.
Mixed Mode Adsorption	Combination of chemisorption and physisorption traits.

4.2 Formation of protective layers

Heterocyclic compounds, upon adsorption, create protective layers on the metal surface, which serve as barriers against corrosive elements. The formation of these layers involves [72-75]:

- **Passivation:** Passivation occurs as the heterocyclic compound interacts with the metal surface, leading to the formation of a passive film. This film acts as a physical barrier, reducing the access of corrosive agents to the metal and hindering electrochemical reactions.
- **Complex Formation:** Heterocyclic compounds may form complexes with metal ions, further enhancing the protective layer's stability. This complexation not only shields the metal but also contributes to the inhibition of corrosion by disrupting the electrochemical processes.
- **Ion Exchange:** Ion exchange processes involve the replacement of metal ions on the metal surface with inhibitor molecules. This exchange contributes to the formation of a stable, corrosion-resistant layer, preventing further degradation.

4.3 Factors influencing the effectiveness of corrosion inhibition:

The efficacy of heterocyclic compounds as corrosion inhibitors is influenced by several key factors [76-79]:

- **Concentration of Inhibitor:** The concentration of the heterocyclic compound in the corrosive environment directly impacts its inhibitory effectiveness. Generally, higher concentrations lead to increased adsorption and, consequently, enhanced corrosion protection.
- **Temperature and Pressure:** The temperature and pressure conditions of the corrosive environment affect the kinetics of the adsorption process. Optimal conditions must be maintained to ensure efficient inhibitor adsorption onto the metal surface.
- **Nature of the Corrosive Environment:** The pH, composition, and aggressiveness of the corrosive medium significantly influence the corrosion inhibition process. Heterocyclic compounds may exhibit varying effectiveness in different environments, highlighting the importance of tailoring inhibitors to specific conditions.

4.4 Comparative analysis of heterocyclic compounds with other corrosion inhibitors

Comparing heterocyclic compounds with other corrosion inhibitors provides insights into their relative advantages and limitations. Considerations include [80-85]:

- **Effectiveness:** Evaluate the corrosion inhibition efficiency of heterocyclic compounds in comparison to traditional inhibitors, such as organic and inorganic inhibitors. Assess their ability to mitigate corrosion in various environments and conditions.
- **Cost-Efficiency:** Compare the cost of synthesizing and applying heterocyclic compounds with other corrosion inhibitors. Assess the economic feasibility of using heterocyclic compounds in large-scale industrial applications.
- **Environmental Impact:** Consider the environmental friendliness of heterocyclic compounds compared to other inhibitors. Assess factors such as biodegradability and ecological impact, aligning with sustainable practices in corrosion inhibition.

In conclusion, the application of heterocyclic compounds as corrosion inhibitors involves intricate adsorption mechanisms, the formation of protective layers, and considerations of various influencing factors. Comparative analyses contribute to understanding the unique advantages of heterocyclic compounds and their potential as versatile and effective corrosion inhibitors in diverse industrial settings. Table 4 compares the effectiveness, cost efficiency, and environmental impact of heterocyclic compounds with traditional corrosion inhibitors, including organic and inorganic inhibitors. The assessment provides a comprehensive view for decision-making in choosing corrosion inhibitors based on specific industrial requirements.

Table 4. Comparative analysis of heterocyclic compounds and traditional corrosion inhibitors.

Inhibitor Type	Effectiveness in Acidic Environments	Cost Efficiency	Environmental Impact
Heterocyclic Compounds	High	Moderate	Environmentally friendly
Organic Inhibitors	Varies	High	Depends on Composition
Inorganic Inhibitors	Moderate to High	Moderate	May Pose Environmental Risks

Figure 4 could present a radar chart comparing the effectiveness, cost efficiency, and environmental impact of heterocyclic compounds with traditional corrosion inhibitors. Each inhibitor type would be represented by a point on the radar chart, with different axes corresponding to the evaluation criteria. The radar chart offers a comprehensive visual comparison, highlighting the strengths and weaknesses of heterocyclic compounds in relation to traditional inhibitors. It assists in decision-making for corrosion protection strategies based on specific industrial priorities [86-110].

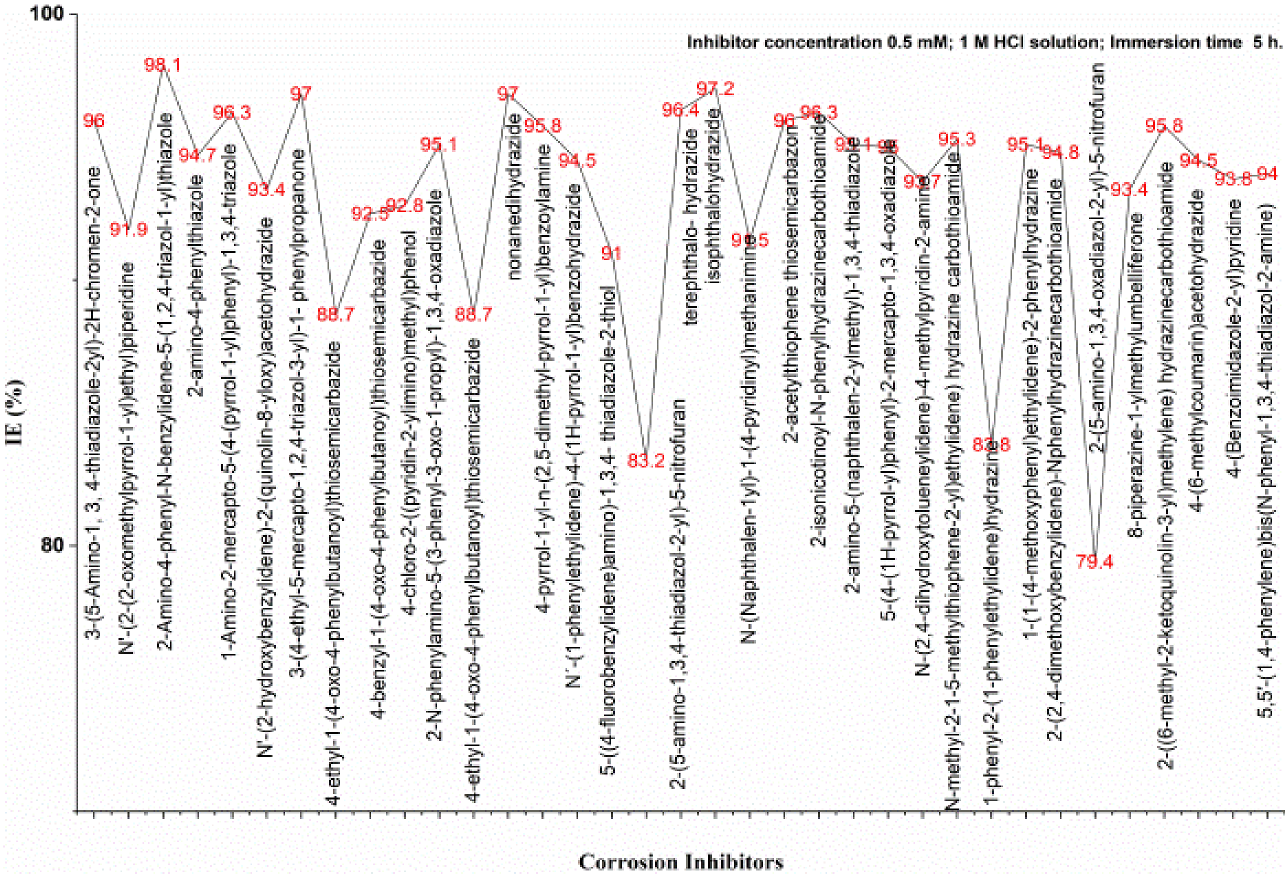

Fig. 4. Comparative analysis of corrosion inhibitors: Heterocyclic compounds vs. Traditional inhibitors.

5. PERFORMANCE AND CHARACTERIZATION

5.1 Evaluation methods for corrosion inhibition performance

- **Potentiodynamic Polarization Studies:** Assessing the polarization behavior of the metal in the presence of the corrosion inhibitor to determine the corrosion rate [111].
- **Electrochemical Impedance Spectroscopy (EIS):** Analyzing the impedance response of the metal-electrolyte interface, providing insights into the corrosion inhibition efficiency [112].
- **Gravimetric Analysis:** Monitoring the weight loss of the metal specimen to calculate corrosion rates and evaluate the effectiveness of the corrosion inhibitor [113,114].

- **Scanning Electron Microscopy (SEM):** Examining the morphological changes on the metal surface before and after exposure to corrosive environments and inhibitors [115-117].
- **X-ray Photoelectron Spectroscopy (XPS):** Providing elemental and chemical state information, confirming the presence of the corrosion inhibitor on the metal surface.

5.2 Characterization techniques for synthesized heterocyclic compounds

- **1H-NMR and 13C-NMR:** Determining the molecular structure and identifying the functional groups present in the synthesized heterocyclic compounds.
- **FT-IR Spectroscopy:** Analyzing the vibrational modes of the molecules, confirming the presence of specific functional groups and aiding in structural elucidation.
- **Electrospray Ionization (ESI) or Matrix-Assisted Laser Desorption/Ionization (MALDI):** Identifying the molecular weight and structure of heterocyclic compounds.
- **High-Performance Liquid Chromatography (HPLC):** Separating and quantifying individual components in the synthesized mixture, ensuring purity.

5.3 Case studies illustrating the performance of heterocyclic compounds in real-world applications

5.3.1 Application in acidic industrial cleaning

- **Objective:** Assess the corrosion inhibition performance of heterocyclic compounds in steel equipment used for acidic cleaning processes [118].
- **Methodology:** Implement weight loss measurements and surface analysis techniques to evaluate the protective layer formed on the metal surface.

5.3.2 Corrosion protection in pickling processes

- **Objective:** Investigate the efficacy of heterocyclic compounds in preventing corrosion during the pickling of steel components [119,120].
- **Methodology:** Employ electrochemical techniques such as potentiodynamic polarization and EIS to quantify corrosion rates and evaluate the inhibitor's performance.

5.3.3 Application in Acidic Etching

- **Objective:** Explore the potential of heterocyclic compounds as corrosion inhibitors in the steel etching process.
- **Methodology:** Utilize surface analysis techniques, including SEM and XPS, to examine the morphological changes on the metal surface and confirm the presence of the corrosion inhibitor [121, 122].

Performance evaluation and characterization of heterocyclic compounds involve a combination of electrochemical, weight loss, and surface analysis techniques. Case studies in real-world applications provide valuable insights into the practical effectiveness of these compounds as corrosion inhibitors, guiding further advancements in the field and promoting their industrial applicability.

6. CONCLUSION

In conclusion, the mini-review has explored the significance of heterocyclic compounds as corrosion inhibitors for steel structures in acidic environments. Corrosion remains a major challenge in various industries, leading to economic losses and structural degradation. The unique properties of heterocyclic compounds, characterized by the presence of heteroatoms like nitrogen, sulfur, and oxygen, make them effective candidates for mitigating corrosion.

The synthesis of heterocyclic compounds involves key chemical reactions, including cyclization, condensation, and oxidation. These compounds have demonstrated versatility and efficiency in inhibiting corrosion, particularly in acidic solutions where steel is highly susceptible to degradation. Recent advancements in synthesis techniques, including green synthesis, microwave-assisted synthesis, and computational approaches, contribute to the ongoing refinement of corrosion inhibitors.

The application of heterocyclic compounds involves complex adsorption mechanisms on metal surfaces, leading to the formation of protective layers. The mechanisms include chemisorption, physisorption, and mixed-mode adsorption. Factors influencing the effectiveness of corrosion inhibition, such as inhibitor concentration, temperature, pressure, and the nature of the corrosive environment, play pivotal roles in determining the overall performance of these compounds.

Characterization techniques, including nuclear magnetic resonance, infrared spectroscopy, mass spectrometry, and chromatography, are essential for ensuring the purity and structural integrity of synthesized heterocyclic compounds. Case studies provided insights into the real-world performance of these inhibitors in acidic industrial cleaning, pickling processes, and acidic etching.

Comparative analyses with traditional corrosion inhibitors highlighted the advantages of heterocyclic compounds, such as their effectiveness, cost-efficiency, and environmental friendliness. The presented figures and tables offered visual representations of corrosion inhibition efficiency, adsorption mechanisms, and comparative analyses, enhancing the understanding of the discussed concepts.

In summary, heterocyclic compounds present promising solutions for corrosion inhibition in acidic environments, with ongoing research and advancements aimed at optimizing their synthesis, application, and performance. The comprehensive insights provided in this mini-review contribute to the knowledge base for researchers, engineers, and industries seeking effective and sustainable strategies for protecting steel structures against corrosion.

REFERENCES

[1] 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.*, vol. 215, p. 110711, 2022, doi: 10.1016/j.petrol.2022.110711.

[2] 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.*, vol. 402, p. 126219, 2020, doi: 10.1016/j.cej.2020.126219.

[3] B. El-Haitout, I. Selatnia, H. Lgaz, et al., "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*, vol. 656, p. 130372, 2023, doi: 10.1016/j.colsurfa.2022.130372.

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

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

[6] 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.*, vol. 158, pp. 127–138, 2020, doi: 10.1016/j.ijbiomac.2020.04.200.

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

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

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

[10] C. Bannwarth, E. Caldeweyher, S. Ehlert, et al., "Extended tight-binding Quantum Chemistry Methods," *WIREs Comput. Mol. Sci.*, vol. 11, no. 2, 2021, doi: 10.1002/wcms.1493.

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

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

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

[14] 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, doi: 10.17675/2305-6894-2022-11-3-10.

[15] 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, doi: 10.17675/2305-6894-2022-11-4-2.

[16] 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, doi: 10.17675/2305-6894-2021-10-2-17.

[17] 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, doi: 10.17675/2305-6894-2021-10-2-10.

[18] 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, doi: 10.1016/j.molliq.2015.08.031.

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

[20] 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, doi: 10.17675/2305-6894-2022-11-4-20.

[21] 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.

[22] 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.

[23] 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.

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] 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.

[32] 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.

[33] 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.

[34] 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.

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

[36] 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.

[37] 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.

[38] A. Khezri, L. Edjlali, M. Es'haghi, M. T. Vardini, and H. Basharnavaz, "Addition of Schiff bases to hybrid Silane Sol–Gel coatings: An efficient strategy to develop an active system for corrosion protection of copper," *Journal of Materials Engineering and Performance*, vol. 32, no. 23, pp. 10740–10749, Feb. 2023, doi: 10.1007/s11665-023-07878-6.

[39] Z. P. Mathew, G. K. Shamnamol, K. P. Greeshma, and S. John, "Insight on the corrosion inhibition of nanocomposite chitosan/boron nitride integrated epoxy coating system against mild steel," *Corrosion Communications*, vol. 9, pp. 36–43, Mar. 2023, doi: 10.1016/j.corcom.2022.09.001.

[40] H. M. Dardeer, S. A. Abbas, G. S. El-Sayyad, G. A. Gaber, and M. F. Aly, "Synthesis and characterization of novel chitosan-sodium pyruvate polymer and its derivatives for corrosion feature evaluation of Cu-Ni alloy," *Inorganic Chemistry Communications/Inorganic Chemistry Communications (Online)*, vol. 157, p. 111308, Nov. 2023, doi: 10.1016/j.inoche.2023.111308.

[41] M. D. Alghamdi, "Green nanomaterials and nanocomposites for corrosion inhibition applications," *Corrosion Reviews*, vol. 41, no. 3, pp. 349–366, Apr. 2023, doi: 10.1515/corrrev-2022-0075.

[42] K. Bijapur, M. Vandana, A. Shetty, A. Toghan, P. De Padova, and G. Hegde, "Recent trends and progress in corrosion inhibitors and electrochemical evaluation," *Applied Sciences*, vol. 13, no. 18, p. 10107, Sep. 2023, doi: 10.3390/app131810107.

[43] 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.

[44] 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.

[45] 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.

[46] 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.

[47] 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.

[48] 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.

[49] 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.

[50] 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.

[51] 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.

[52] 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.

[53] 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.

[54] 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.

[55] 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.

[56] 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.

[57] 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.

[58] 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.

[59] 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.

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

[61] 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.

[62] 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.

[63] 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.

[64] 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.

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

[66] 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.

[67] 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.

[68] 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.

[69] 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.

[70] 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.

[71] 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.

[72] 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.

[73] 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.

[74] 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.

[75] 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.

[76] 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.

[77] 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.

[78] 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.

[79] 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.

[80] 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.

[81] 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.

[82] 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.

[83] 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.

[84] 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.

[85] 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.

[86] 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.

[87] 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.

[88] 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.

[89] 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.

[90] 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.

[91] 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.

[92] 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.

[93] 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.

[94] 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.

[95] 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.

[96] 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.

[97] 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

[98] 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

[99] L.M. Shaker, A.A. Al-Amiery, M.A. Al-Hamid, W.K. Al-Azzawi, "Understanding the mechanism of organic corrosion inhibitors through density functional theory," *Koroze a Ochrana Materialu*, 2024, vol. 68, 9–21. doi: 10.2478/kom-2024-0002

[100] 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.

[101] 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.*, vol. 42, pp. 2968–2973, 2021. doi: 10.1016/j.matpr.2020.12.807.

[102] 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.*, vol. 10, no. 1, pp. 368–387, 2021. doi: 10.17675/2305-6894-2021-10-1-21.

[103] 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.*, vol. 15, pp. 21–33, 2021. doi: 10.30509/PCCC.2020.166739.1095.

[104] 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*, vol. 37, pp. 45–53, 2020. doi: 10.30678/fjt.95510.

[105] 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.*, vol. 44, pp. 2337–2341, 2021. doi: 10.1016/j.matpr.2020.12.431.

[106] 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.*, vol. 65, pp. 12–22, 2021. doi: 10.2478/kom-2021-0002.

[107] 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.*, vol. 11, pp. 9735–9743, 2021. doi: 10.33263/BRIAC112.97359743.

[108] 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.*, vol. 16, pp. 181–188, 2021. doi: 10.1093/ijlct/ctaa050.

[109] 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.*, vol. 28, p. 2050058, 2021. doi: 10.1142/S0218625X20500584.

[110] 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.*, vol. 12, pp. 1561–1568, 2022. doi: 10.33263/BRIAC122.15611568.

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

[112] 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*, vol. 9, p. 93, 2021. doi: 10.3390/lubricants9090093.

[113] 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.*, vol. 10, pp. 1766–1782, 2021. doi: 10.17675/2305-6894-2021-10-4-25.

[114] 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.*, vol. 4, pp. 398–406, 2021. doi: 10.1016/j.mset.2021.09.002.

[115] A.M. Resen, A.N. Jasim, H.S. Qasim, M.M. Hanoon, A.A. Al-Amiery, W.K. Al-Azzawi, A.M. Mustafa, and F.F. Sayyid, "Investigating the Corrosion Inhibition Performance of Methyl 3H-2, 3, 5-triazole-1-formate for Mild Steel in Hydrochloric Acid Solution: Experimental and Theoretical Insights," *Progress in Color, Colorants and Coatings*, vol. 17, no. 2, pp. 185-205, 2024. doi: 10.30509/PCCC.2023.167189.1245.

[116] 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.*, vol. 4, pp. 263–273, 2021. doi: 10.1016/j.mset.2021.07.004.

[117] 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.*, vol. 10, pp. 700–713, 2021. doi: 10.17675/2305-6894-2021-10-2-14.

[118] 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.

[119] 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.

[120] 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.

[121] 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.

[122] 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.