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Review article

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

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A B S T R A C T

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.

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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.

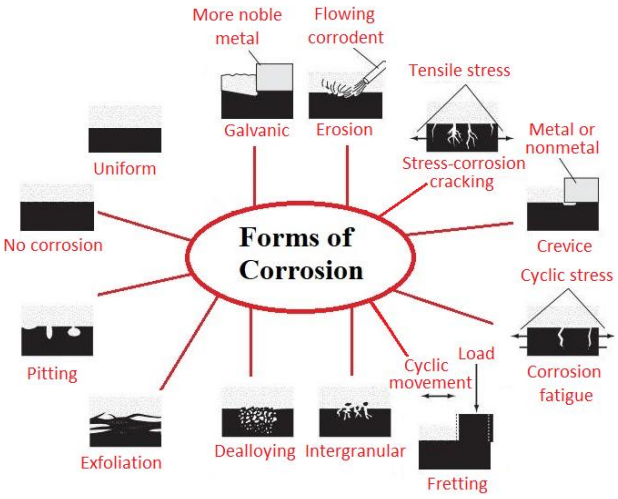


Fig. 1. Types of corrosion.

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.

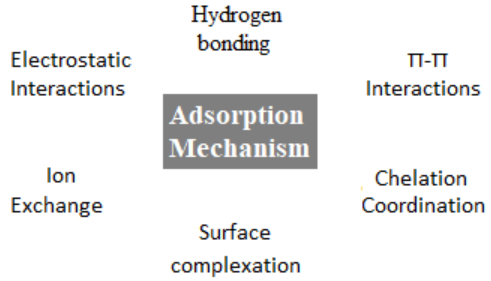


Fig. 2. Adsorption mechanisms of heterocyclic compounds on metal surfaces.

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.

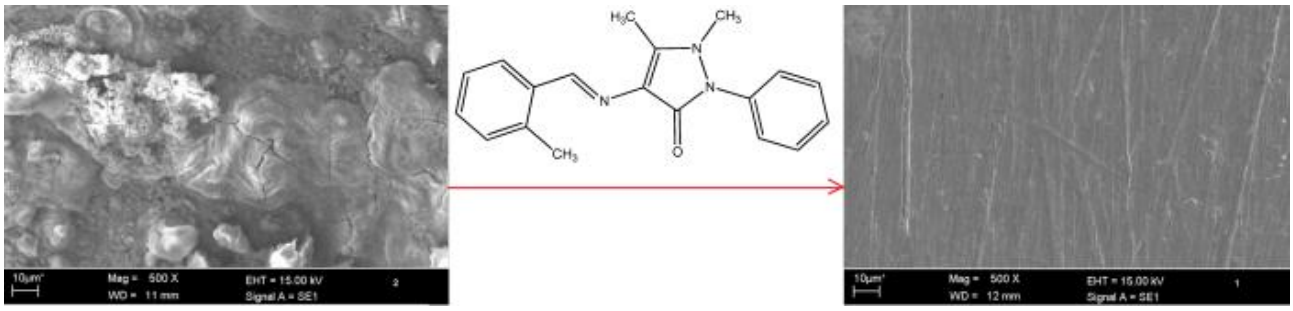


Fig. 3. Morphological changes on metal surface after heterocyclic compound treatment.

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].

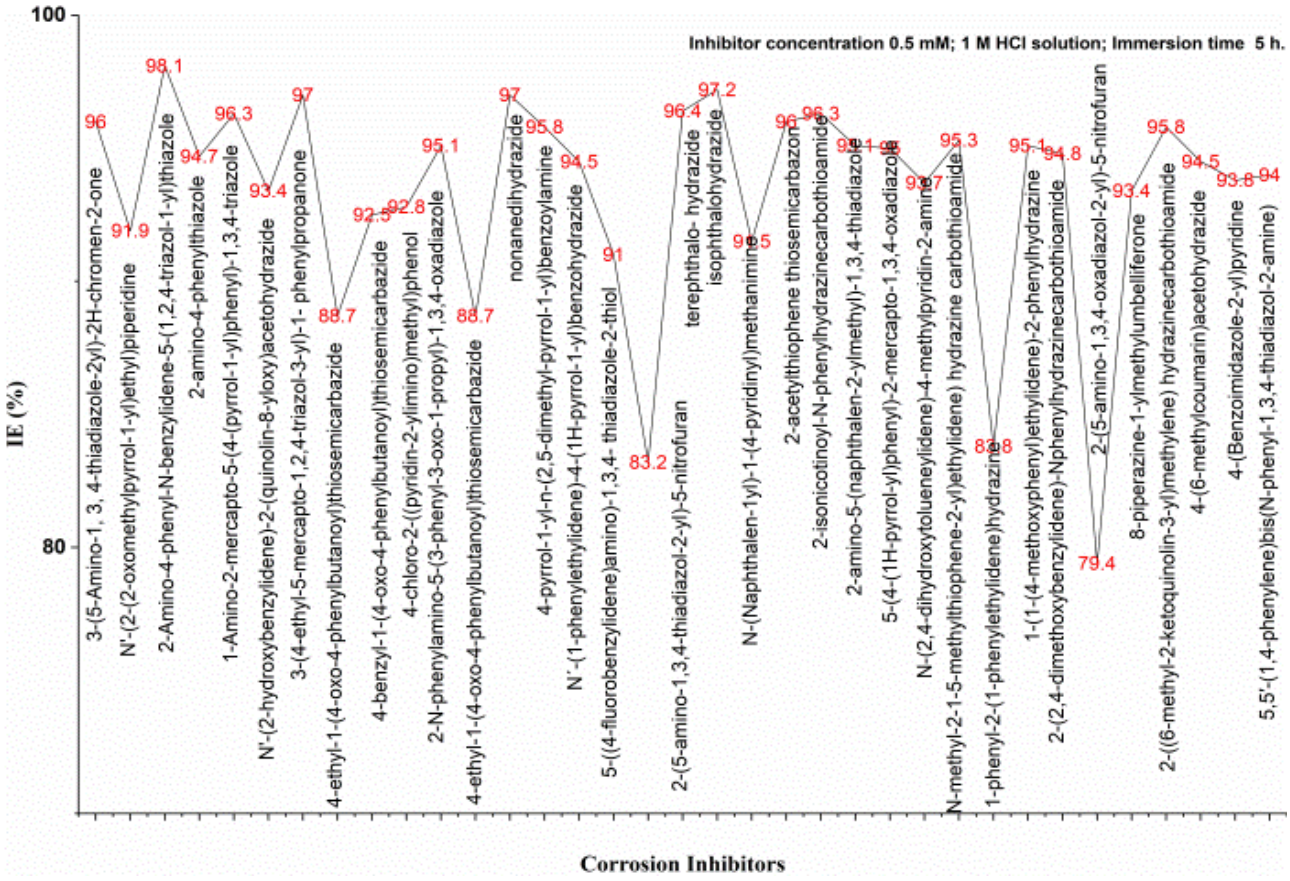


Fig. 4. Comparative analysis of corrosion inhibitors: Heterocyclic compounds vs. Traditional inhibitors.

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.

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