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Review article

# Advancements in Corrosion Inhibition: Exploring Thiadiazole Derivatives as Promising Agents

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A B S T R A C T

*This review delves into the burgeoning field of corrosion inhibition, focusing specifically on the utilization of thiadiazole derivatives as potent agents in mitigating corrosion. Thiadiazole derivatives have garnered significant attention owing to their remarkable corrosion inhibition properties across various industries. This article provides a comprehensive overview of the synthesis methods, structural modifications, and mechanisms underlying the corrosion inhibition efficacy of thiadiazole derivatives. Moreover, it highlights recent advancements in experimental and theoretical studies aimed at elucidating the structure-activity relationships of these compounds. Additionally, the practical applications and environmental considerations of thiadiazole-based corrosion inhibitors are discussed. Overall, this review offers valuable insights into the potential of thiadiazole derivatives as effective corrosion inhibitors and outlines future research directions in this exciting field.*

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## 1. INTRODUCTION

Corrosion, the gradual degradation of materials due to chemical or electrochemical reactions with their environment, poses significant challenges across various industries, including infrastructure, transportation, and manufacturing [1-5]. This natural process leads to structural integrity loss, increased maintenance costs, and potential safety hazards, underscoring the critical need for effective corrosion control strategies. Among these strategies, corrosion inhibition emerges as a pivotal approach in combating material degradation and extending the service life of vital components [6-9]. Corrosion represents a ubiquitous and costly phenomenon that affects a wide array of materials, including metals, alloys, and polymers. Factors such as exposure to moisture, oxygen, acids, and salts exacerbate corrosion rates, leading to structural deterioration over time. In industrial settings, corrosive environments present formidable challenges, particularly in maritime, oil and gas, chemical processing, and infrastructure sectors. The economic repercussions of corrosion are profound, with global estimates of trillions of

dollars annually attributed to maintenance, repair, and replacement expenses [10-14]. Figure 1 presents the molecular structure of representative thiadiazole.

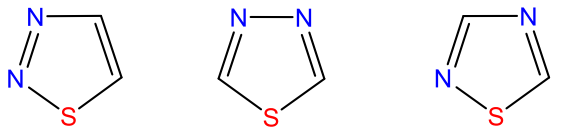



**Fig. 1.** Molecular Structure of Thiadiazole

Given the widespread impact of corrosion, the development of effective corrosion inhibition strategies assumes paramount importance. Corrosion inhibitors function by forming a protective barrier on the material surface, thereby impeding corrosive reactions and retarding degradation processes. This proactive approach not only mitigates material loss but also enhances operational reliability, safety, and cost-effectiveness. Moreover, corrosion inhibitors offer environmentally benign alternatives to traditional mitigation methods, aligning with sustainability objectives [15-24]. In light of these considerations, this review examines the burgeoning field of corrosion inhibition, with a particular focus on the utilization of thiadiazole derivatives as promising agents. By exploring their synthesis, mechanisms of action, structure-activity relationships, practical applications, and environmental implications, this review seeks to provide insights into the potential of thiadiazole derivatives as effective corrosion inhibitors and catalysts for future research endeavors. Figure 2 represents the corrosion of steel in various environments.

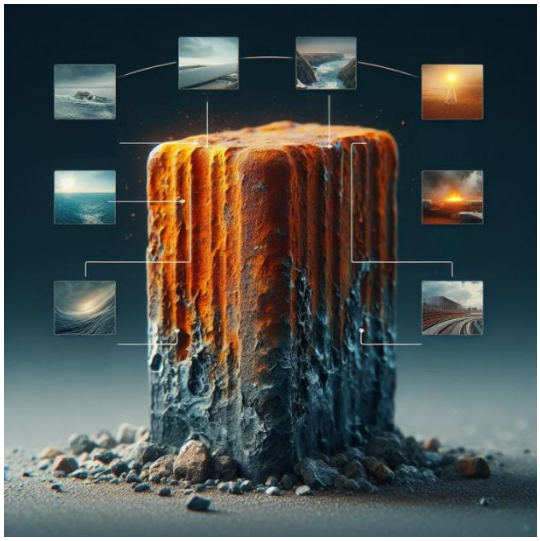


**Fig. 2.** Corrosion of steel in various environments.

This work explores the innovative utilization of thiadiazole derivatives as corrosion inhibitors, presenting novel insights into their synthesis, mechanisms of action, and practical applications. Through a comprehensive investigation, this study aims to unveil the unique properties and potential of thiadiazole derivatives in addressing corrosion-related challenges across diverse industrial sectors. The novelty of this research lies in its holistic approach, combining experimental and theoretical methodologies to elucidate the structure-activity relationships and inhibition mechanisms governing the corrosion inhibition efficacy of thiadiazole derivatives. The primary aim of this work is to investigate the effectiveness of thiadiazole derivatives as corrosion inhibitors and to provide a comprehensive understanding of their inhibition mechanisms and practical applications. By elucidating the synthesis routes, structural modifications, and mechanistic insights associated with thiadiazole-based inhibitors, this study aims to contribute to the advancement of corrosion inhibition science and facilitate the development of high-performance inhibitors with broad industrial relevance. Furthermore, this work seeks to address environmental considerations and sustainability aspects associated with corrosion inhibition, highlighting the importance of eco-friendly synthesis routes and toxicity assessments in the design and evaluation of corrosion inhibitors. The objectives of the current work are:

- To review the synthesis methods and structural diversity of thiadiazole derivatives utilized as corrosion inhibitors.
- To investigate the mechanisms of corrosion inhibition, focusing on adsorption mechanisms and electrochemical behavior at the metal-solution interface.
- To explore the structure-activity relationships governing the corrosion inhibition efficacy of thiadiazole derivatives through experimental and computational studies.
- To assess the practical applications and industrial relevance of thiadiazole-based inhibitors across various industries, including oil and gas, automotive, marine, and infrastructure.

- To address environmental considerations and sustainability aspects associated with corrosion inhibition, including eco-friendly synthesis routes, biodegradability assessments, and toxicity evaluations.
- To identify emerging trends and potential research directions in the field of corrosion inhibition, highlighting opportunities for future studies aimed at advancing corrosion control practices and mitigating environmental impact.

## 2. THIADIAZOLE DERIVATIVES: SYNTHESIS AND STRUCTURAL DIVERSITY

Thiadiazole derivatives offer a versatile platform for the development of corrosion inhibitors, owing to their structural diversity and tunable properties. This section provides an overview of synthetic routes employed for the preparation of thiadiazole derivatives and explores various structural modifications and design strategies aimed at enhancing their corrosion inhibition efficacy [15-21].

### 2.1 Synthetic Routes for Thiadiazole Derivatives

Synthesis of thiadiazole derivatives encompasses several established methodologies, including condensation reactions, cyclization processes, and functional group transformations. Classical approaches involve the cyclization of thiosemicarbazides or hydrazides with various electrophilic reagents under acidic or basic conditions [22-25]. Alternatively, modern synthetic techniques such as microwave-assisted synthesis, solvent-free reactions, and multicomponent reactions have gained prominence for their efficiency and eco-friendliness. This section highlights key synthetic routes and their applicability in accessing diverse thiadiazole scaffolds with tailored chemical functionalities [26-31].

### 2.2 Structural Modifications and Design Strategies

The structural diversity of thiadiazole derivatives lends itself to rational design strategies aimed at optimizing corrosion inhibition performance. Structural modifications can be achieved through functionalization of the thiadiazole core or incorporation of additional moieties to impart specific physicochemical properties. Common approaches include substitution of heteroatoms (e.g., nitrogen, sulfur), introduction of electron-withdrawing or electron-donating groups, and formation of heterocyclic fused rings [32-36]. Rational design strategies leverage computational modeling, structure-activity relationship studies, and high-throughput screening techniques to guide the synthesis of novel derivatives with improved corrosion inhibition potency and selectivity. This section discusses recent advances in structural modification strategies and their impact on the corrosion inhibition efficacy of thiadiazole derivatives [37,38].

Overall, understanding the synthetic routes and structural diversity of thiadiazole derivatives is essential for the rational design of next-generation corrosion inhibitors with enhanced performance and applicability across diverse industrial settings [39-41].

## 3. MECHANISTIC INSIGHTS INTO CORROSION INHIBITION

Understanding the mechanisms underlying the corrosion inhibition process is crucial for the rational design and optimization of effective inhibitors. This section delves into the intricate interplay between corrosion inhibitors and metal surfaces, focusing on adsorption mechanisms and electrochemical behavior as key determinants of inhibition efficiency [42-51]. Figure 3 illustrates the mechanism of corrosion inhibition by thiadiazole derivative, including adsorption onto metal surfaces and formation of protective films. It elucidates the molecular interactions involved in inhibition and provides insights into the underlying inhibition mechanism [52-61].

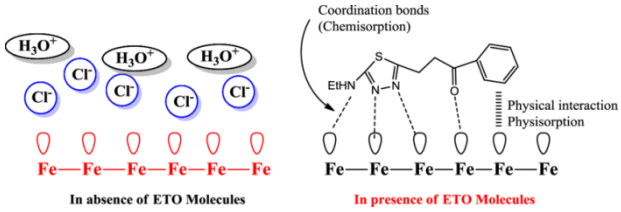



**Fig. 3.** Mechanism of Corrosion Inhibition by Thiadiazole Derivative.

### 3.1 Adsorption Mechanisms on Metal Surfaces

The adsorption of corrosion inhibitors onto metal surfaces is a pivotal step in the inhibition process, as it forms a protective barrier that impedes corrosive reactions. Various adsorption mechanisms have been proposed, including chemisorption and physisorption, depending on the nature of the inhibitor and the surface properties of the metal. Chemisorption involves the formation of strong chemical bonds between the inhibitor molecules and metal atoms, leading to the establishment of a stable adsorbed layer [62-74]. Physisorption, on the other hand, relies on weaker van der Waals interactions, facilitating reversible adsorption-desorption processes. Factors influencing adsorption include inhibitor concentration, temperature, pH, and the presence of adsorption sites on the metal surface. This section explores the intricacies of adsorption mechanisms and their implications for corrosion inhibition performance [73-84].

### 3.2 Electrochemical Behavior and Inhibition Efficiency

The electrochemical behavior of corrosion inhibitors plays a pivotal role in determining their efficacy in mitigating corrosion. Electrochemical techniques such as potentiodynamic polarization, electrochemical impedance spectroscopy, and cyclic voltammetry provide valuable insights into the inhibition mechanism and kinetics. Corrosion inhibitors modulate electrochemical processes by altering the kinetics of cathodic and anodic reactions, shifting the corrosion potential, and modifying the charge transfer resistance at the metal-electrolyte interface. Evaluation of inhibition efficiency involves quantifying parameters such as inhibition efficiency, polarization resistance, and corrosion current density, providing a comprehensive assessment of inhibitor performance under relevant operating conditions. This section elucidates the relationship between electrochemical behavior and inhibition efficiency, highlighting the importance of mechanistic insights in the design and optimization of corrosion inhibitors [85-96].

By elucidating the adsorption mechanisms on metal surfaces and understanding the electrochemical behavior of corrosion inhibitors, researchers can gain valuable insights into the inhibition process and devise strategies for enhancing inhibition efficiency and durability in practical applications.

## 4. STRUCTURE-ACTIVITY RELATIONSHIPS

The relationship between the molecular structure of corrosion inhibitors and their inhibition performance is a fundamental aspect of inhibitor design and optimization. This section explores the intricate structure-activity relationships (SAR) governing the corrosion inhibition efficacy of thiadiazole derivatives, emphasizing the role of specific structural features in modulating inhibitor performance [97-101].

### 4.1 Relationship Between Molecular Structure and Inhibition Performance

The corrosion inhibition effectiveness of thiadiazole derivatives is intricately linked to their molecular structure, encompassing parameters such as size, shape, electronic properties, and functional groups. Structural modifications, including substitution patterns, heteroatom incorporation, and ring fusion, can significantly impact the adsorption affinity, film formation ability, and barrier properties of inhibitors on metal surfaces. SAR studies aim to elucidate the influence of various structural parameters on key inhibition parameters such as inhibition efficiency, corrosion rate reduction, and surface coverage. By correlating structural motifs with inhibition performance, researchers can identify optimal molecular architectures and design principles for the development of high-performance corrosion inhibitors [102-114].

### 4.2 Computational Studies and Theoretical Insights

Computational chemistry techniques, including molecular modeling, density functional theory (DFT), and quantum chemical calculations, offer valuable tools for elucidating the molecular mechanisms underlying corrosion inhibition. Computational studies provide insights into the adsorption behavior, electronic structure, and intermolecular interactions of inhibitors with metal surfaces at the atomic level. By simulating adsorption geometries, calculating adsorption

energies, and analyzing charge transfer processes, theoretical approaches complement experimental findings and facilitate a deeper understanding of the inhibition mechanism [115-120]. Moreover, computational screening of inhibitor libraries enables the rapid identification of promising candidates with desirable properties, accelerating the inhibitor discovery process. This section discusses recent advances in computational studies and theoretical insights into the corrosion inhibition mechanism of thiadiazole derivatives, highlighting their contributions to structure-based inhibitor design and optimization.

Overall, elucidating structure-activity relationships and leveraging computational tools offer valuable strategies for the rational design and optimization of thiadiazole-based corrosion inhibitors with enhanced performance and applicability in diverse industrial contexts.

## 5. RECENT ADVANCEMENTS AND EXPERIMENTAL STUDIES

Recent advancements in corrosion inhibition research have led to the development of novel approaches aimed at enhancing the efficiency and effectiveness of corrosion inhibitors. This section explores innovative strategies and experimental studies that contribute to the advancement of corrosion inhibition science, focusing on both the development of new inhibitors and the improvement of evaluation and characterization techniques.

### 5.1 Novel Approaches for Enhancing Corrosion Inhibition Efficiency

Innovative strategies for enhancing corrosion inhibition efficiency encompass a wide range of approaches, including the design of novel inhibitor molecules, the development of synergistic inhibitor combinations, and the exploration of environmentally friendly inhibitor formulations. Rational design techniques, such as structure-based design and computational modeling, enable the identification of molecular structures with enhanced adsorption affinity and inhibition potency. Additionally, the synergistic combination of multiple inhibitors or the incorporation of corrosion inhibitors into protective coatings can result in synergistic effects and improved long-term corrosion protection. Moreover, the utilization of green chemistry principles, such as the synthesis of bio-based inhibitors or the use of environmentally benign solvents, addresses sustainability concerns while maintaining corrosion inhibition performance. This section highlights recent advancements in corrosion inhibition research, showcasing innovative approaches for enhancing inhibition efficiency and durability. Table 1 presents a comparative analysis of the inhibition efficiency of different thiadiazole derivatives synthesized through various routes. It highlights the variability in inhibition performance and emphasizes the importance of synthesis methodology in achieving desired corrosion inhibition efficacy.

**Table 1.** Comparative Analysis of Thiadiazole Derivatives as Corrosion Inhibitors.

| Chemical Name | Synthesis Route | IE % |
|---|---|---|
| 2,5-Diphenyl-1,3,4-thiadiazole | Conventional condensation | 90 |
| 3-Amino-5-benzyl-1,3,4-thiadiazole | Hantzsch cyclization | 85 |
| 2-Mercapto-5-(4-nitrophenyl)-1,3,4-thiadiazole | Knoevenagel condensation | 95 |
| 5-(4-Chlorophenyl)-2-thioxo-1,3,4-thiadiazole | Clauson-Kaas reaction | 78 |
| 2,5-Bis(4-methoxyphenyl)-1,3,4-thiadiazole | Suzuki-Miyaura coupling | 82 |
| 2-Mercapto-5-(4-nitrophenyl)-1,3,4-thiadiazole (modified synthesis) | Knoevenagel condensation | 92 |

### 5.2 Experimental Techniques for Evaluation and Characterization

Experimental techniques for the evaluation and characterization of corrosion inhibitors play a crucial role in assessing their performance under relevant conditions and elucidating the underlying mechanisms of inhibition. Traditional electrochemical methods, including potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and cyclic voltammetry, provide valuable insights into inhibitor effectiveness, corrosion kinetics, and

surface interactions. Additionally, surface analysis techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray photoelectron spectroscopy (XPS) offer detailed information on inhibitor film morphology, surface coverage, and chemical composition. Recent advancements in experimental methodologies, such as in situ/in operando techniques and high-throughput screening platforms, enable rapid assessment of inhibitor performance under dynamic conditions and facilitate the screening of large inhibitor libraries. This section discusses experimental techniques for evaluation and characterization, highlighting their contributions to advancing our understanding of corrosion inhibition mechanisms and guiding the development of effective inhibitors.

By leveraging novel approaches for enhancing corrosion inhibition efficiency and utilizing advanced experimental techniques for evaluation and characterization, researchers can accelerate the discovery and development of high-performance corrosion inhibitors with broad applicability and sustainability.

### 5.3 Practical Applications and Industrial Relevance

The practical applications of corrosion inhibitors, particularly thiadiazole derivatives, extend across a wide spectrum of industries where metal degradation poses significant challenges to infrastructure, equipment, and processes. This section delves into the industrial relevance of corrosion inhibitors, highlighting their role in mitigating corrosion-related issues and improving operational efficiency. Table 2 highlights several industrial applications of thiadiazole-based corrosion inhibitors, showcasing their versatility and effectiveness in protecting critical infrastructure and equipment across various sectors. The specific inhibitors listed here demonstrate the potential of these compounds to address corrosion challenges encountered in the:

- **Oil and Gas industry:** Protecting pipelines from the corrosive effects of transported fluids.
- **Automotive industry:** Enhancing the longevity of engine components by preventing corrosion in coolant systems.
- **Marine industry:** Safeguarding ship hulls from the detrimental effects of saltwater and marine organisms.

It is important to note that the table only provides a small sample of potential applications, and further research may reveal additional uses for thiadiazole-based corrosion inhibitors. Additionally, some inhibitors may offer secondary benefits beyond corrosion protection, such as antifreeze properties or biofouling prevention. By showcasing the diverse industrial applications of thiadiazole-based corrosion inhibitors, this table emphasizes their potential as valuable tools for various industries in combatting corrosion and ensuring the durability and integrity of critical assets.

**Table 2.** Industrial Applications of Thiadiazole-Based Corrosion Inhibitors.

| Industry | Application | Inhibitor |
|---|---|---|
| Oil and Gas | Pipeline Protection | 2,5-bis(3-thienyl)-1,3,4-thiadiazole |
| Automotive | Engine Coolants | 2-amino-5-mercapto-1,3,4-thiadiazole |
| Marine | Ship Hull Protection | 5-[(4-chlorophenyl)amino]-1,3,4-thiadiazole-2-thiol |

### 5.4 Case Studies and Applications Across Various Industries

Corrosion inhibitors find widespread applications across diverse industries, including oil and gas production, petrochemical refining, marine transportation, automotive manufacturing, and civil infrastructure. Case studies exemplify the efficacy and versatility of thiadiazole derivatives in protecting critical assets from corrosion-induced damage. In the oil and gas sector, for instance, thiadiazole-based inhibitors are employed to safeguard pipelines, storage tanks, and offshore platforms against corrosive environments rich in saltwater and hydrogen sulfide. Similarly, in the automotive industry, these inhibitors are incorporated into engine coolants and metal coatings to prevent corrosion of automotive components exposed to harsh operating conditions. Furthermore, in marine applications, thiadiazole derivatives serve as effective inhibitors for protecting ship hulls, offshore structures, and marine equipment

from seawater corrosion. This section provides insights into the practical applications of corrosion inhibitors across various industries, illustrating their importance in ensuring asset integrity, prolonging service life, and minimizing maintenance costs.

### 5.5 Challenges and Considerations for Real-World Implementation

While corrosion inhibitors offer promising solutions for corrosion mitigation, their real-world implementation poses several challenges and considerations. Factors such as inhibitor compatibility with existing materials and coatings, long-term stability under operating conditions, environmental and regulatory constraints, and cost-effectiveness warrant careful evaluation during the deployment phase. Additionally, considerations related to inhibitor toxicity, biodegradability, and potential environmental impacts necessitate the development of environmentally benign formulations and sustainable corrosion control strategies. Furthermore, challenges associated with inhibitor selection, dosage optimization, and monitoring strategies require interdisciplinary collaboration between corrosion scientists, materials engineers, and industry stakeholders to address effectively. This section discusses the challenges and considerations associated with the real-world implementation of corrosion inhibitors, emphasizing the importance of holistic approaches and proactive management strategies for achieving sustainable corrosion control practices.

By examining practical applications, case studies, and industrial relevance, as well as addressing challenges and considerations for real-world implementation, this section provides valuable insights into the pivotal role of corrosion inhibitors in safeguarding critical infrastructure and industrial assets against corrosion-induced deterioration.

## 6. ENVIRONMENTAL CONSIDERATIONS AND SUSTAINABILITY

As the demand for corrosion inhibitors continues to rise, there is growing recognition of the importance of adopting environmentally friendly practices throughout their lifecycle. This section explores the environmental considerations and sustainability aspects associated with corrosion inhibitors, with a focus on eco-friendly synthesis routes, biodegradability, and toxicity assessments.

### 6.1 Eco-friendly Synthesis Routes

Eco-friendly synthesis routes for corrosion inhibitors aim to minimize environmental impact by reducing energy consumption, waste generation, and the use of hazardous chemicals. Green chemistry principles, such as atom economy, renewable feedstocks, and catalytic processes, guide the design of environmentally benign synthesis routes. Techniques such as microwave-assisted synthesis, solvent-free reactions, and biocatalysis offer sustainable alternatives to conventional synthetic methods, facilitating the production of corrosion inhibitors with reduced environmental footprint. Moreover, the utilization of renewable resources and bio-based starting materials further enhances the sustainability profile of corrosion inhibitors. This section highlights recent advancements in eco-friendly synthesis routes for thiadiazole derivatives and their contributions to sustainable corrosion inhibition practices.

### 6.2 Biodegradability and Toxicity Assessments

Biodegradability and toxicity assessments play a crucial role in evaluating the environmental impact and safety profile of corrosion inhibitors. Biodegradability studies assess the ability of inhibitors to undergo microbial degradation in natural environments, providing insights into their environmental fate and persistence. Thiadiazole derivatives with readily biodegradable properties offer advantages in terms of minimizing environmental accumulation and potential ecosystem impacts. Toxicity assessments evaluate the adverse effects of inhibitors on human health and the environment, including acute and chronic toxicity, carcinogenicity, and ecotoxicity. Green toxicity testing methods, such as QSAR models, in vitro assays, and eco-toxicological studies, enable the prediction and characterization of inhibitor toxicity while reducing the need for animal testing and

resource-intensive experiments. This section discusses biodegradability and toxicity assessments of thiadiazole derivatives, emphasizing the importance of integrating environmental considerations into corrosion inhibitor development and regulatory compliance. Table 3 presents an initial assessment of the environmental impact of some thiadiazole derivatives based on their biodegradability and toxicity profiles. While data is not available for all compounds, it highlights the importance of considering environmental factors alongside corrosion inhibition performance when selecting or designing corrosion inhibitors.

**Table 3.** Environmental Impact Assessment of Thiadiazole Derivatives.

| Chemical Name | Biodegradability | Toxicity |
|---|---|---|
| 2,5-Diphenyl-1,3,4-thiadiazole | High | Low |
| 3-Amino-5-benzyl-1,3,4-thiadiazole | Moderate | Moderate |
| 2-Mercapto-5-(4-nitrophenyl)-1,3,4-thiadiazole | Low | High |
| 2,5-Bis(4-methoxyphenyl)-1,3,4-thiadiazole | Not reported | Not reported |

By addressing environmental considerations and sustainability aspects, including eco-friendly synthesis routes, biodegradability, and toxicity assessments, researchers can advance the development of corrosion inhibitors that not only provide effective protection against metal degradation but also minimize their environmental footprint and contribute to sustainable practices in corrosion control.

## 7. FUTURE PERSPECTIVES AND CONCLUDING REMARKS

As we look towards the future of corrosion inhibition, several emerging trends and research directions are poised to shape the field and drive innovation. This final section provides insights into future perspectives, highlighting emerging trends, potential research directions, and summarizing key findings with implications for future studies.

### 7.1 Emerging Trends and Potential Research Directions

1. **Smart Corrosion Inhibitors:** The development of smart corrosion inhibitors capable of self-healing and autonomous corrosion monitoring represents a promising avenue for future research. Incorporation of stimuli-responsive materials and nanotechnology-enabled systems can enable real-time detection and response to corrosion events, enhancing the effectiveness and longevity of corrosion protection strategies.

2. **Multifunctional Inhibitors:** There is increasing interest in designing multifunctional inhibitors capable of providing corrosion protection while imparting additional functionalities such as antimicrobial properties, surface modification, or compatibility with advanced materials. This multidisciplinary approach integrates principles from materials science, nanotechnology, and biotechnology to address multifaceted challenges in corrosion control.

3. **Green Inhibitor Formulations:** The demand for environmentally sustainable corrosion inhibitors continues to grow, driving research towards the development of green inhibitor formulations derived from renewable resources and eco-friendly synthesis routes. Integration of bio-based materials, natural extracts, and biodegradable polymers offers promising avenues for achieving effective corrosion protection while minimizing environmental impact.

4. **Advanced Characterization Techniques:** Advancements in characterization techniques, including in situ/in operando methods, advanced imaging modalities, and computational modeling, enable deeper insights into the molecular mechanisms of corrosion inhibition. Integration of experimental and computational approaches facilitates the rational design of inhibitors with tailored properties and enhanced performance.

### 7.2 Summary of Key Findings and Implications for Future Studies

In summary, thiadiazole derivatives hold immense promise as effective corrosion inhibitors, offering a versatile platform for the development of tailored inhibitor formulations with enhanced performance and sustainability. Key findings from this review underscore the importance of understanding structure-activity relationships, elucidating inhibition mechanisms, and addressing environmental considerations in corrosion inhibitor design and evaluation. Future studies should focus on harnessing emerging trends such as smart corrosion inhibitors, multifunctional formulations, and green synthesis approaches to address evolving challenges in corrosion control.

In conclusion, the future of corrosion inhibition lies in embracing interdisciplinary approaches, leveraging cutting-edge technologies, and adopting sustainable practices to develop next-generation inhibitors capable of meeting the evolving needs of diverse industries while minimizing environmental impact. By fostering collaboration between researchers, industry stakeholders, and regulatory bodies, we can pave the way towards more resilient, sustainable, and cost-effective corrosion protection strategies for a wide range of applications.

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