Green chemistry solutions: Harnessing pharmaceuticals as environmentally friendly corrosion inhibitors: A review

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Abstract

In recent years, the quest for environmentally friendly corrosion inhibitors has led to the exploration of pharmaceutical compounds as promising alternatives. This mini-review explores the potential of harnessing pharmaceuticals for corrosion inhibition purposes within the framework of green chemistry principles. Highlighting the sustainable aspects of utilizing pharmaceuticals, this article discusses their inhibitive mechanisms, effectiveness, and compatibility with various corrosion protection strategies. Additionally, the environmental impact and biodegradability of pharmaceutical-based inhibitors are scrutinized. By integrating pharmaceutical compounds into corrosion inhibition strategies, this research aims to contribute to the development of eco-friendly solutions for metal protection in diverse industrial applications. Corrosion, a widespread electrochemical process, poses significant challenges across various industries, including infrastructure, manufacturing, and healthcare. Conventional corrosion inhibitors often contain toxic or environmentally harmful compounds, necessitating the search for safer and more sustainable alternatives. Pharmaceutical compounds, with their diverse chemical structures and inherent biocompatibility, present a promising avenue for corrosion inhibition. This review explores the mechanisms by which pharmaceutical compounds interact with metal surfaces to inhibit corrosion, including adsorption-based mechanisms and film-forming processes. Furthermore, the inhibitive performance of pharmaceutical inhibitors is evaluated through experimental and theoretical studies, comparing their effectiveness with conventional inhibitors. In addition to their corrosion inhibition properties, pharmaceutical compounds offer advantages in terms of biodegradability and low environmental impact. By examining the environmental footprint of pharmaceutical-based inhibitors and their compatibility with green chemistry principles, this review assesses their potential for promoting sustainability in corrosion protection practices. Moreover, the integration of pharmaceutical inhibitors into coatings, inhibitors, and

other corrosion protection strategies is discussed, highlighting their versatility and effectiveness in diverse applications. Through interdisciplinary collaboration and innovative research efforts, the utilization of pharmaceutical compounds as corrosion inhibitors holds promise for addressing corrosion challenges while minimizing environmental impact. This review aims to provide researchers and industry professionals with valuable insights into the role of pharmaceuticals in sustainable corrosion protection and to guide future research directions in this evolving field.

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Introduction

Corrosion, the gradual degradation of materials due to chemical or electrochemical reactions with their environment, poses significant challenges across various industries worldwide. From infrastructure to manufacturing and beyond, the economic and safety implications of corrosion are profound [1–5]. Therefore, the development of effective corrosion inhibitors is of paramount importance in mitigating these adverse effects. However, traditional corrosion inhibitors often come with their own set of environmental concerns, ranging from toxicity to persistence in the environment [6–10]. In response to these challenges, the principles of green chemistry have emerged as a guiding framework for designing sustainable solutions to address corrosion issues [11–13]. Corrosion is a ubiquitous phenomenon that affects a wide range of materials, including metals, alloys, and even polymers. It occurs when these materials undergo chemical or electrochemical reactions with their surroundings, leading to their deterioration over time. The consequences of corrosion can be severe, ranging from structural integrity loss to operational failures and safety hazards [14–16]. In industrial settings, corrosion poses significant economic burdens due to maintenance costs, repair expenses, and downtime associated with corroded equipment and infrastructure [17–20]. For example, the oil and gas industry annually incurs billions of dollars in losses due to corrosion-related issues such as pipeline leaks and equipment failures [21]. Similarly, the transportation sector faces challenges from corrosion-related deterioration of bridges, railways, and vehicles, impacting both safety and efficiency [22]. Moreover, corrosion has environmental implications, as it often results in the release of toxic substances into the surrounding ecosystem. For instance, corrosion of metal structures in marine environments can lead to the contamination of water bodies with heavy metals, posing risks to aquatic life and human health. Additionally, the production and use of traditional corrosion inhibitors may contribute to pollution and resource depletion, further exacerbating environmental concerns [23–25]. Through a comprehensive analysis of existing literature and research findings, this review seeks to identify key pharmaceutical compounds that have demonstrated promising inhibitive performance and to evaluate their compatibility with different metal substrates and environmental conditions. Furthermore, the review will discuss potential applications of pharmaceutical inhibitors across various industries, including biomedical devices, marine infrastructure, aerospace, and

renewable energy systems. By synthesizing and critically evaluating the current state of knowledge in this field, this review aims to provide researchers, engineers, and industry professionals with valuable insights into the role of pharmaceutical compounds in corrosion protection and to guide future research directions towards the development of effective and sustainable corrosion inhibition strategies.

1.1. Importance of developing environmentally friendly corrosion inhibitors

Given the widespread impact of corrosion and the environmental challenges associated with traditional corrosion inhibitors, there is a growing imperative to develop environmentally friendly alternatives. Environmentally friendly corrosion inhibitors are those that not only effectively protect materials against corrosion but also minimize adverse effects on human health and the environment throughout their lifecycle [26, 27]. By adopting a proactive approach to corrosion prevention with environmentally friendly inhibitors, industries can reduce the need for costly repairs and replacements, leading to significant cost savings over the long term. Furthermore, environmentally friendly inhibitors can help mitigate environmental pollution and preserve natural resources, aligning with global sustainability goals and regulatory requirements [28, 29]. In addition to economic and environmental benefits, the development and adoption of environmentally friendly corrosion inhibitors can enhance the safety and reliability of infrastructure and industrial processes. By preventing corrosion-induced failures and accidents, these inhibitors contribute to safeguarding human lives and property, promoting sustainable development and resilience in various sectors [30, 31]. Figure 1 provides a comparative analysis of the environmental impact of pharmaceutical inhibitors versus conventional inhibitors. It illustrates key factors such as production processes, usage, and disposal, highlighting the advantages of pharmaceutical inhibitors in terms of greener synthesis routes, lower dosages, and biodegradability. Understanding these environmental aspects is crucial for promoting the adoption of environmentally friendly corrosion protection strategies.

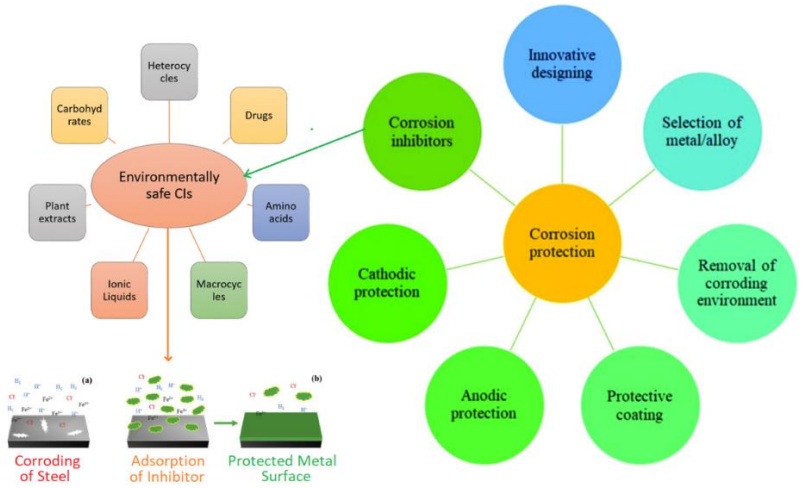

Figure 1. Comparative analysis of environmental impact of pharmaceutical and conventional inhibitors.

1.2. Introduction to pharmaceutical compounds as potential inhibitors

In recent years, researchers have increasingly turned their attention to pharmaceutical compounds as potential corrosion inhibitors due to their diverse chemical structures and biological activities. Pharmaceuticals, which encompass a wide range of organic molecules designed for therapeutic purposes, offer unique opportunities for corrosion inhibition due to their inherent properties such as solubility, reactivity, and bioavailability. The utilization of pharmaceutical compounds as corrosion inhibitors represents a convergence of two distinct fields: pharmaceutical sciences and corrosion engineering. While traditionally viewed as unrelated disciplines, these fields share common principles related to molecular design, structure-activity relationships, and mechanism-based optimization. By leveraging insights from pharmaceutical research and development, corrosion scientists can explore novel avenues for designing innovative inhibitors with enhanced performance and sustainability [32–35]. Moreover, pharmaceutical compounds are often characterized by their biocompatibility and biodegradability, making them attractive candidates for environmentally friendly corrosion inhibition. Unlike some traditional inhibitors that may persist in the environment and pose risks to ecosystems and human health, pharmaceutical-based inhibitors have the potential to degrade into harmless byproducts, minimizing their environmental footprint [36, 37]. Overall, the exploration of pharmaceutical compounds as corrosion inhibitors represents a promising frontier in the quest for sustainable corrosion protection solutions. By harnessing the rich chemical diversity and biological relevance of pharmaceuticals, researchers aim to develop next-generation inhibitors that offer superior performance, safety, and environmental compatibility [38, 39]. The aim of this review article is to explore the potential of pharmaceutical compounds as environmentally friendly corrosion inhibitors and to provide insights into their mechanisms of action, evaluation methods, integration with corrosion protection strategies, and future prospects. The objectives can be summarized as follows:

1. To provide an overview of corrosion and its significance in various industrial sectors.
2. To highlight the importance of developing environmentally friendly corrosion inhibitors as a sustainable alternative to conventional inhibitors.
3. To introduce pharmaceutical compounds as potential corrosion inhibitors and discuss their unique properties and advantages.
4. To examine the principles of green chemistry and their application in corrosion inhibition using pharmaceutical compounds.
5. To explore the mechanisms of corrosion inhibition exhibited by pharmaceutical compounds and their effectiveness in mitigating corrosion processes.
6. To evaluate the inhibitive performance of pharmaceutical compounds through experimental and theoretical studies, including comparisons with conventional inhibitors.

7. To assess the environmental impact and biodegradability of pharmaceutical-based inhibitors and analyze their eco-toxicological aspects.
8. To discuss the integration of pharmaceutical inhibitors into corrosion protection strategies, including coatings, inhibitors, and other approaches.
9. To identify potential applications and future directions in utilizing pharmaceuticals as corrosion inhibitors across various industries.
10. To identify challenges and research needs for further development in the field of pharmaceutical-based corrosion inhibition and propose strategies for overcoming them.

These objectives aim to provide a comprehensive understanding of the role and potential of pharmaceutical compounds in corrosion protection and to guide future research and development efforts in this promising field.

2. Green Chemistry Principles in Corrosion Inhibition

2.1. Brief explanation of green chemistry principles

Green chemistry, also known as sustainable chemistry, is a discipline that aims to design chemical products and processes that minimize the use and generation of hazardous substances. It emphasizes the use of renewable feedstocks, the reduction of energy consumption, and the prevention of pollution to promote environmental and human health. The principles of green chemistry, as outlined by Paul Anastas and John Warner in their seminal work, provide a framework for guiding the development of environmentally benign chemical technologies. These principles include [40–45]:

1. **Prevention:** It is better to prevent waste than to treat or clean up waste after it has been generated.
2. **Atom economy:** Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less hazardous chemical syntheses:** Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. **Designing safer chemicals:** Chemical products should be designed to be effective yet have minimal toxicity and minimal potential for accidents or harmful releases.
5. **Safer solvents and auxiliaries:** The use of auxiliary substances (*e.g.*, solvents, separation agents, *etc.*) should be made unnecessary wherever possible and, when used, innocuous.
6. **Design for energy efficiency:** Energy requirements should be minimized to reduce consumption and waste.
7. **Use of renewable feedstocks:** Whenever possible, raw materials should be renewable rather than depleting.

8. **Reduce derivatives:** Unnecessary derivatization (*i.e.*, unnecessary use of blocking groups, protection/deprotection, temporary modification of physical/ chemical processes) should be minimized or avoided if possible.
9. **Catalysis:** Catalytic reagents are superior to stoichiometric reagents.
10. **Design for degradation:** Chemical products should be designed so that at the end of their function, they break down into innocuous degradation products and do not persist in the environment.

These principles provide a roadmap for chemists and engineers to develop sustainable solutions across various industries, including corrosion inhibition.

2.2. Rationalization of utilizing pharmaceuticals within green chemistry framework

The rationalization of utilizing pharmaceuticals as corrosion inhibitors within the green chemistry framework stems from their inherent properties and the alignment of their design principles with those of green chemistry [46]. Firstly, pharmaceutical compounds are often designed to exhibit specific biological activities while minimizing adverse effects on human health and the environment. This principle aligns with the green chemistry tenet of designing safer chemicals. By leveraging the molecular diversity and structure-activity relationships inherent in pharmaceutical design, researchers can identify compounds with inherent corrosion inhibition properties and low toxicity profiles. This approach not only enhances the safety and sustainability of corrosion inhibition strategies but also minimizes the risks associated with exposure to harmful chemicals in industrial and environmental settings [47, 48]. Secondly, pharmaceutical compounds offer opportunities for atom economy and efficient resource utilization in corrosion inhibition. Unlike traditional inhibitors that may require complex synthesis routes and generate significant waste byproducts, pharmaceuticals can be synthesized using efficient, atom-efficient methodologies. Furthermore, pharmaceutical synthesis often employs catalytic processes and renewable feedstocks, aligning with the green chemistry principles of catalysis and the use of renewable resources. By adopting synthetic strategies that prioritize atom economy and energy efficiency, researchers can minimize the environmental footprint of corrosion inhibitor production while maximizing the incorporation of all materials into the final product [49, 50]. Moreover, the biodegradability and biocompatibility of pharmaceutical compounds make them ideal candidates for environmentally friendly corrosion inhibition. Unlike some traditional inhibitors that persist in the environment and pose risks to ecosystems and human health, pharmaceutical-based inhibitors have the potential to degrade into harmless byproducts through natural processes. This property not only reduces the long-term environmental impact of corrosion inhibition but also facilitates the development of sustainable materials and processes for metal protection [51]. Overall, the rationalization of utilizing pharmaceuticals as corrosion inhibitors within the green chemistry framework offers a holistic approach to sustainable materials design and engineering. By leveraging the principles of green chemistry, researchers can harness the unique properties of

pharmaceutical compounds to develop innovative corrosion inhibition strategies that are effective, safe, and environmentally friendly [52, 53]. Through interdisciplinary collaboration and innovation, the integration of pharmaceuticals into corrosion protection technologies holds promise for advancing towards a more sustainable and resilient future. Figure 2 illustrates the integration of pharmaceutical inhibitors into corrosion protection strategies, including coatings, inhibitors, surface modifications, and corrosion sensors. It demonstrates how pharmaceutical inhibitors can enhance metal protection effectiveness and sustainability when incorporated into various corrosion protection approaches. This integrated approach offers versatile solutions for addressing corrosion challenges across different industries and applications.

Figure 2. Integration of pharmaceutical inhibitors into corrosion protection strategies.

2.3. Specific examples of pharmaceutical compounds as steel corrosion inhibitors in acidic solutions

The exciting field of utilizing expired or repurposed pharmaceuticals as corrosion inhibitors has yielded several promising results, particularly for steel in acidic environments. Here are some specific examples:

- **Antibiotics:** Studies have shown that Ampicillin, Cloxacillin, Flucloxacillin, and Amoxicillin exhibit impressive inhibition efficiencies of up to 90% in acidic media [54]. These antibiotics likely function by forming a protective film on the steel surface, hindering the corrosive species from reaching the metal.
- **Antihypertensives:** Enalapril maleate, Atenolol, and Etilefrine, commonly used for blood pressure control, have also demonstrated significant corrosion inhibition potential for steel in acidic solutions [55].

Their effectiveness is attributed to the presence of specific functional groups within their molecular structure, allowing them to interact with the metal surface and create a protective barrier.

- **Cephapirin:** This antibiotic not only displays promising experimental results but also benefits from theoretical support through Density Functional Theory (DFT) simulations. These simulations suggest that cephapirin effectively inhibits the corrosion process at the atomic level [56].

It's crucial to distinguish between pharmaceutical compounds and other chemical compounds. Pharmaceutical compounds, also known as drugs, are rigorously tested and approved for use in treating specific medical conditions. They often possess complex molecular structures and specific biological activities. In contrast, other chemical compounds encompass a vast array of substances with diverse functionalities, not necessarily intended for medical applications. Therefore, the exploration of pharmaceutical compounds as corrosion inhibitors presents a unique opportunity. By repurposing readily available, often expired, drugs, researchers can contribute to:

3. Mechanisms of Corrosion Inhibition by Pharmaceuticals

3.1. Exploration of various inhibitive mechanisms exhibited by pharmaceutical compounds

Pharmaceutical compounds exhibit a wide range of inhibitive mechanisms that make them promising candidates for corrosion inhibition. These mechanisms can be broadly categorized into adsorption-based and film-forming mechanisms, each of which involves interactions between the inhibitor molecules and the metal surface.

Adsorption-based mechanisms

One of the primary mechanisms by which pharmaceutical compounds inhibit corrosion is through adsorption onto the metal surface. This process involves the formation of a protective layer of inhibitor molecules that physically block the corrosive species from accessing the metal surface. The adsorption of pharmaceutical inhibitors is often driven by electrostatic interactions, hydrogen bonding, and Van der Waals forces between the inhibitor molecules and the metal surface [57, 58]. For example, aromatic compounds such as benzimidazoles and pyridines are known to adsorb onto metal surfaces via π–π interactions between their aromatic rings and the metal atoms. Similarly, heterocyclic compounds

containing nitrogen, oxygen, or sulfur atoms can form coordination complexes with metal ions on the surface, leading to strong adsorption and inhibition [59, 60]. Furthermore, pharmaceutical compounds may undergo chemisorption onto the metal surface, where they form covalent bonds with the metal atoms. This type of adsorption typically involves the donation of electron pairs from the inhibitor molecules to vacant d-orbitals on the metal surface, leading to the formation of stable coordination complexes. For instance, nitrogen-containing compounds such as imidazoles and pyrazoles can coordinate with metal ions through their nitrogen lone pairs, forming stable metal-inhibitor complexes that inhibit corrosion effectively [61, 62]. Figure 3 depicts the adsorption-based mechanism of pharmaceutical inhibitors on a metal surface. Pharmaceutical compounds adsorb onto the metal surface through interactions such as electrostatic forces, hydrogen bonding, and Van der Waals interactions. This adsorption forms a protective layer that blocks corrosive species from accessing the metal surface, thereby inhibiting corrosion. Understanding this mechanism is essential for designing effective pharmaceutical inhibitors and optimizing their corrosion protection properties.

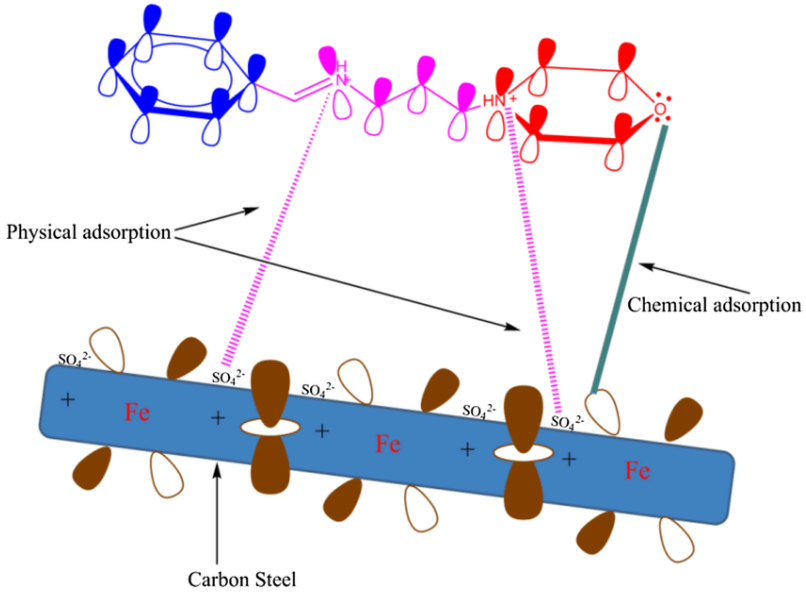

Figure 3. Schematic illustration of adsorption-based mechanism of pharmaceutical inhibitors.

Film-forming mechanisms:

In addition to adsorption-based mechanisms, some pharmaceutical compounds can act as film-forming inhibitors by forming protective films on the metal surface. These films act as physical barriers that separate the metal from the corrosive environment, preventing direct contact and inhibiting corrosion [63]. Film-forming inhibitors may either be passivating, where they promote the formation of stable oxide or hydroxide layers on the metal surface, or barrier-type, where they form dense, impermeable films that block the diffusion of corrosive species [64]. For example, organic acids such as citric acid and tartaric acid can form protective oxide films on metal surfaces through complexation with metal ions and

subsequent precipitation of metal oxides/hydroxides [65]. Similarly, polymeric inhibitors such as polyaniline and polypyrrole can undergo electropolymerization on metal surfaces, forming conductive polymer films that inhibit corrosion by acting as barriers to ion transport. Moreover, some pharmaceutical compounds may exhibit mixed-mode inhibition mechanisms, where they combine both adsorption-based and film-forming mechanisms to achieve synergistic corrosion protection [66]. For instance, organic molecules containing functional groups such as amino, hydroxyl, and carboxyl groups can adsorb onto metal surfaces and subsequently undergo self-assembly or polymerization to form protective films, enhancing the overall inhibition efficiency. Overall, the diverse inhibitive mechanisms exhibited by pharmaceutical compounds highlight their versatility and potential for corrosion inhibition in various environments and applications [67, 68]. By understanding and optimizing these mechanisms, researchers can develop tailored corrosion inhibition strategies that offer effective and long-lasting protection against corrosion. Figure 4 illustrates the film-forming mechanism of pharmaceutical inhibitors on a metal surface. Pharmaceutical compounds form a protective barrier film that covers the metal surface, preventing direct contact with corrosive environments. This film acts as a physical barrier, hindering the diffusion of corrosive species and inhibiting corrosion processes. Film-forming inhibitors offer durable and long-lasting corrosion protection, particularly in aggressive environments such as marine or industrial settings.

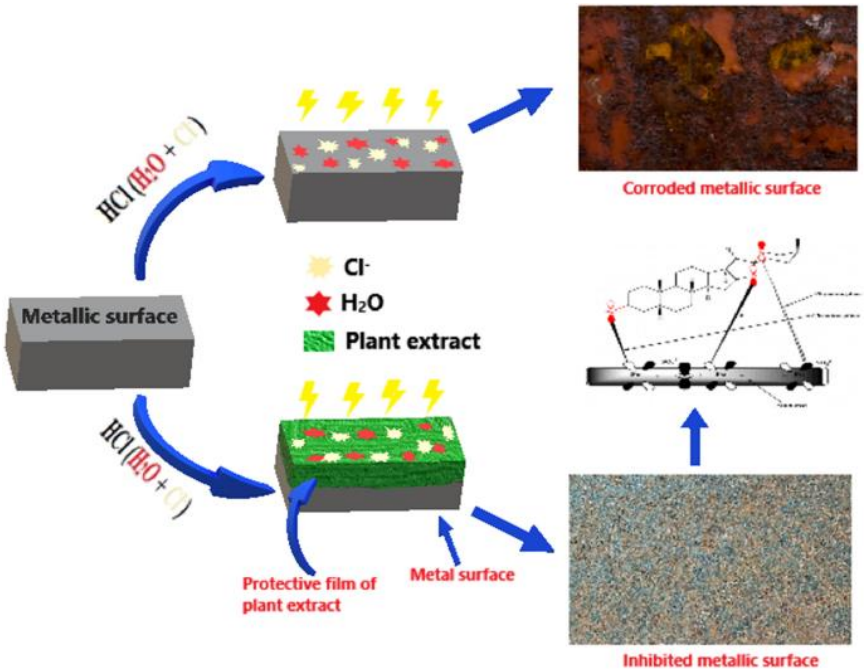

Figure 4. Cross-sectional view of film-forming mechanism of pharmaceutical inhibitors.

Table outlines the various mechanisms of action exhibited by pharmaceutical inhibitors. Understanding these mechanisms is crucial for designing effective corrosion protection strategies. Adsorption-based mechanisms involve the formation of a protective layer through molecular interactions, while film-forming mechanisms create physical

barriers on the metal surface. Mixed-mode inhibition combines both mechanisms, offering enhanced corrosion protection.

Table 1. Comparison of mechanisms of action of pharmaceutical inhibitors.

Mechanism of action	Description	Advantages	Disadvantages	Examples
Adsorption-based	Pharmaceutical molecules physically adhere to the metal surface, forming a protective layer. This layer hinders the diffusion of corrosive ions and reduces the rate of electron transfer involved in corrosion.	– Highly specific to the metal surface – Often effective at low concentrations – Can be self-healing if damaged	– Limited film thickness – May not be effective against all types of corrosion	– Mercaptobenzothiazole (MBT) – Benzotriazole (BTA) – Quaternary ammonium salts
Film-forming	Pharmaceutical molecules create a physical barrier on the metal surface, preventing corrosive species from reaching it. This film can be organic or inorganic and can be formed through various mechanisms like precipitation or polymerization.	– Strong barrier against aggressive environments – Can be durable and long-lasting	– Can be thick and affect other surface properties – May be less effective against localized corrosion	– Polyaniline films – Epoxy coatings – Cerium oxide films
Mixed-mode inhibition	Combines adsorption and film-forming mechanisms, offering synergistic protection. This type of inhibition can be more effective than either approach alone.	– Broad-spectrum protection against various corrosion types – Can be self-healing and offer long-lasting protection	– Requires careful design to achieve optimal adsorption and film formation – Can be more complex and expensive to implement	– Silane-based coatings containing inhibitors – Organic-inorganic hybrid films
Chelation	Pharmaceutical molecules form complexes with metal ions responsible for corrosion, effectively	– Highly effective in removing specific metal ions	– May require high concentrations – Not effective	– EDTA (ethylenediamine tetraacetic acid) – Citric acid – Phosphoric acid

Mechanism of action	Description	Advantages	Disadvantages	Examples
	removing them from the solution and preventing their participation in the corrosion process.	– Can be targeted to specific corrosion mechanisms	against all types of corrosion	
Passivation	Pharmaceutical molecules promote the formation of a passive oxide layer on the metal surface, which significantly reduces its reactivity and susceptibility to corrosion.	– Highly effective and long-lasting protection – Can be self-healing	– Requires specific conditions for oxide formation – May not be compatible with all metals	– Chromates – Nitrates – Molybdates

3.2. Discussion on their effectiveness in mitigating corrosion processes

Pharmaceutical compounds have shown remarkable effectiveness in mitigating corrosion processes across a wide range of metal substrates and corrosive environments. Their ability to inhibit corrosion stems from their unique chemical structures, which enable interactions with metal surfaces and corrosive species, leading to the formation of protective barriers or films [69, 70]. One key factor contributing to the effectiveness of pharmaceutical inhibitors is their ability to adsorb strongly onto metal surfaces. The adsorption of inhibitors reduces the availability of active sites for corrosive species to react, thereby slowing down the corrosion rate. Furthermore, pharmaceutical compounds can form stable coordination complexes with metal ions on the surface, enhancing their adsorption affinity and inhibition efficiency. This strong adsorption ensures the formation of a dense and uniform inhibitor layer, which provides effective corrosion protection over extended periods [71–73]. Moreover, pharmaceutical inhibitors often exhibit excellent film-forming properties, allowing them to create protective barriers on metal surfaces. These barriers effectively block the diffusion of corrosive species, such as oxygen, water, and ions, thereby inhibiting the corrosion process. The formation of protective films is particularly beneficial in aggressive environments where corrosion rates are high, such as acidic or saline conditions. By forming dense and adherent films, pharmaceutical inhibitors can significantly reduce metal dissolution and corrosion product formation, leading to prolonged service life and enhanced durability of metal components [74–76].

Another advantage of pharmaceutical inhibitors is their versatility and compatibility with different corrosion protection strategies. They can be incorporated into coatings, paints, and surface treatments to provide multifunctional corrosion protection. For example, pharmaceutical-based coatings can offer combined barrier and active corrosion inhibition properties, providing comprehensive protection against both mechanical and

electrochemical corrosion mechanisms. Furthermore, pharmaceutical inhibitors can be used in combination with other corrosion inhibitors or synergistic additives to enhance their performance and tailor their properties to specific application requirements [77–79]. Additionally, the effectiveness of pharmaceutical inhibitors is often attributed to their environmentally friendly nature and biocompatibility. Unlike some traditional inhibitors that may contain toxic or hazardous components, pharmaceutical compounds are generally safe for human health and the environment. Their biodegradability ensures minimal environmental impact and allows for eco-friendly disposal at the end of their service life. This inherent sustainability makes pharmaceutical inhibitors attractive options for corrosion protection in environmentally sensitive applications, such as marine, aerospace, and biomedical industries [80–82]. In conclusion, pharmaceutical compounds have demonstrated remarkable effectiveness in mitigating corrosion processes through their strong adsorption and film-forming mechanisms. Their ability to form protective barriers on metal surfaces, combined with their compatibility and sustainability, makes them promising candidates for corrosion inhibition in various industrial sectors. By harnessing the unique properties of pharmaceutical inhibitors and optimizing their performance, researchers can develop innovative corrosion protection solutions that enhance the reliability, safety, and sustainability of metal components and structures.

4. Evaluation of Pharmaceutical Compounds as Corrosion Inhibitors

4.1. Assessment of the inhibitive performance of pharmaceuticals through experimental and theoretical studies

The evaluation of pharmaceutical compounds as corrosion inhibitors involves a comprehensive assessment of their inhibitive performance through a combination of experimental and theoretical studies. These studies aim to elucidate the mechanisms of corrosion inhibition, quantify the effectiveness of inhibitors, and optimize their properties for specific applications [83–86]. Experimental studies play a crucial role in assessing the inhibitive performance of pharmaceutical compounds under relevant corrosion conditions. These studies typically involve conducting corrosion tests using various electrochemical and surface analysis techniques to evaluate the corrosion rate, inhibitor efficiency, and surface morphology of metal samples in the presence of inhibitors [87–90]. Electrochemical techniques, such as potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and cyclic voltammetry, are commonly employed to assess the corrosion kinetics and inhibition efficiency of pharmaceutical inhibitors. These techniques provide valuable insights into the electrochemical behavior of metal-inhibitor systems, including corrosion potential, corrosion current density, polarization resistance, and charge transfer resistance [91–93].

Surface analysis techniques, such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray photoelectron spectroscopy (XPS), are used to investigate the surface morphology, composition, and structure of inhibitor films formed on metal surfaces.

These techniques help elucidate the mechanisms of corrosion inhibition and provide visual evidence of inhibitor adsorption, film formation, and surface protection [93–96]. In addition to experimental studies, theoretical modeling and computational simulations are employed to complement experimental data and provide molecular-level insights into the mechanisms of corrosion inhibition. Quantum chemical calculations, molecular dynamics simulations, and density functional theory (DFT) calculations are used to predict inhibitor adsorption energies, binding geometries, and electronic properties, aiding in the rational design and optimization of pharmaceutical inhibitors [97–105]. By combining experimental and theoretical approaches, researchers can gain a comprehensive understanding of the inhibitive performance of pharmaceutical compounds and identify key factors influencing their effectiveness, such as inhibitor concentration, chemical structure, molecular interactions, and environmental conditions.

4.2. Comparison with conventional corrosion inhibitors

A critical aspect of evaluating pharmaceutical compounds as corrosion inhibitors is comparing their performance with that of conventional inhibitors commonly used in industrial applications. Conventional corrosion inhibitors, such as chromates, phosphates, nitrites, and organic inhibitors like benzotriazoles and mercaptobenzothiazoles, have been extensively studied and employed for corrosion protection in various sectors [106, 107]. Pharmaceutical inhibitors are compared with conventional inhibitors based on several key criteria, including inhibition efficiency, cost-effectiveness, environmental impact, compatibility with coatings and additives, and regulatory compliance. The comparison aims to assess the relative advantages and limitations of pharmaceutical inhibitors and identify areas where they may offer superior performance or address specific challenges associated with conventional inhibitors [108]. In terms of inhibition efficiency, pharmaceutical compounds have demonstrated comparable or superior performance to conventional inhibitors in many cases. Their ability to form strong adsorption layers and protective films on metal surfaces, combined with their inherent biocompatibility and environmental sustainability, makes them attractive alternatives to traditional inhibitors [109]. Furthermore, pharmaceutical inhibitors offer advantages in terms of biodegradability and eco-toxicological properties, minimizing their environmental footprint and reducing risks to human health and ecosystems. Unlike some conventional inhibitors that contain toxic or hazardous components, pharmaceutical compounds are generally safer for use and disposal, making them preferable options for environmentally sensitive applications [110]. Cost-effectiveness is another important consideration when comparing pharmaceutical inhibitors with conventional inhibitors. While pharmaceutical compounds may initially have higher production costs or require specialized synthesis routes, their long-term benefits in terms of corrosion protection, maintenance savings, and environmental compliance may outweigh the initial investment. Moreover, advances in synthetic chemistry and production technologies may further reduce the cost of pharmaceutical inhibitors and enhance their competitiveness in the market [111, 112]. Compatibility with coatings and additives is also crucial for

evaluating the suitability of pharmaceutical inhibitors for practical applications. Pharmaceutical compounds can be incorporated into various coating formulations, paints, and surface treatments to provide multifunctional corrosion protection. Their compatibility with other corrosion inhibitors, pigments, and performance-enhancing additives allows for customized formulations tailored to specific application requirements and substrate materials [113, 114]. Regulatory compliance is an essential consideration for corrosion inhibitors used in industries subject to stringent environmental regulations, such as the aerospace, automotive, and marine sectors. Pharmaceutical compounds, with their favorable environmental profiles and biocompatibility, are more likely to meet regulatory requirements and standards for safety, sustainability, and environmental stewardship. This compliance provides reassurance to end-users and facilitates the adoption of pharmaceutical inhibitors in regulated industries [115, 116]. In summary, the comparison of pharmaceutical compounds with conventional corrosion inhibitors highlights their potential as viable alternatives for corrosion protection in various industrial applications. By leveraging their unique properties, such as strong adsorption, film-forming ability, biodegradability, and environmental compatibility, pharmaceutical inhibitors offer effective and sustainable solutions for mitigating corrosion and preserving the integrity of metal components and structures. Continued research and development efforts are needed to further optimize the performance, cost-effectiveness, and applicability of pharmaceutical inhibitors and accelerate their adoption in practical corrosion protection strategies. Table 2 compares the environmental impact of pharmaceutical inhibitors with conventional inhibitors at various stages, including production, usage, and disposal. Pharmaceutical inhibitors exhibit advantages such as greener synthesis routes and biodegradability, minimizing their environmental footprint compared to conventional inhibitors.

Table 2. Comparison of the environmental impact of pharmaceutical inhibitors and conventional inhibitors.

Environmental impact stage	Pharmaceutical inhibitors	Conventional inhibitors	Advantages of pharmaceutical inhibitors	Disadvantages of pharmaceutical inhibitors
Production processes	– Greener synthesis routes (enzymes, biocatalysis) – Reduced energy consumption – Minimal hazardous byproducts	– Energy-intensive processes (high temperatures, pressure) – Significant solvent and reagent use – Emission of greenhouse gases and air pollutants – Hazardous waste generation	– Lower environmental footprint during production	– Limited information on scalability and cost competitiveness

Environmental impact stage	Pharmaceutical inhibitors	Conventional inhibitors	Advantages of pharmaceutical inhibitors	Disadvantages of pharmaceutical inhibitors
Usage	– Lower dosages due to higher potency – Potential for controlled release formulations – Minimal leaching from coated surfaces	– Higher dosages required for similar protection – Can be readily released into the environment from treated surfaces – May impact non-target organisms	– Reduced environmental exposure and potential toxicity	– May require more complex application methods
Disposal	– Biodegradable (natural products, polymers) – Rapid breakdown in the environment – Minimized persistence	– Persistent in the environment (heavy metals, organic compounds) – Potential for accumulation and long-term effects – Costly and energy-intensive treatment processes	– Reduced risk of long-term environmental contamination	– Limited data on long-term breakdown products and potential impacts
Other Considerations	– May exhibit lower overall toxicity – Potential for biocompatibility and reduced health risks	– May have unintended ecological effects due to novel mechanisms	– Promising area for further research and development	– Lack of established standards and regulations

5. Environmental Impact and Biodegradability

5.1. Examination of the environmental footprint of pharmaceutical-based inhibitors

The environmental footprint of corrosion inhibitors, including pharmaceutical-based inhibitors, encompasses various aspects, such as production processes, usage, and disposal. Understanding and minimizing this footprint are crucial for ensuring the sustainability of corrosion protection strategies and mitigating potential adverse effects on ecosystems and human health.

Production processes:

The production of pharmaceutical-based inhibitors involves chemical synthesis, which may require energy-intensive processes, raw materials, and solvents. However, advancements in

green chemistry and sustainable manufacturing practices have enabled the development of more environmentally friendly synthesis routes for pharmaceutical compounds. These include the use of renewable feedstocks, catalytic reactions, and solvent-free processes to minimize waste generation and energy consumption. By adopting greener production methods, the environmental impact of pharmaceutical inhibitor synthesis can be reduced, leading to more sustainable corrosion protection solutions [117, 118].

Usage:

During the usage phase, pharmaceutical-based inhibitors are applied to metal surfaces to provide corrosion protection. The environmental impact of inhibitors during this phase depends on factors such as dosage, application method, and exposure pathways. In general, inhibitors with lower dosages and minimal leaching from coated surfaces have lower environmental impacts. Additionally, inhibitors that are effective at lower concentrations or require less frequent reapplication can help reduce overall usage and environmental exposure [119, 120].

Disposal:

At the end of their service life, pharmaceutical-based inhibitors may undergo disposal, which can impact the environment if not managed properly. Disposal methods such as recycling, incineration, or landfilling can have different environmental implications depending on factors such as the inhibitor's chemical composition, toxicity, and biodegradability. Ideally, inhibitors should be designed to degrade into harmless byproducts or undergo biodegradation in natural environments, minimizing their persistence and potential for environmental accumulation [121]. Assessing the environmental footprint of pharmaceutical-based inhibitors requires considering their entire lifecycle, from raw material extraction to disposal. Life cycle assessment (LCA) is a systematic approach used to quantify the environmental impacts of products and processes across their lifecycle stages. By conducting LCAs of pharmaceutical inhibitors, researchers can identify hotspots and opportunities for improving their environmental performance, leading to more sustainable corrosion protection strategies [122].

5.2. Analysis of their biodegradability and eco-toxicological aspects

Biodegradability and eco-toxicological aspects are important considerations when evaluating the environmental sustainability of corrosion inhibitors, including pharmaceutical-based inhibitors.

Biodegradability:

Biodegradability refers to the ability of a substance to be broken down into simpler, non-toxic compounds by microbial action or other natural processes. Biodegradable inhibitors are preferable as they minimize environmental persistence and reduce the risk of accumulation in ecosystems. Pharmaceutical compounds, with their organic nature and

structural similarity to naturally occurring molecules, often exhibit high biodegradability. Their carbon-based backbone and functional groups allow them to be metabolized by microorganisms in soil, water, and sediments, leading to degradation into innocuous byproducts such as carbon dioxide, water, and biomass. However, the biodegradability of pharmaceutical inhibitors can vary depending on factors such as chemical structure, molecular weight, and environmental conditions. Therefore, it is essential to assess the biodegradability of specific pharmaceutical compounds under relevant environmental conditions to ensure their environmental compatibility and sustainability as corrosion inhibitors [123, 124].

Eco-toxicological aspects:

Eco-toxicological aspects refer to the potential adverse effects of corrosion inhibitors on ecological systems and organisms. Pharmaceuticals are designed to interact with biological systems and may exhibit specific toxicological properties that could impact non-target organisms in the environment. Therefore, it is important to evaluate the eco-toxicological profile of pharmaceutical-based inhibitors to assess their environmental safety and potential risks [125]. Eco-toxicological studies involve assessing the acute and chronic toxicity of inhibitors to various organisms, including aquatic organisms, plants, and soil microorganisms. These studies use standardized toxicity tests and endpoints to measure the effects of inhibitors on organismal health, growth, reproduction, and survival. Additionally, bioaccumulation and biomagnification studies are conducted to determine the potential for inhibitors to accumulate in food chains and ecosystems [126]. Furthermore, structure-activity relationship (SAR) studies can provide insights into the relationship between inhibitor structure and eco-toxicological properties, guiding the design of safer and more environmentally friendly inhibitors. By identifying structural features associated with toxicity, researchers can optimize inhibitor design to minimize adverse effects on non-target organisms while maintaining corrosion inhibition performance [127]. In conclusion, the biodegradability and eco-toxicological aspects of pharmaceutical-based inhibitors are critical considerations for assessing their environmental sustainability and safety as corrosion inhibitors. By conducting thorough evaluations of these aspects and integrating them into corrosion protection strategies, researchers can develop environmentally friendly inhibitors that provide effective metal protection while minimizing adverse impacts on ecosystems and human health.

6. Integration with Corrosion Protection Strategies

6.1. Integration of pharmaceutical inhibitors into coatings, inhibitors, and other corrosion protection strategies

The integration of pharmaceutical inhibitors into coatings, inhibitors, and other corrosion protection strategies offers a multifaceted approach to enhancing metal protection while leveraging the unique properties of pharmaceutical compounds.

Coatings:

Coatings are commonly used as primary barriers to protect metal surfaces from corrosion. By incorporating pharmaceutical inhibitors into coating formulations, it is possible to impart additional corrosion inhibition properties to the coating system. Pharmaceutical inhibitors can be dispersed in various coating matrices, such as epoxy, polyurethane, acrylic, and alkyd resins, to form composite coatings with synergistic corrosion protection effects [128]. The incorporation of pharmaceutical inhibitors into coatings can be achieved through physical blending or chemical modification of the inhibitor molecules to improve compatibility with the coating matrix. Additionally, nanotechnology-based approaches, such as the use of nanoencapsulation or nanocomposites, can enhance the dispersion and controlled release of pharmaceutical inhibitors within coatings, leading to improved long-term performance and durability [129]. Furthermore, pharmaceutical-based coatings can offer combined functionalities, such as corrosion inhibition, antimicrobial activity, self-healing, and stimuli responsiveness, making them versatile solutions for diverse corrosion protection applications [130].

Inhibitors:

Pharmaceutical inhibitors can also be used as standalone corrosion inhibitors in solution-based treatments or as additives to corrosion inhibitor formulations. Inhibitor solutions containing pharmaceutical compounds can be applied directly to metal surfaces through immersion, spraying, or brushing methods to provide temporary or long-term corrosion protection [131]. Moreover, pharmaceutical inhibitors can be combined with other corrosion inhibitors, such as organic and inorganic inhibitors, to create synergistic effects and enhance overall corrosion inhibition performance. The combination of inhibitors with complementary mechanisms of action can improve corrosion resistance across a broader range of environmental conditions and metal substrates [132].

Other corrosion protection strategies:

In addition to coatings and inhibitors, pharmaceutical inhibitors can be integrated into other corrosion protection strategies, such as corrosion-resistant materials, surface modifications, and corrosion monitoring systems [133]. For example, pharmaceutical compounds can be incorporated into metal alloys, composites, and hybrid materials to impart inherent corrosion resistance properties. Surface modification techniques, such as plasma treatment, chemical conversion, and laser patterning, can be used to immobilize pharmaceutical inhibitors onto metal surfaces, forming self-assembled monolayers or functionalized coatings that provide long-lasting corrosion protection [134]. Furthermore, pharmaceutical inhibitors can be incorporated into corrosion sensors and monitoring devices to detect and mitigate corrosion in real-time, enabling proactive maintenance and corrosion control strategies [135]. Overall, the integration of pharmaceutical inhibitors into coatings, inhibitors, and other corrosion protection strategies offers a holistic approach to corrosion prevention and mitigation. By leveraging the versatility and compatibility of pharmaceutical compounds with existing

corrosion protection technologies, it is possible to develop innovative solutions that provide effective, long-lasting, and environmentally friendly metal protection across various industries and applications.

6.2. Compatibility with different metal substrates and environmental conditions

One of the key considerations when integrating pharmaceutical inhibitors into corrosion protection strategies is their compatibility with different metal substrates and environmental conditions. Compatibility encompasses factors such as inhibitor-metal interactions, coating adhesion, film formation, and performance under diverse corrosion environments.

Inhibitor-metal interactions:

Pharmaceutical inhibitors must exhibit strong adsorption and interaction with metal surfaces to provide effective corrosion protection. The compatibility of inhibitors with different metal substrates depends on factors such as surface chemistry, morphology, and electrochemical properties. For example, inhibitors with functional groups such as amino, hydroxyl, and carboxyl groups can form coordination complexes with metal ions on the surface, enhancing their adsorption affinity and inhibition efficiency. Furthermore, the electronic structure and reactivity of metal surfaces influence the adsorption kinetics and stability of inhibitor films, affecting overall corrosion inhibition performance [136, 137]. Table 3 summarizes the compatibility of pharmaceutical inhibitors with different metal substrates. Pharmaceutical inhibitors demonstrate versatility and effectiveness across various metals, with strong adsorption-based inhibition on steel, film-forming inhibition on aluminum, and compatibility with both mechanisms on copper.

Table 3. Compatibility of pharmaceutical inhibitors with different metal substrates.

Metal substrate	Compatibility with pharmaceutical inhibitors	Mechanism of action	Advantages	Disadvantages	Examples
Steel	Excellent	Adsorption-based, Mixed-mode	–Strong affinity for steel surface –Effective at low dosages –Can offer synergistic protection with mixed-mode inhibitors	–Limited long-term durability of adsorption-based films –Susceptible to wear and tear in high-flow environments	–Benzotriazole (BTA) –Mercaptobenzo-thiazole (MBT) –Imidazoline derivatives

Aluminum	Good	Film-forming, Mixed-mode	–Forms stable and adherent films –Provides long-term protection –Can be self-healing	–May affect surface properties like conductivity or reflectivity –Not as effective as mixed-mode inhibitors in harsh environments	–Silicates –Phosphates –Silane-based inhibitors
Copper	Moderate	Adsorption-based, Film-forming, Mixed-mode	–Versatile, compatible with various mechanisms –Can be tailored for specific copper alloys	–Effectiveness varies depending on copper alloy and inhibitor type –May not be as effective as specialized copper inhibitors	–Quinoxaline derivatives –Organic-inorganic hybrid coatings –Polymeric films
Other metals	Varies	Depends on individual inhibitor and metal properties	–Potential for development of new sustainable corrosion solutions –Can offer unique advantages tailored to specific metals	–Limited research and data compared to common metals –Compatibility and effectiveness need further investigation	–Exploring inhibitors for magnesium, zinc, titanium, *etc*.

Coating adhesion and film formation:

In coating systems, the adhesion of pharmaceutical-based coatings to metal substrates is critical for ensuring long-term performance and durability. Poor adhesion can lead to coating delamination, blistering, and reduced corrosion protection effectiveness. Therefore, it is essential to optimize coating formulations and application methods to promote strong interfacial bonding between the coating and metal substrate. Additionally, the formation of dense, uniform inhibitor films on metal surfaces is essential for providing effective corrosion

protection. Pharmaceutical inhibitors must exhibit film-forming properties and resistance to degradation under corrosive conditions to maintain their protective efficacy over extended periods [138, 139].

Performance under diverse corrosion environments:

Pharmaceutical inhibitors must demonstrate performance under diverse corrosion environments, including atmospheric, marine, industrial, and acidic conditions. The compatibility of inhibitors with different environmental factors such as temperature, humidity, pH, and chemical aggressiveness influences their corrosion inhibition effectiveness. For example, inhibitors designed for marine environments must withstand exposure to seawater, chloride ions, and biofouling organisms, while inhibitors used in industrial settings may encounter aggressive chemicals, high temperatures, and varying pH levels. Therefore, it is crucial to evaluate the corrosion inhibition performance of pharmaceutical inhibitors under relevant environmental conditions to ensure their applicability and reliability in practical corrosion protection applications [140, 141].

Table 4 presents examples of pharmaceutical compounds used as corrosion inhibitors, highlighting their mechanisms of action and corrosion protection effectiveness. Benzimidazoles demonstrate strong adsorption-based inhibition, while pyridines offer durable film-forming protection. Imidazoles exhibit mixed-mode inhibition, providing synergistic corrosion protection in diverse environments.

Table 4. Examples of pharmaceutical compounds as corrosion inhibitors.

Pharmaceutical compound	Mechanism of action	Advantages	Disadvantages	Examples	Applications
Benzimidazoles	Adsorption-based	–Strong affinity for steel surfaces –Effective in acidic environments –Low dosage requirements	–Limited long-term durability –Susceptible to wear and tear –May not be suitable for high-alkaline environments	Albendazole, mebendazole	Steel protection in pipelines, oil and gas industry
Pyridines	Film-forming	–Forms stable and adherent films –Durable protection against marine corrosion –Can be self-healing	–May affect surface properties like conductivity or reflectivity –Complex application methods –Not as effective in highly	Clotrimazole, terconazole	Aluminum protection in marine structures, boats, offshore platforms

Pharmaceutical compound	Mechanism of action	Advantages	Disadvantages	Examples	Applications
			aggressive environments		
Imidazoles	Mixed-mode (adsorption + film-forming)	–Synergistic protection for various metals –Effective in diverse environments –Tailorable properties	–Requires careful selection for specific applications –More complex and expensive than single-mechanism inhibitors	Ketoconazole, miconazole	Corrosion protection in industrial settings, pipelines, boilers, cooling systems
Quinoxalines	Mixed-mode (adsorption + chelation)	–Effective against specific metal ions –Can offer long-term protection –Environmentally friendly options available	–Limited understanding of specific mechanisms –Compatibility with different metals varies –May require higher dosages	Chloroquine, hydroxy-chloroquine	Copper protection in electronics, heat exchangers, historical artifacts
Salicylates	Adsorption-based+ passivation	–Readily available and cost-effective –Can inhibit multiple corrosion mechanisms –Synergistic effect with other inhibitors	–Limited effectiveness in highly aggressive environments –May require pH adjustment for optimal performance	Sodium salicylate, aspirin	Mild steel protection in atmospheric corrosion, indoor applications

In summary, ensuring compatibility with different metal substrates and environmental conditions is essential for the successful integration of pharmaceutical inhibitors into corrosion protection strategies. By optimizing inhibitor-metal interactions, coating adhesion, and performance under diverse corrosion environments, it is possible to develop tailored solutions that provide effective and long-lasting metal protection in various industrial sectors and applications. Continued research and development efforts are needed to advance our understanding of pharmaceutical-based corrosion inhibition and enhance the compatibility and performance of these innovative materials in practical corrosion control strategies. Table 5 illustrates the integration of pharmaceutical inhibitors into various corrosion

protection strategies. By incorporating pharmaceutical inhibitors into coatings, inhibitors, surface modifications, and corrosion sensors, it is possible to enhance metal protection effectiveness and sustainability. These integrated approaches offer versatile solutions for addressing corrosion challenges across different industries and applications.

Table 5. Integration of pharmaceutical inhibitors into corrosion protection strategies.

Corrosion protection strategy	Integration of pharmaceutical inhibitors	Advantages	Disadvantages	Examples	Applications
Coatings	–Encapsulated in organic or inorganic polymer matrices –Covalently bonded to functional groups on the surface	–Controlled release of inhibitors –Synergistic protection with coating barrier –Tailored properties for specific environments	–Complex and expensive formulation process –Potential degradation of inhibitors within the coating	–Benzotriazole-doped epoxy coatings for steel –Pyridine-modified silane coatings for aluminum	Infrastructure protection (pipelines, bridges), marine environments, electronics
Inhibitors	–Formulated as standalone solutions or additives to existing inhibitors	–High inhibitor efficiency at low dosages –Environmentally friendly alternatives to conventional inhibitors	–Potential leaching of inhibitors from the solution –Limited long-term protection compared to coatings	–Imidazole-based inhibitors for industrial cooling systems –Salicylate-based additives for reinforced concrete	Industrial processes, wastewater treatment, oil and gas industry
Surface modifications	–Chemically bonded to the metal surface –Self-assembled monolayers formed on the surface	–Durable protection with strong inhibitor-metal interaction –Can be self-healing	–Requires specialized surface pre-treatment –Compatibility with specific metal surfaces may vary	–Silane-grafted benzimidazoles for steel –Quinoxaline-based self-assembled monolayers for copper	High-performance applications (aerospace, electronics), historical artifact preservation
Corrosion sensors	–Incorporated into sensor membranes or embedded within coatings	–Real-time monitoring of corrosion activity –Early detection and prevention of potential failures	–Sensor development stage, limited commercially available options –Specificity and sensitivity of inhibitor-based sensors under investigation	–Imidazole-doped polymer membranes for electrochemical impedance spectroscopy –Pyridine-functionalized coatings with colorimetric change upon corrosion	Predictive maintenance, infrastructure health monitoring, industrial process control

7. Future Perspectives and Challenges

7.1. Potential applications and future directions in utilizing pharmaceuticals as corrosion inhibitors

The utilization of pharmaceutical compounds as corrosion inhibitors presents a promising avenue for advancing sustainable corrosion protection strategies. Looking ahead, several potential applications and future directions can be explored [140–142]:

1. **Biomedical devices:** Pharmaceutical inhibitors can be incorporated into biomedical devices, implants, and prosthetics to enhance their corrosion resistance and biocompatibility. This application can improve the longevity and reliability of medical implants while minimizing the risk of adverse reactions in the human body.
2. **Marine infrastructure:** Pharmaceuticals inhibitors can be used to protect marine infrastructure such as offshore platforms, ships, and pipelines from corrosive seawater environments. By providing durable and long-lasting corrosion protection, pharmaceutical inhibitors can extend the service life of marine structures and reduce maintenance costs.
3. **Aerospace industry:** Pharmaceutical inhibitors can be employed in the aerospace industry to protect aircraft components and structures from corrosion during operation and storage. Their compatibility with lightweight materials such as aluminum and titanium makes them suitable for aerospace applications where weight reduction and durability are critical.
4. **Renewable energy systems:** Pharmaceutical inhibitors can be utilized in renewable energy systems such as solar panels, wind turbines, and geothermal plants to mitigate corrosion and enhance system reliability. By protecting critical components from corrosion-induced degradation, pharmaceutical inhibitors can contribute to the sustainability and efficiency of renewable energy infrastructure.
5. **Advanced materials:** Pharmaceutical inhibitors can be integrated into advanced materials and coatings to impart corrosion resistance properties. By combining pharmaceutical compounds with nanomaterials, polymers, and functional additives, it is possible to develop innovative materials with tailored corrosion protection capabilities for specific applications.

7.2. Identification of challenges and research needs for further development:

While the potential applications of pharmaceutical inhibitors in corrosion protection are promising, several challenges and research needs must be addressed to further develop this field [143, 144]:

1. **Performance optimization:** There is a need to optimize the performance of pharmaceutical inhibitors in terms of corrosion inhibition efficiency, durability, and compatibility with different environments and substrates. This requires a comprehensive

understanding of the mechanisms of corrosion inhibition and the factors influencing inhibitor effectiveness.

2. **Scale-up and production:** Scaling up the production of pharmaceutical inhibitors for industrial applications presents challenges related to cost-effectiveness, scalability, and reproducibility. Research is needed to develop scalable synthesis routes, purification methods, and formulation strategies to meet the demand for corrosion protection in various sectors.
3. **Environmental impact:** Despite their environmentally friendly nature, pharmaceutical inhibitors may still pose challenges in terms of their environmental impact, biodegradability, and toxicity. Further studies are needed to assess the long-term environmental effects of pharmaceutical inhibitors and develop strategies for their sustainable production, usage, and disposal.
4. **Regulatory approval:** Regulatory approval and certification are essential for the widespread adoption of pharmaceutical inhibitors in corrosion protection applications. Research is needed to address regulatory requirements, safety standards, and certification processes to ensure the commercial viability and acceptance of pharmaceutical inhibitors in industrial settings.
5. **Interdisciplinary collaboration:** Collaboration between researchers, industry stakeholders, and regulatory agencies is essential for advancing the development and adoption of pharmaceutical inhibitors in corrosion protection. Interdisciplinary approaches that integrate expertise from chemistry, materials science, engineering, and environmental science are needed to address the complex challenges and opportunities in this field.

In conclusion, the utilization of pharmaceutical compounds as corrosion inhibitors offers promising opportunities for enhancing sustainability, durability, and efficiency in corrosion protection. However, addressing the identified challenges and research needs is essential for realizing the full potential of pharmaceutical inhibitors and accelerating their adoption in practical applications across various industries.

8. Conclusion

8.1. Summary of the key findings and implications

In conclusion, the utilization of pharmaceutical compounds as environmentally friendly corrosion inhibitors holds significant promise for advancing sustainable corrosion protection strategies. Throughout this mini-review, we have explored various aspects of pharmaceutical-based corrosion inhibition, including mechanisms of action, evaluation methods, and integration with existing corrosion protection strategies.

Key findings from our exploration include:

- Pharmaceutical compounds exhibit diverse inhibitive mechanisms, including adsorption-based and film-forming mechanisms, making them versatile options for corrosion protection.
- Experimental and theoretical studies play a crucial role in assessing the inhibitive performance of pharmaceutical inhibitors and optimizing their properties for specific applications.
- Pharmaceutical inhibitors offer several advantages over conventional inhibitors, including biodegradability, eco-toxicological safety, and compatibility with green chemistry principles.
- Integration of pharmaceutical inhibitors into coatings, inhibitors, and other corrosion protection strategies enhances metal protection effectiveness and sustainability.
- Compatibility with different metal substrates and environmental conditions is essential for the successful implementation of pharmaceutical-based corrosion inhibition.

The implications of these findings are profound, as they underscore the potential of pharmaceutical compounds to address longstanding challenges in corrosion protection while minimizing environmental impact and promoting sustainability. By harnessing the unique properties of pharmaceutical inhibitors and integrating them into corrosion protection strategies, industries can achieve more effective, durable, and environmentally friendly metal protection solutions.

8.2. Final remarks on the potential of pharmaceuticals as environmentally friendly corrosion inhibitors

In conclusion, pharmaceutical compounds offer a promising pathway towards the development of environmentally friendly corrosion inhibitors that meet the growing demand for sustainable materials and technologies. Their inherent biodegradability, low eco-toxicological impact, and compatibility with green chemistry principles make them attractive candidates for corrosion protection in diverse industrial applications.

The potential of pharmaceuticals as environmentally friendly corrosion inhibitors lies not only in their inhibitive performance but also in their ability to contribute to broader sustainability goals. By reducing reliance on traditional inhibitors with environmental and health concerns, pharmaceutical compounds pave the way for cleaner, safer, and more sustainable corrosion protection strategies.

Furthermore, the versatility and compatibility of pharmaceutical inhibitors with existing corrosion protection technologies open up new possibilities for innovation and collaboration across disciplines. By leveraging interdisciplinary approaches and partnerships, researchers and practitioners can accelerate the development and adoption of

pharmaceutical-based corrosion inhibition solutions, driving positive environmental and societal impacts.

In conclusion, the future of corrosion protection lies in harnessing the potential of pharmaceutical compounds as environmentally friendly inhibitors. Through continued research, development, and collaboration, we can realize this potential and pave the way towards a more sustainable and resilient future for metal protection and corrosion control.

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