

Oxazoles: A Promising Frontier in Corrosion Inhibition for Steel in Acidic Environments

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(Received July 30, 2024; Revised August 27, 2024; Accepted September 22, 2024)

Steel corrosion in an acidic environment is a serious problem in various sectors of the economy. It must be controlled by developing an effective corrosion protection plan. In this review, oxazole derivatives as iron inhibitors in acid solutions are summarized. Corrosion in acids and corrosion inhibition of steel as a means of controlling corrosion are described first. The possibility of oxazole derivatives being corrosion inhibitors are then introduced. Details about the means by which oxazole derivatives can prevent corrosion of metals are explained. Classical methods and the latest trends in the synthesis of new oxazole's are described, especially the journey of obtaining oxazole derivatives. Laboratory investigations focusing on oxazoles' inhibition effects, factors affecting their efficiencies, and comparative analyses with other inhibitors are then discussed. Industrial applications of oxazoles as corrosion inhibitors by oil and gas, chemical processing, automotive, marine water treatment industries are also discussed. Concerns and possibilities of future studies and how oxazoles could be exploited for corrosion resistance will extend our knowledge of corrosion within the scientific community. This study demonstrates the potential of oxazoles as corrosion inhibitors and their importance. It provides new ideas for improving corrosion treatment of steel in acidic environments.

Keywords: Oxazoles, Corrosion inhibition, Steel, Acidic environments, Mechanisms

1. Introduction

Steel is widely used as an engineering material due to its good tensile strength and affordable price. However, steel corrosion has restricted its applications and has negative effects such as destruction and ultimately failure of components, financial loss, and environmental issues [1-3]. Corrosion is, by definition, the natural deterioration of metals in their environment caused by chemical and physical processes. However, the presence of acid usually accelerates corrosion and significantly increases its rate of deterioration. In general, steel corrosion under normal atmospheric conditions depends to a great extent on the surrounding humidity, the concentration of gases, temperature, properties, and impurities present on the

surface, type of surface exposure, and ultimately, the corrosive nature of the environment in which it is placed [4-6]. Acidic media leads to intensely active corrosion of most metals, including steel. Consequently, acid is commonly used as an essential industrial pickling agent for efficiently cleaning surfaces of steels [7-9]. This area of discussion covers corrosion beyond acidic solutions, which showcases the significance of corrosion inhibition for the integrity of steel. The deterioration of materials due to chemical or electrochemical reactions with their environment (referred to as corrosion) offers a multilayered picture where the level of the temperature, pH conductivity, and corrosive agents play a part. The opened environment, especially the acidic area, is where corrosion rate generally increase as the sign of the heightened activity of hydrogen ions (H^+) and other corrosive species. Fig. 1 illustrates the impact of acidic environments on steel corrosion. The

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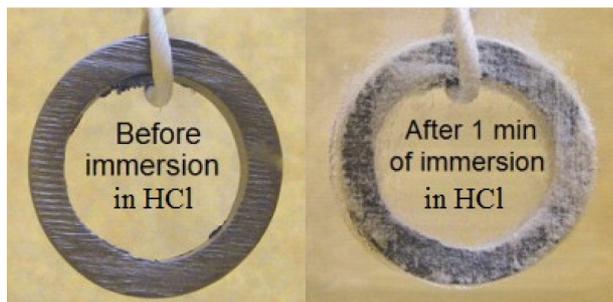


Fig. 1. Visual Impact of Corrosion on Mild Steel in 1 M HCl Solution

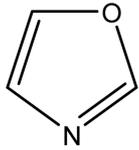
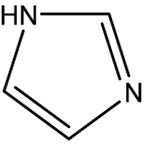
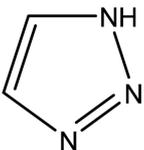
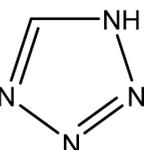
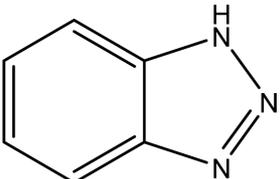
figure shows a mild steel sample before (left) and after (right) 1 minute of immersion in 1 M HCl solution, demonstrating the rapid onset of corrosion in an acidic environment. This image starkly illustrates the aggressive nature of hydrochloric acid (HCl) on mild steel surfaces, even within a very short exposure time. The mild steel ring before immersion is seen to be in good condition with no sign of deterioration and its surface is smooth showing their pre-corrosion condition. As it can be observed, after one minute of being immersed in the HCl solution, the surface of the steel has already deteriorated significantly and there is formation of reddish brown corrosion products on the steel surface. The fast alteration highlights the aggressive corrosion process started by the acidic nature, where the steel interact with HCl, leading to the formation of iron chloride and hydrogen gas, which accelerates surface deterioration. This visible evidence highlights the critical necessary for effective corrosion inhibitors or protective coatings to inhibit such rapid deterioration, particularly in industrial settings where mild steel is commonly used and exposed to corrosive agents like HCl. This type of rapid initiation of corrosion is compelling evidence of why corrosion prevention in acidic environments is urgently necessary to prevent deterioration of steel structures [10].

Steel corrosion is the most significant challenge for all industrial, including oil, gas, chemical processing, as well as national infrastructure. Acids with pH in the range of 1, 2 are commonly found in these settings, such as hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and acetic acid (CH_3COOH). The acids may have the ability to pass through the passive film on the steel surfaces and thus cause enhanced corrosion with resulting structural integrity breakdown [11-13]. The exact corrosion mechanisms

governing acidic corrosion are often complicated, with the dissolution of iron ions from the metal surface followed by their oxidation as part of the formation of corrosion products like iron oxides and hydroxides among others playing a central role. These corrosion products become the facilitators of the perpetuation of chemical reactions by speeding up chemical reactions and allowing corrosion to spread unhindered covered over the surface of the metal [14-16]. Many protective mechanisms, particularly the passive approach, have been proposed. The use of corrosion inhibitors is one of the most practical, effective, and inexpensive ways to extend the useful life of steel [17-19]. Organic compounds such as amines, mercaptan derivatives, imidazoles, pyridines, and purines are good corrosion inhibitors for steel in acidic environments [20-22]. Recently, heterocyclic compounds have been widely studied as potential corrosion inhibitors for acid media. Compounds possessing N, O, S, P, and a mixture of heteroatoms are of special interest because of their bond rupture ability and better adsorption behavior [23-25]. Azoles are a group of five-membered heterocycles containing a $-C=N-$ group and have an effect in various fields of science, health, and industrial applications. They are highly important, widely distributed in natural products, and many of them possess interesting biological activities like anti-asthmatic, anti-stress, anti-HIV, anti-cancer, tuberculosis, spasmolytic, anesthetic, and many more. Not only in biological activities, oxazole derivatives also act as corrosion inhibitors and dyes for corrosion of various metals in different environments [26-28]. Oxazoles and their derivatives are classified as promising corrosion inhibitors, mostly for steel and AA 2024-T3 aluminum in acidic media [29-31]. Oxazoles, as a class of heteroaromatic compounds containing a ring with oxygen and nitrogen, show aptitude for corrosion inhibition of many metals in recent times. It has excellent anti-corrosion properties due to its unique chemical structure. The oxazole derivative structure consider suitable for corrosion protection particularly in acidic environments [32-34]. Table 1 provide a comprehensive overview of the different azoles used as corrosion inhibitors, highlighting their chemical structures and specific roles in preventing corrosion in various environments [35].

Oxazoles exhibit an important property in the form of metal surface adsorption. Thereafter, the protective barrier

Table 1. Detailed Description of Azoles Used as Corrosion Inhibitors

Azole Type	Chemical Structure	Key Features and Relevance to Corrosion Inhibition
Oxazole		Contains one nitrogen and one oxygen atom in a five-membered ring. Effective in acidic environments due to its ability to form protective films on metal surfaces.
Imidazole		Aromatic ring with two nitrogen atoms. Forms stable complexes with metal ions, enhancing the protective barrier against corrosion. Useful in various industrial applications.
Triazole		Contains three nitrogen atoms in a five-membered ring. Strong chelation with metal ions helps in creating protective layers on metals. Effective in harsh environments, including acidic conditions.
Tetrazole		Composed of four nitrogen atoms and one carbon atom in a five-membered ring. Known for its strong binding affinity to metal surfaces, forming protective films. Useful in cooling systems and anti-corrosion coatings.
Benzotriazole		An aromatic compound with a benzene ring fused to a triazole ring. Effective in protecting copper and its alloys by forming stable complexes with metal ions. Widely used in cooling systems and protective coatings.

inhibits the destruction of the metal surface by corrosion. Nitrogen and oxygen atoms due to the presence of electrons in the oxazole ring express strong interaction which consequently free formation of stable complexes at the interface of electrolyte and metal [36-38]. Furthermore, Oxazoles can provide various chemical reaction substrates under acidic conditions which can be also able to participate in redox reactions and inhibit corrosion by multiple different mechanisms. This process may happen in the form of passive film formation, the scavenging process of corrosive species, or the inhibition of cathodic or anodic reaction which are involved in corrosion process [39-41]. In addition, oxazole derivatives can be synthesized, which also have tunable corrosion inhibitory properties. Therefore, they can be used for specific applications in diverse environmental conditions. This flexibility, achieved through customized design of molecules, thus expands the choice of inhibitors specifically designed for corrosion treatment that are expected to deliver enhanced

efficacy and stability [42-44]. In the following sections, we will explore the mechanisms of oxazoles inhibition in corrosion processes, the methods of synthesis used for their preparation and the studies conducted under acidic, and we will conclude with a detailed discussion on their applications and the future directions in this growing field of study. We will review a comprehensive study related to corrosion inhibitors of steel in acidic environments, and the best example that will be discussed are oxazole derivatives. Putting the spotlight on the design of corrosion inhibitors based mainly on oxazoles' exclusive structure and inhibition features, however, is an innovative approach.

This paper utilizes oxazole synthesis, mechanism, experimental studies, and industrial applications as its domains of study with the aim of unravelling secret answers and hence identifying opportunities for future research in corrosion science. The goal of this piece is to make an extensive presentation of the process of oxazoles usage as corrosion inhibitors in the steel environment that

contains acid. The review focuses on a literature survey and synthesis revealing the actual oxazoles abilities as anti-corrosion. Consequently, it lists out the efficacy and mechanisms and discusses the industrial applications of the derived outcomes. As oxazoles participate in experimental studies, synthesis as well as inhibition mechanisms are examined on a systematic basis, the goal is to provide useful ammunition to reveal the role of oxazoles in the control of corrosion, and, accordingly, to emphasize the prospects and the areas for further research in both fields. The main objectives of the current work can be summarized as follows:

- (1) To illustrate the issue of the corrosion of steel immersed in acids and the role of corrosion control for such a steel.
- (2) The use of oxazole analogs as inhibitors demands compliance with specific chemical structure, synthesis methods, and inhibitive mechanisms.
- (3) The review is centered on experimental corrosion performance of oxazoles, consideration of factors leading to inhibition performance and analysis of that performance in comparison to similar inhibitors.
- (4) Corrosion inhibition ability of oxazoles in oil and gas, chemical processing, automotive, marine, and water treatment sectors has been demonstrated through industrial application of oxazoles as corrosion inhibitors.
- (5) To spot both challenges and factors that benefit utilization of oxazole for anti-corrosion purposes and then

make decisions about oxazoles employment for future corrosion inhibition in oxide materials.

2. Mechanisms of Corrosion Inhibition by Oxazoles

Oxazoles exhibit remarkable corrosion inhibition properties owing to their ability to interact with metal surfaces and alter the electrochemical processes involved in corrosion. In this section, we discuss the different reasons through which oxazoles appearance their inhibition activity including adsorption mechanisms, film formation and electrochemical methods [45–47]. Fig. 2 clarifies the chemical structure of an oxazole structure, highlighting its key functional groups, including the nitrogen and oxygen atoms in the five-membered ring. The figure illustrates the corrosion inhibition effects by oxazoles through adsorption on metal surface, formation of protective film and modulation of electrochemistry. This process occurs due to the absorption of oxazoles at the surface metal-oxazole interaction and results in a coating layer that resists ingress of corrosive species. Moreover, oxazoles could be chemically converted into stable films or coordinated with metal ions to increase their corrosion inhibition properties. Comprehension of these mechanisms is significant for improving the activity of oxazole inhibitors and designing their corrosion protection approaches.

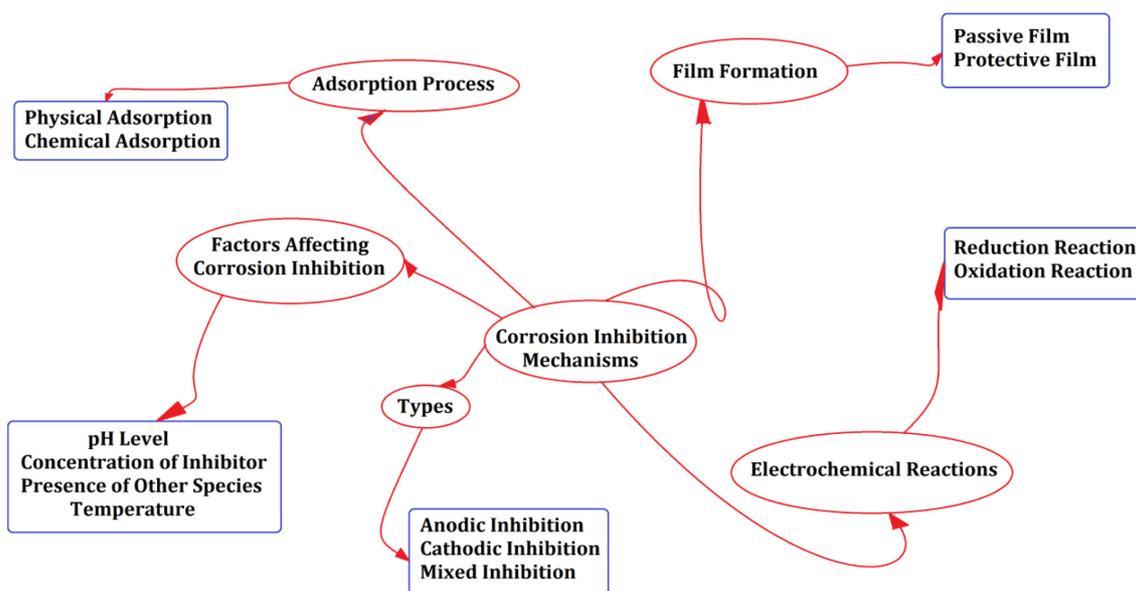


Fig. 2. Schematic Representation of Oxazole Structure and Mechanisms of Corrosion Inhibition

2.1 Adsorption mechanisms

After the metal surface is exposed to an oxidizing atmosphere, the oxazole molecules adhere to the metal surface on a weak chemical basis, such as Van der Waals forces, hydrogen bonding, and π - π interactions. Adsorption onto the oxazole groups, with the nitrogen and oxygen atoms, is powered by the attractive interactions with the metal ions already on the surface. Both physical and chemical interactions are observed within this adsorption process [48-50]. Oxazoles adsorption at metal surface follows layer formation, both processes act together against the corrosion by the deprivation of the harmful species reaching the metal substrate beneath. This physisorbed layer can be considered as a physical barrier which because of this retards the diffusion of the destructive ions (chloride and sulfates) and as a result decreases the corrosion rate. Also as oxazoles being adsorbed can induce the exchange of water molecules that settle at the metal surface, this effect may be expected to augment the protective efficiency [51-53]. Adsorption behavior of oxazoles is affected by several factors, including chemical structure of the molecule, type in the preparation of the metal surface, composition of solutions, and at the time prevailing environment. For example, the existence of such functional group as thiol or amino groups in oxazole molecule could be beneficial because these ligands provide a strong sorption by forming stable bonds between the metal atoms [54-56].

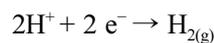
2.2 Film formation

Apart from being adsorbed, these compounds remarkably react with metal ions by forming protective film layers of the surface and its result is a higher corrosion inhibition. The adsorption of oxazole molecules leads to the interaction or shifting of the molecular structure through many chemical reactions resulting in a continuous film that covers the whole metallic surface [57-59]. The physical virtue of the oxazoles films stands out here with respect to them shielding the metal from the corrosive environment and hence no direct contact with the destructive reactions. Furthermore, a lot of film could be presented. It includes corrosion products and inhibitor compounds. They are responsible for keeping the passive layer stable, and long-term corrosion resistance [60-62].

The structure of the protective layer mold formed by oxazoles depends on parameters like the concentration of inhibitor, pH, temperature, energetic levels, as well as anodic and cathodic conditions which affect its composition. For instance, a cartridge with the initial oxazole molecules amounts will form a monolayer on the metal surface. However, twitching of the concentrations may lead to the formation of the thicker multilayer cartridge [63,64]. In addition to that, the integrity of the protective film over long periods of time determines a shielding of the corrodes. Along with high film-forming quality, these azoles are coated by no chemical or mechanical factors can be degraded, hence, they offer excellent long-term corrosion resistance in harsh combinations of environments. Fig. 3 illustrates the electrochemical processes involved in the corrosion of steel in an acidic environment, highlighting the roles of anodic and cathodic reactions in the overall corrosion mechanism. At the anodic sites on the steel surface, iron (Fe) undergoes oxidation, losing electrons to form iron ions (Fe^{2+}). This process can be represented by the following reaction:



When electrons are lost at the anode, pits or crevices will develop on the surface of the steel and lead to deterioration of the material. The electrons produced from the anodic reaction will then flow through the steel to the cathodic sites where they reduce oxygen molecules and water to form hydroxide (OH^{-}) at the cathodic sites. In an acidic environment, the cathodic reaction will generally not involve oxygen and instead reduce (H^{+}) ions; while that is not present here it is an important consideration with acidic environments:



However, in the context of the figure, if oxygen is present, the reaction might proceed as follows:



The generation of hydroxide ions is a key factor in the formation of iron hydroxides, which then reacts to produce rust (iron oxide), a typical corrosion product.

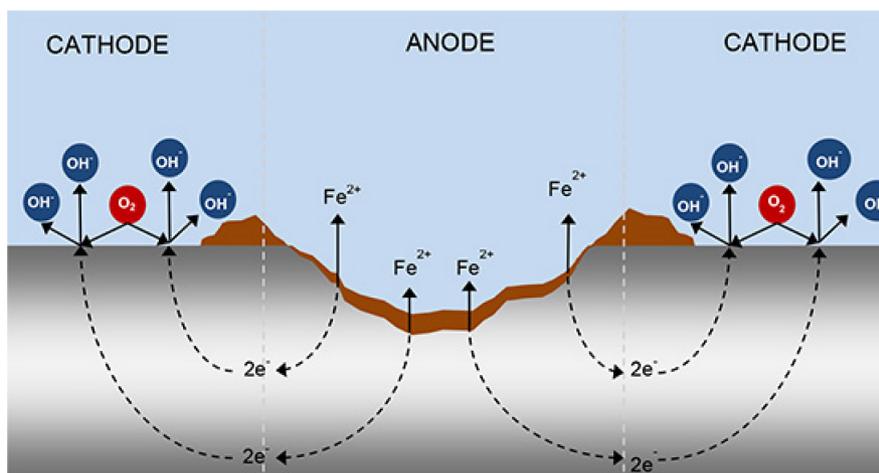


Fig. 3. Corrosion Mechanisms in Acidic Environments

The combination of the anodic and cathodic reactions products in the degradation of the steel surface. The figure shows how localized electrochemical cells form on the steel surface, resulting in the formation of corrosion products (e.g. rust) at the anode, and continual dissolution of metal. In acidic conditions, the concentration of H⁺ ions is high, which can help the anodic dissolution of iron. The oxygen available at the cathodic sites can further encourage the cathodic reactions, promoting the overall corrosion process. It is very necessary to understand these mechanisms in order develop a proper corrosion prevention strategies including the use of various types of inhibitors, coatings and cathodic protection systems. It is possible to slow down the rate of corrosion and protect metal structures from premature failure by targeting either the anodic or cathodic reactions, or both. This figure is a graphic representation of the complex interplay of electrochemical corrosion systems. Its is crucial to assist understand the basis on designing effective methods to inhibit and minimize those corrosive destruction processes [65].

2.3 Electrochemical processes

Along with their chemical effect to form corrosive barriers, oxazoles can also regulate electrochemical processes hence participating in suppression of corrosion rates that can be inhibited due to electrochemical mechanism. Moreover, azole molecules may perform either as cathodic or anodic inhibitors which means that their behavior is directly related with the electrochemical reactions appeared at the metal surface [66-68]. Crossion

inhibitors consist of oxazoles which slow down the oxygen as well as cathodic depolarizers reduction process that can suppress the process of corrosion instigated by the cathodic reaction. Alkyl-substituted oxazoles, which have a nitrogen and oxygen ring, address this problem by preventing oxygen and nitrogen atoms from being reduced during oxidative reactions [69]. In another case, the oxazoles can also show the anodic inhibition behavior by blocking the release of the metal ions of the anodic sites while they further dissolve in the surface of the metal. This mechanism is related is the formation of complexes that are insoluble or layers that passivate the metal ions which normally be released to the electrolyte solution [70]. Oxazoles effectiveness as anode chemical inhibitors is dependent on the selective adsorption either at the cathodic or anodic sites of the metal surface and by the number of the oxazoles that participate in the controlled or slowing of a specific electro-chemical reaction. For instance, pH, temperature, and other chemical entities in the electrolytic solution are the main variables that govern the electrocatalytic productivity of oxazoles and their possible function as corrosion inhibitors [71]. In the last, strong corrosion inhibitors come from oxazole group that operate in various mechanisms such as adsorption onto metal surfaces, formation of barrier films and change of redox processes. The processes, in aggregate, effectively confer this better corrosion inhibition in an acidic environment. This makes oxazole derivatives promising candidates for multiple industrial applications involving the use of corrosion control strategies [72].

3. Synthesis Methods of Oxazoles

The cyclic nitrogen containing heterocyclic compound oxazoles can be synthesized by different ways. Following up, here we walk through both old and contemporary oxazole synthesis, emphasizing further they are superior to other methods as well as their shortcomings and applications [73,74].

3.1 Traditional synthesis approaches

To date, oxazoles have been achieved through the employment of which are considered classical organic chemistry methods which normally entail taken a condensation reaction of two suitable precursors at specified reaction conditions. The first and most popular method in the synthesis of the oxazole is the Robinson-Gabriel synthesis: oxazole is formed via the condensation of β -ketoesters (or β -diketones) and amidoximes with dehydrating agent in an acid environment, such as phosphorous pentoxide (P_2O_5) or thionyl chloride [75,76]. Cyclization of α -hallo carbonyl compounds with amidoximes or semicarbazones into oxazoles performed under basic conditions is another traditional method. Using the Fisher synthesis, which is the simpler one which requires easily available starting materials that gives an access to the oxazoles, has been demonstrated. Also the Fischer synthesis can be adapted to introduce a different substituents on oxazole ring, thus the synthesis is modified, and various oxazole derivatives with differing structures are obtained [77,78]. Besides simple classical methods of oxazole synthesis designated as oxidative cyclization of α -amino ketones or α -amino acids with amidoximes or hydroxylamines, one can distinguish synthesis methods characterized by cyclization of α -hydroxyketones with amidoximes or hydrazines under acidic conditions. Whereas the conventional/old-fashioned methods of oxazoles' construction have found broad utilization among the synthetic applications, they are still costly and limited in terms of yield and use of environmentally unfavorable reagents [79,80]. However, there are some weak points in these classical method versions and they are still perfect tools for the synthesis of oxazoles, which are in use mainly in the academic research and the small-scale organic synthesis. The requirement for more economical and simple chemical

processes along with those which are environmentally friendly and scalable has led to new ways of producing the oxazole compound [81].

3.2 Recent developments in oxazole synthesis

During last few years the organic community has finished to get knowledge about new artificial methods that are characterized by high efficiency and sustainability in the synthesis of oxazoles. These innovative synthesis techniques primarily utilize transition metal catalysis, organocatalysis or biomimetic reactions to achieve the synthesis of oxazoles with higher yields, more functional group compatibility and atom economy [82]. Transition metal catalyzed procedures constitute a prominent way of constructing oxazole by using inexpensive metal complexes which possess great reactivity and activate bonds. Using palladium as a catalyst, for instance, amide or nitrile molecules have been cross-coupled with halides to produce oxygen heterocycles through C–N bond formation. Another analogous yttrium-catalyzed cyclization processes of alkynes with amidoximes or nitriles have been set up for the selective formation of substituted oxazoles [83]. Another useful tool that has shown effectiveness in the oxazole synthesis is organocatalytic methods, they being a very effective route to oxazole synthesis, which is done under mild reaction conditions and producing high levels of stereo- and regioselectivity. Likewise, organocatalyzed cyclization reactions of α -hydroxy ketones with amidoximes and hydrazines adding in separate steps have now been reported for the synthesis of functionalized oxazoles under mild acidic conditions. In addition to that, the cross-catalyzed condensation of β -ketoesters and β -diketones with amidoximes initiated by imidazole have been done as an alternative route to oxazole derivatives with different substitutions [84,85]. Biomimetic oxazole syntheses are based on the biochemistry of diverse nature in search of the most exact and selective enzymatic catalysis possible with the help of the synthetic catalyst. As a case in point, chiral oxazole development via an asymmetric cyclization reaction applying peptide-based catalysts that result from the amino acid building blocks is currently under investigation. Besides metalloenzymes like cytochrome P450 are also exploited for the hydroxylation of specific α -amino ketones, that a process which makes the synthesis of oxazoles possible from carbon-neutral feedstocks [86,87].

The main benefit of latest approaches to synthesis of oxazoles is increased efficiency, reliability and sustainable procedures as against the classical methods. To sum up, the discoveries in the area of oxazole synthesis have finally led to the appearance of the new and alternative methods that work more efficiently, more selectively, and more sustainable than the traditional methodologies. These approaches can reveal new opportunities for the synthesis of complex oxazole-based compounds that can be used in different areas of medicine, materials science, or drug research [88,89].

4. Performance of Oxazoles in Acidic Environments

Oxazoles are compounds that exhibit exceptional efficacy in inhibiting the corrosion of steel in acidic media. Many oxazoles possess multifunctional chemical structures that demonstrate significant inhibition potential. This section will highlight the behavior of oxazole derivatives in acidic media, with an emphasis on experimental studies regarding their corrosion inhibiting performance, and considering the major factors that contribute to their efficiency. A qualitative comparison of oxazole derivatives developed as patented corrosion inhibitors is shown in Table 2. Table 2 demonstrates a thorough covalent comparison of the molecular derivatives of the oxazole ring including structural features, method of synthesis, and the inhibition efficiency of the oxazole derivatives. For illustration, Oxazole 1 was synthesized via the Robinson-Canterbury route and has a dihydro-1,3-oxazol-4-yl-methanol fundamental that highlights nitrogen and oxygen heteroatoms within the five-member ring along with several aromatic substituents. Oxazole 1 has 90% corrosion inhibition efficiency and the combination of structural features contributes to corrosion inhibition

effectiveness. Oxazole 2 is another significant derivative that contains a thiol functional group attached to an electron-rich aromatic ring, specifically produced through a transition-metal-catalyzed cyclization. Oxazole 2 exhibits an 85% inhibition efficiency which was still significant, despite being slightly less than that of Oxazole 1, the presence of the thiol group plays a essential responsibility in its inhibition mechanism. The oxazole derivative exhibiting the highest inhibition efficiency at 95% is Oxazole 3. Oxazole 3 is composed of amino and hydroxy groups in addition to alkenyl substituents, and was synthesized by a multicomponent reaction, specifically Ugi-azide reaction type. Consequently, a multicomponent reaction route is generally able to make more structurally complicated derivatives with superior inhibition properties. The structure-activity relationships (SAR) of oxazole derivatives is highly significant in monitoring their corrosion inhibiting behavior. The structural features of oxazole derivatives contribute towards a structure inhibition mechanisms via consideration to certain structural features, the presence of functional groups and heteroatoms, and the methodology chosen to synthesis these derivatives appropriately, which enables investigators to optimize and modify oxazole derivatives for more efficient corrosion inhibiting applications. As evidence supporting this conclusion, the content of Table 2 indicates the variety of oxazole derivatives in corrosion inhibition by their overall inhibition efficiency corresponding to their structural characters and synthesis method for each oxazole derivative.

4.1 Experimental studies on corrosion inhibition

Experimental studies aiming at confirming the effectiveness of the corrosion inhibition of oxazoles are conducted using a number of techniques, including

Table 2. Corrosion inhibition efficiency of molecular derivatives of oxazole ring: comparative approach

Oxazole Derivative	Structural Features	Synthesis Method	Inhibition Efficiency (%)	Ref.
Oxazole 1	dihydro-1,3-oxazol-4-yl- methanol; Nitrogen and oxygen atoms in the five-membered ring, aromatic substituents	Robinson-Gabriel synthesis	90	[90]
Oxazole 2	(3-(1,3-oxazol-5-yl)aniline); Thiol functional group, electron-rich aromatic ring	Transition-metal-catalyzed cyclization	85	[91]
Oxazole 3	(5-((4, 5-dihydro-oxazol-2-yl) methyl) quinolin-8-ol); Amino and hydroxy groups, alkynyl substituents	Multicomponent reaction (Ugi-azide reaction)	95	[92]

electrochemical techniques, weight loss (mass loss) analysis, surface characterization, and corrosion morphology studies. There are different types of studies that are carried out for this purpose which are to be conducted to determine the active mechanisms in corrosion inhibition by oxazoles, to evaluate their effectiveness under different conditions, and to optimize their performance for practical applications [93]. Electrochemical measurements (PD (Polarization Depolarization), EIS (Electrochemical Impedance Spectroscopy), and CV (Cyclic Voltammetry).), which define the kinetics of oxazoles corrosion and its mechanism of inhibition, are therefore very important. The inhibitory capacity of oxazoles can be quantified by monitoring changes in corrosion potential, polarization resistance and charge transfer resistance. Furthermore, the electrochemical mechanisms which govern the process can be explored by using these techniques [94,95]. The mass loss is investigated by weight loss analysis and the measure of the mass loss while soaking metal samples in corrosive solutions that contains the oxazole inhibitors as well as the other corrosive solutions. The flowchart in Fig. 4 illustrates the approach to carry out an experiment of corrosion inhibition while providing focus on the preparation, monitoring, and optimization of performance inhibitors in a controlled environment. These experiments consists of various stages which may be subdivided into organized key stages. The process starts with the use of diluting a corrosive solution normally in an acidic form

such as hydrochloric acid to which the inhibitor is added. Another parameter which should be kept most consistent in this experiment is temperature. Once the solution has been heated to the necessary temperature the inhibitor is introduced. If the temperature is unstable, the process of corrosion will similarly not be stable. Besides, the way the inhibitor interacts with the metal surface is likewise heavily contingent on the temperature. Finally, temperature might have a significant impact on the reaction kinetics. This inhibitor is then in a large concentration because it plays significantly high roles in the rates of corrosion and inhibition. Subsequently the mixture is stirred so as to allow for the distribution of the inhibitor. This stirring process is important to ensure consistency as well as reliability of the results as required. The stirring of the solution is essential because without it, the solution may not be uniform. This is of critical importance because in order for the corrosion to be prevented effectively, the concentration of the inhibitor in the solution has to be constant. Subsequent to stirring, a metal specimen normally made of mild steel is then placed in the solution. Afterwards, the rate of corrosion is ascertained through several methods which may include the measurement of weight loss or undertaking other electrochemical or surface analysis. These observations assist in a decision-making process when it comes to establishing the effectiveness of the inhibitor in enhancing corrosion control. Corrosion is the main problem that must be dealt

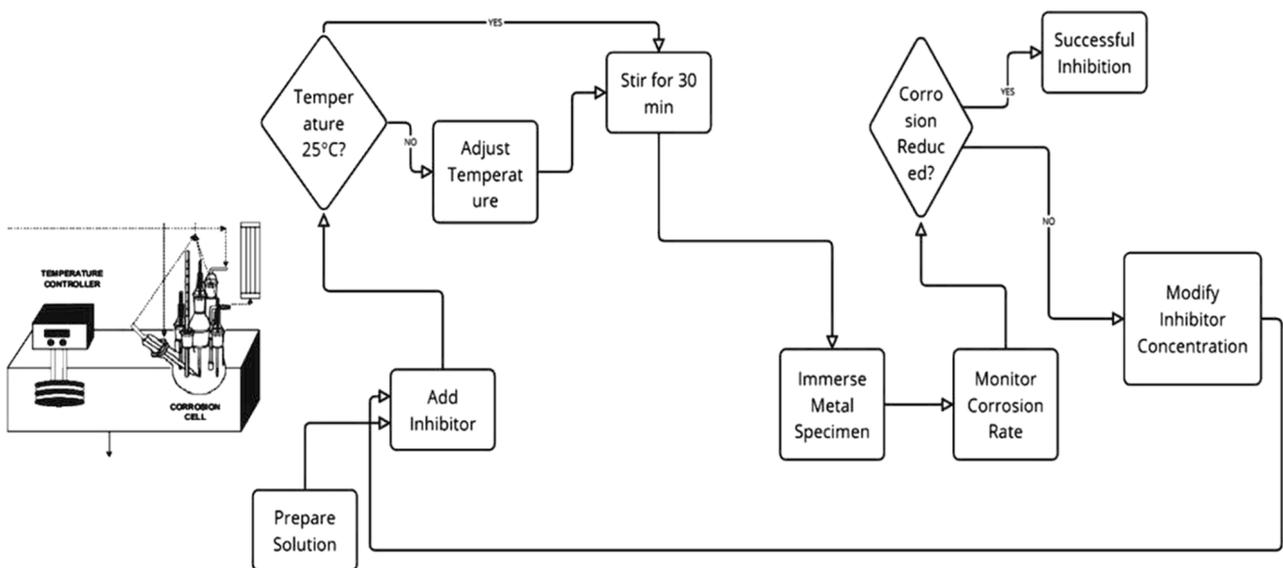


Fig. 4. Experimental Setup for Corrosion Inhibition Testing

with in this process; and if the corrosion rate has been effectively brought down, the process is regarded as a success. However, if the reduction is not enough, then the inhibitor concentration will be changed. The experiment is then carried on with additional alterations and more monitoring until the degree of corrosion control that is required is attained.

This flowchart offers a structured method for assessing and enhancing corrosion inhibitors, which is crucial for creating effective strategies to prevent corrosion in different industrial settings. By adhering to this process, researchers can identify the optimal concentration and conditions for inhibitor effectiveness, ultimately ensuring the successful safeguarding of metal surfaces against corrosive environments.

The rate at which the oxazole and non-oxazole samples lose surface material provides quantifiable data for determining corrosion inhibition efficiency. The next step in the experimental design involves using surface modification techniques like scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-Transform infrared spectroscopy (FTIR) to assess how the surface morphology, composition, and corrosion phases respond in the presence of the oxazole inhibitors [96,97]. The

studies examining corrosion morphology utilize methods such as visual inspection and the analysis of corroded surfaces through optical microscopy, scanning electron microscopy (SEM), and atomic force microscopy (AFM). Through these multiple analytic methods, researchers can distinguish such corrosion features as pitting, cracks and surface scale formation, and estimate the degree of corrosion inhibition reached by oxazoles [98]. Scanning electron microscopy (SEM) pictures in Fig. 5 offer see-with-your-own-eyes visual proof of what oxazole inhibitors do in terms of corrosion inhibition by showing the surface of corroded steel with and without the presence of oxazole inhibitors. The pictures are the visual evidence of gullying formation, oxidation, embrittlement, and morphological changes happening to the surface of the metal in a highly corrosive environment. The outcome of an experimental comparison between corrosion inhibitors and clean steel specimens leads to viewing diverse corrosion crack morphology, with inhibitor surfaces demonstrating higher corrosion resistance, smoother surface topography, and fewer and reliable corrosion features such as pits and cracks. This surface morphology analysis conforms with the argument linking oxazoles with corrosion inhibition and how these compounds act to protect steel substrates

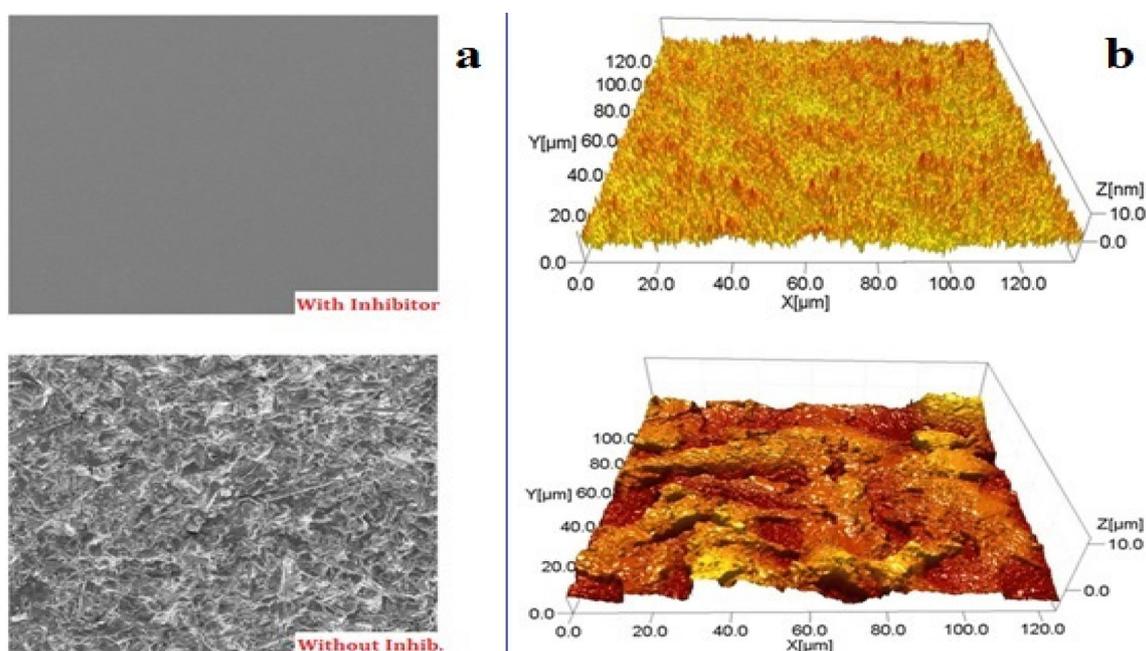


Fig. 5. Surface Morphology of Mild Steel in 1 M HCl Solution: With and Without Corrosion Inhibitor. (a) SEM images showing the surface of mild steel after immersion in 1 M HCl with (top) and without (bottom) the addition of a corrosion inhibitor. (b) 3D surface profilometry images corresponding to the same conditions)

from corrosive attack. Fig. 5 demonstrate the significant effect of the corrosion inhibitor on the surface morphology of mild steel immersed in 1 M HCl. The surface (with inhibitor) appears smooth and uniform, with minimal corrosion damage evident in both the SEM and 3D profilometry images. This indicates effective protection of the steel surface by the inhibitor, likely due to the formation of a protective film that prevents aggressive chloride ions from interacting with the steel surface as seen in image (a) of Fig. 5. The surface (without inhibitor) is heavily corroded, with deep pits and rough textures clearly visible in both the SEM and 3D profilometry images as seen in image (b) of Fig. 5. Certain types of surface roughness examined on the metal surface and pits point to the fact that corrosion found on the unshielded steel in the acidic solutions. These experiments show how corrosion inhibitors play a part in preventing the corrosion of steel configurations in an acidic environment, enhancing their service abilities and mechanical properties. The efficiency of this damper can be verified quantitatively, by taking a closer look at the phylometric data where the surface roughness values are likely to have been significantly reduced, especially with respect to the damped sample [99].

Generally, the exploration of solutions has concluded that oxazoles are effective inhibitors in corrosion conditions while the inhibition efficiency varies from moderate to excellent level depending on several factors such as concentration, the composition of the solution, temperature and metal.

4.2 Factors affecting inhibition efficiency

The acidity in a solvent system may either enable or hinder the oxazoles inhibitors performance. This behavior is dependent on the molecular structure, concentration, solution pH, temperature as well as the other coexistent chemical species. Comprehension of the balances and close relationship between these factors is the key to the development of ideal oxazole inhibitors, which can give the best protection from corrosion [100,101]. The molecular structure needs to be considered carefully because it affects the ability of oxazoles to exert corrosion inhibition. For example, nitrogen and oxygen atoms, carbon ring structures, etc. have great advantages for their interaction with metal and represent the nature of metal adsorption

due to its importance in inhibiting corrosion. Also, the presence of h-bond acceptors or h-bond donors on the oxazole ring can modulate the electronic characteristics of the inhibitor molecule and thus influence its adsorptive capacity towards the receptors and inhibition potential [102,103]. The mole percent oxazole inhibitor in the corrosive solution may be the contributing factor towards corrosion inhibition. When the insufficient inhibitor coverage takes place at the low concentration the inhibition efficiency can be quite reduced and this can be attributed to inconclusive corrosion arrest. Alternately, a higher inhibitor concentration can reach an equilibrium with a better coverage and a production of thicker and better sticking films leading to improved corrosion inhibition [104-106]. Table 3 displays that trials on corrosion inhibition efficiency due to oxazole concentration have yielded results either by electrochemical measurements or weight loss analysis. The results are shown to give a concentration which is the maximum inhibition efficiency, and this was accompanied by a concentration-dependence nature, with higher levels of oxazole leading to a maximum protection against corrosion. This linear correlation between the concentration of the inhibitor and its response emphasizes the necessity of optimal inhibitor dosage in terms of achieving the best corrosion prevention, but at affordable cost and while maintaining a safe environment [107-109].

Solution pH is another factor that mediates the breakdown of oxazole inhibitors and turns them into less reactive substances under acidic conditions. Changes in pH can have an impact on the protonation-deprotonation state of polar atoms of oxazole molecule and thus facilitate magnet adsorption, surface charge, and inhibition, among other things. The optimum pH for corrosion inhibition by oxazoles contents which is separate from each inhibitor and depending on the metal substrate with the acidic pH ranges that is mostly aids the adsorption and inhibition

Table 3. Oxazole Solution Concentration Impact on Anticorrosive Activity [107-109]

Oxazole Concentration (ppm)	Inhibition Efficiency (%)
50	70
100	85
200	95
300	98

efficacy [110-112]. Fig. 6, establish the relationship between the several factors that would determine the corrosion inhibition efficiency, especially the function of pH points. It further describes how the acidity, neutrality and alkalinity of a solution affects various aspects of corrosion protection mechanisms such as adsorption, film as well as passivation formation. The types of inhibitors include organic inhibitors, inorganic inhibitors and mixed inhibitors as depicted here as they relate to these mechanisms under different pH. Essentially, the diagram illustrates the relationship between the level of pH and effectiveness of corrosion inhibition mechanisms formulating it an important aspect of the inhibitors investigation. In acidic conditions, inhibitors are likely to give better results by adsorbing at the metal interface and creating shielding layers. The illustration indicates that these type of inhibitors: organic, inorganic or mixed influences these mechanisms in differential manners based on the pH. For instance, organic inhibitors could depend on adsorption especially at low pH as the main source of inhibition while inorganic inhibitors could depend on passivation processes.

Although the temperature is believed to be a major contributor of the kinetics of corrosion and the activity of oxazole inhibitors, further investigations are necessary to confirm this. Higher temperature elected a corrosion rate as well as it is not assured that the stability and specific bonding kinetics of corrosion inhibitor molecules to the metal surface will not be affected. Hence, the efficacy of oxazoles to act as the corrosion inhibitors is highly dependent on temperature, thus necessitating careful design of the conditions of operation in a practical industry [113,114]. The chemistry of copper is often not only understood by researchers but also a significant factor in industrial wastewater management. An example of such consequences is a competitive sorption or binding of oxazole inhibitor molecules to other components. All of these processes cause an increase or decrease in the concentration of oxazoles in the mitigation of corrosion of welding joints. This is a clear proof of the importance of understanding the relationship between all these factors in corrosion environments that are real world [115-117]. Briefly, the effectiveness of oxazoles as inhibitors in an

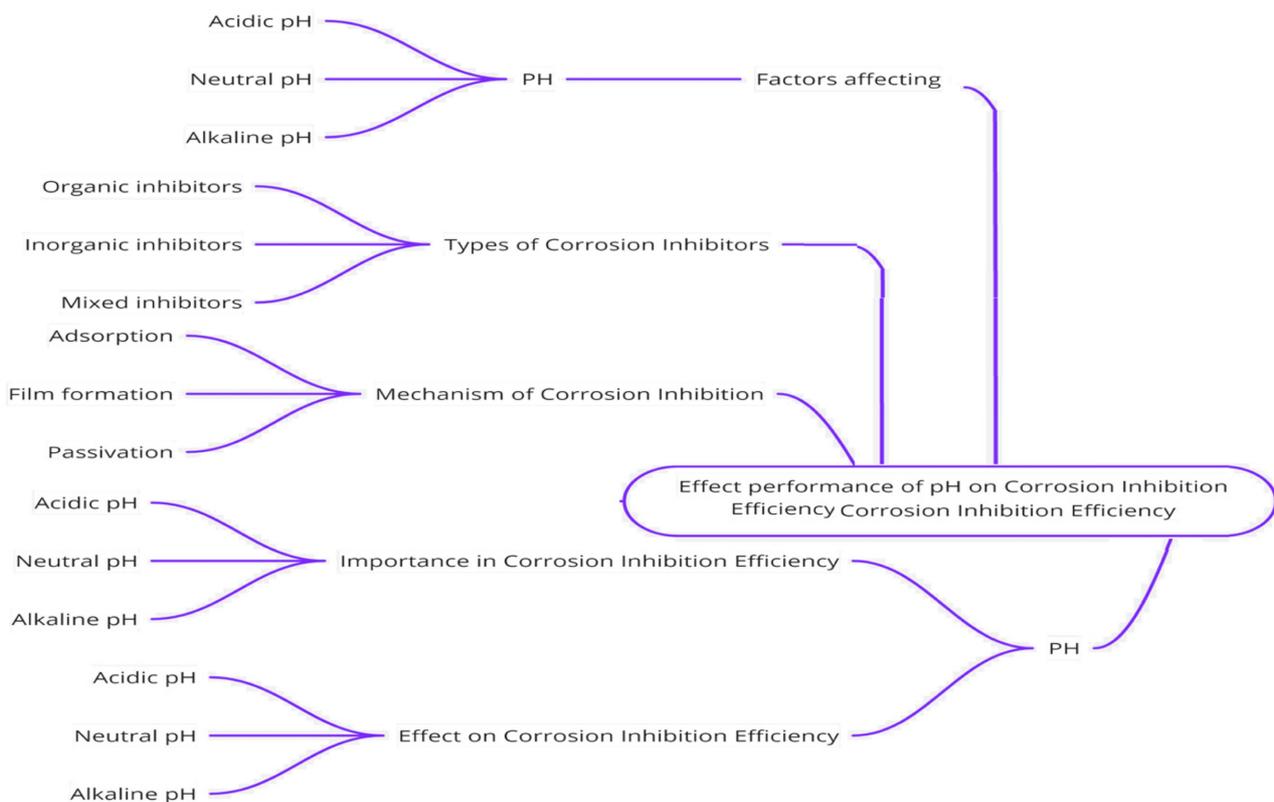


Fig. 6. Influence of pH on Corrosion Inhibition Efficiency and Related Mechanisms

acidic solution results from unique structures that include the number of oxazoline rings, molarity, pH and organic and inorganic species in the solution. Understanding and tuning these parameters together and finding the right interconnections are the backbone of building efficient corrosion inhibition mechanisms using oxazole-based inhibitors [118].

4.3 Comparative analysis with other inhibitors

In addition to oxazoles, a wide range of organic and inorganic compounds have been investigated as corrosion inhibitors for steel in acidic environments. Comparative analysis between oxazoles and other inhibitors provides valuable insights into their relative effectiveness, mechanism of action, and suitability for specific applications [119]. Oxazoles, imidazoles among others, are already under detailed investigations and their behavior is similar to that of benzimidazoles, thioureas and quinolines which involve adsorption onto metal surfaces as well as the formation of protective films [120]. Through various comparative studies, it has been shown that oxazoles display a great inhibitor efficiency that in some cases is even better than that of most organic inhibitor undergone single each time. The winning dominance of oxazole in this situation is caused by the effect of the combination of the oxygen and the nitrogen atoms within the oxazole ring, which enhance the adsorption of the metal ions [121-123]. Inorganic inhibitors like chromates, phosphates, and molybdates are widely used for the prevention of corrosion in acidic environments due to their capacities to form passivating films on the metals to facilitate formation of the insoluble corrosion products. Unlike organic inhibitors which might provide short-term care

solutions to such problems, the inorganic inhibitors are a source of toxic materials which are likely to cause pollution of water bodies and kill marine life animals as well as other creatures. While oxazoles popularly function as an eco-friendly substitute to conventional inorganic inhibitors with comparable inhibition ability, there remain environmental concerns that need further exploration [124,125]. The same applies to corrosion inhibitors and their efficacy and cost-effectiveness. Hence, comparative studies of various oxazoles versus other stationary obstacles are highly important as they can greatly contribute to informed decision-making regarding corrosion mitigation strategies. Compound properties as inhibitor stability, arrangement with the rest of the system, simplicity of application, and environmental sustainability have to be analyzed deep to guarantee the excellent corrosion prevention without negative influence on health of people and environment [126-130]. The table 4 evaluates the efficiency of different coating systems that were based on oxazoles and were applied for corrosion protection on steel substrates. It is a proprietary technology that involves the application of a unique set of oxazole derivatives in every coating solution. The thickness of each coating (μm) in wear tests is indicative of the protection level achieved (%). The results suggest that this kind of oxazole paint could be used to significantly decrease the corrosion rates at steel surfaces as well as protect the steel from aggressive environments. The shape up of coating composition and oxazole derivative is central to the improvement the performance of coating and to meet the specific needs of the application process.

In a general way, oxazoles are corrosion inhibitors for steel in acidic surroundings which are advantaged as

Table 4. Comparative Analysis of Oxazole-Based Coatings for Corrosion Protection

Coating Formulation	Oxazole Derivative	Coating Thickness (μm)	Corrosion Rate Reduction (%)	Ref
2-butyl-hexahydropyrrolo[1,2- <i>b</i>][1,2]oxazole (BPOX)	Oxazole 1	50	95	[131]
poly(2-ethyl-2-oxazoline) (PEOX)	Oxazole 2	100	79	[132]
2-methyl-4-(4-methoxyphenyl)thiazole-5-carboxylic acid ethyl ester (MTTCE)	Oxazole 3	75	88	[133]
4-(4-hydroxyphenyl)-2-(1-methyl-1H-imidazol-2-yl)thiazole (HPIT)	Oxazole 4	60	83	[134]
2-(4-chlorophenyl)-4-(4-fluorophenyl)thiazole (CPT)	Oxazole 5	40	90	[135]
2,4-dimethyl-5-(4-nitrophenyl)thiazole (DMT)	Oxazole 6	80	85	[136]
3-(2,4-dimethoxyphenyl)-4-(3-chloro-2-hydroxyphenyl)thiazole (DPT)	Oxazole 7	55	87	[137]

compared to other inhibitors' traditional organic and inorganic, due to better performance, eco-friendly character and sufficient molecular designing flexibility. The research and development work is still on-going so that the molecule mechanisms by oxazoles that cause corrosion inhibition can be understood, the performance of the oxazoles can be optimized under different conditions and the applicability of oxazoles in the industries tiding against corrosion can be broadened [138,139].

5. Applications and Future Perspectives

Oxazoles have recently draw attention to as actively corrosion inhibitors for steel in acidic environments, the aim is to investigate corrosion inhibition functionality under different circumstances through extensive research. In this section, we investigate the options for use of oxazoles in the industry as corrosion inhibitors, outline stubbornness and challenges toward the research expansion, and project future directions of using oxazoles for corrosion prevention [140-142]. Fig. 7 illustrates key future research directions in the study of microbial ecology and biofilm formation, focusing on localized gradients, sorption, exposure retention, cooperation, competition, and resistance mechanisms. The broader image on the right symbolizes the intricate and interconnected nature of microbial communities in urban and industrial settings. This figure highlights the complication and multifaceted environment of biofilm formation and microbial community interactions, especially in environments relevant to industrial and ecosystems. There

are several key aspects that contribute to this complexity as explained below:

(1) Localized Gradients: Given the presence of spatial heterogeneity inside biofilms, it is possible to create microenvironments capable of influencing microbial diversity as well as activity. In addition to this concept, future research could be aimed at understanding how such gradients affect both the resilience and functioning of a biofilm.

(2) Sorption: One of the key processes of biofilm formation is the interaction of microbial cells with different surfaces by means of sorption. It is also possible to find out how specific materials and conditions affect sorption can lead to enhance control techniques.

(3) Exposure Retention: Maintaining environmental exposure such as nutrients and antimicrobials in biofilm affects microbial survival and evolution. How biofilms both maintain and react to these exposures is worth studying, for improved future treatments of biofilm problems.

(4) Cooperation and Competition: Microbial communities are often a equilibrium of cooperative and competitive interactions. Future investigate can explore in what way these dynamics impact the stability and functionality of biofilms, especially in various and violently populated environments.

(5) Tolerance and Resistance: The greatest challenge is the development of resistance to antimicrobials within biofilms. Understanding the mechanisms of resistance and the factors that contribute to increased tolerance in biofilm-associated microbes is crucial for developing new therapeutic strategies.

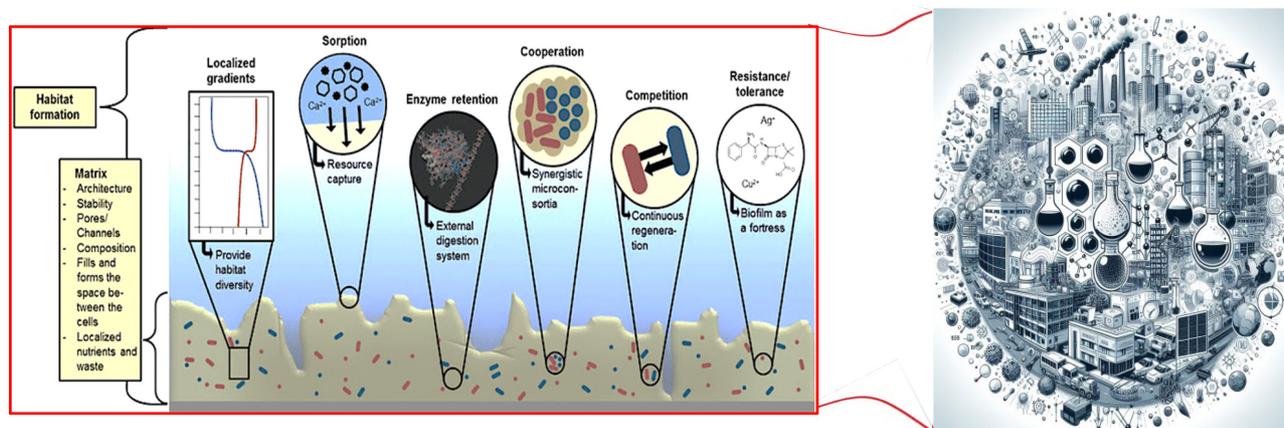


Fig. 7. Future Directions in Microbial Ecology and Biofilm Research

The overarching theme suggests that advancing our knowledge of these areas could lead to more effective management and manipulation of microbial communities in various settings, particularly in urban and industrial environments where biofilms play a significant role.

5.1 Industrial applications of oxazoles as corrosion inhibitors

The oxazoles are essential currently in industrial segments where steel frames are exposed to acidic chemicals in the environment as well as an acidic environment and hence prone to corrosion. Some key industrial applications of oxazoles as corrosion inhibitors include [143-148]:

(1) Oil and Gas Industry: The corrosive environment in oil and gas sector involves steel tubing, storage tanks and associated equipment that are continually exposed to strong acid solutions which contain various hydrocarbons, hydrogen sulfide and other aggressive species. Oxazoles could be utilized in the form of corrosion inhibitors to protect assets of the oil and gas industry from damage and prolonging their service life which in turn will reduce repairs expenses and production downtimes.

(2) Chemical Processing: Chemical process plants commonly have such industry constituents as steel tanks, pipelines, and pumps that are used for the purpose of storing corrosive solutions and acidic solutions. Oxazoles have a reliable wear resistance for these environments, especially the action of being chemically resistant coatings that impede the penetration of corrosive elements and subsequent breakdowns of the structural elements.

(3) Automotive Industry: As an example, in the automotive industry, steel-made parts such as chassis, body panels and exhaust system are much prone to corrosion where the vehicle will spend often the time in harsh climate condition or where the vehicle will have to be on the road which is salted. Oxazoles can be grafted into anti-corrosive coating systems and solutions to maintain the endurance and longevity of automobile parts, which consequently lead the vehicle performance and safety to be improved.

(4) Marine and Offshore Structures: The risks from marine environments for metallic structures become more severe if submerged in sea water, salt mist and atmospheric corrosion are involved. Oxazoles used as inhibitors of corrosion processes being marine and

offshore structures protected, including ships, offshore platforms and coastal infrastructure, look to retention of structural reliability for these assets.

(5) Water Treatment Facilities: The steel pipelines, tanks and facilities used in the water treatment include greenery, chlorinated water and other chlorides that have great potential to corrode. Oxazoles might be employed as corrosion preventive agents in water treatment operations for the protection of steel items and the adherence to the water quality security standards, hence assuring the availability of the water delivery systems hardware.

To sum up, the multifunctional role of oxazoles in corrosion inhibitors is a benefit in cost-effective management of corrosion destruction of steel assets and infrastructure because they are useful in protecting steel from disintegration failures induced by corrosion.

5.2 Challenges and opportunities for further research

While oxazoles show considerable promise as corrosion inhibitors, several challenges and opportunities for further research remain to be addressed as discussed below [149-154]:

(1) Structure-Activity Relationships: The relationship between the oxazole compounds structural change with corrosion inhibition ability should be clearly known for the development of rational design and optimization. Still, more research will be required to examine and understand the structure-activity relationship of oxazoles. The key structural characteristics that account for their increasable inhibition efficiency and selectivity would also have to be identified.

(2) Mechanistic Studies: Getting to the bottom of corrosion inhibition mechanisms via oxazoles helps to understand their primary effects and fine-tune their performance under different circumstances. Relevant spectroscopic techniques such as FTIR, UV-Vis, and XRD provide detailed information on the adsorption behavior, kinetics, and electrochemical processes. Computational simulations further help in understanding the inhibition mechanism while surface analysis methods allow direct visualization of the film formation.

(3) Environmental Sustainability: Steering environmentally friendly corrosion inhibition formulations using oxazoles derived from renewable sources will be crucial for

sustainable members of industry. Research needs to look for non-toxic ways of synthesis, inhibitors and formulations that are biodegradable and have less effect on the environment and their corrosion attack efficacy should not be compromised.

(4) Compatibility and Durability: The compatibility of oxazole inhibitors with different metals, coatings, the system’s components, as well as metal dissolution is the core factor that leads to the long-term corrosion protection within practical applications. Research is required to establish and set the criteria for oxazole-containing corroder inhibitors which under different environmental conditions (heat, humidity, dust, rain) and with operational stresses last long and perform well.

(5) Multifunctional Inhibitors: Oxazoles that are multifunctional and oxidized with additional features such as antibacterial properties or self-healing capacities, as well as surface modification capabilities, as a concept present new ways to advance corrosion prevention and to solve comprehensive corrosion issues in industrial circumstances.

Overall, addressing these research challenges and capitalizing on emerging opportunities will drive further advancements in the development and application of oxazoles as corrosion inhibitors, enabling more effective and sustainable corrosion control strategies in diverse industries [155]. Table 5 outlines key challenges and opportunities in oxazole-based corrosion inhibition research, along with potential strategies for addressing them. Challenges include elucidating structure-activity

relationships, enhancing environmental sustainability, assessing compatibility and durability, and exploring multifunctional applications. Opportunities lie in leveraging computational modeling, green synthesis methods, compatibility testing, and additive design to advance the development and application of oxazole inhibitors for corrosion control. Addressing these challenges and capitalizing on emerging opportunities will drive further advancements in oxazole-based corrosion inhibition research and foster innovation in the field [156, 157].

5.3 Future directions in utilizing oxazoles for corrosion protection

Looking ahead, several promising avenues can be explored to harness the full potential of oxazoles for corrosion protection [158, 159]. Below is an explanation of some of these methods:

(1) Tailored Inhibitor Design: By means of computations and analysis, high-throughput screening and structure-activity correlation, we design and optimize the oxazole-based corrosion inhibitors which have particular characteristics and improved performance for the certain applications and other environments.

(2) Nanostructured Materials: Infusion of oxazole inhibitors in nanoscale items such as nanoparticles, nanocomposites, and thin films that increase their solubility, durability, and surface coverage paving way for successful corrosion protection and a prolonged inhibitor release are the key roles of these nanostructured materials.

Table 5. Challenges and Opportunities in Oxazole-Based Corrosion Inhibition Research

Challenge/Opportunity	Description	Potential Strategies
Structure-Activity Relationships	Elucidating the relationship between oxazole structure and corrosion inhibition properties	Computational modeling, Quantitative Structure-Activity Relationship (QSAR) studies, experimental design, statistical analysis
Environmental Sustainability	Developing environmentally friendly oxazole inhibitors with minimal environmental impact	Green chemistry principles, bio-based starting materials, life cycle assessment (LCA), biodegradable formulations, reduced toxicity
Compatibility and Durability	Assessing the compatibility and durability of oxazole inhibitors with different substrates and coatings under various environmental conditions	Compatibility testing (adhesion, corrosion resistance), long-term exposure studies, accelerated aging tests, surface characterization techniques
Multifunctional Applications	Exploring the potential of oxazole inhibitors for multifunctional applications, such as antimicrobial and self-healing coatings	Combinatorial chemistry, additive manufacturing, synergistic effects, hybrid materials, coating formulation optimization

(3) Smart Coating Technologies: Designing smart coatings by hybridizing polymers containing oxazole inhibitors and oxidation-responsive polymers to provide on-demand corrosion prevention, auto-healing, and simultaneously monitor corrosion processes in real-time leading to proactive maintenance and asset management.

(4) Multifunctional Additives: Synthesizing the synergistic effect of combining chelating agents having oxazole into the mixture with other useful additives (corrosion inhibitors, biocides, scale inhibitors and antifouling agents) to design multifunctional solutions with less additives that will deal with the multiple challenging problems concurrently.

(5) Field Testing and Validation: Carrying out extensive field trials and performance validations to assess the capabilities, reliability, and affordability of the sliced sulfur compounds(oxazoles) in actual manufacturing sectors, working with prestigious novelties to apply mitigation techniques and enhance the guarding system through the optimization of the oxazole inhibitor design.

inhibitors, focusing on sustainable methods, industrial applications, and the exploration of new corrosion inhibition mechanisms. This figure presents a comprehensive roadmap for advancing oxazole-based compounds in corrosion protection, emphasizing both environmental sustainability and broad industrial applicability. The key areas of focus:

(1) Development of Biodegradable Corrosion Inhibitors: In recent years, the synthesis of biodegradable corrosion inhibitors has become a hot spot for most researchers. Therefore, replacing the hazardous inhibitors by eco-friendly inhibitors is an Environment Protection Agency (EPA) strategy for commercial purposes. Biodegradable inhibitors are alternative products and the best strategy for minimizing the usage of toxic inhibitors, reducing pollution, competing with existing toxic inhibitors and the procedure of renewable resources to design environmentally friendly corrosion protection methods. The standard principles of green chemistry are explicitly obeyed by biodegradable inhibitors and may lead to the development of eco-friendly anticorrosive systems. To contribute to reducing environmental pollution and protecting resources, safe and efficient green corrosion inhibitors have become highly crucial and attractive for practical applications.

Fig. 8 outlines the key future research directions in the development and application of oxazole-based corrosion

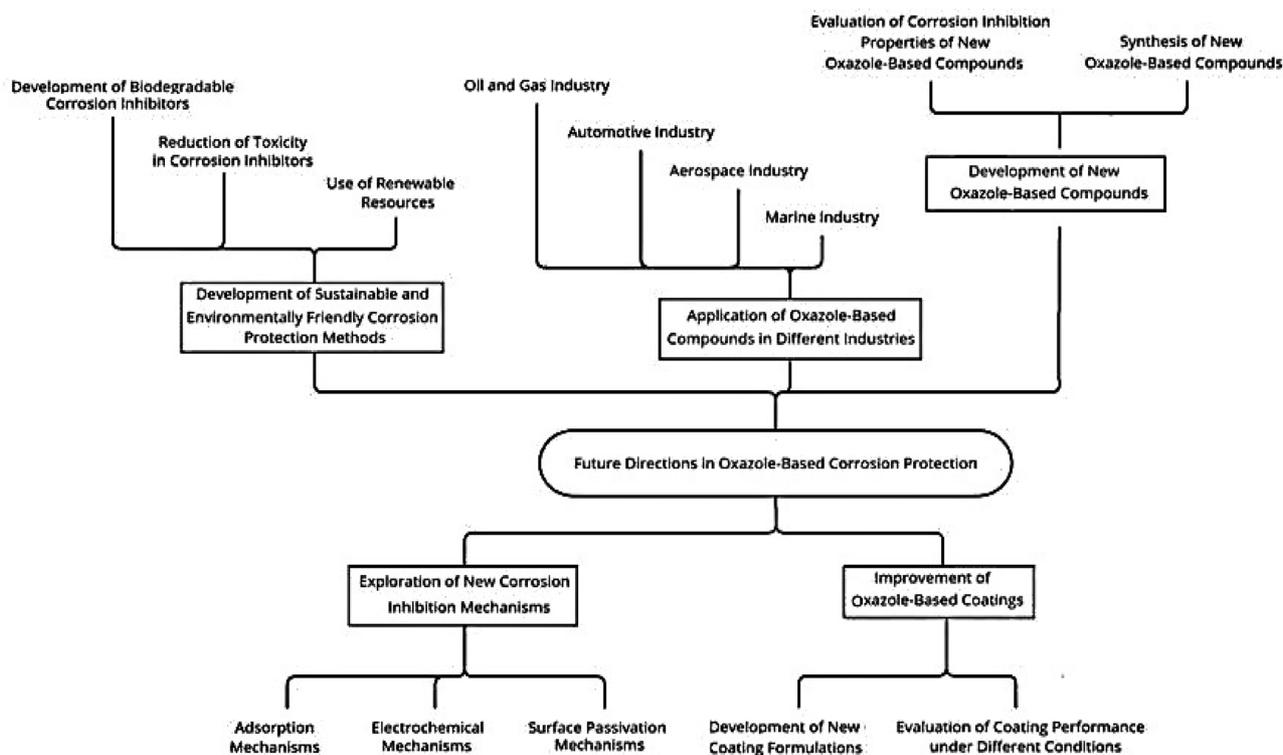


Fig. 8. Future Directions in Oxazole-Based Corrosion Protection

Thus, greener inhibitors are being the focus of great attention in the last decades.

(2) Development of Sustainable and Environmentally Friendly Corrosion Protection Methods: The incorporation of biodegradable substances and low toxicity substances, the industry can transfer towards corrosion protection strategies that are not only successful but also environmentally friendly. This method is crucial in industries such as oil and gas, automotive, aerospace, and marine, where large-scale application of corrosion inhibitors is common.

(3) Development of New Oxazole-Based Compounds: The requirement to develop novel oxazole-based compounds for corrosion inhibition continues to govern the research program; this is because there is the need to understand the efficiency of the compounds under various environmental conditions. These compounds can therefore be used in different industrial fields such as oil and gas industries, automotive industries, aerospace industries and the marine industries among others thus making them be more responsive to the various requests of the industrial world.

(4) Exploring New Mechanisms of Corrosion Inhibition: This field covers the consideration of adsorption mechanisms, electrochemical processes and surface passivation methods which are critical to understanding the way oxazole based inhibitors interact with metal surfaces. Understanding these mechanisms is important for improving the effectiveness of corrosion inhibitors and developing new formulations that provide better protection.

(5) Improvement of Oxazole-Based Coatings: An attempt made to enhance the Oxazole based coating is the modification of the coating systems to be multipurpose for use in different industries. Evaluation of coating performance under different environmental conditions is essential to ensure that these coatings provide long-lasting protection, especially in harsh and variable industrial environments.

The future directions in oxazole-based corrosion protection outlined in the figure emphasize a balanced approach between developing innovative materials and ensuring their environmental sustainability. As industries seek to reduce their ecological footprint while maintaining high-performance standards, the development of biodegradable and efficient corrosion inhibitors will play a crucial role. By focusing on the key areas highlighted, researchers and

industry professionals can work towards more effective and environmentally responsible corrosion protection solutions.

Nevertheless, the future directions of oxazoles in which synergy and interdisciplinary collaboration between academia, industry and governmental agencies will be nurtured, cannot be underestimated since these can result in more sustainable and durable structures, which will manifest more dependable assets as well as improved safety in various industrial sectors.

6. Conclusion

This systematic review has evaluated the use of oxazoles as corrosion inhibitors for steel in acidic media. The results of our analyses of experimental studies, methods of synthesis, mechanisms of corrosion inhibition, and industrial cases indicate some striking observations:

(1) Corrosion Inhibition Properties: It can deduced that oxazoles have good anticorrosion ability. They can attach on the metal surface to produce protective films and then inhibit electrochemical reactions, reducing the corrosion rate of the metal.

(2) Advancements in Synthesis: Traditional synthesis methods to synthesis oxazoles, such as Fischer synthesis and the Robinson-Gabriel synthesis, have been enhanced by recent advances. Oxazole synthesis has become more efficient and accessible due to inventions in transition-metal-catalyzed reactions, multicomponent reactions and bioinspired approaches.

(3) Efficiency in Acidic Media: Experimental findings have established that oxazole is an effective corrosion inhibitor in acidic media. The factors influencing its rate of inhibition include molecular structure, concentration, pH, temperature and presence other chemical species.

(4) Industrial Applications: In many industries such as oil and gas, chemical manufacturing, automotive, marine, water treatment, oxazoles are used. These materials prevent acid attack on steel structures in these sectors.

(5) Challenges and Future Research: Key challenges in the research opportunities include investigating structure-activity relationships, investigating mechanistic aspects of corrosion inhibition, environmental sustainability enhancements, compatibility and strength evaluations, and exploring multifunctional applications of oxazoles.

Conclusively, the study of oxazoles as corrosion inhibitors is a changeable field with great implications on corrosion science and industrial uses. This review has provided us with a pathway for future research and innovation that may be used in mitigating complex corrosion challenges in various environments.

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