Optimization of Iron Utilization through Corrosion Control: A Chemical Approach

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Abstract: *Corrosion is a material degradation phenomenon that occurs due to chemical and electrochemical reactions with the environment, which significantly impacts both technical and economic aspects. Iron and steel, as widely used materials in various industrial sectors, are highly susceptible to corrosion, thus requiring effective prevention methods. This study aims to review various corrosion prevention methods for metals, particularly through protective coating approaches. The method used in this study is a literature review by collecting various references from scientific journals and other relevant sources. The results of the review indicate that protective coatings are among the most common and effective methods in inhibiting corrosion processes through barrier protection and galvanic protection mechanisms. Protective coatings can be classified into organic, inorganic, and metallic coatings, each having its own advantages and limitations. However, traditional coating systems still have weaknesses, especially when damage occurs, which can accelerate localized corrosion. Therefore, the development of more advanced coating technologies, such as active coating systems and smart materials, is essential to enhance corrosion protection performance in iron and steel materials.*
Keywords: *Corrosion, Iron, Steel, Protective Coating, Corrosion Prevention*

1. INTRODUCTION

The main Corrosion is a global phenomenon that causes permanent damage to metals through chemical and electrochemical reactions that occur naturally in the environment. This process is generally initiated by the interaction between metals and their surrounding environment, which triggers oxidation-reduction reactions, leading to the gradual degradation of the metal. These chemical reactions occur due to continuous exposure to corrosive elements such as seawater, oxygen, chloride ions, and microorganisms, particularly sulfate-reducing bacteria that can accelerate the corrosion rate. Such aggressive environmental conditions are the main factors that accelerate the deterioration of metallic materials [1].

Globally, corrosion is a very common issue with widespread impacts, affecting not only technical aspects but also economic ones. The losses caused by corrosion are estimated to reach between 1 and 5% of the Gross Domestic Product (GDP) in various countries, making it a significant industrial problem These economic impacts include repair costs, material replacement, and operational disruptions that can reduce overall system efficiency [2].

The estimated global cost of corrosion was USD 2.5 trillion/year in 2013, equivalent to 3.8% of the global GDP (Gross Domestic Product), based on NACE (National Statistical Classification of Economic) International in 2016. In the European Region, the total cost of corrosion (for 2013) was USD 701.5 billion. The distribution of corrosion costs in the United States is presented in Figure 1 [2]. Most countries anticipate corrosion costs to range between 1% and 5% of their GDP annually. According to NACE International applying efficient corrosion management measures already available may cut these expenses by 15–35%, resulting in worldwide savings of USD 375–875 trillion annually [2].

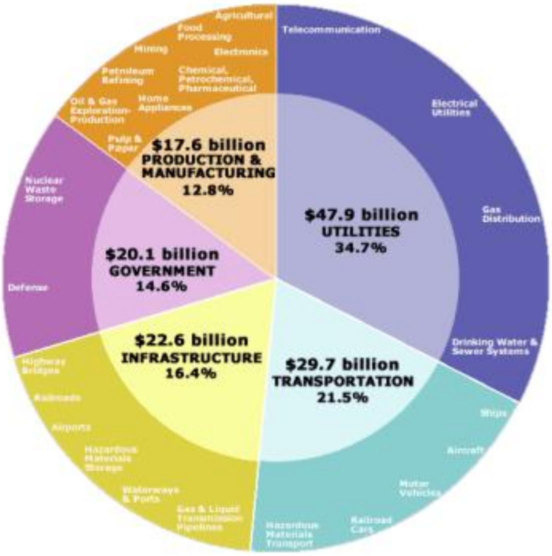

Figure 1. Distribution of corrosion costs in the United States in 2013 [2].

In addition, corrosion directly affects material performance and infrastructure durability. Degradation caused by corrosion can reduce the mechanical strength of metals, thereby accelerating structural damage and shortening the service life of materials. On a larger scale, this condition can potentially lead to dangerous structural failures, especially in critical infrastructure such as bridges, pipelines, and industrial facilities [3].

Furthermore, corrosion in iron and steel is a major concern because these materials are widely used across various industrial sectors. Damage caused by corrosion not only significantly increases maintenance costs but also raises serious concerns regarding safety and operational reliability. Therefore, a comprehensive understanding of corrosion phenomena and the factors influencing them is essential [3].

Based on these issues, numerous studies have been conducted to develop more effective and efficient corrosion prevention methods. In this context, advancements in technology and innovations in corrosion control methods have become a primary focus to minimize the negative impacts and enhance the resistance of materials against corrosive environments [4].

Corrosion is a natural degradation phenomenon of metallic materials that occurs due to interactions between metals and their surrounding environment through chemical and electrochemical reactions. This process can occur in various types of metals, such as aluminum, copper, and steel, with different corrosion characteristics and rates depending on environmental conditions and material properties. In general, corrosion is a global issue that cannot be avoided, as it occurs continuously and has significant impacts on material durability as well as economic and safety aspects [9].

However, among various types of metals, iron and steel receive the most attention in corrosion studies. This is due to their widespread use in everyday life, particularly in construction and infrastructure sectors. In addition, corrosion in iron is commonly known as rusting, which is the process of forming hydrated iron oxide ($Fe_2O_3 \cdot nH_2O$) as the final product of electrochemical reactions between iron, oxygen, and water. Therefore, understanding the corrosion mechanism of iron is essential as a basis for developing effective prevention methods [8].

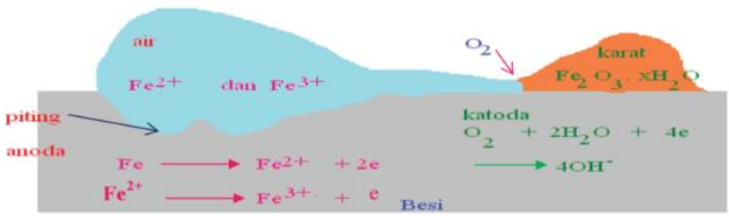

Figure 2. Corrosion process of iron in aqueous and oxygen (O_2) enviroment

Protective coatings are one of the most common and effective methods for preventing corrosion in metals, particularly iron and steel. In general, coatings function by forming a barrier layer that isolates the metal surface from the corrosive environment, thereby inhibiting electrochemical reactions that lead to material degradation. In their development, protective coatings can be classified into three main categories: organic coatings, inorganic coatings, and metallic coatings, each possessing distinct characteristics and protection mechanisms [4].

Organic coatings are based on organic compounds, which in many cases utilize polymer materials as their primary component. These coatings are widely used due to their ability to form continuous layers that are impermeable to water, oxygen, and corrosive ions. Common examples of organic coatings include epoxy, polyurethane, and acrylic coatings, which are widely applied in various steel structures. The primary protection mechanism of organic coatings is barrier protection, which prevents the penetration of corrosive substances to the metal surface, thereby significantly slowing the corrosion rate [5].

In contrast, inorganic coatings are based on non-organic materials such as metal oxides, ceramics, and cement-based materials. One commonly used example is Portland cement-based coating (cementitious coating), which is widely applied in reinforced concrete structures and aggressive environments. Inorganic coatings generally exhibit good resistance to high temperatures and harsh chemical environments. Additionally, some inorganic coatings can provide extra protection by forming a passive layer on the metal surface, thereby enhancing corrosion resistance [5].

On the other hand, metallic coatings are protective methods in which the metal surface is coated with another metal that is more resistant to corrosion. Common examples include zinc coating (galvanization), as well as coatings using nickel and chromium. The protection mechanism of metallic coatings is not only based on physical barrier protection but can also involve galvanic protection, where the more reactive coating metal corrodes first, thereby protecting the base metal (substrate). This approach is highly effective in extending the service life of materials, especially in highly corrosive environments [6].

Despite the various advantages of protective coatings, this method also has limitations, particularly in traditional coating systems. When the protective layer is damaged or defective, corrosive agents such as water, oxygen, and chloride ions can easily penetrate the coating and reach the metal surface. This condition can trigger localized electrochemical reactions that accelerate corrosion in specific areas. Therefore, traditional coatings are often referred to as passive protection, as their effectiveness largely depends on the integrity of the coating layer [6].

Thus, the selection of appropriate coating types and the development of more advanced coating technologies are crucial to improving corrosion protection effectiveness. Innovations in coating technology, including the development of active coating systems and smart materials, are expected to overcome the limitations of conventional methods and provide more optimal protection for metallic materials under various environmental conditions [9].

2. METHOD

This study is a literature review aimed at examining various corrosion prevention methods for metals, particularly iron and steel. Data and information were collected from various scientific sources, including international journals, conference proceedings, and reference books relevant to the research topic.

The literature search was conducted through scientific databases such as Google Scholar, ScienceDirect, and SpringerLink using keywords including "iron corrosion," "corrosion protection," "coating corrosion," and "corrosion inhibitor." The selected literature was limited to publications within a certain time range and those with high relevance to the research topic.

The collected data were then analyzed descriptively by comparing various corrosion prevention methods, particularly coating techniques, based on their protection mechanisms, advantages, and limitations.

3. RESULTS AND DISCUSSION

Corrosion inhibitors can be classified into organic, inorganic, and natural inhibitors based on their composition, as well as anodic, cathodic, and mixed inhibitors based on their mechanism of action. Organic inhibitors, particularly those containing nitrogen, oxygen, and sulfur atoms, are widely used due to their ability to form a protective layer on the metal surface through an adsorption process. These inhibitors function by slowing down electrochemical reactions on the metal surface, thereby reducing the corrosion rate. However, conventional inhibitors, such as chromates, are associated with environmental and health hazards due to their toxic nature (3). Consequently, the development of environmentally friendly corrosion inhibitors, known as green corrosion inhibitors, has become a major focus of recent research [7].

One promising alternative is the use of plant extracts as corrosion inhibitors. Plant extracts contain active compounds (phytochemicals) such as phenols, flavonoids, and organic acids, which can interact with metal surfaces through adsorption mechanisms. This interaction leads to the formation of a protective layer on the metal surface, preventing direct contact between the metal and corrosive environment. Moreover, plant extracts offer several advantages, including availability, low cost, biodegradability, and environmental safety [8].

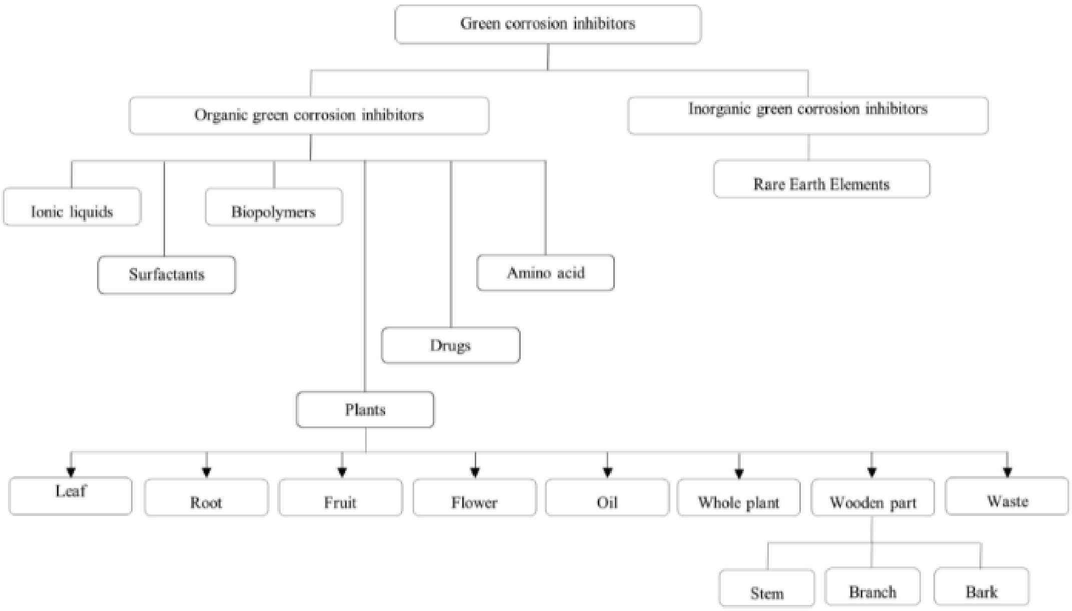

Figure 3 Groups of green corrosion inhibitor

Numerous studies have demonstrated that plant extracts exhibit high inhibition efficiency, often exceeding 80% to 95%, depending on the type of extract and environmental conditions. The inhibition mechanism generally follows adsorption isotherms, such as the Langmuir isotherm, indicating that inhibitor molecules adhere to the metal surface to form a stable protective film [8].

For instance, Ceratonia siliqua seed extract has been reported to achieve an inhibition efficiency of up to 95% on carbon steel in acidic solutions, attributed to the adsorption of active molecules on the metal surface. Similarly, Milletia aboensis leaf extract has shown an inhibition efficiency of up to 88.6%, accompanied by the formation of a protective layer confirmed through electrochemical and microscopic analyses [1].

In addition, studies on henna extract have revealed that active compounds such as lawsone and gallic acid exhibit strong chemisorption on iron surfaces through the formation of O–Fe or C–Fe bonds. These interactions result in the formation of an effective protective layer that inhibits the corrosion process. This indicates that the effectiveness of corrosion inhibitors depends not only on the type of extract but also on the molecular structure and its interaction with the metal surface [7].

Therefore, the use of plant extracts as green corrosion inhibitors represents a promising and sustainable solution for mitigating corrosion in metals, particularly iron and steel. However, further studies are still required to better understand the inhibition mechanisms and to optimize their performance under various environmental conditions [10].

Furthermore, recent studies have reported even higher inhibition efficiencies using plant extracts. For example, extracts of Rauiella Fuiisana (Paris) Reimers have demonstrated excellent corrosion inhibition performance for pure iron in 1 M HCl solution, with efficiency reaching up to 96.19%. This high performance is attributed to the presence of active compounds such as 2-ethyl-3,5-dimethylpyrazine and 2,5-di-tert-butylphenol, which play a crucial role in the inhibition process (12) [10].

Experimental and surface analysis techniques, including SEM-EDS, XPS, and electrochemical measurements, confirmed that the extract forms a protective film layer on the metal surface. This layer effectively prevents direct interaction between the metal and the corrosive environment, thereby reducing the corrosion rate.

The inhibition mechanism was further explained through adsorption behavior, where inhibitor molecules are physically adsorbed onto the iron surface via van der Waals forces. These molecules replace water in the Helmholtz layer and hinder charge transfer processes, which are essential for corrosion reactions to occur [11].

This finding reinforces that plant-based corrosion inhibitors not only provide high efficiency but also operate through well-defined physicochemical mechanisms, including adsorption and protective film formation. Therefore, plant extracts continue to gain attention as effective and sustainable alternatives to conventional corrosion inhibitors [11].

In addition, the effectiveness of Milletia aboensis leaf extract as a green corrosion inhibitor has been further validated through both experimental and theoretical approaches. The extract exhibits a maximum inhibition efficiency of 88.6%, indicating its strong potential in reducing corrosion of mild steel in acidic environments [11].

Electrochemical analyses revealed that the extract acts as a mixed-type inhibitor, meaning it can simultaneously suppress both anodic and cathodic reactions involved in the corrosion process. This dual-action mechanism enhances its overall inhibition performance and stability [12].

Furthermore, molecular simulations, including density functional theory (DFT) and molecular dynamics (MD), demonstrated strong interactions between inhibitor molecules and the iron surface. These interactions confirm that the adsorption of phytochemical compounds plays a crucial role in forming a protective layer on the metal surface [12].

Surface characterization studies also confirmed the presence of inhibitor molecules on the iron surface, supporting the formation of a compact and stable protective film. This film effectively reduces metal dissolution and prevents further corrosion by blocking active sites on the metal surface [13].

These findings further strengthen the understanding that plant-based corrosion inhibitors not only exhibit high efficiency but also involve complex electrochemical and molecular-level mechanisms. Therefore, the integration of experimental and computational approaches is essential to fully elucidate the inhibition behavior and optimize the performance of green corrosion inhibitors [13].

In addition to organic inhibitors, inorganic and coordination compounds have also been widely studied as corrosion inhibitors due to their effectiveness in aggressive environments. Inorganic inhibitors, such as chromates, phosphates, and nitrites, are known to provide protection by forming passive oxide layers on metal surfaces, thereby reducing corrosion rates. However, many of these compounds are associated with toxicity and environmental concerns, which limit their long-term application [13].

Coordination compounds, which involve metal-ligand interactions through atoms such as nitrogen, oxygen, sulfur, and phosphorus, have also shown potential as corrosion inhibitors. These compounds can adsorb onto metal surfaces and form protective layers, thus inhibiting corrosion processes. However, their inhibition efficiencies are often relatively low compared to newer alternatives, and a comprehensive understanding of their adsorption mechanisms is still lacking [14].

Furthermore, corrosion in industrial environments, particularly in acidic media such as sulfuric acid (H_2SO_4), presents significant challenges for metals and alloys. These harsh conditions accelerate material degradation, necessitating the use of inhibitors and protective coatings to extend the lifespan of industrial components. Studies have shown that corrosion behavior depends on factors such as acid concentration, temperature, and environmental conditions, highlighting the need for more efficient and sustainable corrosion protection strategies [14].

In reinforced concrete structures, corrosion of steel reinforcement is another critical issue. Although concrete provides an initially protective alkaline environment, the passive oxide layer can be destroyed by carbonation or chloride ion penetration, leading to corrosion initiation. This process significantly reduces the durability and service life of structures and results in high maintenance costs. The use of corrosion inhibitors has therefore become an essential method to mitigate such degradation [14].

4. CONCLUSION

Corrosion remains a major challenge that affects the durability and performance of metallic materials, particularly iron and steel, in various industrial environments. Although conventional corrosion inhibitors, including inorganic and coordination compounds, have demonstrated effectiveness, their application is often limited due to environmental and health concerns.

In recent years, green corrosion inhibitors derived from plant extracts have emerged as promising alternatives due to their eco-friendly, biodegradable, and cost-effective nature. Numerous studies have shown that plant extracts can achieve high inhibition efficiencies, often exceeding 80% and even reaching up to 95–96% under certain conditions.

The effectiveness of these inhibitors is primarily attributed to the presence of phytochemical compounds that interact with metal surfaces through adsorption mechanisms, forming protective films that prevent corrosion. Both physical adsorption (physisorption) and chemical adsorption (chemisorption) mechanisms have been identified, supported by experimental and theoretical approaches such as electrochemical analysis, surface characterization, and computational simulations.

Therefore, plant-based corrosion inhibitors represent a sustainable and effective solution for corrosion protection of metals. However, further research is still required to better understand their mechanisms and to optimize their performance for broader industrial applications.

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