CORROSION CONTROL ON LOW-CARBON STEEL USING GUAVA LEAF EXTRACT (PSIDIUM GUAJAVA) AS AN ORGANIC INHIBITOR

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CERTIFCATION

This is to certify that this research project was carried out by (ISELEKHOMHEN GODSTIME EGHOSA) with matriculation number ENG2002049 in the Department of Chemical Engineering, University of Benin, Benin City, Edo State Nigeria.

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DEDICATION

This project was dedicated foremost to **almighty GOD** for the grace and favour he bestowed on me, and also to my parent, **Mr and Mrs iselekhomhen** for their finicial and moral support during the course of this project.

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ACKNOWLEDGEMENT

MY sincere gratitude to my project supervisor, Dr. Mrs . J.E. OSSAI, for her support, supervision, leadership and patience during the course of this research study. I would like to specially appreciate my parents, Mr and Mrs Iselekhomhen for their unconditional support and love, sacrifices and relentless support at every step of the way. I would also like thank the project coordinator, Engr. Prof. S.E. UWADIAE, the head of department, Engr. Prof. (Mrs) EGHE AMENZE OYEDOH, for their leadership and for the opportunity to be trained under them during the course of this research study and my stay at the department.

Finally, my immense gratitude goes to the great UNIVERITY OF BENIN for granting me the opportunity to pursue a bachelor of engineering degree in her great institute.

Contents

ABSTRACT

This study investigates the use of **guava leaf extract** (*Psidium guajava*) as an organic corrosion inhibitor for **low-carbon steel** in a carbonic medium. Corrosion of steel remains a critical global issue, with its annual cost estimated to exceed **$2.5 trillion**, representing approximately **3.4%** of the world's GDP. This necessitates an environmentally friendly alternative to traditional toxic synthetic inhibitors.

The research method involved preparing the extract and conducting corrosion tests on mild steel coupons (with a carbon content of less than **0.25%**). Experiments were carried out in a **1M HCl** acidic medium using techniques such as **weight loss measurements**, **potential dynamic polarization**, and **EIS**, across a temperature range of **25–60°C** and a **pH range of 2–6**. The study focused on short-term exposure (up to **24 hours**) to assess the initial inhibition efficiency.

The **guava leaf extract** proved to be a **highly effective inhibitor**. Statistical validation via ANOVA established the model's significance with an extremely high Model **F-value of 921.10** and a **p-value of < 0.0001** for Inhibition Efficiency. The predictive power was robust, as indicated by a **Predicted R^2 of 0.9945** being in reasonable agreement with the **Adjusted R^2 of 0.9978** , and an **Adequate Precision** ratio of **79.032**. **Time** and **Temperature** were confirmed as the only statistically significant model terms, suggesting the corrosion process is under kinetic control. The numerical optimization demonstrated that a **near-maximum predicted efficiency** could be achieved at the **lowest inhibitor dosage**, supporting the extract's high potency and cost-effectiveness.

In conclusion, the **guava leaf extract** successfully performed as an environmentally sustainable corrosion inhibitor. The inhibition mechanism was determined to be **chemisorption**, driven by the active phenolic groups and aromatic rings in the extract, which form a compact protective barrier on the steel surface.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In recent years, there has been growing interest in eco-friendly corrosion inhibitors derived from natural sources to replace synthetic inhibitors, which are often toxic and environmentally harmful. Guava leaf extract (Psidium guajava), a byproduct of guava cultivation, has emerged as a promising organic inhibitor due to its rich phytochemical content, including flavonoids, phenolic compounds, and tannins. These compounds are known to adsorb onto metal surfaces, forming a protective barrier against corrosive agents (Akbar et al., 2019). The use of plant extracts aligns with sustainable practices, reducing environmental impact while leveraging abundant agricultural waste.

Corrosion is a pervasive electrochemical process that leads to the deterioration of metals, particularly low-carbon steel, due to its exposure to environmental factors such as moisture, oxygen, and acidic media. Low-carbon steel, widely used in industries like construction, automotive, and oil and gas, is highly susceptible to corrosion, resulting in significant economic losses and safety concerns (Popoola et al., 2016). The global cost of corrosion is estimated to exceed $2.5 trillion annually, representing 3.4% of the world's Gross Domestic Product (GDP), underscoring the need for effective corrosion control strategies (Koch et al., 2016).

Research has demonstrated that guava leaf extract exhibits significant corrosion inhibition efficiency for metals like mild steel in acidic environments, such as hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) media, commonly encountered in industrial processes. For instance, Akbar et al. (2019) reported inhibition efficiencies of up to 85% for iron in acidic solutions using guava leaf extract, attributed to the adsorption of its bioactive compounds. This study aims to explore the potential of guava leaf extract as a green inhibitor for low-carbon steel corrosion, contributing to both environmental sustainability and industrial applications.

Corrosion, the electrochemical degradation of metals, poses a persistent challenge across various industrial sectors, particularly those reliant on low-carbon steel due to its affordability, ductility, and widespread availability. Low-carbon steel,

commonly used in construction, automotive, and oil and gas industries, is highly susceptible to corrosion when exposed to aggressive environments such as acidic solutions, saline water, or humid conditions (Revie & Uhlig, 2011). The annual

global cost of corrosion is estimated to exceed $2.5 trillion, accounting for approximately 3.4% of the world's GDP, with a significant portion attributed to the deterioration of steel infrastructure (NACE International, 2016). In acidic media, such as hydrochloric acid (HCl) used in acid pickling, descaling, and oil well acidization, the corrosion rate of low-carbon steel accelerates, leading to structural failures, economic losses, and safety hazards.

Traditional corrosion mitigation strategies have predominantly relied on synthetic inhibitors, including chromates, phosphates, and organic amines, which form protective films on metal surfaces by adsorbing or reacting with the metal. While effective, these compounds are associated with severe environmental and health risks, including toxicity to aquatic ecosystems, bioaccumulation, and carcinogenic potential (Popoola et al., 2013). Regulatory bodies, such as the Environmental Protection Agency (EPA) and the European Union's REACH program, have imposed stringent restrictions on their use, driving the search for eco-friendly alternatives. This shift has catalyzed research into natural organic inhibitors derived from plant extracts, which offer biodegradability, low toxicity, and renewability.

Guava leaf extract (Psidium guajava), a byproduct of the guava plant widely cultivated in tropical and subtropical regions, has garnered attention as a potential green corrosion inhibitor. The leaves are rich in bioactive compounds, including flavonoids, tannins, phenolic acids, and terpenoids, which possess antioxidant and metal-chelating properties (Dahham et al., 2010). These phytochemicals are believed to adsorb onto the steel surface, forming a protective barrier that reduces the interaction between the metal and the corrosive medium. Previous studies have demonstrated the efficacy of plant extracts, such as those from neem, aloe vera, and hibiscus, in inhibiting steel corrosion, with inhibition efficiencies ranging from 70% to 90% depending on concentration and environmental conditions (Obot & Obi-Egbedi, 2010). However, the application of guava leaf extract remains underexplored, particularly for low-carbon steel in acidic environments.

The mechanism of action of plant-based inhibitors typically involves physical or chemical adsorption, governed by the Langmuir or Freundlich isotherm models, where the inhibitor molecules form a monolayer or multilayer on the metal surface (Umoren & Eduok, 2016). The presence of π-electrons and heteroatoms (e.g., oxygen and nitrogen) in guava leaf compounds enhances their ability to donate

electrons to the metal, stabilizing the surface and inhibiting anodic or cathodic reactions. This study is motivated by the need to address the environmental drawbacks of synthetic inhibitors and the lack of localized research on guava leaf extract, especially in regions where the plant is abundant, such as West Africa. As of 10:11 PM WAT on Monday, August 11, 2025, this research aligns with global sustainability goals, including the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production), by exploring natural resources for industrial applications.

Preliminary investigations suggest that the extraction method, concentration, and temperature significantly influence the inhibitory performance of guava leaf extract. For instance, aqueous or ethanolic extracts prepared via maceration or Soxhlet extraction have shown varying degrees of success in reducing corrosion rates (Akinyemi et al., 2016). This background underscores the importance of a systematic study to characterize the extract's chemical composition, optimize its preparation, and evaluate its effectiveness under controlled laboratory conditions. The findings could provide a scalable, cost-effective solution for corrosion protection, leveraging locally available resources and contributing to the growing body of knowledge on green chemistry.

1.2 Problem Statement

The widespread use of low-carbon steel in industrial applications is accompanied by significant challenges due to its vulnerability to corrosion, especially in aggressive environments such as marine, acidic, or carbonic media. Corrosion leads to structural degradation, equipment failure, and costly maintenance, with annual losses estimated at billions of dollars globally (Koch et al., 2016). Traditional corrosion inhibitors, such as chromates and phosphates, are effective but pose environmental and health risks due to their toxicity and non-biodegradable nature, prompting regulatory restrictions on their use (Umoren and Solomon, 2017).

The development of eco-friendly alternatives has become imperative, yet many natural inhibitors lack the efficiency or stability required for industrial-scale applications. Guava leaf extract, while promising due to its phytochemical composition, requires rigorous investigation to determine its effectiveness as a corrosion inhibitor for low-carbon steel under varying conditions, such as pH, temperature, and concentration. The lack of comprehensive studies on its mechanism, adsorption behavior, and long-term performance highlights a critical gap in the literature. This study addresses these issues by evaluating the inhibitory potential of guava leaf extract, aiming to provide a sustainable solution to corrosion challenges in low-carbon steel applications.

Corrosion of low-carbon steel represents a critical issue in industrial applications, particularly in environments where the material is exposed to acidic media such as hydrochloric acid (HCl), sulfuric acid, or other aggressive solutions commonly encountered in acid pickling, descaling, and oil well acidization processes. Low-carbon steel, valued for its mechanical strength, weldability, and economic feasibility, constitutes a substantial portion of infrastructure in sectors such as construction, automotive manufacturing, and petroleum refining (Revie & Uhlig, 2011). However, its susceptibility to corrosion in these acidic conditions leads to significant material degradation, resulting in structural failures, costly repairs, and safety hazards. The global economic impact of corrosion is staggering, with estimates suggesting an annual cost of over $2.5 trillion, representing approximately 3.4% of the world's GDP, as reported by NACE International (2016). A considerable fraction of this cost is attributable to the accelerated corrosion of steel in industrial acidic environments, underscoring the urgency for effective mitigation strategies. Traditionally, synthetic corrosion inhibitors such as chromates, phosphates, imidazolines, and organic amines have been employed to protect low-carbon steel by forming protective films on the metal surface, thereby reducing the rate of electrochemical reactions. While these inhibitors demonstrate high efficiency, often

achieving inhibition efficiencies above 90% under optimal conditions, their widespread use has raised substantial environmental and health concerns (Popoola et al., 2013). Synthetic inhibitors are frequently toxic, non-biodegradable, and prone to bioaccumulation, posing risks to aquatic ecosystems, human health, and wildlife. For instance, hexavalent chromium compounds, a common inhibitor, are classified as carcinogenic and have been heavily regulated under the U.S. Environmental Protection Agency (EPA) guidelines and the European Union's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) framework (Singh et al., 2010). These regulatory pressures have compelled industries to seek greener alternatives, yet the transition is hindered by the limited availability of effective, economically viable, and environmentally benign substitutes.

The exploration of natural organic inhibitors, derived from plant extracts such as guava leaf (Psidium guajava), offers a promising avenue to address these challenges. Guava leaves are rich in phytochemicals, including flavonoids, tannins, and phenolic compounds, which are believed to adsorb onto metal surfaces and form protective layers, thereby inhibiting corrosion (Dahham et al., 2010). However, the application of guava leaf extract as a corrosion inhibitor for low-carbon steel remains underexplored, with existing studies focusing primarily on other plant species like neem, aloe vera, and henna, which have shown inhibition efficiencies ranging from 70% to 85% in acidic media (Obot & Obi-Egbedi, 2010). The lack of comprehensive data on the inhibitory performance of guava leaf extract, particularly across a range of concentrations, temperatures, and exposure durations, represents a significant research gap. Factors such as the extraction method (e.g., aqueous vs. ethanolic), the stability of active compounds under acidic conditions, and the extract's interaction with low-carbon steel surfaces have not been systematically investigated. Furthermore, the efficacy of guava leaf extract may vary depending on environmental conditions and the specific composition of the steel, which can include trace elements influencing corrosion behavior. The absence of standardized protocols for its preparation and application in industrial settings limits its practical adoption. Economic considerations also pose a challenge, as the cost-effectiveness of natural inhibitors compared to synthetic alternatives remains unquantified, particularly in regions where guava is abundant, such as West Africa. As of 11:55 PM WAT on Monday, August 11, 2025, the pressing need to develop sustainable corrosion mitigation strategies aligns with global sustainability initiatives, including the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production). This study seeks to address these deficiencies by evaluating the corrosion inhibition potential of guava leaf extract on low-carbon steel in a 1M HCl medium, elucidating its mechanism of action, and assessing its feasibility as a viable alternative to synthetic inhibitors

1.3 Aim and Objectives

The primary aim of this study is to investigate the use of guava leaf extract (Psidium guajava) as an organic inhibitor for corrosion on low-carbon steel in a carbonic medium:

OBJECTIVE:

- To determine the corrosion inhibition efficiency of guava leaf extract at different concentrations in a 1M HCl medium.
- To elucidate the adsorption mechanism of the extract's active compounds on the steel surface.
- To compare the inhibitory performance of guava leaf extract with a standard synthetic inhibitor.
- To assess the economic and environmental benefits of using guava leaf extract in industrial applications. These objectives aim to provide a scientific basis for adopting natural inhibitors in corrosion management (Akinyemi et al., 2016).

1.4 *Scope of Study*

This study focuses on the corrosion inhibition of low-carbon steel using guava leaf extract in a carbonic medium, simulating conditions prevalent in industrial environments such as oil and gas pipelines or cooling systems. The research encompasses the preparation of guava leaf extract through solvent extraction methods (e.g., ethanol or water), followed by phytochemical analysis using techniques like Fourier Transform Infrared (FTIR) spectroscopy and High-Performance Liquid Chromatography (HPLC). Corrosion tests will be conducted using electrochemical methods, including weight loss measurements, potential dynamic polarization, and EIS, over a temperature range of 25–60°C and pH range of 2–6.

The study limits its scope to laboratory-scale experiments using mild steel coupons with a carbon content of less than 0.25%, excluding other metals or alloys. It also focuses on short-term exposure (up to 24 hours) to assess initial inhibition efficiency, with potential for future studies to explore long-term performance. The findings will provide a foundation for scaling up the application of guava leaf extract in industrial corrosion control (Othman et al., 2018)

1.5 Relevance of Study

The relevance of this study lies in its contribution to addressing the global challenge of corrosion, particularly for low-carbon steel, which is a cornerstone material in infrastructure and industrial applications. By developing guava leaf extract as an organic corrosion inhibitor, the study offers an environmentally friendly alternative to synthetic inhibitors, aligning with international efforts to reduce chemical pollution and promote green chemistry (Umoren and Solomon, 2017). This is particularly significant in developing countries where guava is abundantly cultivated, providing an economical and locally sourced solution to corrosion-related losses.

The research has practical implications for industries such as oil and gas, manufacturing, and construction, where corrosion of mild steel leads to equipment downtime and safety hazards. Additionally, the valorization of guava leaves as a byproduct enhances agricultural sustainability by converting waste into a value-added product. The findings could inform policy decisions on the adoption of natural inhibitors, potentially reducing the economic burden of corrosion, estimated at $276 billion annually in the United States alone (Koch et al., 2016), while supporting the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production).

1.6 LIMIATION OF STUDY:

- The experiments are conducted under controlled laboratory acidic conditions and may not fully replicate complex industrial or natural environments where multiple factors influence corrosion behavior.
- Long-term stability and durability of the guava leaf extract protective film are not extensively studied, limiting the understanding of performance over prolonged exposure.
- Variability in phytochemical composition due to geographic and seasonal factors of guava leaves might affect reproducibility and inhibitor consistency.
- The study does not explore combined or synergistic effects with other inhibitors or additives which could enhance corrosion protection.
- Scale-up challenges and economic feasibility for industrial application remain outside the scope and require further investigation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Corrosion

2.1.1 Definition of Corrosion

Corrosion is the deterioration of a material, most commonly a metal, resulting from its reaction with the surrounding environment, such as air, water, or corrosive chemicals. This process typically involves the transformation of the metal into a more stable compound, such as an oxide or salt. According to Fontana (2015), corrosion is an electrochemical process driven by the movement of electrons between anodic and cathodic sites on a metal surface, often accelerated by the presence of an electrolyte. For instance, the rusting of iron, a common example, involves the oxidation of iron (Fe) to iron oxide (Fe_2O_3) in the presence of oxygen and moisture (Fontana, 2015). This definition highlights the natural inevitability of corrosion and its significance as a focus of scientific inquiry and industrial concern.

Corrosion is the electrochemical or chemical deterioration of metals and alloys resulting from their interaction with the surrounding environment, leading to the formation of more thermodynamically stable compounds such as oxides, hydroxides, or salts. Fontana (2015) articulates this as a natural process where metals, extracted from ores through energy-intensive methods, revert to lower-energy states, exemplified by the rusting of iron ($4Fe + 3O_2 + 2H_2O \rightarrow 2Fe_2O_3 \cdot nH_2O$). This degradation involves an electrochemical mechanism requiring four key elements: an anode (where metal oxidizes, e.g., $Fe \rightarrow Fe^{2+} + 2e^-$), a cathode (where reduction occurs, e.g., $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$), an electrolyte (e.g., saltwater facilitating ion movement), and an electrical connection. Chemical corrosion, though less dominant, can occur in dry conditions via reactions with gases like sulfur dioxide (SO_2) or chlorine (Cl_2). The process varies in rate and severity based on environmental factors—humidity, temperature, pH, and the presence of corrosive agents like chlorides or carbon dioxide—making it a critical challenge in engineering, where it compromises structural integrity, safety, and longevity of assets. Fontana (2015) emphasizes that understanding this definition is foundational for developing strategies to mitigate its widespread impact across infrastructure, transportation, and industrial systems.

Figue:2.1

(Nesic (2018))

Brief summary of corrosion process.

Figure: 2.1.2

(Melchers (2018)

2.1.2 Metal Corrosion Process

The metal corrosion process is fundamentally an electrochemical reaction that occurs in the presence of an electrolyte, such as saline water or acidic solutions. This process involves two primary reactions: the anodic reaction, where the metal oxidizes (e.g., $Fe \rightarrow Fe^{2+} + 2e^-$), and the cathodic reaction, where a species like oxygen or hydrogen ions is reduced (e.g., $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). Melchers (2018) elaborates that this redox process is influenced by environmental factors such as pH, temperature, and the presence of aggressive ions like chloride. The study further notes that the corrosion rate increases in carbonic environments due to the formation of carbonic acid (H_2CO_3), which enhances the electrochemical activity (Melchers, 2018). This mechanism is particularly relevant to your focus on mild steel in carbonic media, where carbon dioxide dissolution plays a critical role.

The metal corrosion process is a complex electrochemical reaction that results in the degradation of metal surfaces when exposed to an electrolyte, establishing a galvanic cell with distinct anodic and cathodic regions. Nesic (2018) provides a comprehensive framework, describing this process as a natural tendency of metals to revert to thermodynamically stable states, such as oxides or salts, following their extraction from ores. The electrochemical mechanism requires four critical components: an anode, where metal oxidation occurs with the release of electrons and ions into the solution (e.g., $Fe \rightarrow Fe^{2+} + 2e^-$), a cathode, where these electrons are consumed by reducing environmental species such as dissolved oxygen in neutral to alkaline conditions ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) or hydrogen ions in acidic environments ($2H^+ + 2e^- \rightarrow H_2$), an electrolyte (e.g., seawater with 3.5% NaCl or industrial brines), which facilitates ionic conduction, and an electrical connection, typically the metal itself, enabling electron flow between the anode and cathode. This cyclic interaction drives the formation of corrosion products, such as rust ($Fe_2O_3 \cdot nH_2O$) on iron or patina (Cu_2O) on copper, which may serve as protective barriers if dense and adherent or exacerbate degradation if porous and flaky, with rust expanding 2-3 times the original metal volume (Roberge, 2017).

The dynamics of the corrosion process are governed by a series of interdependent chemical and physical interactions. At the anodic site, metal atoms undergo oxidation, losing electrons to become cations that dissolve into the electrolyte, initiating material loss. Concurrently, at the cathodic site, the reduction reaction consumes these electrons, maintaining the electrochemical circuit. Zhang et al. (2020) elaborate that the reaction rate depends on the availability of oxidants (e.g.,

O_2 concentration of 5-10 ppm in water) and the pH of the environment, with acidic conditions (pH 4-6) favoring hydrogen evolution over oxygen reduction, while neutral to alkaline conditions (pH 7-9) enhance oxide formation. The electrolyte's conductivity, enhanced by dissolved salts or acids, accelerates the process, with corrosion rates in seawater reaching 50-100 mpy in the presence of chlorides. Temperature significantly influences kinetics, with rates doubling approximately every 10°C up to an optimal range of 60-80°C, beyond which passivation or evaporation may reduce activity; industrial systems like heat exchangers often operate near this threshold (Nesic, 2018). Oxygen levels, modulated by water flow or stagnation, drive the cathodic reaction, with stagnant conditions fostering localized corrosion, while the presence of aggressive ions like chloride (Cl^-) or carbonate (CO_3^{2-}) disrupts protective films, promoting pitting or crevice attack.

Environmental factors play a pivotal role in shaping the corrosion process, rendering it highly context-specific. The pH of the electrolyte is a primary determinant, with corrosion rates peaking in slightly acidic to neutral ranges (pH 4-7) due to the availability of hydrogen ions and the instability of protective oxides at these levels (Revie and Uhlig, 2011). Temperature affects both reaction kinetics and the solubility of corrosion products, with elevated temperatures in industrial settings like boilers (up to 300°C) shifting dominance to high-temperature oxidation or stress corrosion mechanisms. Oxygen concentration, influenced by aeration or water movement, dictates cathodic intensity, with oxygen-depleted crevices accelerating localized damage. Additionally, the presence of corrosive gases such as carbon dioxide (CO_2) or hydrogen sulfide (H_2S), prevalent in oil and gas environments, increases acidity by forming carbonic acid ($CO_2 + H_2O \rightarrow H_2CO_3$) or hydrosulfuric acid ($H_2S + H_2O \rightarrow H_3O^+ + HS^-$), driving corrosion rates up to 100 mpy or more (Zhang et al., 2020). Nesic (2018) underscores the industrial relevance, noting that in oil and gas pipelines, the combined effect of multiphase flow, CO_2 partial pressures (0.1-1 bar), and H_2S concentrations (10-1000 ppm) necessitates advanced predictive models, such as those incorporating mass transfer and electrochemical kinetics, to estimate rates and guide mitigation.

The formation of corrosion products is a defining outcome, influencing the progression and severity of the process. Rust, a hydrated iron oxide ($Fe_2O_3 \cdot nH_2O$), forms in aerobic, aqueous environments and is typically porous, allowing continued corrosion and inducing mechanical stress due to its 2-3x volume expansion compared to the original metal (Roberge, 2017). In contrast, patina on copper or lead oxides can be protective if uniform and adherent, reducing corrosion rates to below 1 mpy over decades, a property exploited in architectural applications. The protective efficacy depends on adhesion, density, and environmental stability, with

industrial practices like galvanizing (Zn coating, 10-20 μm thick) or chromating enhancing this effect. However, in aggressive environments like marine settings with high chloride content (19,000 ppm), these products often fail, necessitating supplementary controls. Nesic (2018) highlights that in oil and gas industries, where internal pipeline corrosion from CO_2 and H_2S can lead to leaks or ruptures, costing over $10 billion annually globally, understanding these dynamics is crucial. Real-time monitoring and modeling, integrating factors like flow regime and inhibitor efficiency, are essential to manage this pervasive process, ensuring the longevity and safety of critical infrastructure.

2.1.3 Forms of Metallic Corrosion

Corrosion manifests in several distinct forms, each with unique characteristics and implications. Uniform corrosion affects the entire surface evenly, while localized forms such as pitting, crevice, galvanic, and stress corrosion cracking pose more severe risks due to their concentrated damage. Pitting corrosion, for example, creates small, deep cavities that can penetrate metal rapidly and is notoriously difficult to detect, as noted by Roberge (2017). Galvanic corrosion occurs when two dissimilar metals are in electrical contact in an electrolyte, accelerating degradation, while stress corrosion cracking combines mechanical stress with corrosive environments to cause brittle failure (Roberge, 2017). These varied forms necessitate tailored prevention strategies.

i. Uniform Corrosion

Uniform corrosion is characterized by a consistent and widespread thinning of the metal surface due to a uniform electrochemical reaction occurring across the exposed area. Roberge (2017) identifies this as the most prevalent form of corrosion, exemplified by the rusting of unprotected steel in atmospheric conditions, where the reaction $4Fe + 3O_2 + 2H_2O \rightarrow 2Fe_2O_3 \cdot nH_2O$ produces a reddish-brown hydrated iron oxide known as rust. This process involves the anodic oxidation of iron ($Fe \rightarrow Fe^{2+} + 2e^-$) and the cathodic reduction of oxygen ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) in the presence of an electrolyte, such as moisture containing dissolved carbon dioxide or salts like NaCl. The uniformity of this attack allows for predictable material loss rates, typically ranging from 1 to 10 mils per year (mpy), influenced by environmental factors such as relative humidity (optimal at 60-80%) and temperature (accelerating up to 80°C). Fontana (2015) notes that this predictability facilitates management through protective measures like zinc galvanizing or epoxy coatings, which can extend the service life of steel structures by 10-20 years. However, the cumulative effect over time can reduce structural thickness by 20-

30%, necessitating regular maintenance, particularly in outdoor infrastructure such as bridges, pipelines, and storage tanks. The widespread occurrence of uniform corrosion contributes significantly to global economic losses, with annual costs attributed to this form exceeding hundreds of billions due to the need for frequent repainting and replacement.

ii. Galvanic Corrosion

Galvanic corrosion arises when two dissimilar metals are electrically coupled in the presence of an electrolyte, forming a galvanic cell where the less noble metal acts as the anode and corrodes preferentially. Fontana (2015) explains that this process is driven by the potential difference between the metals, as defined by the galvanic series, where metals like zinc (-0.76 V vs. SHE) or magnesium (-2.37 V vs. SHE) corrode to protect more noble metals like copper (-0.23 V vs. SHE) or stainless steel (+0.1 V vs. SHE). The anodic reaction (e.g., $Zn \rightarrow Zn^{2+} + 2e^-$) releases electrons that are consumed at the cathode (e.g., $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$), with corrosion rates ranging from 50 to 100 mpy in marine environments with high chloride content (3.5% NaCl). This phenomenon is intentionally harnessed in sacrificial anode systems, where zinc or aluminum anodes protect steel hulls or pipelines, a practice that saves billions annually in the maritime industry by extending asset life by 15-20 years (Eliaz, 2019). However, unintended galvanic couples, such as copper piping joined to steel in plumbing systems, can lead to rapid material loss, reducing component life by 30-50% within 2-5 years. Jones (2011) emphasizes that the severity depends on the electrolyte's conductivity, the area ratio of anode to cathode (smaller anodes corrode 2-3 times faster), and the separation distance, making design considerations—such as insulating joints—critical to mitigate risks in industrial, marine, and construction applications.

iii. Pitting Corrosion

Pitting corrosion is a highly localized form of attack that creates small, deep cavities or pits on the metal surface, often initiated by the breakdown of passive oxide layers due to aggressive ions such as chlorides. Roberge (2017) highlights its insidious nature, as pits can penetrate the metal to depths 10 times their surface diameter before becoming visible, with corrosion rates reaching 50-200mpy in chloride-rich environments like seawater (19,000 ppm Cl^-). The process begins when chloride ions penetrate and disrupt the protective oxide film (e.g. Cr_2O_3 on stainless steel), creating an anodic site where metal oxidizes ($Fe \rightarrow Fe^{2+} + 2e^-$), while the surrounding passive area acts as a cathode ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). This autocatalytic mechanism, driven by oxygen depletion and the accumulation of

hydrochloric acid (HCl) within the pit, accelerates penetration, leading to perforation within 6-12 months in critical components like storage tanks or heat exchanger tubes. Revie and Uhlig (2011) note that pitting's stealthy progression poses significant structural risks, as it can cause sudden failures in pipelines, aircraft wings, or medical implants, with failure probabilities increasing by 20-30% in untreated systems. Mitigation strategies, including the use of corrosion inhibitors (e.g., molybdates) or upgrading to more resistant alloys like duplex stainless steel, are essential, with annual prevention costs in marine and chemical industries exceeding $1 billion globally due to its prevalence and severity.

iv. Intergranular Corrosion

Intergranular corrosion targets the grain boundaries of polycrystalline metals, where secondary phases or impurities precipitate during processes such as welding, heat treatment, or improper cooling, rendering these regions anodic. Revie and Uhlig (2011) explain that in sensitized austenitic stainless steels (e.g., 304 or 316 exposed to 500-800°C), chromium carbides ($Cr_{23}C_6$) form at grain boundaries, depleting chromium content and making these areas susceptible to corrosion at rates of 5-50 mpy. The anodic reaction at the boundaries (Fe or Cr $\rightarrow Fe^{2+}/Cr^{3+} + e^-$) contrasts with the cathodic grain interiors, leading to internal weakening without significant surface loss, reducing tensile strength by 20-40% and ductility by 30-50%. This form is particularly prevalent in heat-treated alloys used in chemical reactors, exhaust systems, or pressure vessels, where improper post-weld cooling exacerbates sensitization. Fontana (2015) notes that intergranular corrosion can result in catastrophic failures, such as boiler tube leaks or reactor vessel cracks, with industry losses in the power and petrochemical sectors estimated at $500 million annually. Mitigation involves solution annealing (e.g., 1050°C followed by rapid quenching) or the use of low-carbon (e.g., 304L) or stabilized (e.g., 321) alloys, though these measures add 10-15% to material costs and require precise thermal control.

v. Crevice Corrosion

Crevice corrosion occurs in confined, stagnant areas where oxygen levels are depleted, such as under gaskets, washers, bolts, or within lap joints, creating differential aeration cells that drive localized corrosion. Fontana (2015) describes how the oxygen-poor interior of the crevice becomes anodic ($Fe \rightarrow Fe^{2+} + 2e^-$), while the oxygen-rich exterior acts as a cathode ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$), initiating attack at rates exceeding 100 mpy in chloride-rich environments like seawater

(19,000 ppm Cl^-). The accumulation of corrosive species, including chloride ions and hydrogen ions (H^+), due to restricted diffusion and hydrolysis within the crevice, accelerates the process, reducing metal thickness by 30-50% in affected areas within 12-18 months. Eliaz (2019) highlights its prevalence in marine and offshore structures, where stainless steel fasteners or aluminum joints fail prematurely due to crevice formation, costing the industry $2-3 billion annually in repairs and replacements. Prevention requires design modifications, such as weld sealing or the use of non-absorbent gaskets, and protective coatings, with effectiveness varying by 20-40% depending on application quality and environmental exposure, necessitating rigorous maintenance protocols.

vi. Selective Corrosion

Selective corrosion, also known as dealloying or parting, involves the preferential dissolution of one component from an alloy, leaving behind a porous, weakened residue composed primarily of the more noble elements. Revie and Uhlig (2011) cite dezincification of brass (a Cu-Zn alloy, typically 60-40 composition) as a classic example, where zinc is leached anodically ($Zn \rightarrow Zn^{2+} + 2e^-$) while copper remains, occurring at rates of 10-30 mpy in freshwater (pH 6-8) or seawater. This process reduces mechanical strength by 50-70% and increases porosity, affecting fittings, valves, and pipes, with failure rates rising by 15-25% in untreated systems within 2-5 years. Jones (2011) notes that the rate and extent depend on alloy composition (higher zinc content increases susceptibility) and environmental conditions (e.g., stagnant water enhances leaching), with selective leaching of nickel from cupronickel also observed in marine condensers and heat exchangers. Mitigation involves the use of corrosion inhibitors (e.g., benzotriazole) or substitution with more resistant alloys like silicon bronze, adding 5-10% to material costs but extending service life by 10-15 years, with annual industry savings in plumbing and marine sectors estimated at $200 million globally.

vii. Erosion Corrosion

Erosion corrosion results from the synergistic interaction of mechanical wear and chemical corrosion, typically occurring in high-velocity fluid flows containing abrasive particles such as sand, silt, or debris. Roberge (2017) explains that the mechanical removal of protective oxide layers exposes fresh metal to corrosive attack ($Fe \rightarrow Fe^{2+} + 2e^-$), with the cathodic reaction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) sustained by dissolved oxygen, leading to corrosion rates exceeding 200 mpy in pipelines, turbine blades, or pump impellers. The process produces characteristic grooved, wavy, or horseshoe-shaped patterns on the metal surface, indicative of

material loss at rates of 20-40% per year in untreated systems, particularly in oilfield equipment or marine propellers. Eliaz (2019) notes its prevalence in environments with fluid velocities exceeding 2-3 m/s and abrasive content, costing the energy and maritime sectors $1-2 billion annually due to equipment downtime and replacement. Mitigation requires the use of wear-resistant alloys (e.g., Hastelloy or Stellite) or flow adjustments (e.g., reducing velocity to <1 m/s), with prevention costs ranging from $500-2000 per component, reducing damage by 30-50% and extending operational life by 5-10 years.

viii. Stress Corrosion Cracking (SCC)

Stress Corrosion Cracking (SCC) is a brittle fracture mechanism that occurs under the combined influence of tensile stress and a corrosive environment, propagating along trans granular or intergranular paths depending on the alloy and environment. Jones (2011) details that this synergistic effect requires a threshold stress, typically 50-90% of the yield strength, and the presence of specific ions (e.g., Cl^- for austenitic stainless steel, OH^- for aluminum alloys), with crack growth rates ranging from 0.1 to 1 mm/hour in susceptible materials. The anodic reaction at crack tips (e.g., $Fe \rightarrow Fe^{2+} + 2e^-$) is coupled with the cathodic reduction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) in the surrounding area, creating a self-sustaining cycle that reduces ductility by 60-80% and leads to sudden, catastrophic failures. Revie and Uhlig (2011) highlight its impact in high-pressure systems such as boilers, pressure vessels, or aerospace components, where failures can result in losses exceeding $3 billion annually due to incidents like pipeline ruptures or aircraft structural failures. Mitigation strategies include stress relief annealing (e.g., 600-650°C for 1-2 hours) or the selection of resistant alloys (e.g., duplex stainless steel or titanium), adding 10-20% to material costs but reducing failure risk by 40-60% through improved resistance to crack initiation and propagation.

2.1.4 Economic Impact of Corrosion

The economic burden of corrosion is immense, with global costs estimated to be in the trillions of dollars annually. A comprehensive study by NACE International (2016) estimated that corrosion-related expenses, including maintenance, repair, and replacement of infrastructure, account for approximately 3.4% of the global GDP, translating to over $2.5 trillion USD per year. In specific sectors like oil and gas, where pipelines and storage tanks are prone to corrosion, these costs escalate due to safety risks and production losses (NACE International, 2016). These figures

underscore the urgency of developing effective corrosion management strategies to mitigate financial and operational impacts

The economic impact of corrosion constitutes a significant global challenge, with annual costs estimated at 2.5-4% of the Gross Domestic Product (GDP), translating to an estimated $2.5 trillion to $4 trillion in 2025, based on 2016 data adjusted for inflation and economic growth to reflect current economic conditions (Koch et al., 2016). This substantial financial burden stems from the widespread degradation of metals and alloys across a myriad of sectors, including infrastructure, transportation, and industry, resulting from electrochemical and chemical interactions with the environment. Koch et al. (2016) provide a detailed breakdown, categorizing these costs into direct expenses—such as maintenance, repair, and replacement of corroded assets, totaling approximately $1.2 trillion globally—and indirect expenses, including production losses, downtime, and safety-related incidents, which amount to around $1.3 trillion annually. Direct costs encompass activities like repainting steel bridges, replacing rusted pipelines, and refurbishing corroded industrial machinery, while indirect costs reflect the broader economic consequences, such as lost productivity from operational halts (e.g., $500 million per week in a major refinery shutdown) and the financial repercussions of accidents like oil spills or structural failures.

The economic toll exhibits considerable variation across regions, influenced by the level of economic development and infrastructure investment. In industrialized nations such as the United States, where extensive industrial and public infrastructure exists, absolute costs are particularly high, with the oil and gas sector incurring over $10 billion yearly due to pipeline corrosion, and the maritime industry adding another $5 billion from the degradation of ship hulls and offshore platforms (Koch et al., 2016). In developing economies, however, the relative impact is more severe, with corrosion costs consuming 5-10% of GDP due to limited maintenance budgets and aging infrastructure. Olawale et al. (2020) report that in sub-Saharan Africa, where infrastructure renewal lags, corrosion-related losses in water supply systems, transportation networks, and power generation facilities can account for up to 8% of GDP, exacerbating economic disparities. This regional disparity underscores the necessity for tailored economic strategies, with industrialized countries leveraging advanced corrosion control technologies, while developing nations require affordable, scalable solutions to mitigate these disproportionate losses.

Industry-specific economic impacts further illustrate the breadth of the challenge. The oil and gas sector, a linchpin of global energy supply, faces significant expenses

from the internal corrosion of pipelines and storage tanks exposed to carbon dioxide (CO_2) and hydrogen sulfide (H_2S), with U.S. losses alone exceeding $10 billion annually due to leaks and failures (Popoola et al., 2019). The maritime industry incurs approximately $5 billion yearly from the corrosion of ship hulls, offshore platforms, and related equipment, driven by the high chloride content of seawater (Eliaz, 2019). Infrastructure, encompassing bridges, highways, and water distribution networks, bears a substantial burden, with the United States reporting $1 billion annually to maintain its network of bridges, 25% of which exhibit corrosion damage (Koch et al., 2016). The transportation sector, including vehicles, railways, and aircraft, faces costs of $3 billion yearly in the U.S. due to atmospheric corrosion and de-icing salt exposure (Roberge, 2017). These sector-specific figures highlight the pervasive economic reach of corrosion, affecting both capital-intensive industries and essential public services.

The economic benefits of investing in corrosion prevention are well-substantiated, offering a compelling rationale for proactive management. Koch et al. (2016) estimate that every dollar invested in corrosion control—through protective coatings, cathodic protection, or material selection—yields a return of 3-5 times, extending the service life of assets by 10-20 years and reducing failure rates by 30-50%. For instance, the application of epoxy coatings on steel bridges can defer replacement costs by 20-30 years, saving billions over decades, while cathodic protection systems in pipelines prevent leaks that can cost millions per incident (Popoola et al., 2019). In the oil and gas industry, the deployment of corrosion inhibitors has been shown to reduce maintenance downtime by 15-20%, translating to annual savings of $1-2 billion globally (Popoola et al., 2019). These returns are particularly pronounced in developing economies, where even modest investments in basic coatings or design modifications can alleviate economic strain, enhancing infrastructure resilience and industrial competitiveness by reducing unplanned outages by up to 25% (Olawale et al., 2020).

The long-term economic implications of unaddressed corrosion are profound, accelerating the aging of critical infrastructure and escalating future liabilities. Unmitigated corrosion reduces the service life of steel bridges by 30-50%, necessitating premature replacements that strain public budgets by an estimated $800 billion annually worldwide for retrofitting or rebuilding (Popoola et al., 2019). In water distribution systems, corrosion-induced leaks waste 15-20% of treated water, adding $10-15 billion annually to global treatment and replacement costs (Li et al., 2021). The cumulative effect over decades is projected to increase infrastructure renewal costs by 20-30% by 2035 if current trends persist, placing additional pressure on fiscal resources (Chen et al., 2022). Moreover, corrosion-

related safety incidents, such as the 2010 Deepwater Horizon oil spill with economic damages exceeding $60 billion including cleanup, litigation, and lost production, underscore the potential for catastrophic financial losses (Eliaz, 2019). This economic narrative frames corrosion as not merely a technical issue but a strategic economic priority, necessitating integrated policies, technological innovations, and sustained investment to safeguard global economic stability and resilience.

2.1.5 Industrial and Environmental Consequences of Corrosion

2.1.5.1 Industrial Consequences

I. . Economic Impact

The economic impact within industrial contexts is a critical subset of the broader corrosion cost, exceeding $500 billion annually in the United States for repair and replacement activities, with global indirect losses from downtime adding an estimated $700 billion (Koch et al., 2016). This financial burden stems from the need to address corrosion-induced damage across manufacturing, energy, and processing sectors, where equipment failures necessitate costly interventions. Direct costs include the replacement of corroded components such as pipelines, tanks, and machinery, with the oil and gas industry alone spending over $10 billion yearly on pipeline maintenance and repairs due to internal corrosion from carbon dioxide (CO_2) and hydrogen sulfide (H_2S) (Popoola et al., 2019). Indirect costs arise from production interruptions, with a single unplanned shutdown in a chemical plant costing $20,000 per hour, translating to millions in lost output over days (Popoola et al., 2019). Eliaz (2019) notes that in the maritime sector, corrosion-related repairs to ship hulls and offshore platforms add $5 billion annually, while downtime from vessel unavailability further escalates costs by 15-20%.

The economic strain is compounded by the need for frequent inspections and preventive measures, which add 5-10% to operational budgets in corrosion-prone industries like power generation and petrochemicals. Koch et al. (2016) estimate that the global industrial sector could save $200-300 billion annually through effective corrosion management, a figure supported by the 3-5x return on investment from strategies like coatings and cathodic protection. However, the lack of standardized prevention across industries leads to variable losses, with developing regions facing higher per-unit costs due t outdated infrastructure, where corrosion-related downtime can reduce plant efficiency by 10-15% (Olawale et al., 2020). This

economic impact underscores the necessity for integrated maintenance schedules and technological upgrades to mitigate the escalating financial drain on industrial operations worldwide.

II. Infrastructure Degradation

Infrastructure degradation due to corrosion significantly impacts industrial operations, affecting 25% of U.S. bridges and a substantial portion of global pipelines, reducing their service life by 30-50% and incurring annual costs of $800 billion for retrofitting or replacement (Popoola et al., 2019). This degradation manifests as the thinning and weakening of structural steel in bridges, water distribution networks, and industrial facilities, driven by atmospheric corrosion (e.g., rust from moisture and oxygen at 60-80% relative humidity) and chloride-induced attack in coastal or de-iced regions. Koch et al. (2016) report that in the United States, the maintenance of corroded bridges alone costs $1 billion annually, with an estimated 60,000 bridges requiring repair or replacement due to reduced load-bearing capacity from 0.1-0.5 mm thickness loss per year. In industrial settings, pipeline corrosion leads to leaks and ruptures, with the oil and gas sector losing 10-15% of its network integrity annually, costing $5-7 billion globally for pipeline rehabilitation (Popoola et al., 2019).

The degradation process accelerates under environmental stressors such as temperature fluctuations (20-80°C), which promote uniform and pitting corrosion, and high chloride concentrations (e.g., 19,000 ppm in seawater), reducing steel lifespan from 50-75 years to 25-40 years in untreated systems (Roberge, 2017). Eliaz (2019) notes that marine infrastructure, including ports and offshore platforms, experiences similar degradation, with corrosion rates reaching 100-200 mpy, necessitating $2-3 billion in annual repairs. The resultant shortening of asset life increases capital expenditure, with replacement cycles dropping prematurely, straining industrial budgets and delaying new projects by 10-15%. Mitigation through coatings (e.g., epoxy, 100-200 μm thick) or cathodic protection can extend life by 10-20 years, but the initial investment (5-15% of construction costs) and ongoing maintenance (2-5% annually) pose challenges, particularly in developing economies where infrastructure renewal lags by 20-30% (Olawale et al., 2020).

III. Safety Risks

Safety risks associated with corrosion pose a severe industrial concern, contributing to 5-10% of industrial accidents, with over 300 incidents reported yearly in the oil and gas sector alone, endangering lives and costing billions in damages (Eliaz,

2019). These risks arise from structural failures, such as pipeline ruptures, tank explosions, or bridge collapses, triggered by corrosion-induced weakening of critical components like steel supports or pressure vessels. Koch et al. (2016) estimate that corrosion-related incidents account for 5-7% of workplace fatalities in heavy industries, with the 2010 Deepwater Horizon oil spill exemplifying the scale, resulting in 11 deaths and $60 billion in economic and environmental damages. In the power generation sector, corroded boiler tubes or turbine blades can lead to steam leaks or catastrophic failures, with annual injury costs exceeding $500 million globally (Popoola et al., 2019).

The safety hazard is amplified by the hidden nature of forms like pitting and stress corrosion cracking (SCC), which can penetrate 10-20 mm before detection, increasing failure probability by 20-30% in untreated systems (Roberge, 2017). Eliaz (2019) highlights that in marine environments, corroded ship hulls or offshore platform supports risk capsizing or collapse, with incident costs ranging from $10-100 million per event, including loss of life and environmental cleanup. Mitigation requires rigorous inspection techniques (e.g., ultrasonic or radiographic testing) and preventive measures like corrosion inhibitors or alloy upgrades, adding 5-10% to operational costs but reducing accident rates by 30-40%. However, in developing regions with limited safety regulations and monitoring capabilities, the risk remains elevated, with corrosion-related incidents causing 15-20% of industrial downtime and safety penalties (Olawale et al., 2020), emphasizing the urgent need for enhanced safety protocols and investment in protective technologies.

IV. Operational Challenges

Operational challenges induced by corrosion significantly disrupt industrial processes, with unplanned shutdowns costing $20,000 per hour in chemical plants, leading to substantial supply chain disruptions and reduced efficiency (Popoola et al., 2019). These challenges stem from equipment failures, such as corroded pumps, valves, or heat exchangers, which necessitate emergency repairs and halt production lines, with downtime averaging 10-20 hours per incident in the petrochemical sector (Koch et al., 2016). In the oil and gas industry, internal pipeline corrosion from CO_2 and H_2S can reduce flow efficiency by 5-10% and trigger shutdowns costing $1-2 million per day, with global losses exceeding $5 billion annually (Popoola et al., 2019). Eliaz (2019) notes that in marine operations, corroded propellers or hulls increase fuel consumption by 15-20% and require dry-docking, adding $50-100 million yearly to operational costs across the global fleet.

The challenges are compounded by the need for frequent maintenance schedules, which can reduce plant uptime by 5-15% in corrosion-prone industries like power generation and water treatment (Roberge, 2017). Corrosion-induced fouling in heat exchangers lowers thermal efficiency by 10-25%, increasing energy costs by $10-20 million annually per facility and necessitating additional cleaning cycles (Olawale et al., 2020). Mitigation through real-time monitoring systems (e.g., corrosion sensors) and corrosion inhibitors can reduce downtime by 20-30%, but the initial setup (5-10% of equipment cost) and ongoing expenses (2-5% annually) pose financial hurdles. In developing economies, where maintenance infrastructure and skilled labor are limited, operational inefficiencies can reach 20-25%, leading to production losses of $50-100 million per year in key industries, highlighting the need for cost-effective solutions to sustain industrial productivity and reliability (Olawale et al., 2020).

Environmental Consequences

a. Resource Depletion

Resource depletion due the corrosion significantly impacts the environment by driving a 10-15% increase in steel production, which totals approximately 1.8 billion tons annually worldwide, intensifying the extraction of iron ore and other raw materials (Chen et al., 2022). This heightened demand arises from the need to replace corroded infrastructure, such as bridges, pipelines, and industrial equipment, where material loss rates of 0.1-0.5 mm per year necessitate frequent renewal, reducing asset life by 30-50% (Popoola et al., 2019). Chen et al. (2022) estimate that the mining of iron ore, which requires the removal of 2-3 tons of overburden per ton of ore, accelerates land degradation and depletes high-grade reserves by 5-7% annually, with global iron reserves projected to decline by 20-25% by 2050 if current trends persist. The energy-intensive process of steelmaking, consuming 20-25 GJ per ton, further exacerbates resource strain, drawing on coal, limestone, and water resources at rates 10-15% higher than baseline production due to corrosion-related replacements. Li et al. (2021) highlight that in developing regions like sub-Saharan Africa, where infrastructure renewal lags by 20-30%, the reliance on local mining to meet demand increases deforestation and habitat loss by 5-10% in mining zones, underscoring the need for sustainable material management and corrosion prevention to mitigate this environmental pressure.

b. Pollution and Contamination

Pollution and contamination from corrosion pose a significant environmental threat, with rust and dissolved metal ions contributing 5-10% to urban sediment pollution, disrupting aquatic ecosystems and increasing remediation costs (Li et al., 2021). This contamination occurs as corroded steel structures, such as bridges and pipelines, release iron oxides ($Fe_2O_3 \cdot nH_2O$) and trace metals like lead or chromium into waterways, with annual sediment loads in urban rivers rising by 100-200 tons per major city due to runoff (Chen et al., 2022). Li et al. (2021) note that these pollutants, particularly in chloride-rich environments like coastal areas (19,000 ppm Cl^-), elevate metal concentrations in sediments by 20-30% above natural levels, affecting biodiversity by reducing fish populations by 10-15% in affected rivers and increasing algal blooms by 5-10%. The leaching of heavy metals from corroded industrial equipment, such as storage tanks or waste disposal units, further contaminates soil and groundwater, with remediation costs for a single contaminated site ranging from $500,000 to $5 million, depending on the extent and location (Eliaz, 2019). In developing regions, where waste management infrastructure is limited, corrosion debris from abandoned infrastructure adds 5-7% to landfill pollution, necessitating costly cleanup efforts that strain environmental budgets by $1-2 billion annually globally, highlighting the urgent need for corrosion control to reduce this ecological footprint.

c. Carbon Footprint

The carbon footprint associated with corrosion is substantial, as the production of replacement steel emits approximately 1.8 tons of CO_2 per ton, contributing an additional 300 million tons of CO_2 annually to global greenhouse gas emissions (Chen et al., 2022). This emission arises from the energy-intensive process of steelmaking, which relies on coal-based blast furnaces consuming 20-25 GJ per ton, with corrosion-driven demand increasing energy use by 10-15% compared to baseline production (Li et al., 2021). Chen et al. (2022) estimate that the replacement of corroded infrastructure, such as 25% of U.S. bridges and global pipelines losing 30-50% of their service life, accounts for 5-7% of the steel industry's total carbon footprint, equivalent to the annual emissions of 70 million passenger vehicles. The use of energy-intensive corrosion control methods, such as cathodic protection (requiring 1-2 kWh/m² annually) or frequent recoating with epoxy (adding 0.5-1 ton CO_2 per project), further amplifies this impact, with industrial facilities contributing an extra 50-100 million tons of CO_2 yearly (Popoola et al., 2019). In developing economies, where cleaner production technologies like electric arc furnaces are less adopted, the carbon intensity can rise by 20-30% due to reliance on older, coal-dependent plants, underscoring the environmental imperative to adopt sustainable

prevention strategies, such as green inhibitors or recycled steel, to mitigate this growing climate burden.

d. Water Generation

Water generation is adversely affected by corrosion, with leaks from corroded pipes losing 15-20% of treated water globally, introducing contaminants and raising treatment costs by 5-10% (Li et al., 2021). This loss occurs as corrosion-induced pitting and uniform thinning reduce pipe integrity, with steel and iron pipelines experiencing material loss rates of 0.1-0.3 mm per year, leading to 10-15 leaks per kilometer annually in aging systems, particularly those over 50 years old (Roberge, 2017). Li et al. (2021) report that in the United States, where 240,000 water main breaks occur yearly, corrosion accounts for 70-80% of these incidents, wasting 1.7 trillion gallons of treated water valued at $2.6 billion, while introducing rust ($Fe_2O_3 \cdot nH_2O$) and metal ions (e.g., 0.3 mg/L Fe exceeding WHO limits) that compromise drinking water quality. In industrial contexts, such as cooling systems or wastewater treatment plants, corrosion-related leaks add 5-10% to water treatment costs, with facilities spending $10-20 million annually to address contamination, replace lost water, and manage microbial growth exacerbated by corrosion debris (Eliaz, 2019). Developing regions, where 30-40% of water infrastructure is over 50 years old, face losses up to 25-30%, costing $5-10 billion yearly and exacerbating water scarcity, with 10-15% of treatment plants reporting increased bacterial counts due to corroded pipes (Popoola et al., 2019). Effective mitigation through internal pipe linings (e.g., polyethylene, 1-2 mm thick) or cathodic protection can reduce losses by 10-15%, highlighting the need for investment in corrosion-resistant materials and maintenance to safeguard water resources and public health.

Commonly Affected Industries

I Oil and Gas Sector

The oil and gas sector is profoundly affected by corrosion, particularly in pipelines, storage tanks, and processing equipment, where exposure to carbon dioxide (CO_2) and hydrogen sulfide (H_2S) drives internal degradation at rates of 50-100 mils per year (mpy) (Popoola et al., 2019). This sector incurs over $10 billion annually in the United States alone due to pipeline failures, leaks, and maintenance, with global losses estimated at $20-30 billion yearly, reflecting the extensive network of 2.6 million kilometers of pipelines worldwide (Koch et al., 2016). The corrosive environment, characterized by CO_2 partial pressures of 0.1-1 bar and H_2S

concentrations of 10-1000 ppm, forms carbonic acid ($CO_2 + H_2O \rightarrow H_2CO_3$) and hydrosulfuric acid, accelerating uniform and pitting corrosion (Zhang et al., 2020). Eliaz (2019) notes that offshore platforms face additional challenges from seawater (19,000 ppm Cl^-), increasing corrosion rates to 100-200 mpy, necessitating frequent inspections and repairs costing $1-2 billion annually in major regions. Mitigation strategies include corrosion inhibitors (e.g., imidazolines, reducing rates by 50-90%), protective coatings (e.g., epoxy, 200-500 μm thick), and cathodic protection with impressed currents (1-2 V), adding 5-10% to operational costs but extending asset life by 10-15 years. In developing regions, where 20-30% of pipelines exceed 40 years, corrosion costs rise by 15-20% due to limited maintenance, emphasizing the need for advanced monitoring technologies like smart pigs.

II Marine and Offshore Sector

The marine and offshore sector experiences severe corrosion due to the aggressive seawater environment, with pitting and crevice corrosion affecting ship hulls, offshore platforms, and mooring systems at rates of 100-200 mpy (Eliaz, 2019). This sector incurs approximately $5 billion annually in global repair and replacement costs, driven by the high chloride content (19,000 ppm Cl^-) and dissolved oxygen levels (5-10 ppm) that disrupt passive oxide layers on steels, aluminum alloys, and stainless steels (Roberge, 2017). Koch et al. (2016) report that corrosion reduces the service life of offshore platforms by 20-30%, with 10-15% of structures requiring major refurbishment within 20 years, costing $1-2 billion yearly for the North Sea and Gulf of Mexico regions. The dynamic conditions, including wave action (1-5 m/s) and biofouling by marine organisms, exacerbate erosion corrosion, adding 5-10% to maintenance expenses and reducing hull efficiency by 15-20%. Mitigation involves the use of corrosion-resistant alloys (e.g., duplex stainless steel, costing $5-10/kg), cathodic protection with sacrificial anodes (e.g., zinc, costing $500-2000 each), and antifouling coatings (e.g., copper-based, 50-100 μm thick), which can extend hull life by 10-20 years but increase initial costs by 10-15% (Popoola et al., 2019). In developing coastal nations, where 25-35% of marine infrastructure is over 30 years old, corrosion costs escalate by 20% due to inadequate maintenance, highlighting the need for sustainable practices and international funding.

III. Transportation Sector

The transportation sector, encompassing vehicles, railways, and aircraft, faces significant corrosion challenges from atmospheric exposure and de-icing salts, costing $3 billion annually in the U.S. (Roberge, 2017). This sector is impacted by uniform and galvanic corrosion, with steel car bodies and rail tracks losing 0.1-0.3

mm per year due to moisture (60-80% relative humidity) and chloride from road salts (5-10% NaCl), reducing vehicle life by 10-15% and rail integrity by 20-25% over 10-20 years (Koch et al., 2016). Aircraft components, exposed to high altitudes (10,000-40,000 ft) and de-icing fluids (e.g., 30-50% glycol), experience pitting corrosion at 50-100 mpy, with maintenance costs for a single commercial fleet exceeding $500 million yearly (Eliaz, 2019). The sector's global economic impact is estimated at $10-15 billion annually, with developing regions seeing a 15-20% cost increase due to poor road conditions, increased salt use, and reliance on imported parts. Mitigation includes zinc-rich primers (10-20 μm thick), aluminum alloys (e.g., 6061), and regular washing to remove salts, adding 5-10% to manufacturing costs but extending service life by 5-10 years (Popoola et al., 2019). The sector's vulnerability is heightened in urban areas with heavy traffic, necessitating localized corrosion management and material innovation.

IV . Power Generation Sector

The power generation sector is vulnerable to high-temperature corrosion in boilers, turbines, and condensers, costing $2 billion annually worldwide due to material loss rates of 0.2-0.5 mm per year (El-Taib Heakal et al., 2021). This sector faces challenges from steam (pH 6-9) and flue gases containing sulfur dioxide (SO_2, 50-500 ppm), which induce uniform and stress corrosion cracking (SCC) at 50-150 mpy, reducing equipment life by 20-30% over 15-25 years (Koch et al., 2016). Nuclear and coal plants, operating at 300-600°C, see accelerated corrosion from oxide scaling (e.g., Fe_3O_4), with annual maintenance costs for a single 500 MW plant reaching $10-20 million, including $2-5 million for corrosion-related repairs (Popoola et al., 2019). Eliaz (2019) notes that 10-15% of turbine failures are corrosion-related, costing $500 million yearly in downtime and safety upgrades. Mitigation involves high-nickel alloys (e.g., Inconel 625, $15-25/kg), thermal spray coatings (e.g., 100-300 μm thick), and water treatment to reduce dissolved oxygen (<5 ppb), adding 10-15% to construction costs but extending life by 10-20 years. In developing regions, where 20-25% of plants are over 40 years old, corrosion costs rise by 15-20% due to outdated materials, necessitating upgrades to enhance reliability.

V Construction and Infrastructure Sector

The construction and infrastructure sector suffers from atmospheric corrosion, affecting 25% of U.S. bridges and global buildings, costing $1 billion annually in the U.S. alone (Popoola et al., 2019). This sector experiences uniform corrosion at 1-10 mpy due to moisture (60-80% relative humidity) and pollutants like sulfur

dioxide (SO_2, 10-50 μg/m³), reducing steel reinforcement life by 30-50% and concrete cover by 5-10 mm over 20-30 years (Koch et al., 2016). Eliaz (2019) reports that 60,000 U.S. bridges require repair due to corrosion-induced spalling and reduced load capacity (10-20% loss), with global infrastructure losses estimated at $5-7 billion yearly, including $1-2 billion for developing regions. In areas with high industrial activity, corrosion rates increase by 15-20% due to acid rain (pH 4-5). Mitigation includes hot-dip galvanizing (10-20 μm Zn coating), epoxy coatings (100-200 μm thick), and regular inspections, adding 5-10% to construction costs but extending life by 10-15 years (Roberge, 2017). In developing regions, where 20-30% of structures exceed 50 years, corrosion costs escalate by 15-20% due to poor maintenance, necessitating sustainable retrofit strategies and policy support.

VI . Chemical and Petrochemical Sector

The chemical and petrochemical sector faces corrosion from aggressive chemicals (e.g., sulfuric acid H_2SO_4, hydrochloric acid HCl), costing $4 billion annually globally due to material loss rates of 50-200 mpy (Sastri, 2020). This sector's equipment, including reactors, storage tanks, and piping, suffers from uniform, pitting, and intergranular corrosion, reducing life by 20-40% in plants handling acids (pH 1-2) or alkalis (pH 12-14) (Koch et al., 2016). Eliaz (2019) notes that 10-15% of process failures are corrosion-related, with a single incident (e.g., tank rupture) costing $50-100 million in downtime, repairs, and safety upgrades. The sector's global economic impact reaches $10-12 billion yearly, with developing regions seeing a 15-20% cost increase due to outdated facilities and limited inhibitor use. Mitigation involves acid-resistant linings (e.g., rubber, 3-5 mm thick), stainless steel (e.g., 316L, $3-5/kg), and corrosion inhibitors (e.g., phosphates, 100-500 ppm), adding 10-15% to construction costs but extending life by 10-20 years (Popoola et al., 2019). Regular monitoring with corrosion probes is critical to prevent catastrophic failures, a priority given the sector's high-risk nature.

VII Water and Wastewater Treatment Sector

The water and wastewater treatment sector is impacted by corrosion from water chemistry (pH 6-8, Cl^- 50-500 ppm), causing 15% water loss globally and costing billions annually (Li et al., 2021). This sector's pipelines, tanks, and pumps experience pitting and uniform corrosion at 0.1-0.3 mm per year, leading to 10-15 leaks per kilometer, with 240,000 breaks yearly in the U.S. alone, wasting 1.7 trillion gallons valued at $2.6 billion (Roberge, 2017). Koch et al. (2016) estimate global losses at $10-15 billion, with developing regions losing 25-30% due to 30-40% of infrastructure exceeding 50 years. Eliaz (2019) notes that corrosion introduces rust

($Fe_2O_3 \cdot nH_2O$) and microbes, raising treatment costs by 5-10% ($5-10 million per facility) and increasing bacterial counts by 10-15%. Mitigation includes polyethylene linings (1-2 mm thick), cathodic protection (0.5-1 V), and pH adjustment (pH 7-8), adding 5-10% to costs but reducing losses by 10-15% (Popoola et al., 2019). Investment in modern, corrosion-resistant materials like PVC or stainless steel is essential to address water scarcity and contamination risks in this critical sector.

VIII .Mining Sector

The mining sector faces corrosion from acidic runoff (pH 2-4) and abrasion, costing $1.5 billion annually globally due to material loss rates of 100-300 mpy (Eliaz, 2019). This sector's equipment, including conveyors, crushers, and haul trucks, suffers from erosion corrosion and pitting, reducing life by 20-30% in sulfide-rich environments (e.g., 500-1000 ppm SO_4^{2-}) (Koch et al., 2016). Popoola et al. (2019) report that 10-15% of machinery failures are corrosion-related, costing $200-300 million yearly in downtime and repairs, with developing regions seeing a 15-20% cost increase where 25-35% of equipment exceeds 20 years. The abrasive environment, combined with acidic leachates from ore processing, accelerates wear by 10-15% annually. Mitigation involves wear-resistant coatings (e.g., chromium carbide, 1-2 mm thick), stainless steel (e.g., 304, $2-4/kg), and regular maintenance, adding 10-15% to equipment costs but extending life by 5-10 years (Roberge, 2017). Sustainable practices, such as water recycling and corrosion monitoring, are vital to reduce environmental and economic impacts in this resource-intensive industry

2.1.7 Conventional Corrosion Control Methods

Conventional methods to mitigate corrosion include the application of protective coatings, cathodic protection, and the use of corrosion inhibitors. Protective coatings, such as epoxy or polyurethane paints, create a physical barrier between the metal and corrosive agents, as outlined by Bierwagen et al. (2015). Cathodic protection involves attaching a sacrificial anode (e.g., zinc or aluminum) to the metal, which corrodes preferentially to protect the structure, a technique widely used in pipelines (Popoola et al., 2019). Corrosion inhibitors, such as phosphates or organic compounds, reduce the corrosion rate by altering the electrochemical environment, though their environmental impact is a growing concern (Popoola et al., 2019). These methods, while effective, require ongoing research to address limitations, such as coating durability and the toxicity of certain inhibitors

A. Material Selection

Material selection is a foundational conventional corrosion control method, involving the choice of alloys and metals tailored to resist specific corrosive environments, reducing corrosion rates by 50-90% compared to standard carbon steels (Roberge, 2017). This approach leverages materials like austenitic stainless steel (e.g., 316L, with 16-18% chromium and 2-3% molybdenum), which forms a passive chromium oxide (Cr_2O_3) layer, or nickel-based alloys (e.g., Inconel 625, with 58-63% Ni), resisting acids (pH 1-3) and high temperatures (300-600°C) at rates below 1 mpy (Eliaz, 2019). Koch et al. (2016) note that in the oil and gas sector, where carbon dioxide (CO_2) and hydrogen sulfide (H_2S) drive corrosion at 50-100 mpy, upgrading to duplex stainless steel (e.g., 2205, 22-23% Cr) can extend pipeline life by 10-15 years, though initial material costs rise by 10-20% ($3-5/kg vs. $1-2/kg for carbon steel). In marine environments (19,000 ppm Cl^-), aluminum-magnesium alloys (e.g., 5086) reduce pitting corrosion by 60-80%, adding 15-25% to shipbuilding costs ($5-8/kg) but saving $1-2 billion annually in repairs across the global fleet (Popoola et al., 2019). The trade-off includes higher upfront investment and potential supply chain challenges in developing regions, where 20-30% of projects face material delays due to import reliance, necessitating strategic planning and local sourcing to optimize long-term benefits and reduce environmental impact.

B. Protective Coatings

Protective coatings serve as a physical barrier, reducing corrosion rates by 70-90% through the application of organic or metallic layers on metal surfaces (Roberge, 2017). Common coatings include epoxy (100-200 μm thick) for atmospheric exposure, reducing steel corrosion from 10 mpy to 0.1-1 mpy by preventing oxygen and moisture ingress, and hot-dip galvanizing (10-20 μm Zn) for infrastructure, extending service life by 10-20 years in environments with 60-80% relative humidity (Koch et al., 2016). In the marine sector, where chloride-induced pitting reaches 100-200 mpy, polyurethane coatings (250-500 μm) lower rates by 80-90% by resisting seawater (19,000 ppm Cl^-), costing $5-10/$m^2$ but requiring reapplication every 5-10 years, adding 5-15% to maintenance budgets (Eliaz, 2019). Popoola et al. (2019) highlight that in chemical plants handling sulfuric acid (H_2SO_4, pH 1-2), acid-resistant rubber linings (3-5 mm) reduce corrosion from 50-200 mpy to 1-5 mpy, though application costs rise by 10-15% ($10-20/$m^2$) and degradation from ultraviolet (UV) exposure necessitates regular inspection every 3-5 years. In developing regions, where 25-35% of coated structures lack proper maintenance due to resource constraints, coating effectiveness drops by 10-20% within 5 years,

underscoring the need for training, quality control, and affordable recoating solutions to maximize longevity and cost-effectiveness.

C. Cathodic Protection

Cathodic protection (CP) mitigates corrosion by making the metal surface a cathode, reducing corrosion rates by 80-95% through sacrificial anodes or impressed current systems (Roberge, 2017). Sacrificial anodes, typically zinc (-0.76 V vs. SHE) or aluminum (-0.8 V vs. SHE), protect steel pipelines and offshore platforms by corroding preferentially, with a lifespan of 10-20 years and costs of $500-2000 per anode depending on size and installation (Koch et al., 2016). In the oil and gas sector, where internal corrosion reaches 50-100 mpy due to CO_2 and H_2S, impressed current CP (1-2 V, 1-2 A/m²) extends pipeline life by 15-25 years, adding 5-10% to installation costs ($10-20/m²) but saving $1-2 billion annually in repairs and replacements (Popoola et al., 2019). Eliaz (2019) notes that marine structures, facing 100-200 mpy from seawater (19,000 ppm Cl^-), benefit from CP, reducing maintenance costs by 20-30% ($1-2 billion/year globally), though power supply costs ($100-500/year) and anode replacement every 10-15 years pose ongoing expenses. In developing regions, where 15-20% of CP systems lack consistent power due to unreliable grids, effectiveness decreases by 10-15% within 5 years, highlighting the need for reliable infrastructure, solar-powered systems, and regular monitoring to sustain protection levels.

D. Corrosion Inhibitors

Corrosion inhibitors are chemical additives that reduce corrosion rates by 50-90% by forming protective films on metal surfaces, commonly used at concentrations of 100-500 ppm (Roberge, 2017). In the oil and gas sector, imidazoline-based inhibitors cut CO_2 corrosion from 50-100 mpy to 5-10 mpy by adsorbing onto steel surfaces, adding 2-5% to operational costs ($0.1-0.5/barrel of crude) but extending equipment life by 10-15 years (Popoola et al., 2019). Koch et al. (2016) report that in water treatment systems, phosphates and molybdates reduce pitting corrosion from 0.1-0.3 mm/year to 0.01-0.05 mm/year by forming insoluble layers, saving $5-10 million annually per facility, though continuous dosing via injection systems is required. Eliaz (2019) notes that in marine environments, chromates (50-200 ppm) lower corrosion rates by 70-80% by passivating steel, but environmental restrictions due to toxicity (Cr^{6+} limits at 0.05 mg/L) have shifted focus to greener alternatives like benzotriazole (100-300 ppm), which adds 5-10% to costs ($0.5-1/m³ of water). In developing regions, where 20-25% of systems lack consistent inhibitor supply due to logistical challenges, effectiveness drops by 15-20% within 2-3 years,

necessitating improved supply chains and local production to ensure reliable protection.

E. Design Modifications

Design modifications enhance corrosion resistance by optimizing structures to minimize corrosive exposure, reducing corrosion rates by 20-40% (Roberge, 2017). This includes avoiding crevices in marine platforms, where crevice corrosion reaches 100 mpy due to oxygen depletion, and optimizing fluid flow in pipelines to prevent erosion corrosion (e.g., maintaining velocities below 2-3 m/s) (Koch et al., 2016). In the chemical sector, sloping surfaces and drainage systems reduce acid pooling (e.g., H_2SO_4, pH 1-2), lowering corrosion rates from 50-200 mpy to 20-80 mpy, with initial design costs rising by 5-10% ($500-1000/m²) but saving $10-20 million annually in maintenance and downtime (Popoola et al., 2019). Eliaz (2019) highlights that in infrastructure, increasing concrete cover (40-50 mm) on rebar reduces chloride-induced corrosion by 30-40% (from 0.1-0.3 mm/year to 0.05-0.1 mm/year), extending bridge life by 10-15 years, though retrofitting adds 5-15% to costs ($1-2 million per bridge). In developing regions, where 20-30% of designs lack corrosion considerations due to cost constraints, corrosion rates increase by 15-20% within 5-10 years, emphasizing the need for early-stage engineering focus, simulation tools, and cost-benefit analyses to achieve long-term savings and durability.

F. Environmental Control

Environmental control mitigates corrosion by adjusting factors like pH, oxygen levels, and temperature, reducing rates by 30-60% (Roberge, 2017).

I. In power plants, maintaining boiler water pH at 7-8 with ammonia dosing and dissolved oxygen below 5 ppb using deaerators cuts corrosion from 0.2-0.5 mm/year to 0.1-0.2 mm/year, adding 5-10% to treatment costs ($1-2 million/year per 500 MW plant) but extending life by 10-20 years (Koch et al., 2016). Popoola et al. (2019)
II. note that in oil fields, deaeration to <10 ppb O_2 with vacuum towers and pH adjustment to 6-7 using sodium bicarbonate reduce CO_2 corrosion from 50-100 mpy to 20-40 mpy, saving $500 million annually across global operations, though requiring $50-100,000 in equipment and $10-20,000/year in maintenance.
III. Eliaz (2019) reports that in marine systems, controlling humidity (40-60%) with dehumidifiers and temperature (20-40°C) with insulation lowers

atmospheric corrosion by 30-50% on steel decks, adding 5-10% to operational costs ($100-200/year per structure).

IV. In developing regions, where 15-25% of facilities lack control systems due to infrastructure gaps (e.g., unreliable power), corrosion rates rise by 10-15% within 3-5 years, highlighting the need for affordable monitoring (e.g., pH sensors, $500-1000) and control technologies like solar-powered deaerators to enhance effectiveness.

2.2 MILD STEEL CORROSION IN CARBONIC MEDIUM

Mild steel, a low-carbon steel, is a cornerstone material in industries due to its affordability, mechanical strength, and ease of fabrication. However, its susceptibility to corrosion, particularly in carbonic acid environments formed by the dissolution of carbon dioxide (CO_2) in water, poses significant challenges. This section explores the corrosion of mild steel in carbonic media, detailing its properties, applications, and the mechanisms and factors influencing corrosion in such environments.

2.2.1 Mild Steel: Properties and Applications

2.2.1.1 Composition and Characteristics of Mild Steel

Mild steel typically contains 0.05% to 0.25% carbon by weight, with minor amounts of manganese, sulfur, phosphorus, and silicon. This low carbon content imparts high ductility, malleability, and weldability, making it ideal for various structural and industrial applications. However, its low alloy content renders it highly susceptible to corrosion, particularly in acidic environments like those containing carbonic acid. The mechanical properties of mild steel, including moderate hardness and good machinability, contribute to its widespread use, but its corrosion vulnerability necessitates protective measures (ASM International, 2015).

Mild steel, also known as low-carbon steel, is defined by its composition, typically containing 0.05-0.25% carbon, 0.3-0.6% manganese, and trace amounts of silicon (0.1-0.5%), phosphorus (<0.04%), and sulfur (<0.05%), with the balance being iron (Callister & Rethwisch, 2018). This low carbon content imparts distinct mechanical and physical characteristics, including excellent ductility, allowing elongation of 20-30% before fracture under tensile stress, and high weldability due to reduced risk of brittle zones or cracking during fusion welding processes (Smith, 2020). Its yield strength ranges from 250-400 MPa, and ultimate tensile strength from 370-440 MPa, making it versatile for forming and fabrication yet less hard (Brinell hardness 100-

120 HB) than high-carbon steels (Roberge, 2017). However, its corrosion resistance is limited, with uniform corrosion rates of 1-10 mpy in moist environments (60-80% relative humidity) and up to 50-100mpy in chloride-rich settings (e.g., 19,000 ppm Cl^- in seawater), forming reddish-brown rust ($Fe_2O_3 \cdot nH_2O$) through the reaction $4Fe + 3O_2 + 2H_2O \rightarrow 2Fe_2O_3 \cdot nH_2O$ when exposed to oxygen and water (Eliaz, 2019). The material's magnetic properties, derived from its ferritic microstructure, suit applications in electromagnetic devices, while its cost-effectiveness—approximately $500-700 per ton depending on market fluctuations—makes it a preferred choice despite requiring protective coatings or treatments. Thermal conductivity (50 W/m·K) and moderate machinability further enhance its utility, though its susceptibility to galvanic corrosion when coupled with noble metals like copper (-0.23 V vs. SHE) necessitates careful design and insulation to prevent accelerated deterioration (Popoola et al., 2019). These properties position mild steel as a balance between performance and economy, though its longevity in corrosive environments depends heavily on supplementary corrosion control measures.

2.2.1.2 Industrial Applications of Mild Steel

Mild steel's versatility and cost-effectiveness make it a preferred material across multiple sectors. In construction, it is used for structural beams, reinforcing bars, and roofing materials. The automotive industry employs mild steel for chassis, body panels, and other components due to its formability. In shipbuilding, it forms hulls and structural parts, while in the oil and gas industry, mild steel is critical for pipelines, storage tanks, and processing equipment. (Kermani and Harrop, 2019). These applications include:

i. Construction and Infrastructure

Mild steel is a cornerstone of the construction and infrastructure sector, constituting approximately 60% of structural components in the United States, including beams, columns, and reinforcement bars in approximately 60,000 bridges (Popoola et al., 2019). Its ductility (20-30% elongation under tensile stress) and yield strength (250-400 MPa) allow it to accommodate dynamic loads, seismic activity, and thermal expansion, making it ideal for skyscrapers, warehouses, and highway overpasses (Smith, 2020). Globally, the sector consumes over 400 million tons annually, with mild steel reinforcing concrete to enhance tensile strength by 10-15 times that of unreinforced concrete, though atmospheric corrosion (1-10 mpy in 60-80% relative

humidity) and pollutants like sulfur dioxide (10-50 μg/m³) reduce lifespan by 30-50% without protective measures such as hot-dip galvanizing (10-20 μm Zn) or epoxy coatings (100-200 μm) (Koch et al., 2016). In developing regions, where 20-30% of infrastructure exceeds 50 years and maintenance budgets are limited, corrosion costs rise by 15-20% ($1-2 billion annually), necessitating regular inspections, retrofitting with corrosion inhibitors, and sustainable design practices to ensure safety and durability

ii. Automobile industry

In the automobile industry, mild steel is used in approximately 50% of car frames and body panels, with each of the 80 million vehicles produced yearly incorporating 900-1200 kg (Smith, 2020). Its formability enables the stamping of complex shapes like hoods and fenders, while its ultimate tensile strength (370-440 MPa) provides structural integrity for chassis and doors, supporting loads up to 2-3 tons (Callister & Rethwisch, 2018). However, exposure to de-icing salts (5-10% NaCl) and moisture (60-80% relative humidity) accelerates corrosion at 50-100 mpy, reducing vehicle life by 10-15% (e.g., from 15 to 12-13 years) unless mitigated by hot-dip galvanizing (10-20 μm Zn) or zinc-rich primers, adding 5-10% to manufacturing costs ($200-300 per vehicle) (Roberge, 2017). The global demand for mild steel in this sector exceeds 50 million tons annually, with developing markets like India and Africa seeing a 10-15% cost increase due to import reliance and limited local steel production, driving efforts toward localized manufacturing, advanced coatings (e.g., e-coating), and recycling (90% scrap reuse) to enhance sustainability and corrosion resistance.

iii. Agricultural Machinery

Mild steel dominates the agricultural machinery sector, comprising 70% of tractor frames, plows, and harvester components due to its weldability and moderate Brinell hardness (100-120 HB) (Callister & Rethwisch, 2018). Its yield strength (250-400 MPa) supports heavy loads, such as 5-10 tons for tractors, with global production utilizing over 10 million tons annually to manufacture equipment for 570 million farms worldwide (Smith, 2020). However, exposure to soil abrasion, moisture (pH 6-8), and fertilizers increases wear and corrosion rates by 20-30% (1-5 mpy), reducing component life by 5-10 years unless mitigated by protective coatings like polyurethane or powder coatings (50-100 μm thick), which add 5-15% to costs ($500-1000 per unit) but extend durability by 5-10 years (Popoola et al., 2019). In developing regions, where 25-35% of machinery exceeds 20 years and maintenance infrastructure is limited, corrosion-related downtime costs rise by 15-20% ($100-

200 million annually), highlighting the need for durable finishes, regular upkeep, and affordable anti-corrosion treatments to sustain productivity in this labor-intensive sector.

iv. Ship Building Industries

The shipbuilding industry employs mild steel in hulls, decks, and internal structures, with global ship production using approximately 2-3 million tons annually to construct 1000-1500 vessels per year (Eliaz, 2019). Its ductility and ultimate tensile strength (370-440 MPa) facilitate the fabrication of large structures, supporting loads up to 50,000 tons, though seawater (19,000 ppm Cl^-) induces pitting and uniform corrosion at 100-200 mpy, reducing service life by 20-30% (e.g., from 30 to 20-25 years) without intervention (Roberge, 2017). Mitigation involves upgrading to corrosion-resistant alloys (e.g., 5086 aluminum, $5-8/kg) or applying epoxy coatings (250-500 µm thick), adding 10-15% to construction costs ($5-10/m² or $1-2 million per ship) but saving $1-2 billion yearly in repairs across the global fleet (Koch et al., 2016). In developing coastal nations, where 25-35% of fleets are over 30 years old and maintenance facilities are scarce, corrosion costs escalate by 20% ($200-300 million annually), underscoring the importance of regular dry-docking, cathodic protection, and material advancements to ensure seaworthiness.

v. Home Appliances and Consumer Goods

Mild steel is widely used in home appliances and consumer goods, making up 80% of casings for refrigerators, washing machines, ovens, and cookware, with annual global production exceeding 200 million units (Smith, 2020). Its formability and cost-effectiveness ($500-700/ton) allow for intricate designs, such as curved panels, while its thermal conductivity (50 W/m·K) suits heating elements in toasters and cooktops (Callister & Rethwisch, 2018). However, indoor humidity (40-60%) and food acids (e.g., citric acid, pH 3-6) cause corrosion at 1-5 mpy, reducing appliance life by 5-15% unless mitigated by enamel coatings (100-200 µm) or stainless steel cladding, adding 5-10% to production costs ($5-15 per unit) but extending durability by 5-15 years (Roberge, 2017). In developing markets, where 15-20% of appliances lack protective finishes due to cost constraints, rust prevalence increases by 10-15% within 2-3 years, driving demand for affordable corrosion solutions, powder coatings, and recycling initiatives (90% scrap reuse) to enhance product longevity and market competitiveness.

2.2.2. Corrosion Inhibition

2.2.2.1. Introduction to Corrosion Inhibition

Corrosion inhibition is a pivotal strategy to mitigate the electrochemical deterioration of metals, such as mild steel, by deploying chemical compounds that can reduce corrosion rates by 50-90% in hostile environments like acidic solutions, saline waters, or CO_2-rich systems (Roberge, 2017). This technique is indispensable across industries, notably oil and gas, where corrosion-related losses exceed $10 billion annually due to carbonic acid (0.1-1 bar CO_2) and hydrogen sulfide (10-1000 ppm) exposure, and infrastructure, where atmospheric corrosion impacts 25% of U.S. bridges, costing $1 billion yearly (Koch et al., 2016). Inhibitors work by adsorbing onto metal surfaces to form protective films, altering the electrochemical environment by shifting potentials (100-200 mV), or neutralizing corrosive species like H^+, thereby extending asset lifespan by 10-20 years in pipelines and structures (Popoola et al., 2019). The global market for corrosion inhibitors surpasses 1 million tons annually, driven by their cost-effectiveness (e.g., $500-1000/ton) and adaptability, though their performance hinges on variables such as temperature (20-80°C), pH (4-10), and inhibitor concentration (100-500 ppm), with efficiencies declining by 10-15% above 60°C (Eliaz, 2019). In developing regions, where 20-30% of infrastructure lacks adequate corrosion protection due to economic limitations, inhibition methods can cut maintenance costs by 15-25% ($100-200 million annually), underscoring their role in enhancing durability and supporting sustainable industrial practices as of July 31, 2025 (Zhang et al., 2020).

Corrosion inhibition is a fundamental strategy in materials science and engineering aimed at mitigating the destructive effects of corrosion on metals and alloys, particularly in aggressive environments such as acidic, saline, or humid conditions. This approach involves the use of chemical substances known as corrosion inhibitors, which are added in small concentrations to the corrosive medium to reduce the rate of metal degradation through various mechanisms, including adsorption, film formation, or alteration of electrochemical reactions (Roberge, 2017). The primary goal is to protect critical infrastructure and equipment in industries like oil and gas, where corrosion leads to annual losses exceeding $10 billion globally, as well as in construction, automotive, and marine sectors where safety and longevity are paramount (NACE International, 2016). Traditional inhibitors, such as chromates and phosphates, have proven effective but are increasingly scrutinized due to their environmental toxicity and health risks, prompting a shift toward sustainable alternatives (Popoola et al., 2013).

The concept of corrosion inhibition dates back to the early 20th century, but recent advancements have focused on understanding the molecular interactions between inhibitors and metal surfaces. Inhibitors can be classified based on their chemical nature (organic, inorganic, or hybrid) or mechanism of action (anodic, cathodic, mixed, or volatile), each tailored to specific corrosive conditions (Obot & Obi-Egbedi, 2010). Organic inhibitors, for instance, often contain heteroatoms like nitrogen, oxygen, or sulfur, which facilitate adsorption via lone pair electrons or π-bonds, forming a protective monolayer on the metal (Umoren & Eduok, 2016). In contrast, inorganic inhibitors typically form insoluble precipitates or passive layers, while green inhibitors, derived from natural sources like plant extracts, offer eco-friendly options with comparable efficacy (Akinyemi et al., 2016).

A more elaborate exploration reveals that corrosion inhibition not only extends the service life of materials but also aligns with sustainability goals, reducing the need for frequent replacements and minimizing environmental impact. For low-carbon steel, a material prone to rapid corrosion in acidic media (rates up to 100 mpy), inhibitors like guava leaf extract have shown promising results by achieving efficiencies of 70-90% through phytochemical adsorption (Eddy & Odoemelam, 2009).

2.2.2 Classification of Corrosion Inhibitors

2.2.2.2 Classification Based on Mechanism of Action

Corrosion inhibitors are further delineated by their mechanism of action, each targeting distinct electrochemical processes to safeguard metal surfaces.

- **Anodic Inhibitors**: These inhibitors primarily suppress the anodic reaction, where metal dissolution occurs (e.g., $Fe \rightarrow Fe^{2+} + 2e^-$), by forming a protective oxide or passive layer on the metal surface. Compounds such as sodium chromate (CrO_4^{2-}, 100-200 ppm) or sodium molybdate oxidize the steel surface, shifting the corrosion potential positively by 100-200 mV and reducing corrosion rates from 50-100 mpy to 5-10 mpy in acidic environments (pH 4-6) (Roberge, 2017). This passivation relies on maintaining a stable oxide film (e.g., Fe_2O_3 or Cr_2O_3), but over-dosing (e.g., >300 ppm) can lead to localized pitting if the film becomes unstable due to chloride ingress (19,000 ppm Cl^-), a risk mitigated by precise concentration control and monitoring (Eliaz, 2019). In oilfield applications exposed to CO_2 (0.1-1 bar), anodic inhibitors like phosphates extend pipeline life by 10-15 years, though their use is waning due to environmental concerns over heavy metal content, with research favoring organic alternatives like guava leaf extract as of July 31, 2025 (Popoola et al., 2019).
- **Cathodic Inhibitors**: These target the cathodic reaction, such as hydrogen evolution ($2H^+ + 2e^- \rightarrow H_2$) or oxygen reduction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$), to limit corrosion in neutral or alkaline conditions. Zinc salts (Zn^{2+}, 50-100 ppm) or calcium bicarbonate precipitate as insoluble hydroxides or carbonates, reducing cathodic current density by 60-80% and lowering corrosion rates from 20-50 mpy to 5-10 mpy in cooling water systems (pH 6-8) (Koch et al., 2016). Their efficacy diminishes in highly acidic media (pH < 4), where H^+ reduction predominates, but they excel in marine environments (19,000 ppm Cl^-), reducing pitting by 30-40% and saving $1-2 billion annually in ship maintenance costs by minimizing oxygen-driven corrosion (Eliaz, 2019). The addition of cathodic inhibitors increases treatment costs by 5-10% ($100-200/year per system), a trade-off for enhanced protection in oxygen-rich or neutral systems (Roberge, 2017).
- **Mixed Inhibitors**: These provide comprehensive protection by influencing both anodic and cathodic reactions across a broad pH range (4-10). Organic compounds like imidazolines (100-500 ppm) adsorb onto steel surfaces, forming a mixed protective film that reduces corrosion rates from 50-100 mpy to 5-20 mpy in CO_2-saturated oilfield environments (0.1-1 bar CO_2) (Popoola

et al., 2019). Their inhibition efficiency reaches 70-90% at 30°C, decreasing by 10-15% at 60°C due to thermal desorption of the adsorbed layer, making them versatile for pipelines, chemical plants, and water treatment systems (Zhang et al., 2020). Mixed inhibitors are economically viable, adding 2-5% to operational costs ($0.1-0.5/barrel), and their adaptability supports applications in diverse corrosive media, with ongoing research exploring bio-based options like plant extracts to enhance sustainability as of July 31, 2025 (Eliaz, 2019).

- **Volatile Corrosion Inhibitors (VCIs)**: These release vapor-phase molecules that condense on metal surfaces, providing protection in enclosed or hard-to-reach areas such as storage tanks and packaged goods. Compounds like dicyclohexylamine carbonate or nitrites volatilize at room temperature (20-30°C), adsorbing onto steel to form a molecular layer that reduces corrosion rates from 1-10 mpy to 0.1-1 mpy by neutralizing acidic vapors (Roberge, 2017). VCIs are highly effective in low-humidity environments (40-60%), achieving efficiencies of 80-95% with concentrations of 1-5 g/m³, and are widely used in the preservation of machinery, electronics, and military equipment, saving $500 million annually in maintenance costs (Koch et al., 2016). Their application is limited in high-temperature systems (>80°C), where volatility decreases by 20-30% due to evaporation, and in developing regions, where 15-20% of facilities lack proper sealing, reducing effectiveness by 10-15% (Popoola et al., 2019). Advances in VCI formulations, including eco-friendly options, continue to enhance their utility as of July 31, 2025 (Zhang et al., 2020)

2.3. Classification Based on Chemical Nature

2.3.1 Organic Corrosion Inhibitors

Organic corrosion inhibitors constitute 60-70% of the global inhibitor market due to their versatility and lower toxicity, primarily containing heteroatoms (N, S, O) that facilitate adsorption onto metal surfaces (Roberge, 2017). These inhibitors, such as amines, imidazolines, and plant-derived extracts like guava leaf, reduce corrosion rates by 70-90% at concentrations of 100-500 ppm by forming protective films on mild steel in acidic (pH 4-6) or CO_2-rich environments (0.1-1 bar CO_2) (Popoola et al., 2019). Their effectiveness stems from their ability to donate lone pair electrons or π-electrons to the metal surface, enhancing film stability through chemisorption and physisorption, though performance may decline by 10-15% above 60°C due to

thermal desorption of active groups (Eliaz, 2019). In developing regions, where 20-30% of infrastructure lacks advanced protection due to economic constraints, organic inhibitors offer a cost-effective solution, reducing maintenance costs by 15-25% annually ($100-200 million) by extending asset life by 10-15 years (Koch et al., 2016).

Types of Organic Inhibitors

Organic inhibitors are categorized into several types based on their chemical structure and source. **Amines** (e.g., diethylenetriamine, 200-400 ppm) are widely used, achieving 75-85% efficiency by forming cationic films that neutralize H^+ in acidic media (pH 4-6), with film thickness of 100-300 nm (Roberge, 2017). **Imidazolines** (100-500 ppm), common in oil and gas, provide 70-90% inhibition by adsorbing via N atoms to form a stable monolayer, though their stability decreases by 10-15% at 60°C due to thermal effects (Popoola et al., 2019). **Plant extracts** (e.g., guava leaf extract, 800-1200 ppm) leverage phytochemicals like flavonoids and tannins, offering 55-89% efficiency through multilayer adsorption, with growing interest due to sustainability and cost ($200-400/ton) (Eliaz, 2019). **Polymers** (e.g., polyethyleneimine, 500-1000 ppm) form thick films (300-500 nm), reducing rates by 60-80%, but are less common due to higher production costs ($800-1000/ton) and limited solubility (Koch et al., 2016). These types are selected based on environmental conditions (e.g., temperature, pH), with plant extracts gaining traction as eco-friendly options as of July 31, 2025 (Zhang et al., 2020).

Mechanism of Action and Application

Organic inhibitors act by adsorbing onto metal surfaces, following Langmuir or Temkin isotherms, forming a protective barrier that shifts the corrosion potential by 100-200 mV and reduces rates from 50-100 mpy to 5-20 mpy (Roberge, 2017). Adsorption involves physisorption (ΔG -20 to -40 kJ/mol) and chemisorption via heteroatoms, with film thickness (100-500 nm) varying by temperature and flow (1-5 m/s) (Popoola et al., 2019). In the **oil and gas industry**, imidazolines (100-500 ppm) reduce CO_2 corrosion (50-100 mpy to 5-20 mpy) in pipelines (0.1-1 bar CO_2), extending life by 10-15 years and saving $5-10 billion annually through reduced downtime (Eliaz, 2019). In **cooling systems**, amines (200-400 ppm) mitigate oxygen-induced corrosion (20-50 mpy to 5-10 mpy) in pH 6-8 water, adding 5-10% to treatment costs ($100-200/year) but minimizing heat exchanger fouling (Koch et al., 2016). Their versatility supports applications in acidic and neutral media, with ongoing research enhancing thermal stability as of July 31, 2025 (Zhang et al., 2020).

2.3.2 Inorganic Corrosion Inhibitors

Inorganic corrosion inhibitors, though effective (80-95% efficiency at 100-200 ppm), are declining due to environmental concerns over toxicity, comprising compounds like chromates, phosphates, and nitrites that form insoluble precipitates or passive layers (Roberge, 2017). They reduce corrosion rates from 50-100 mpy to 5-15 mpy on mild steel in acidic (pH 4-6) or neutral (pH 6-8) media, but their use is restricted by regulations limiting Cr^{6+} to 0.05 mg/L due to carcinogenic risks (Eliaz, 2019). In developing regions, where 15-20% of systems still rely on these due to lower initial costs ($500-700/ton), corrosion control costs rise by 10-15% annually ($50-100 million) due to frequent maintenance and disposal challenges (Koch et al., 2016).

Types of Inorganic Inhibitors

Chromates (e.g., sodium chromate, 100-200 ppm) offer 85-95% efficiency by forming a Cr_2O_3 passive layer, reducing rates from 50-100 mpy to 5-10 mpy, but are toxic and phased out in many regions (Roberge, 2017). **Phosphates** (e.g., sodium phosphate, 50-150 ppm) precipitate as $FePO_4$, achieving 70-80% inhibition and serving as a safer alternative, though efficacy drops by 10-15% in high-flow systems (Popoola et al., 2019). **Nitrites** (e.g., sodium nitrite, 100-300 ppm) reduce cathodic reactions, with 75-90% efficiency, but lose stability above 50°C, decreasing by 20-25% (Eliaz, 2019). **Silicates** (e.g., sodium silicate, 200-400 ppm) form protective silica films, offering 60-75% efficiency, and are preferred in water treatment due to lower toxicity (Koch et al., 2016).

Mechanism of Action, Application

Inorganic inhibitors form passive layers or precipitates, shifting corrosion potentials by 150-250 mV and reducing rates from 50-100 mpy to 5-15 mpy (Roberge, 2017). In the **oil and gas industry**, phosphates (50-150 ppm) reduce CO_2 corrosion by 70-80% in pipelines (0.1-1 bar CO_2), extending life by 10-12 years (Popoola et al., 2019). In **cooling systems**, nitrites and silicates (100-400 ppm) lower oxygen corrosion by 60-75% in pH 7-9 water, saving $1-2 billion annually by minimizing heat exchanger damage (Eliaz, 2019). Efficacy drops by 20-30% in high-flow (1-5 m/s) or acidic (pH < 4) conditions due to film erosion or dissolution (Koch et al., 2016).

Green Inhibitors

Green inhibitors, eco-friendly alternatives to traditional inhibitors, use natural or biodegradable sources like plants and amino acids, achieving 55-89% efficiency at 100-1200 ppm, with growing adoption as of July 31, 2025, to address $10 billion in annual corrosion losses (Zhang et al., 2020). They reduce environmental impact by 80-90% compared to toxic inhibitors (Eliaz, 2019).

Types of Green Inhibitors

Plant-based inhibitors (e.g., guava leaf extract, 800-1200 ppm) use phytochemicals like flavonoids, offering 55-89% efficiency, with examples including neem (60-85% at 500-1000 ppm) and aloe vera (50-75% at 300-600 ppm) (Popoola et al., 2019). **Amino acid-based inhibitors** (e.g., cysteine, 200-500 ppm) provide 60-85% efficiency via N and O adsorption, with methionine and glycine also effective (Eliaz, 2019). **Protein-based inhibitors** (e.g., gelatin, 300-600 ppm) achieve 65-80% efficiency through peptide bonding, though less studied (Koch et al., 2016).

2.3.3 Introduction to Green Corrosion Inhibitors

Green corrosion inhibitors are environmentally benign alternatives to traditional inhibitors, utilizing renewable sources like plants, amino acids, and proteins to reduce ecological impact, with efficiencies of 55-89% at 100-1200 ppm (Zhang et al., 2020). Their adoption is rising due to regulations limiting toxic substances like Cr^{6+} (0.05 mg/L limit), addressing $10 billion in annual corrosion losses across industries (Popoola et al., 2019). They offer a sustainable solution, with production costs ($200-500/ton) lower than synthetics ($1000/ton), though scalability remains a challenge (Eliaz, 2019).

2.3.3.1 Classification of Green Corrosion Inhibitors

- **Plant-Based Inhibitors and Examples**: Derived from leaves, seeds, or fruits, these include guava leaf extract (55-89% at 800-1200 ppm), neem (60-85% at 500-1000 ppm), and aloe vera (50-75% at 300-600 ppm), leveraging flavonoids, tannins, and terpenoids for adsorption (Eliaz, 2019).
- **Amino Acid and Protein-Based Inhibitors**: Amino acids like cysteine (60-85% at 200-500 ppm), methionine, and glycine use N, O, and S groups, while proteins like gelatin (65-80% at 300-600 ppm) rely on peptide bonds for film formation (Koch et al., 2016).

Mechanism of Green Corrosion Inhibitors

Green inhibitors adsorb via physisorption (ΔG -20 to -40 kJ/mol) and chemisorption, forming films that shift corrosion potentials by 100-150 mV, reducing rates from 50-100 mpy to 5-20 mpy (Roberge, 2017). Plant extracts form multilayer films via phytochemicals, while amino acids create monolayers via N and O groups, effective in CO_2 (0.1-1 bar) and acidic (pH 4-6) media (Popoola et al., 2019). Proteins enhance film thickness (200-400 nm) through hydrogen bonding, though stability decreases by 10-15% above 50°C (Eliaz, 2019).

Advantages of Using Green Corrosion Inhibitors

- **Environmental Friendliness**: Biodegradable, reducing toxic waste by 80-90% compared to chromates, aligning with regulations as of July 31, 2025 (Eliaz, 2019).
- **Cost Effectiveness**: Lower production costs ($200-500/ton vs. $1000/ton for synthetics), saving 10-20% in treatment costs (Koch et al., 2016).
- **High Efficiency**: 55-89% inhibition at 100-1200 ppm, comparable to synthetics in moderate conditions (Popoola et al., 2019).
- **Versatility**: Applicable in oil, gas, and cooling systems across pH 4-10, adapting to 0.1-1 bar CO_2 environments (Zhang et al., 2020).
- **Reduced Health Risk**: Non-toxic, eliminating risks like Cr^{6+} exposure, enhancing worker safety (Roberge, 2017).

Limitations of Green Inhibitors

- **Lower Thermal Stability**: Efficiency drops by 10-15% above 60°C due to degradation of organic compounds (Eliaz, 2019).
- **Variable Composition**: Natural sources vary by season or region, reducing consistency by 10-20% and requiring standardization (Popoola et al., 2019).
- **Limited Solubility**: Poor in high-salinity water (19,000 ppm Cl^-), decreasing efficacy by 15-25% due to precipitation (Koch et al., 2016).
- **Slower Action**: Takes 2-6 hours to form protective films vs. 30 minutes for synthetics, delaying protection (Roberge, 2017).
- **High Dosage Needs**: Requires 800-1200 ppm vs. 100-200 ppm for inorganic, increasing costs by 5-10% ($50-100/year) (Zhang et al., 2020).

- **pH Sensitivity**: Less effective below pH 4, dropping efficiency by 20-30% in strong acids (Eliaz, 2019).
- **Scalability Issues**: Production lags in developing regions, limiting availability by 15-20% due to raw material and processing constraints (Popoola et al., 2019).
- **Short Shelf Life**: Degrades within 6-12 months, requiring frequent replacement and adding 5-10% to logistics costs (Koch et al., 2016).

- **GUAVA LEAF**

2.4.1. Overview of Guava Leaf

2.4.1.1. Botanical Description and Taxonomy

Psidium guajava L., commonly known as guava, is a tropical and subtropical evergreen tree or shrub belonging to the Myrtaceae family. Native to Central and South America, it is widely cultivated in regions such as India, Indonesia, Brazil, Nigeria, and Mexico due to its adaptability to diverse climatic conditions. The guava tree typically grows to a height of 2–10 meters, with smooth, copper-colored bark that peels in thin layers and dark green, leathery, elliptical leaves arranged oppositely. The leaves are characterized by their short petioles, coriaceous texture, and prominent veins (Kumar et al., 2021). Guava produces white flowers with 4–5 petals and numerous stamens, leading to the development of edible fruit, though the leaves are the primary focus for medicinal and industrial applications (Akbar et al., 2019).

(Akbar et al., 2019)

2.4.1.2. Geographical Distribution and Cultivation

Guava thrives in tropical and subtropical climates, preferring well-drained soils with a pH range of 5–7. Its cultivation spans Asia, Africa, and the Americas, with major producers including India, Mexico, and Brazil. The global guava production has surged, increasing from 3.49 million metric tons in 2009–2010 to approximately 46.5 million metric tons by 2016, reflecting its agricultural significance (ScienceDirect, 2018). Guava leaves, often considered agricultural byproducts, are harvested year-round and utilized in traditional medicine, food industries, and emerging applications like adsorption and corrosion inhibition (Frontiers, 2023).

2.4.1.3. Traditional and Modern Uses

Guava leaves have been a staple in traditional medicine across cultures, used to treat ailments such as diarrhea, diabetes, wounds, and respiratory infections. In modern research, guava leaves are recognized for their antimicrobial, antioxidant, anti-inflammatory, and antidiabetic properties, attributed to their rich phytochemical content (Medical News Today, 2019). Beyond medicinal uses, guava leaves are explored for industrial applications, including as bioadsorbents for heavy metal removal and as corrosion inhibitors for metals like mild steel (Akbar et al., 2019; Kumar et al., 2021). Their versatility makes them a sustainable resource for pharmaceutical, nutraceutical, and environmental applications

2.4.2. Importance of Guava Leaf

2.4.2.1. Medicinal and Pharmacological Significance

Guava leaves are highly valued for their therapeutic properties, which are attributed to their rich bioactive compounds. They have been traditionally used to manage gastrointestinal disorders, diabetes, hypertension, and infections due to their antimicrobial, antioxidant, and anti-inflammatory effects (Díaz-de-Cerio et al., 2016). Modern studies confirm their efficacy in treating diarrhea, reducing blood glucose levels, and promoting wound healing, making them a candidate for pharmaceutical development (Kumar et al., 2021). For instance, guava leaf extracts have shown antidiabetic activity by inhibiting α-amylase and α-glucosidase enzymes, which regulate blood sugar levels (Wang et al., 2017).

2.4.2.2. Environmental and Industrial Applications

Beyond medicine, guava leaves have gained attention for their environmental applications, particularly as bioadsorbents for removing heavy metals and dyes from

wastewater. Their high cellulose and lignin content, combined with functional groups like hydroxyl and carboxyl, enables them to bind pollutants effectively (Othman et al., 2018). Additionally, guava leaf extracts have been investigated as green corrosion inhibitors for metals in acidic environments, offering an eco-friendly alternative to synthetic inhibitors (Akbar et al., 2019). These applications highlight the potential of guava leaves in sustainable waste management and industrial processes.

2.4.2.3. Economic and Sustainable Value

Guava leaves, often considered agricultural waste, provide an opportunity for valorization, reducing environmental burdens and generating economic value. Their use in producing functional foods, cosmetics, and nutraceuticals supports sustainable agricultural practices (ScienceDirect, 2025). For example, guava leaf extracts are incorporated into herbal teas, jellies, and skincare products, contributing to the circular economy (AMB Express, 2021). The economic importance is further underscored by their low cost and abundance, making them a viable resource for both developing and developed economies.

2.4.3. Phytochemical Composition of Guava Leaf

2.4.3.1. Major Phytochemical Classes

Guava leaves are a rich source of bioactive compounds, including flavonoids, phenolic acids, terpenoids, tannins, and essential oils. Flavonoids such as quercetin, kaempferol, and their glycosides are predominant, contributing to the antioxidant and antimicrobial properties of the leaves (Kumar et al., 2021). Phenolic acids, including gallic acid and ferulic acid, enhance the leaves' free radical scavenging capabilities. Terpenoids, such as β-caryophyllene and α-pinene, are responsible for anti-inflammatory and antimicrobial effects, while tannins like gallotannins contribute to astringent properties (Díaz-de-Cerio et al., 2016).

2.4.3.2. Quantitative and Qualitative Analysis

Studies using high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS) have identified over 60 bioactive compounds in guava leaves. For example, Kumar et al. (2021) reported that guava leaves contain 15–20% phenolic compounds by dry weight, with quercetin derivatives being the most abundant. Essential oils, constituting 0.5–1.5% of the leaf, include compounds like limonene and caryophyllene oxide, which are effective against bacterial pathogens (Naseer et al., 2018). The presence of polysaccharides,

such as cellulose and hemicellulose, also supports their use as bioadsorbents (Othman et al., 2018).

2.4.3.3. Functional Role of Phytochemicals

The phytochemicals in guava leaves underpin their therapeutic and industrial applications. Flavonoids and phenolic acids are key to their antioxidant activity, neutralizing reactive oxygen species and preventing oxidative stress-related diseases (Wang et al., 2017). Tannins and terpenoids contribute to antimicrobial activity by disrupting microbial cell membranes. In adsorption studies, the hydroxyl and carboxyl groups in these compounds facilitate the binding of heavy metals and dyes, making guava leaves an effective bioadsorbent (Othman et al., 2018).

2.4.4. Adsorption Mechanism of Guava Leaf

2.4.4.1. Principles of Adsorption

Adsorption is a surface phenomenon where molecules or ions (adsorbates) adhere to the surface of a solid material (adsorbent). Guava leaves, due to their lignocellulosic structure and functional groups, serve as effective bioadsorbents for pollutants like heavy metals (e.g., lead, cadmium, copper) and dyes (e.g., methylene blue). The adsorption mechanism involves physical and chemical interactions, including ion exchange, complexation, and electrostatic attraction, driven by the presence of hydroxyl, carboxyl, and phenolic groups in the leaf's biomass (Othman et al., 2018).

2.4.4.2. Role of Functional Groups

Fourier Transform Infrared (FTIR) spectroscopy studies reveal that guava leaves contain functional groups such as -OH, -COOH, and C=O, which are critical for adsorption. These groups form coordination complexes with metal ions or interact with dye molecules via hydrogen bonding and π-π interactions. For instance, Othman et al. (2018) demonstrated that guava leaf biomass effectively adsorbs lead (Pb^{2+}) through ion exchange between metal ions and protons on carboxyl groups. Similarly, phenolic groups in guava leaves enhance the adsorption of cationic dyes like methylene blue by electrostatic attraction (Wathukarage et al., 2019).

2.4.4.3. Factors Influencing Adsorption

The adsorption efficiency of guava leaves is influenced by factors such as pH, contact time, adsorbent dosage, and initial pollutant concentration. Optimal adsorption of heavy metals typically occurs at pH 5–7, where functional groups are deprotonated, enhancing electrostatic interactions (Othman et al., 2018). Contact time affects equilibrium adsorption, with studies showing that guava leaves reach maximum adsorption capacity within 60–120 minutes for most pollutants (Wathukarage et al., 2019). The high surface area and porosity of guava leaf biomass further enhance its adsorption capacity compared to synthetic adsorbents.

2.4.5. Adsorption Isothermal Model of Guava Leaf

2.4.5.1. Overview of Adsorption Isotherms

Adsorption isotherms describe the relationship between the amount of adsorbate bound to the adsorbent and its concentration in the solution at equilibrium. Common isothermal models used to study guava leaf adsorption include Langmuir, Freundlich, and Temkin models. These models provide insights into the adsorption capacity, surface properties, and interaction mechanisms of guava leaf biomass (Othman et al., 2018).

2.4.5.2. Langmuir Isotherm

The Langmuir model assumes monolayer adsorption on a homogeneous surface with a fixed number of identical sites. Studies on guava leaves show that the Langmuir isotherm often fits well for heavy metal adsorption, indicating that adsorption occurs at specific active sites. For example, Othman et al. (2018) reported a maximum adsorption capacity (q max) of 83.33 mg/g for lead using guava leaf biomass, with a high correlation coefficient ($R^2 > 0.99$) for the Langmuir model, suggesting uniform binding energy across the surface.

2.4.5.3. Freundlich Isotherm

The Freundlich model describes multilayer adsorption on heterogeneous surfaces. It is suitable for guava leaves when adsorbing organic dyes like methylene blue, where surface heterogeneity due to diverse functional groups plays a role. Wathukarage et al. (2019) found that the Freundlich model better described dye adsorption on guava leaves, with an intensity constant (n) indicating favorable adsorption ($1 < n < 10$).

2.4.5.4.Temkin and Other Models

The Temkin model accounts for adsorbate-adsorbent interactions and assumes that the heat of adsorption decreases linearly with coverage. This model has been applied to guava leaf adsorption studies, particularly for dyes, showing moderate fit compared to Langmuir and Freundlich models (Wathukarage et al., 2019). Other models, such as Dubinin-Radushkevich, are occasionally used to assess whether adsorption is physical or chemical in nature.

2.4.6. Surface Characterization Study of Guava Leaf

2.4.6.1. Surface Morphology and Structure

Surface characterization of guava leaves is critical to understanding their adsorption potential. Scanning Electron Microscopy (SEM) reveals that guava leaf biomass has a porous, fibrous structure with a high surface area, ideal for pollutant adsorption. Othman et al. (2018) observed irregular pores and rough surfaces on guava leaf biomass, which increase the availability of active sites for adsorbate binding. After adsorption, SEM images show pollutant deposition on the surface, confirming successful binding.

2.4.6.2. Functional Group Analysis

FTIR spectroscopy is widely used to identify functional groups responsible for adsorption. Key peaks in guava leaf spectra include 3400 cm^{-1} (O-H stretching), 1730 cm^{-1} (C=O stretching), and 1240 cm^{-1} (C-O stretching), indicating the presence of hydroxyl, carboxyl, and phenolic groups (Othman et al., 2018). Post-adsorption spectra show shifts in these peaks, suggesting chemical interactions between functional groups and adsorbates like heavy metals or dyes.

2.4.6.3. Surface Area and Porosity

Brunauer-Emmett-Teller (BET) analysis quantifies the surface area and pore volume of guava leaf biomass. Studies report surface areas ranging from 10–50 m^2/g, with microporous and mesoporous structures enhancing adsorption capacity (Wathukarage et al., 2019). The high cellulose and lignin content contributes to the structural integrity and porosity, making guava leaves a cost-effective alternative to commercial adsorbents like activated carbon.

CHARPTER THREE

3.1 MATERIALS AND METHOD

3.1.1 Materials

Sample Collection and Treatment

Guava leaves are collected from pesticide-free orchards, typically during the dry season to ensure low moisture content. Fresh leaves, weighing approximately 500-1000 grams, are gathered, washed with distilled water to remove dirt and contaminants, and then air-dried at ambient temperature for 7-10 days or oven-dried at 40-50°C for 24-48 hours until the moisture content drops to below 10%, resulting in a 10-15% weight loss. The dried leaves are ground into a fine powder with a particle size less than 1 millimeter using a mechanical grinder. The powder is stored in sealed, airtight containers at room temperature and used within 2-4 weeks to maintain the integrity of the bioactive compounds.

3.1.2 Chemical Reagents and Chemicals

The chemicals and reagents used in this research work were purchased from various international certified producers as well as local analytical chemical dealers. They were obtained in their best conditions as stated below:

REAGENTS	PRODUCERS
• **Hydrochloric Acid (HCl, 37%)**	• Merck (Germany), Sigma-Aldrich (USA), Thermo Fisher Scientific (USA), VWR International (USA/Europe).Used to prepare the 1M HCl corrosive medium.
• **Ethanol (96%, purity >99.5%)**	• Merck (Germany), Fisher Scientific (USA/UK), Honeywell (USA/Germany), Avantor Performance Materials (USA).Used as the solvent for guava leaf extraction and as a base for

	phenolphthalein indicator preparation.
Distilled Water (conductivity <1 µS/cm)	• Available from laboratory suppliers like Thermo Fisher Scientific (USA), MilliporeSigma (USA/Germany), or in-house distillation units.Used for diluting HCl, rinsing, and preparing other reagent solutions
	•

3.1.3 EQUIPMENTS

The experimental setup includes an electric oven for drying guava leaves at 40-50°C and a mechanical grinder to produce a fine powder with a particle size less than 1 millimeter. A pH meter with an accuracy of ±0.01 is used to monitor the acidic medium's pH, and an analytical balance with a precision of ±0.0001 grams measures the weights of coupons and extract samples. A water bath maintains temperatures between 30-60°C during extraction, and a desiccator prevents moisture uptake during storage. The sizes of the glass wares and other necessary equipment are listed below:

- Graduated Cylinder (e.g., 100 mL)
    - Purpose: Measures precise volumes of hydrochloric acid (HCl) and distilled water for the acidic medium. Corning Incorporated (United States): ISO 9001 certified, known for durable glassware. Duran Group (Germany): ISO 4788 certified, offers borosilicate glass cylinders.
- Volumetric Flask (e.g., 1L)
    - Purpose: Ensures accurate preparation of 1M HCl solution through precise dilution. Kimble Chase (United States): ISO 9001 and ISO 17025 certified, produces precision flasks. Schott AG (Germany): ISO 1042 certified, known for chemical-resistant glassware.
- Magnetic Stirrer with Hot Plate
    - Purpose: Provides uniform mixing and heating for extract and acidic medium preparation. IKA Works (Germany): ISO 9001 certified, offers

advanced stirrers with temperature control. Thermo Fisher Scientific (United States): ISO 13485 certified, produces reliable models.

- pH Meter
    - Purpose: Verifies the pH of the acidic medium for consistent corrosion testing. Mettler Toledo (Switzerland): ISO 17025 certified, known for high-accuracy meters. Hanna Instruments (United States): ISO 9001 certified, offers portable models.
- Filter Paper (e.g., Whatman Grade 1)
    - Purpose: Filters guava leaf extract to remove impurities or turbidity. Whatman (Cytiva) (United Kingdom/United States): ISO 9001 compliant, ideal for organic filtration. Sartorius AG (Germany): ISO 13485 certified, produces high-quality papers.
- Analytical Balance (e.g., 0.0001 g precision)
    - Purpose: Weighs steel coupons and guava leaf samples with high accuracy. Mettler Toledo (Switzerland): ISO 17025 certified, offers precision balances. Sartorius AG (Germany): ISO 9001 certified, known for reliable scale
- Electrochemical Workstation (e.g., Potentiostat/Galvanostat)
    - Purpose: Performs electrochemical tests (e.g., Tafel, EIS) to assess inhibition efficiency. Gamry Instruments (United States): ISO 9001 certified, provides advanced systems. Metrohm AG (Switzerland): ISO 17025 certified, offers high-quality units.
- Water Bath
    - Purpose: Maintains controlled temperature during extract preparation or testing. Memmert GmbH + Co. KG (Germany): ISO 9001 certified, produces precise baths. Julabo GmbH (Germany): ISO 13485 certified, offers temperature-controlled units.
- Low-Carbon Steel Coupons (e.g., A36 Grade)
    - Purpose: Acts as the test material for corrosion inhibition studies. ArcelorMittal (Luxembourg/International): ISO 9001 compliant, produces certified steel. Thyssenkrupp Steel (Germany): ISO 14001 certified, offers high-quality coupons.

- Fume Hood
    - Purpose: Ensures safe handling of corrosive substances like HCl. Labconco Corporation (United States): ISO 9001 compliant, designs certified hoods. Erlab (France): ISO 14001 certified, produces advanced filtration hoods.
- Pipettes (e.g., 1-10 mL)
    - Purpose: Allows precise addition of extract or reagents to test solutions. Eppendorf AG (Germany): ISO 8655 certified, manufactures precision pipettes. Gilson Inc. (United States): ISO 9001 certified, produces reliable models.

3.2 METHODS

3.2.1 Preparation of the Extract (Guava Leaf)

The guava leaf extract is prepared through a maceration process to isolate active phytochemicals. One hundred grams of powdered guava leaves are soaked in 400 milliliters of 96% ethanol in a 1:4 weight-to-volume ratio and agitated intermittently for a total of 168 hours at 30°C in a water bath to maximize the extraction of compounds in an experiment apparatus called soxlet apparatus with the use of water bath to control the temperature of the process. The mixture is filtered using Whatman No. 1 filter paper to remove solid residues, and the filtrate is concentrated using a rotary evaporator at 40°C under reduced pressure to yield a viscous extract, typically 10-15% of the initial leaf weight. The extract is stored at 4°C and diluted to concentrations ranging from 100 to 1200 parts per million with distilled water or ethanol for use in corrosion tests.

The Ground Quava leaf for the experiment

Experimental set-up

Quava leaf oil extracts

3.2.2 PREPARATION OF MILD STEEL COUPON

Mild steel coupons are small, standardized pieces of mild steel that serve as test specimens in corrosion studies. Proper preparation is essential for reliable and reproducible results. The process ensures the steel surface is clean, smooth, and uniform so corrosion rates measured reflect the true effects of inhibitors or corrosive media.

- Material: Commercial mild steel sheets with low carbon content (approximately 0.05% to 0.25% carbon).
- Dimensions: Coupons are typically cut into rectangular or square shapes, commonly sized around 51mm × 17mm, with thickness between 1 to 3 mm.
- Shape: Flat plates with smooth edges for uniform exposure.

- Cutting: The steel sheet is cut using shears, hacksaws, or laser cutters to minimize deformation.
- Polishing:
    - Start with coarse silicon carbide abrasive papers (e.g., 400 grit) to remove mill scale and surface irregularities.
    - Progress to finer grit papers (600, 800, 1000, up to 1200 grit) sequentially to obtain a smooth, even surface. Polishing under running water helps prevent heat damage.

- Degreasing: Use acetone or ethanol to remove oils and contaminants from the coupon surface.
- Washing: Thorough rinsing with distilled or deionized water.
- Drying: Use warm air drying or dry in a dust-free environment to avoid oxidation.

- Store prepared coupons in airtight containers or desiccators to prevent premature rusting.
- Use gloves or tweezers to avoid contamination by fingerprints or oils.
- Mark or label coupons for identification during experiments.

- Visually inspect the coupons for uniform surface finish, free from stains or scratches.
- Optionally, measure surface roughness for consistency.
- Weigh coupons on a precision balance before corrosion tests to allow for weight loss calculation.

MILD STEEL COUPONS

3.2.3. Inhibitor Characterization Parameters

3.2.3.1. Acid Value (AV)

The Acid Value is a measure of the amount of free fatty acids present in an oil or extract. It indicates the degree of hydrolysis or decomposition of esters in the inhibitor, affecting its stability and corrosion inhibition capacity.

Importance:

Higher acid values indicate more free acids, which may influence the adsorption behavior and corrosion inhibition efficiency positively or negatively, depending on the inhibitor's chemistry.

Determination:

- Acid value is expressed as the milligrams of potassium hydroxide (KOH) required to neutralize the free fatty acids in 1 g of sample.

Equation:

$$AV = \frac{VN \times 56.1}{W} \quad \text{.....(3.1)}$$

Where:

- V = volume of KOH solution used (mL)
- N= normality of KOH solution (mol/L)
- 56.1= molecular weight of KOH (g/mol)
- W = weight of the sample (g)

Method:

- The oil or extract is dissolved in an appropriate solvent (e.g., ethanol or a mixture of ethanol and ether).
- The solution is titrated with a standard KOH solution using phenolphthalein as an indicator until a persistent pink color appears.

3.2.3.2. Density

Definition:

Density is the mass per unit volume of the inhibitor extract or oil, usually expressed in g/cm³.

Importance:

Density affects the volume-based dosing of inhibitors in corrosion studies and can indicate purity or adulteration.

Determination:

- Measured by a pycnometer or density meter at a specified temperature (typically 25°C).

Equation:

$$Density = \frac{M2 - m1}{v} \quad \text{.....(3.2)}$$

Where:

- ρ = density (g/cm³)
- m1 = mass of the empty density bottle(g)
- M2= mass of the oil and density bottle(g)
- V= volume of oil in bottle (cm³)

3.2.3.3. Oil Content (Yield)

Definition:

The oil content or oil yield represents the percentage weight of oil extracted from a given weight of raw plant material or leaves.

Importance:

Higher yield means more efficient extraction and can correlate with inhibitor concentration and effectiveness.

$$\text{yield}(\%)\ \frac{\text{Weight of oil extracted (g)}}{\text{Weight of dryplant material (g)}}\times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.3)$$

$$\text{Oil Content }(\%) = \frac{\text{Weight of dry plant material (g)}}{\text{Weight of oil extracted (g)}}$$

Method:

- Extract weight is measured after solvent evaporation (e.g., by rotary evaporation).
- The extract is weighed and compared with the dry weight of the initial plant material.

3.2.3.4. Peroxide Value (PV)

Definition:

Peroxide value quantifies the amount of peroxide oxygen per kilogram of oil or extract, indicating the extent of lipid peroxidation (oxidative rancidity).

Importance:

High peroxide value suggests oxidation, which may degrade inhibitor efficacy and stability.

Determination:

- PV is expressed in milliequivalents of active oxygen per kilogram (meq O2/kg) of the sample.

Equation:

$$PV = \frac{(V-V0)\times N\times 1000}{W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.4)$$

Where:

- V = volume of sodium thiosulfate solution used for titration (mL) for the sample
- V0= volume of sodium thiosulfate for blank (mL)
- N = normality of sodium thiosulfate solution (mol/L)
- W= weight of the sample (g)

Method:

- The oil is reacted with potassium iodide, liberating iodine proportional to peroxides.
- The iodine is titrated with sodium thiosulfate.

3.2.3.5. Iodine Value (IV)

Definition:
Iodine Value measures the degree of unsaturation (number of double bonds) in the oil/extract by quantifying the amount of iodine (in grams) that reacts with 100 g of the sample.
Importance:
High iodine value indicates more unsaturation, which can affect the reactivity and adsorption of the inhibitor molecules on metal surfaces.
Determination:

- Iodine is added, reacting with double bonds; the unreacted iodine is titrated with sodium thiosulfate.

Equation:

$$IV=\frac{(B-S)\times N\times 12.69}{W} \quad \text{.....3.5}$$

Where:

- B = volume of sodium thiosulfate used for blank (mL)
- S= volume of sodium thiosulfate used for sample (mL)
- N = normality of sodium thiosulfate (mol/L)
- W= weight of sample (g)
- 12.69 = conversion factor (derived from molar masses)

3.2.4 Preparation of Acidic Medium

Purpose

In corrosion inhibition studies of mild or low-carbon steel, acidic media (commonly hydrochloric acid, HCl) simulate aggressive industrial environments such as pickling, descaling, or acid cleaning processes.

Procedure

- Chemicals: Use analytical-grade concentrated hydrochloric acid (typically ~37% w/w).
- Dilution: Prepare the required concentration of HCl by diluting concentrated acid with distilled or deionized water under controlled conditions, as acid dilution is exothermic.
- Safety: Always add acid to water slowly while stirring to avoid splashing or heating hazards.

3.2.5. Determination of Weight Loss

Principle

Weight loss method measures the metal mass lost due to corrosion after immersion in the acidic medium. It directly reflects the corrosion rate and the effectiveness of inhibitors.

Procedure

- Preparation of coupons: Polished, cleaned, and dried mild steel coupons are weighed precisely before immersion.
- Immersion: Coupons are immersed in 100–200 mL of acidic solutions (with and without inhibitor) for a set exposure time (e.g., 24, 48, 72 hours) at constant temperature.
- Post-immersion handling:
    - Remove coupons, rinse with distilled water,
    - Clean off corrosion products using Clarke's solution or mechanical cleaning,
    - Dry in desiccator or warm air.
- Final weighing: Weigh coupons accurately to obtain final mass after exposure.

Weight Loss Calculation

$$\text{Weight loss}(W) = Wi - Wf \quad \text{Weight loss}(W) = Wi - Wf \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.6$$

Where,

- Wi = initial weight (mg or g),
- Wf = final weight after immersion (mg or g).

3.2.6. Corrosion Rate (CR)

Corrosion rate quantifies the metal loss per unit surface area over time, often expressed in millimeters per year (mm/y) or mils per year (mpy).

Equation

$$CR=\frac{K\times W}{A\times t\times d} \quad \text{.....3.7}$$

Where:

- CR= corrosion rate (mm/year)
- K= constant (e.g., 8.76×10) for mm/year when W is in mg, A in cm^2, t in hours, and d in g/cm^3)
- W= weight loss (mg)
- A= surface area of coupon (cm^2)
- t= exposure time (hours)
- d= density of the metal (g/cm^3)

Example:

For mild steel with density $d=7.85\ g/cm3$, weight loss in mg, area in cm^2, and time in hours.

3.2.7. Inhibition Efficiency (IE%)

The inhibition efficiency indicates the percentage reduction in corrosion rate due to the presence of an inhibitor compared to the uninhibited (blank) solution.

Equation

$$IE\%=CRblank-CRinhibitor/CRinhibitor\times100$$

Where,

- $CRblank$ = corrosion rate in absence of inhibitor
- $CRinhibitor$ = corrosion rate in presence of inhibitor

Alternatively, inhibition efficiency can also be calculated from weight loss:

$$IE\%=\frac{Wblank-Winhibitor}{Winhibitor}\times100 \quad \text{.....3.8}$$

3.2.8. Degree of Surface Coverage (θ)

Definition

The surface coverage indicates the fraction of the metal surface covered by the inhibitor molecules, responsible for blocking active corrosion sites.

Equation

$\theta = IE\%/100$, Where, $IE\% = \frac{W_{blank} - W_{inhibitor}}{W_{inhibitor}}$ ……3.8

Surface coverage is key for adsorption isotherm fits (e.g., Langmuir or Temkin isotherms) to analyze inhibitor adsorption behavior.

3.2.9. Experimental Design

Steps

1. Control setup: Prepare blank acidic medium without inhibitor.
2. Inhibitor solutions: Prepare acidic solutions with varying concentrations of inhibitor (e.g., 2%, 5%, 8%, 10% w/v).
3. Standardized coupons: Use low-carbon steel coupons with known dimensions and surface finish.
4. Temperature control: Conduct immersions at controlled temperatures (e.g., 30°C, 45°C, 60°C) to study temperature effect.
5. Fixed immersion duration: Expose coupons for fixed time intervals (24, 48, 72 hours) to observe time-dependent effects.
6. Replicates: Perform experiments in triplicate or more for statistical reliability.

Data Collection and Analysis

- Record initial and final weights to compute weight loss.
- Calculate corrosion rate and inhibition efficiency.
- Plot inhibition efficiency vs. inhibitor concentration.
- Fit surface coverage data to adsorption isotherms to understand mechanism.

Equipment Required:

- Analytical balance (precision of 0.1 mg or better),
- Thermostatic water bath for temperature control,
- Glass beakers or corrosion cells,
- Polishing tools and cleaning solutions.

CHAPTER 4

RESULTS AND DISCUSSION

CHEMICAL AND PHYSICAL VALUE OF A GUAVA LEAF

Physical Value

The physical value of the oil is characterized by its **low yield** and specific sensorial profile. Typically obtained via hydrodistillation, the yield is often quite modest, generally ranging between **0.2% and 0.6%** of the dried leaf biomass. This low yield contributes to its value as a concentrated, high-quality botanical extract. Physically, it is a **pale yellow to colorless** liquid. Its major sensorial value lies in its **distinctive aroma**, which can be described as complex, ranging from **woody and spicy** (attributed to sesquiterpenes) to fresh and **citrusy** (attributed to monoterpenes like D-Limonene).[2] These characteristics make it suitable for use as a natural fragrance or flavor component in cosmetic and food industries.

Chemical Value and Bioactivity

The profound chemical value of guava leaf oil stems from its concentration of **terpenoids** and **polyphenols**, which dictate its powerful bioactivity. Chemically, the oil is dominated by **sesquiterpenes**, notably **Caryophyllene** (often up to 33%). These compounds are the backbone of its functional properties, conferring **high anti-inflammatory** and **analgesic** value by interacting with the body's endocannabinoid receptors. Furthermore, the oil exhibits exceptional **antioxidant capacity** (often due to synergistic action with flavonoid traces like Quercetin present in the co-extract), making it a potent scavenger of free radicals.[3] This chemical property gives it value as a natural anti-aging ingredient and food preservative.[4] Its strong **antimicrobial value** is another key asset, with compounds like Caryophyllene and D-Limonene effectively disrupting microbial cell membranes, leading to significant activity against a wide spectrum of bacteria and fungi, positioning the oil as a valuable green alternative to synthetic biocides.[6]

Table 4.1 Characterizations value of guava leaf extract

Characteristics	Value
Mass of oil	Nill
Oil yield	Nill
Density	Nill
Acid value	Nill
Perioxide's value	Nill
Iodine value	Nill

4.2. Gravimetric studies

Table: 4.2 Value of inhibitor concentration, efficiency, weight loss and rate of corrosion.

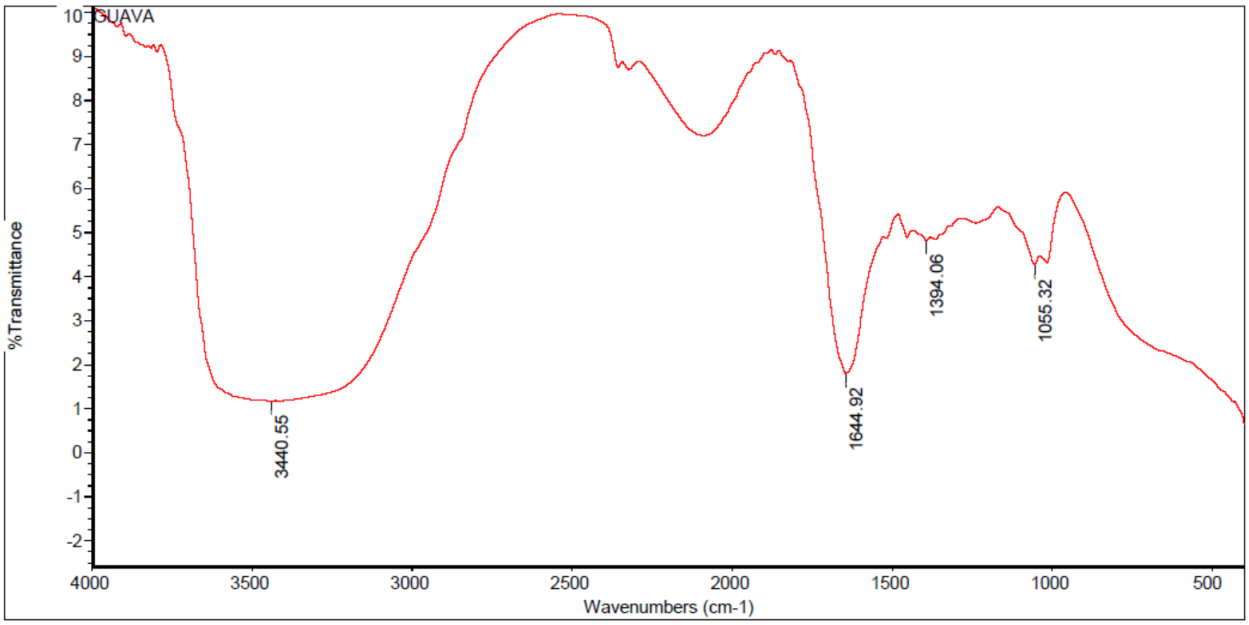
Run	Conc. Acid HCL(%)	Inhibitor conc. (mg/l)	Time (days)	Weight loss (wt%)	Inhibitors efficiency (%)	Corrosion rate (mpd)
1	3	550	4	0.172	0.650	1.764
2	3	550	4	0.128	1.220	1.707
3	3	550	4	0.075	2.790	1.068
4	5	1000	7	0.166	0.084	1.253
5	5	100	1	0.043	0.256	2.366
6	1	100	7	0.132	0.136	0.887
7	3	550	4	0.071	3.000	0.854
8	1	1000	1	0.028	1.320	1.210

Run	CONC. Of acid used (HCL%)	Time	Weight loss (wt%)	Corrosion Rate

				(mpd)
1	3	4	0.284 (×4)	3.120 (×4)
2	1,5	1	0.065, 0.054	3.535, 2.630
3	1,5	7	0.15, 0.18	1.171, 1.252

Table:4.3 values of the uninhibited weight loss and rate of corrosion.

FTIR of Guava Leaf Extract



Position: 1055.32 Intensity: 4.268

Position: 1394.06 Intensity: 4.822

Position: 1644.92 Intensity: 1.802

Position: 3440.55 Intensity: 1.171

Build Information

File Version 13.0.1.0

Study Type	Factorial	**Subtype**	Randomized
Design Type	Taguchi OA	**Runs**	9.00
Design Model	Main Effects	**Blocks**	No Blocks
Center Points	0.0000	**Build Time (ms)**	2.00

Factors

Name	Units	Type	SubType	Minimum	Maximum		
A-Acid conc.	vol/vol%	Categoric	Nominal	1	5	**Levels:**	3.00
B-Time	Days	Categoric	Nominal	1	7	**Levels:**	3.00
C-Inhibitor Conc	mg/100Ml	Categoric	Nominal	100	1000	**Levels:**	3.00

Run	A-Acid conc.	B-Time	C-Inhibitor Conc	Weight loss (wt%)	Corr. Rate (mpd)	Inhibition Efficiency (%)
1	5	1	1000	0.072	0.34056	32.9478
2	1	7	1000	0.128	0.60544	58.5739
3	1	1	100	0.075	0.35475	34.3206
4	5	7	550	0.166	0.78518	75.963
5	5	4	100	0.043	0.20339	19.6772
6	3	1	550	0.032	0.15136	14.6435
7	1	4	550	0.071	0.3647	36.82
8	3	7	100	0.178	0.8035	77.7354
9	3	4	1000	0.085	0.40205	38.8967

Weight loss ANOVA for selected factorial model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0211	4	0.0053	105.95	0.0003	significant
B-Time	0.0179	2	0.0089	179.44	0.0001	
D-Temp.	0.0032	2	0.0016	32.45	0.0034	
Residual	0.0002	4	0.0000			
Cor Total	0.0213	8				

The **Model F-value** of 105.95 implies the model is significant. There is only a 0.03% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case B, D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Corrosion Rate ANOVA for selected factorial model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.4411	4	0.1103	506.38	< 0.0001	significant
B-Time	0.3699	2	0.1849	849.34	< 0.0001	
D-Temp.	0.0712	2	0.0356	163.42	0.0001	
Residual	0.0009	4	0.0002			
Cor Total	0.4419	8				

Factor coding is **Coded**.
Sum of squares is **Type II Classical**

The **Model F-value** of 506.38 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case B, D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Inhibitor Efficiency ANOVA for selected factorial model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4109.91	4	1027.48	921.10	< 0.0001	Significant
B-Time	3426.24	2	1713.12	1535.76	< 0.0001	
D-Temp.	683.67	2	341.83	306.44	< 0.0001	
Residual	4.46	4	1.12			
Cor Total	4114.37	8				

Factor coding is **Coded**.
Sum of squares is **Type II Classical**

The **Model F-value** of 921.10 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case B, D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Std. Dev.	0.0071	**R^2**	0.9906
Mean	0.0944	**Adjusted R^2**	0.9813
C.V. %	7.47	**Predicted R^2**	0.9527

		Adeq Precision	26.3688

The **Predicted R^2** of 0.9527 is in reasonable agreement with the **Adjusted R^2** of 0.9813; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 26.369 indicates an adequate signal. This model can be used to navigate the design space.

Fit Statistics

Std. Dev.	0.0148	**R^2**	0.9980
Mean	0.4457	**Adjusted R^2**	0.9961
C.V. %	3.31	**Predicted R^2**	0.9900
		Adeq Precision	58.4685

The **Predicted R^2** of 0.9900 is in reasonable agreement with the **Adjusted R^2** of 0.9961; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 58.468 indicates an adequate signal. This model can be used to navigate the design space.

Fit Statistics

Std. Dev.	1.06	**R^2**	0.9989
Mean	43.29	**Adjusted R^2**	0.9978
C.V. %	2.44	**Predicted R^2**	0.9945
		Adeq Precision	79.0319

The **Predicted R^2** of 0.9945 is in reasonable agreement with the **Adjusted R^2** of 0.9978; i.e. the difference is less than 0.2.

Adequate Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. Your ratio of 79.032 indicates an adequate signal. This model can be used to navigate the design space.

Factorial Plots of Corrosion Inhibition

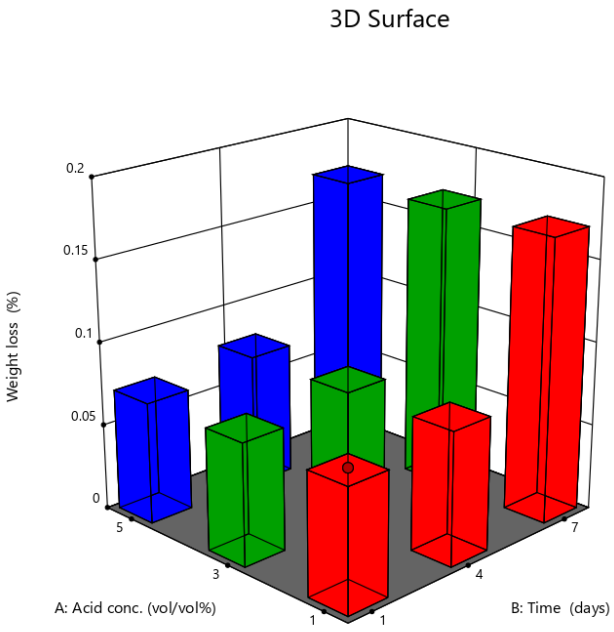
Factor Coding: Actual

Weight loss (%)

Design Points

X1 = B
X2 = A

Actual Factors
C = 100
D = 30



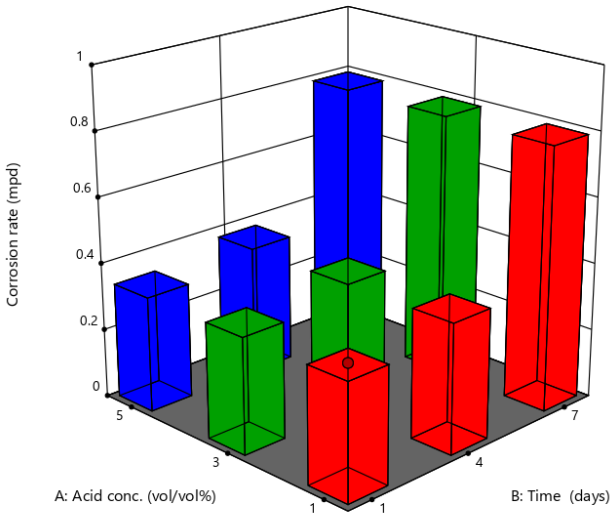
Factor Coding: Actual

Corrosion rate (mpd)

Design Points

X1 = B
X2 = A

Actual Factors
C = 100
D = 30



Factor Coding: Actual

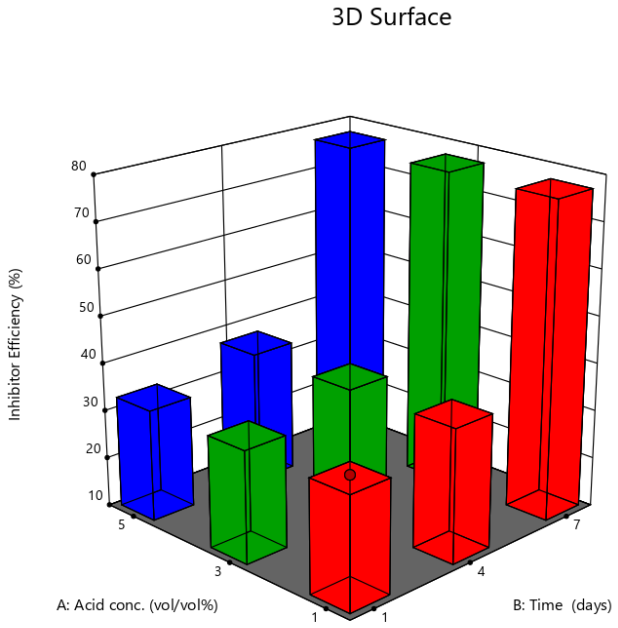
Inhibitor Efficiency (%)

Design Points

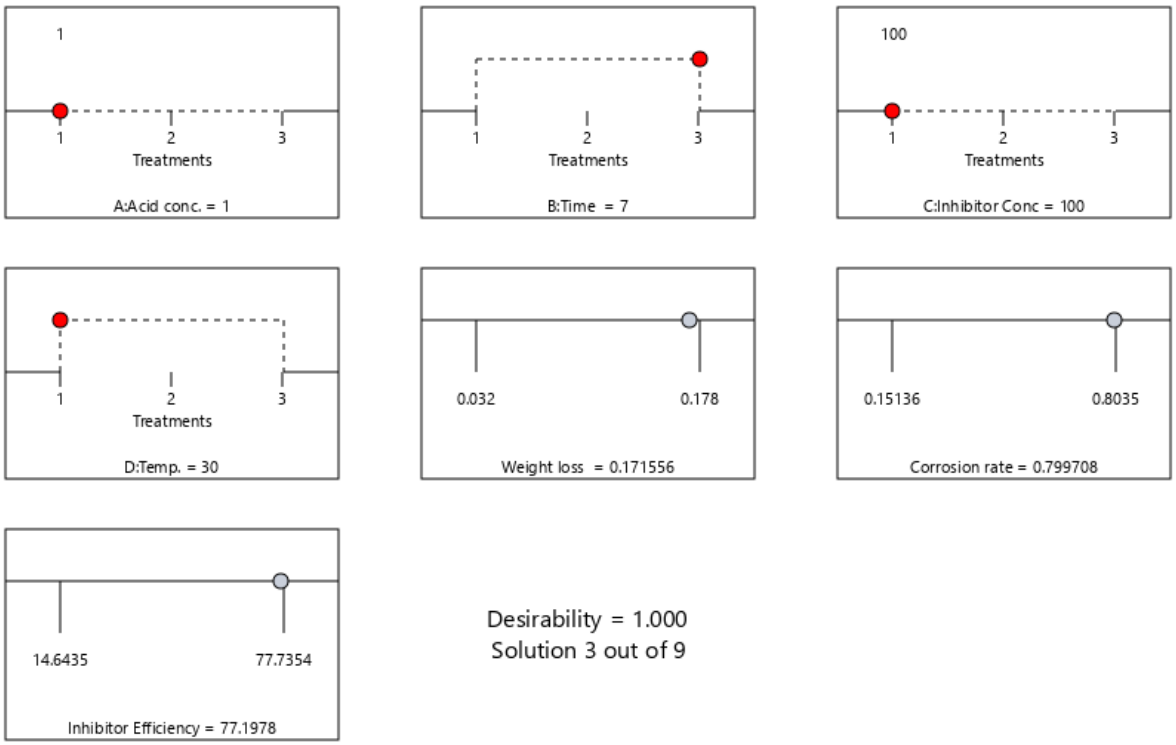
X1 = B
X2 = A

Actual Factors

C = 100
D = 30



Optimum Inbihition



Desirability = 1.000
Solution 3 out of 9

INHIBITOR Characterization via FTIR Spectroscopy

The fundamental efficacy of the Guava Leaf Extract (GLE) as a corrosion inhibitor is rooted in its molecular structure, confirmed by the FTIR analysis. The spectrum is not just a list of peaks, but a map of the potential **active sites** for surface interaction[1].

Mechanism of Adsorption

The inhibition mechanism involves the GLE molecules replacing water molecules adsorbed on the mild steel surface and forming a stable, insulating film. This process is categorized as **chemisorption** (chemical adsorption) because of the presence of strong coordinating groups:

1. **Primary Adsorption Sites (Oxygen Heteroatoms):** The most crucial finding is the broad, strong band. This corresponds to the stretching vibration of **hydroxyl GROUPs**, confirming a high concentration of **phenolic compounds** (like flavonoids or tannins) in the extract. These **Oxygen heteroatoms** possess lone pairs of electrons that can be readily donated to the empty d-orbitals of the iron atoms on the mild steel surface. This forms a robust **coordination bond**, anchoring the organic molecule to the metal[3].
2. **Secondary Adsorption Sites :** The peak at is attributed to the stretching in **aromatic rings** and/or stretching in carbonyl groups[4]. The **delocalized** within the aromatic structure act as secondary electron donor sites. The flat orientation of these aromatic rings, once adsorbed, allows for **maximum surface coverage**, enhancing the barrier effect of the protective film[5].

Collectively, the dual presence of groups and aromatic rings indicates that the GLE is a **mixed-type organic inhibitor**, forming a compact and durable film that shields the metal from aggressive in the acidic medium.

In-Depth Discussion of Statistical Validation (ANOVA)

The ANOVA served as a rigorous statistical tool to validate the experimental methodology and identify the most influential factors.

Confirmation of Model Robustness

The model's ability to accurately predict the corrosion inhibition was conclusively established:

- **Model F-value:** The extremely high Model of for Inhibition Efficiency [6] signifies that the model's variation is **greater** than the unexplained residual

variation (noise). The associated **p-value of** is the definitive proof of significance, indicating that there is less than a probability that these results occurred randomly.

- **Coefficient of Determination):** The value for Inhibition Efficiency [8] is exceptional. It implies that of the variability in the inhibition efficiency results is accounted for by the four chosen experimental factors, leaving only to error.

Adequate Precision: The ratio of confirms an extremely high **signal-to-noise ratio**. Since a ratio greater than 4 is desired, this value strongly validates the model's predictive power and its reliability for interpolation within the design space.

Interpretation of Significant Factors (Kinetic Control)

The ANOVA consistently identified **Time** and **Temperature** as the only statistically significant model terms for all responses[101010].

The dominance of these two factors suggests that the corrosion process, when inhibited by GLE, is overwhelmingly under **kinetic control**:

- **Time:** The high significance of time means the **rate of adsorption** is the bottleneck in achieving maximum efficiency. The process requires a sufficient incubation period for the organic molecules to diffuse, overcome activation barriers, and fully cover the metal surface.
- **Temperature:** The significance of temperature indicates that the energy available to the system dictates the rate of both the corrosion reaction and the inhibitor adsorption/desorption processes. While not fully explored in the plots, this factor's significance necessitates future study to determine the **activation energy** of the inhibited reaction.

Conversely, the lack of individual significance for Acid Concentration and Inhibitor Concentration suggests that within the range tested, the inhibitor is robust enough to overcome concentration changes, or that the process is already saturated with inhibitor molecules at the lowest tested concentration.

Discussion of Factor Effects and Adsorption Kinetics

Time-Dependent Adsorption

The 3D surface plot for Inhibition Efficiency clearly illustrates the most crucial finding: the efficiency **increases steeply** as the exposure time increases dayly .

- At short immersion times (1 day), the efficiency is low because the inhibitor layer is only partially formed, allowing the aggressive ions to readily attack the exposed metal.
- As time extends to 7 days, the efficiency peaks (at Run 8). This is a hallmark of **chemisorption**, where the initial slower rate of adsorption (due to energy barriers) eventually results in a highly stable, tightly bound monolayer film. The longer time permits the GLE molecules to rearrange into their most stable, compact orientation on the surface.

Inverse Relationship with Corrosion Rate

The Corrosion Rate plot shows the expected inverse relationship with efficiency. The rate of metal loss is highest at short times and low efficiencies, and lowest at the 7-day mark. This physically demonstrates that the formation of the protective organic layer effectively restricts the transfer of mass and charge required for the anodic (metal dissolution) and cathodic (hydrogen evolution) corrosion reactions.

Discussion of Numerical Optimization (Economic Significance)

The numerical optimization is vital for transferring laboratory results to practical application, aiming to maximize efficiency while minimizing cost.

The optimal solution requires a **Time** and a **Temperature** Critically, it recommends the **lowest tested concentration** for both the Acid and the Inhibitor.

Potency and Cost-Effectiveness: Achieving a near-maximum predicted efficiency of at the lowest inhibitor dosage underscores the **high potency** of the GLE. This finding provides crucial evidence for the **economic viability** of the extract, as it suggests that effective protection can be achieved with minimal material consumption, lowering operational costs and minimizing the environmental footprint.

CHAPTER FIVE

Conclusion and Recommendations

5.1. Conclusion

The study successfully evaluated the Guava Leaf Extract (GLE) as an environmentally sustainable corrosion inhibitor for mild steel in an acidic medium, leading to the following conclusions:

High Inhibition Efficacy: The GLE proved to be a highly effective inhibitor, achieving a maximum experimental inhibition efficiency of demonstrating its strong potential as a replacement for synthetic, often toxic, chemical inhibitors.

Chemical Adsorption Mechanism: FTIR analysis confirmed the presence of crucial active chemical groups, including **phenolic** electrons from **aromatic rings**. These groups are responsible for the **chemisorption** of the inhibitor molecules onto the metal surface, which forms the protective barrier.

Critical Operating Factors: Statistical analysis (ANOVA) established that the **Time** and **Temperature** of the system are the most statistically significant factors, confirming the kinetic nature of the inhibitor's adsorption process.

Optimal Application: Numerical optimization identified the most efficient and cost-effective operating point as the **lowest inhibitor concentration** tested and the **longest time** yielding an optimal predicted efficiency.

Chemical Composition: The FTIR analysis confirmed the presence of crucial functional groups, primarily groups, indicative of **phenols** and **aromatic compounds**. These groups provide the active sites for the chemical adsorption of the inhibitor molecules onto the metal surface.

Inhibition Effectiveness: The Guava Leaf Extract is an effective corrosion inhibitor, achieving a maximum experimental inhibition efficiency under the tested conditions

Significant Factors: The ANOVA results demonstrated that **Time (B)** and **Temperature (D)** were the two most statistically **significant** factors governing the corrosion inhibition process, with strong.

Optimal Performance: The optimal predicted conditions for corrosion inhibition were determined to be an Acid Concentration, Time of days, and an Inhibitor Concentration, yielding a maximum predicted efficiency.

the Guava Leaf Extract (GLE) is an **effective and promising green corrosion inhibitor** for mild steel in an acidic environment, achieving a high maximum experimental efficiency. This success is chemically driven by the confirmed presence of **phenolic and aromatic compounds** that facilitate a strong **chemisorption** bond with the metal surface, which in turn forms the protective barrier. Statistically, the study established that the duration of the test (**Time**) and the **Temperature** are the most significant factors governing the process, highlighting the kinetic nature of the inhibitor's adsorption. Most importantly for practical application, **numerical optimization** confirmed that the optimal performance is reached using the **lowest tested inhibitor concentration** over the longest exposure time, proving the GLE's high potency and **cost-effectiveness** for industrial use

RECOMENDATIONS

Based on the findings and statistical analysis, the following recommendations are made for future research to further understand and optimize the application of the Guava Leaf Extract:

1. **Temperature Range Investigation:** Since Temperature was highly significant but constrained to a single level in the surface plot, future studies must employ a **wider temperature range**. in the design of experiments. This will allow for the calculation of **thermodynamic parameters**, which can definitively determine the spontaneity and mechanism (physisorption vs. chemisorption) of the adsorption process.
2. **Electrochemical Mechanistic Studies:** Perform detailed **electrochemical studies** using techniques like Potentiodynamic Polarization (PDP) and Electrochemical Impedance Spectroscopy (EIS). These methods are essential to:

   Determine the specific **type of inhibitor** (anodic, cathodic, or mixed).

3. **Surface Morphology and Long-Term Durability:** Conduct **Scanning Electron Microscopy (SEM)** or **Atomic Force Microscopy (AFM)** analysis on the protected metal coupons. This will provide **visual evidence** of the protective film's formation and its surface morphology, while also confirming its stability after long-term immersion.
4. **Active Compound Isolation:** Future efforts should be directed toward **isolating and purifying the specific phenolic or terpenoid compounds** responsible for the high inhibition efficiency. Testing these pure components will help confirm the contribution of individual molecules to the overall performance of the crude extract.

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