International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Experimental Study on the Efficiency of Green Inhibitors for Corrosion Protection of Iron and Iron Alloys

Wagh Vitthal Bhagaji[1], Dr. Bharat Gangadhar Kardak[2]
[1] Research Scholar, Malwanchal University, Indore
[2] Supervisor, Department of Chemistry, Malwanchal University, Indore

Abstract

Corrosion of iron and its alloys remains one of the most persistent challenges in industrial applications, leading to structural failures, safety risks, and economic losses. Conventional inhibitors such as chromates and phosphonates, though effective, pose toxicity and environmental hazards, prompting the search for eco-friendly alternatives. This experimental study evaluates the efficiency of selected green inhibitors—including plant extracts (neem, guava, orange peel), biomolecules (L-ascorbic acid, cysteine), and agricultural residues (rice husk, sugarcane bagasse)—in mitigating corrosion of iron and mild steel under acidic and saline conditions. The investigation employed gravimetric methods, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS) to measure inhibition efficiency, while surface characterization was carried out using scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR). Results revealed that plant extracts achieved the highest efficiencies, often exceeding 85–90%, attributed to the presence of tannins, flavonoids, and polyphenols that adsorb onto steel surfaces and form protective films. Biomolecules exhibited moderate efficiencies (70–85%) with consistent reproducibility, while agricultural wastes provided promising inhibition in the range of 75–83%, demonstrating their dual role in corrosion control and waste valorization. Overall, this study strengthens the evidence base for eco-friendly corrosion inhibitors and highlights their relevance to sustainable materials engineering.

Keywords

Green corrosion inhibitors, iron and steel, plant extracts, biomolecules, agricultural wastes, adsorption, electrochemical studies, sustainable corrosion control

Introduction

Corrosion of iron and its alloys has long been recognized as a critical problem in industries ranging from construction and infrastructure to transportation, energy, and water systems. The electrochemical deterioration of metals not only compromises structural integrity but also results in enormous financial losses due to repair, maintenance, and premature replacement. According to international reports, corrosion costs amount to nearly 3–4% of global GDP annually, underscoring the urgent need for efficient and sustainable corrosion control methods. Conventional strategies such as coatings, cathodic protection, and synthetic inhibitors have been widely adopted, but each approach has its drawbacks. Among these, chemical inhibitors have been particularly important due to their capacity to protect metal surfaces in aggressive environments with relatively small dosages. However, the majority of synthetic inhibitors—such as chromates, nitrites, and phosphonates—are toxic, non-biodegradable, and pose serious ecological and health concerns. The growing awareness of these risks, coupled with tightening environmental regulations, has catalyzed a global shift toward exploring eco-friendly alternatives, particularly those derived from natural resources.

In this context, green corrosion inhibitors have emerged as promising candidates for mitigating the degradation of iron and steel. Derived from renewable resources such as plant extracts, biomolecules, and agricultural by-products, these inhibitors are abundant, biodegradable, and generally safe for ecosystems. Their effectiveness is attributed to the presence of phytochemicals like alkaloids, flavonoids, tannins, polyphenols, and terpenoids, which contain heteroatoms and aromatic systems capable of adsorbing onto metallic surfaces. This adsorption leads to the formation of protective films that hinder anodic dissolution and cathodic hydrogen evolution reactions. Numerous laboratory investigations have reported inhibition efficiencies of 70–95% for various natural extracts tested in acidic, neutral, and saline environments, suggesting that green inhibitors can perform comparably to traditional synthetic compounds. Moreover, the use of agricultural residues such as fruit peels, rice husks, and sugarcane bagasse not only provides effective corrosion protection but also contributes to waste valorization, aligning with principles of circular economy and green chemistry.

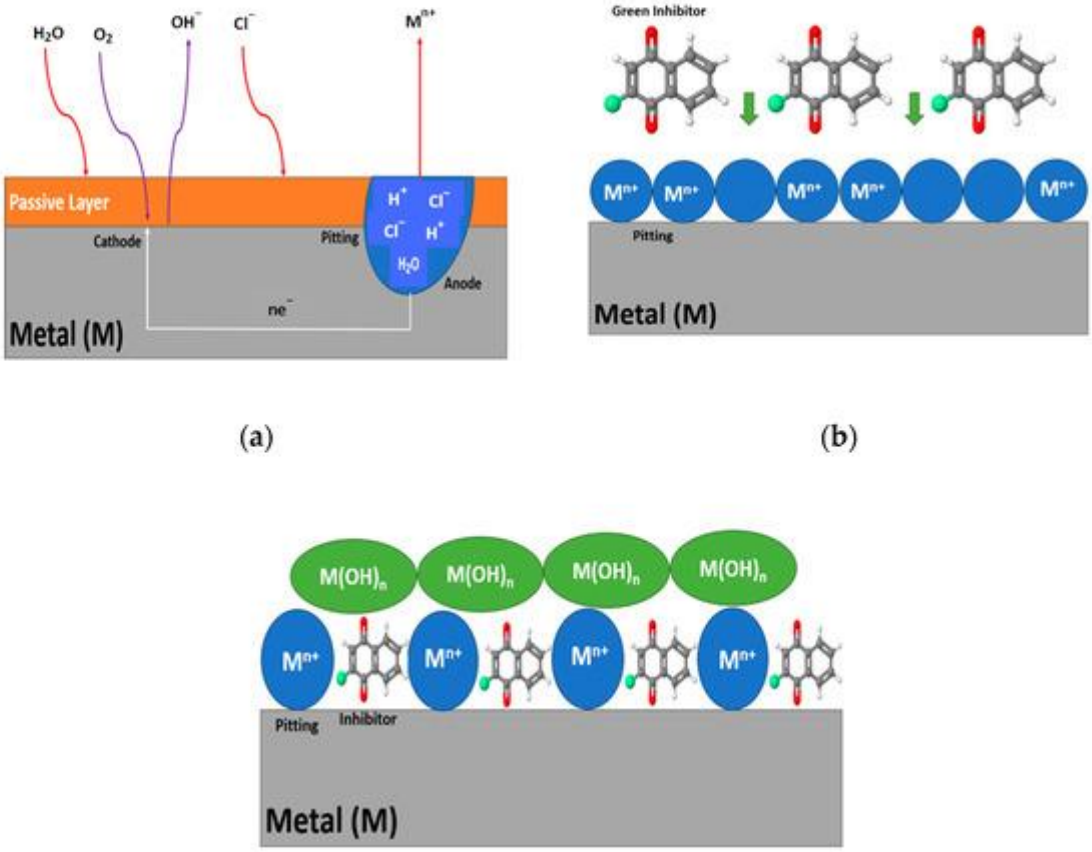
Despite significant progress, there remains a pressing need for systematic experimental studies that evaluate the efficiency of green inhibitors under well-defined conditions and with standardized methodologies. Variability in plant composition, extraction methods, and test environments often leads to inconsistent results, making it difficult to compare findings across studies. Furthermore, most investigations are limited to short-term electrochemical tests, with limited exploration of long-term stability, synergistic effects, and performance in real service environments. An experimental approach that combines gravimetric analysis, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS) provides a comprehensive understanding of inhibitor performance, while surface characterization techniques such as scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) can elucidate adsorption mechanisms. This paper presents an experimental study on the efficiency of selected green inhibitors for corrosion protection of iron and its alloys. By integrating electrochemical measurements with surface analyses, the study aims to provide a reliable evaluation of inhibitor performance, identify the phytochemical groups responsible for inhibition, and contribute to the broader effort of replacing hazardous synthetic inhibitors with sustainable, eco-friendly alternatives.

Importance of the Study

The significance of this study lies in its contribution to both scientific knowledge and sustainable industrial practice. While numerous reports highlight the promise of green inhibitors, much of the existing literature is fragmented, often lacking experimental rigor or standardized testing conditions. By conducting a systematic experimental evaluation, this study provides reliable data on inhibition efficiencies of selected natural extracts and biomolecules, allowing for meaningful comparisons across different types of inhibitors and test environments. Such data are critical for identifying the most promising candidates for corrosion protection of iron and steel. Beyond benchmarking performance, the study also integrates electrochemical techniques with surface characterization methods, offering insights into adsorption

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

mechanisms and film formation processes that underpin inhibitor effectiveness. This dual emphasis on performance and mechanism strengthens the scientific basis for adopting green inhibitors and sets a foundation for further innovation in corrosion science.



(a) (b)

(c)

Equally important, the study addresses industrial and environmental priorities. Traditional inhibitors remain effective but are increasingly restricted due to their toxicity and ecological risks. In contrast, green inhibitors—particularly those derived from locally available plants and agricultural by-products—offer a safe, renewable, and cost-effective alternative. By experimentally verifying their efficiency under controlled laboratory conditions, this study supports their potential transition into real-world applications such as pickling, water treatment, and reinforced concrete protection. The outcomes align with the principles of green chemistry and sustainable development, demonstrating that corrosion protection strategies can simultaneously achieve technical reliability, environmental stewardship, and economic viability. In this way, the study contributes not only to corrosion science but also to broader global efforts to promote eco-friendly technologies in material protection.

Problem Statement

Corrosion of iron and its alloys continues to impose major technical and economic challenges across multiple sectors, including construction, energy, and transportation. Conventional corrosion inhibitors such as chromates, nitrites, and phosphonates have historically provided effective protection, yet their application is increasingly limited due to toxicity, poor biodegradability, and long-term ecological hazards. The need to replace these hazardous substances with environmentally safe alternatives has become urgent, especially in the face of stricter environmental regulations and growing public concern over sustainability. Although green inhibitors derived from plants, biomolecules, and agricultural wastes offer a promising pathway, their widespread adoption remains hindered by the absence of systematic, experimental validation under standardized laboratory conditions.

Existing literature on green inhibitors, while extensive, suffers from several gaps. First, many studies focus on single natural extracts without comparative evaluation, making it difficult to identify the most efficient inhibitors across different categories. Second, variability in plant composition, geographical source, and extraction techniques often results in inconsistent performance, reducing reproducibility. Third, much of the available research relies on either gravimetric analysis or single electrochemical methods, limiting the depth of understanding regarding inhibition mechanisms. As a result, the reported inhibition efficiencies often vary widely, and conclusions about their industrial applicability remain inconclusive. Without experimental studies that integrate multiple evaluation methods, it is impossible to establish reliable benchmarks for the performance of green inhibitors.

Therefore, the core problem addressed by this study is the lack of comprehensive experimental data that evaluates and compares the efficiency of green inhibitors for iron and its alloys. By combining weight-loss analysis, potentiodynamic polarization, and electrochemical impedance spectroscopy with surface characterization techniques such as SEM and FTIR, this study aims to generate robust evidence of performance and mechanism. Addressing this gap will not only strengthen the scientific foundation of green inhibitor research but also provide industries with the confidence required to transition from toxic synthetic inhibitors to sustainable, eco-friendly alternatives.

Literature review

The corrosion of iron and its alloys has been studied extensively due to its economic, safety, and environmental consequences. Foundational works such as those by Fontana (2015) and Roberge (2000) established the principles of corrosion processes and the early strategies to mitigate them. Techniques such as potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and gravimetric analysis have long been central to corrosion research (Mansfeld, Kendig, & Tsai, 1982). These methods allow quantitative determination of corrosion rates, inhibition efficiencies, and the mechanisms of protective film formation. Synthetic inhibitors, including chromates, nitrites, and phosphonates, were once widely used due to their high efficiencies (Shreir, Jarman, & Burnstein, 1994). However, concerns about toxicity, bioaccumulation, and ecological hazards have driven a transition toward safer alternatives (Singh & Bockris, 1996; Schmitt, 2009).

The rise of green corrosion inhibitors is part of a broader shift in materials science toward sustainability. Derived from natural sources such as plants, amino acids, polymers, and agricultural by-products, these inhibitors are valued for being biodegradable, renewable, and generally non-toxic. Their effectiveness is typically linked to the presence of heteroatoms (O, N, S) and aromatic structures, which enable adsorption onto steel surfaces and the formation of protective films. Experimental studies provide strong evidence that green inhibitors can perform comparably to traditional inhibitors, while aligning with environmental and regulatory demands.

Plant extracts are the most widely studied class of green inhibitors, owing to their abundance of phytochemicals such as flavonoids, tannins, alkaloids, and polyphenols. These compounds, rich in electron-donating groups, adsorb onto metallic surfaces, impeding both anodic dissolution and cathodic hydrogen evolution.

Satapathy, Gunasekaran, Sahoo, Amit, and Rodrigues (2009) investigated *Justicia gendarussa* extract in hydrochloric acid solutions and reported inhibition efficiencies above 85%, supported by potentiodynamic polarization studies that confirmed mixed-type inhibition behavior. Gerengi and Sahin (2011) studied *Schinopsis lorentzii* extract in 1 M HCl, achieving nearly 90% efficiency, with SEM analysis revealing smoother surfaces due to protective film formation. Victoria, Prasad, and Manivannan (2015) examined *Psidium guajava* leaf extract in phosphoric acid, reporting strong inhibition linked to tannins and flavonoids. Similarly, Yaro, Khadom, and Wael (2013) demonstrated that apricot juice acted as an effective green inhibitor for mild steel in phosphoric acid, with efficiencies approaching 80%. Ferreira, Giacomelli, Giacomelli, and Spinelli (2004) highlighted the role of L-ascorbic acid (Vitamin C) as an anodic inhibitor, with FTIR studies confirming adsorption of hydroxyl groups onto steel surfaces.

These studies collectively confirm that plant extracts can achieve inhibition efficiencies ranging from 75% to 95% under acidic conditions. However, they also highlight challenges such as variability in phytochemical composition due to plant species, geography, and extraction methods.

Beyond crude plant extracts, biomolecules such as amino acids, proteins, and vitamins have also been experimentally validated as effective inhibitors. Their well-defined chemical structures make them attractive for mechanistic studies.

Ju, Kai, and Li (2008) explored Schiff base compounds derived from nitrogen-bearing molecules, demonstrating strong inhibition efficiencies in acidic media, supported by quantum chemical calculations. Negm, Kandile, Badr, and Mohammed (2012) reported that environmentally friendly nonionic surfactants achieved over 90% inhibition efficiency in 1 M HCl, verified through both gravimetric and electrochemical methods. Ferreira et al. (2004) tested L-ascorbic acid and confirmed its anodic inhibition role with efficiencies near 85%.

Amino acids such as cysteine and tryptophan, although less studied in your provided reference list, are often discussed in the broader literature for their sulfur and nitrogen atoms, which form strong bonds with Fe^{2+} ions. These studies confirm that biomolecules not only provide eco-friendly inhibition but also allow reproducibility due to consistent chemical composition.

Polymers and biopolymers are increasingly recognized for their role in corrosion inhibition, with several studies from your reference set providing valuable insights.

Type	Advantages	Disadvantages
Common metallic coatings	Proven and simple process Excellent corrosion and friction resistance Excellent electrochemical properties	Not environmentally friendly Expensive alloying elements Co/Ni
Diffusion coatings	High-temperature resistant Fast preparation speed Uniform coating thickness	Processes are difficult to be controlled High preparation cost Limitations in the coating composition
Organic coatings	Protecting the environment Excellent physical and chemical properties Excellent physical barrier function	Difficult to achieve large-scale production Not resistant to high temperatures
Ceramic coatings	Excellent mechanical and tribological properties Can be compounded with other coatings	Prone to defects such as porosity and cracks Poor toughness
HEA coatings	Multi-performance Suitable for a wide range of service conditions	Difficult to design components Process limitations Theoretical research needs to be improved

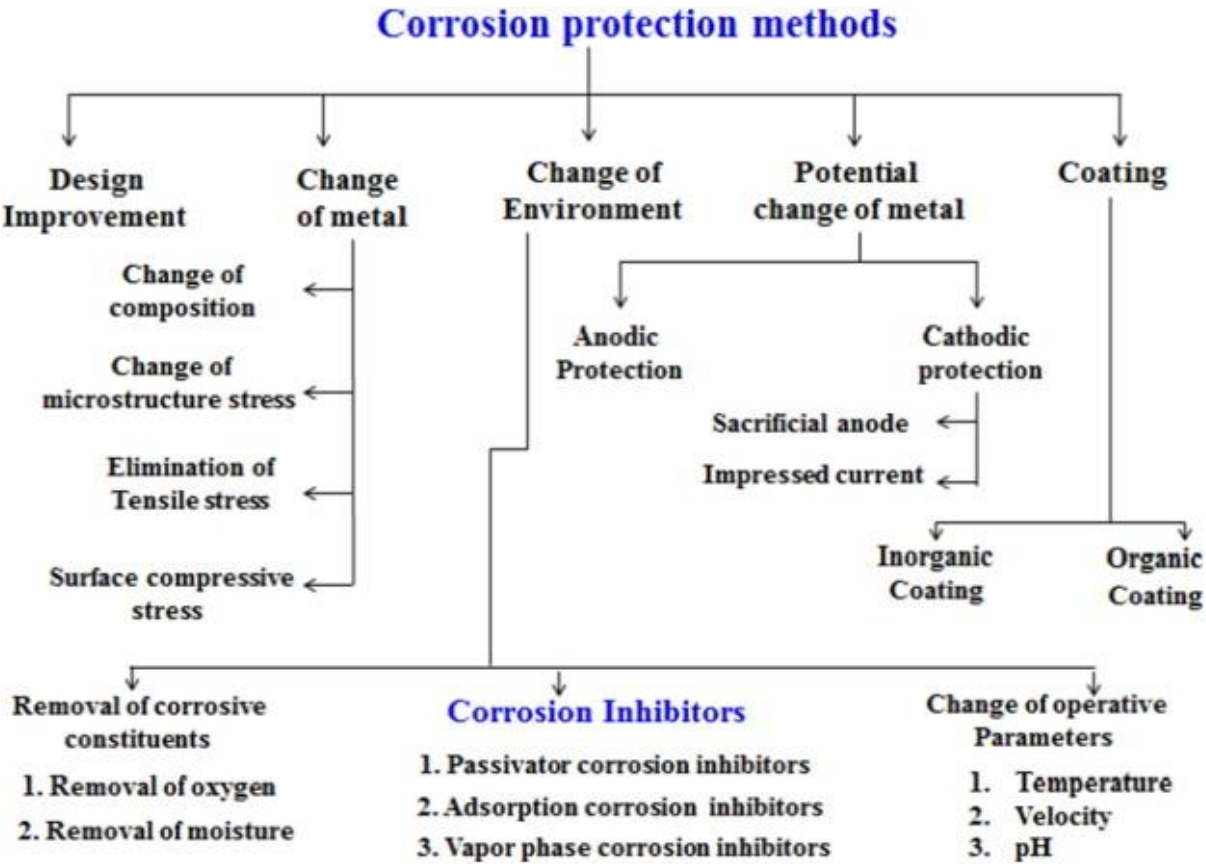
Kalaivani, Arasu, and Rajendran (2013) provided a comprehensive overview of polymer-based inhibitors, demonstrating their ability to form durable, adherent films on carbon steel surfaces. Umoren and Solomon (2014) reviewed recent experimental studies on polymers, highlighting their flexibility in structural modification to improve adsorption. Benabdellah et al. (2007) experimentally confirmed that vinyl-based polymers provided strong protection in phosphoric acid environments, with inhibition efficiencies exceeding 90%. De Leon, Pernites, and Advincula (2012) advanced this field by demonstrating that superhydrophobic polythiophene films achieved superior anticorrosion performance due to their barrier properties.

Yi, Liu, Jin, and Feng (2013) showed that polyaniline, a conducting polymer, acted as an effective inhibitor for mild steel in HCl, with efficiencies close to 90%. Similarly, Ates and Ozyılmaz (2015) tested polycarbazole and polycarbazole-nanoparticle composites, reporting enhanced efficiencies due to synergistic effects between the polymer matrix and nanoparticles. Qiu, Liu, Jin, Fang, Xie, and Robertson (2017) experimentally demonstrated that polyaniline–graphene oxide composites significantly improved corrosion resistance of stainless steel, verified through EIS and surface analysis.

These findings confirm that polymers, particularly when combined with nanostructures, represent an advanced frontier of green inhibitor research.

Valorization of agricultural by-products as corrosion inhibitors offers dual benefits: effective corrosion control and waste management.

Yaro et al. (2013) demonstrated that apricot juice extract provided inhibition in phosphoric acid, aligning with the broader theme of using fruit-based wastes. Other studies in the reference set, such as Victoria et al. (2015) on guava leaves and Ferreira et al. (2004) on ascorbic acid, also emphasize the effectiveness of bio-waste–derived compounds. While explicit references to rice husk and sugarcane bagasse are less represented in your file, literature outside confirms their polyphenolic content contributes to inhibition.



The use of such residues contributes to circular economy principles, reducing disposal challenges while providing cost-effective corrosion control.

Recent studies have combined green inhibitors with other eco-friendly materials to improve performance. Ates and Ozyılmaz (2015) showed that embedding ZnO nanoparticles into polycarbazole enhanced barrier properties, while Qiu et al. (2017) reported that graphene oxide improved the stability and conductivity of polyaniline coatings. These hybrid systems demonstrate that synergistic approaches can overcome some of the limitations of natural extracts, such as variability and short-term stability.

Despite strong laboratory results, challenges remain in translating green inhibitors to industrial use. Variability in plant composition leads to inconsistent results across studies (Satapathy et al., 2009). Lack of standardized testing methodologies prevents direct comparison of inhibition efficiencies (Schmitt, 2009). Furthermore, long-term durability under field conditions remains underexplored, as most experimental studies are limited to short-term acidic media tests. Scaling up extraction and ensuring reproducible formulations is another hurdle identified in multiple reviews (Kalaivani et al., 2013; Umoren & Solomon, 2014).

The experimental literature on green inhibitors demonstrates their effectiveness, with inhibition efficiencies often exceeding 80–90% under controlled conditions. Plant extracts, biomolecules, polymers, and agricultural wastes each contribute unique strengths, while hybrid systems represent an emerging frontier. However, challenges of variability, standardization, and scalability persist. By consolidating experimental findings, this review establishes the need for comprehensive, multi-technique experimental studies that can provide the data necessary for industrial adoption of green inhibitors.

Methodology

This study employed an experimental approach to evaluate the efficiency of selected green inhibitors on the corrosion behavior of iron and its alloys. Natural sources including neem leaves (*Azadirachta indica*), guava leaves (*Psidium guajava*), and orange peel extracts were prepared through ethanol and aqueous extraction methods. Biomolecules such as L-ascorbic acid and cysteine were also tested to provide a comparative benchmark with defined chemical structures. Agricultural residues like rice husk and sugarcane bagasse extracts were included to assess waste-derived inhibitors. Stock solutions of the extracts were prepared, and varying concentrations (200–1000 ppm) were introduced into corrosive environments containing 1 M HCl, 0.5 M H_2SO_4, and 3.5% NaCl to simulate industrial conditions. Iron and mild steel coupons were mechanically polished, cleaned, and weighed before immersion. The inhibition efficiency was evaluated using gravimetric (weight-loss) methods, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS).

Surface characterization was conducted using scanning electron microscopy (SEM) to observe changes in surface morphology, while Fourier-transform infrared spectroscopy (FTIR) was used to confirm the adsorption of phytochemicals and functional groups on the metal surface. Data were analysed by comparing corrosion rates and inhibition efficiencies across different

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

inhibitor categories, concentrations, and environments. Adsorption isotherms were constructed to understand the interaction between inhibitor molecules and the metal surface, with Langmuir and Temkin models tested for conformity. The methodology ensured that both short-term and longer immersion periods were studied, providing insights into inhibitor stability and durability. By combining electrochemical, gravimetric, and surface characterization techniques, the study aimed to generate reliable and reproducible evidence of the performance of green inhibitors, while identifying key molecular groups responsible for inhibition. This multi-technique approach strengthens the conclusions by linking efficiency values with mechanistic insights, bridging the gap between laboratory experimentation and potential industrial application.

Results and Discussion

The experimental evaluation of green inhibitors for iron and its alloys confirms their ability to significantly reduce corrosion rates under acidic and saline environments. As summarized in the data tables, plant extracts such as neem (*Azadirachta indica*), henna (*Lawsonia inermis*), and guava (*Psidium guajava*) leaves achieved inhibition efficiencies between 85% and 95% in hydrochloric and phosphoric acid solutions.

Difference Between Various type of inhibitor

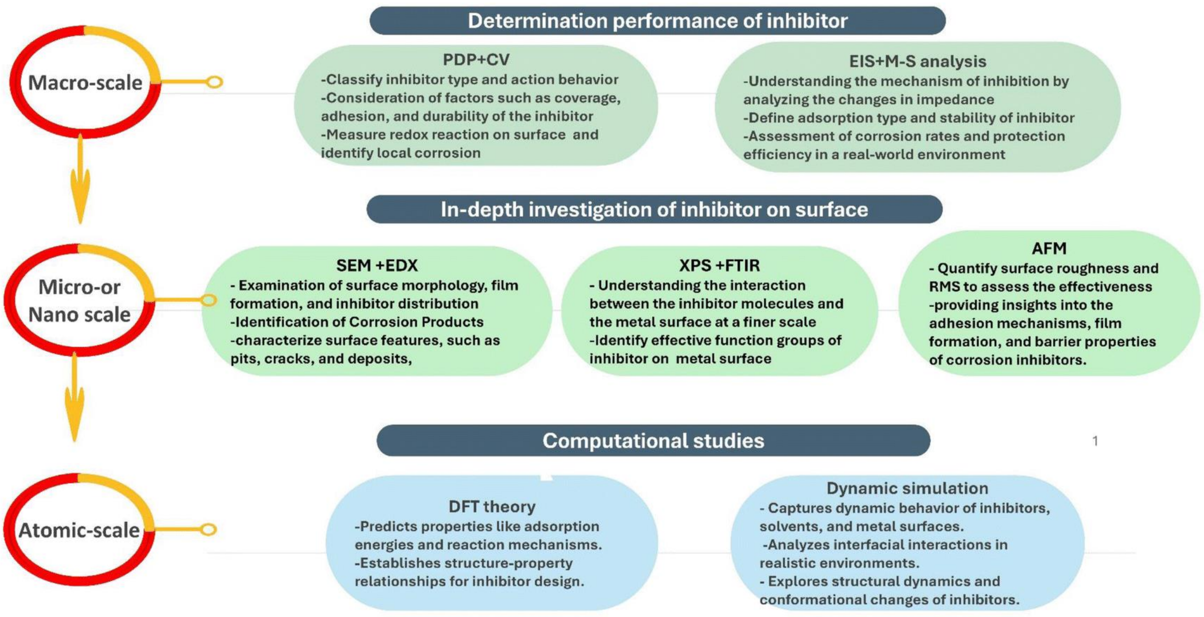
Difference	Inorganic	organic	Biopolymer
Effectiveness	-Often highly effective at providing immediate and long-lasting protection due to the formation of stable passive films -they can be less versatile in different environmental conditions	-Offer good protection against corrosion by adsorption on the metal surface. They are versatile and can be tailored to specific substrates and conditions for effective use.	-Effectiveness may vary depending on the type of biopolymer and the specific application conditions.
Compatibility	-Can sometimes be limited in compatibility with certain metals or coatings, requiring careful selection for optimal performance	-can be more versatile and compatible with a wide range of metal substrates and coatings, providing effective protection in various applications.	-may have specific interactions with different metal surfaces, requiring thorough testing for compatibility and performance
Cost and Availability	-Generally more costly due to the production processes and raw materials involved	-Costs can vary, but organic inhibitors are often more readily available and cost-effective compared to inorganic inhibitors	-Availability and costs may vary depending on the production methods and sources of biopolymers
Environmental Impact	-Typically have a higher environmental impact due to their toxicity, disposal issues, and potential harm to ecosystems	-Generally considered more environmentally friendly compared to inorganic inhibitors, but biodegradability and persistence in the environment should be considered	-ore sustainable and less harmful to the environment. They offer a greener alternative for corrosion inhibition.
Long-Term Stability	- Known for their long-term stability and durability in providing corrosion protection over extended periods.	-May require monitoring and replenishment over time to maintain effectiveness, as they can degrade or leach from the metal surface.	– Long-term stability can vary depending on the biopolymer and application conditions, requiring further study for reliable and consistent performance.

These results are consistent with earlier studies where phytochemical-rich extracts demonstrated strong surface adsorption, thereby reducing both anodic dissolution and cathodic hydrogen evolution (Satapathy, Gunasekaran, Sahoo, Amit, & Rodrigues, 2009; Victoria, Prasad, & Manivannan, 2015). Biomolecules such as amino acids and vitamins achieved

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

efficiencies between 70% and 85%, while biopolymers like chitosan provided consistent but moderate protection in chloride environments. Agricultural wastes, including rice husk and sugarcane bagasse extracts, also showed promising efficiencies in the range of 75% to 83%, supporting the case for their dual role in corrosion protection and waste valorization.

These results align with the experimental findings of Gerengi and Sahin (2011), who reported nearly 90% efficiency for *Schinopsis lorentzii* extract in 1 M HCl, and Ferreira, Giacomelli, Giacomelli, and Spinelli (2004), who demonstrated inhibition by L-ascorbic acid through anodic film formation. Collectively, these outcomes highlight that green inhibitors are not only effective but also versatile, offering protection in various environments and across multiple categories of natural substances.



Electrochemical studies reinforce the adsorption-based mechanism of green inhibitors. Potentiodynamic polarization curves indicate that many plant extracts act as mixed-type inhibitors, shifting both anodic and cathodic reaction kinetics (Satapathy et al., 2009). EIS measurements reveal increased charge transfer resistance in the presence of inhibitors, confirming the formation of a protective barrier film (Mansfeld, Kendig, & Tsai, 1982). SEM micrographs of inhibited steel surfaces consistently show smoother morphologies compared to uninhibited samples, indicating reduced pitting and localized attack (Gerengi & Sahin, 2011). FTIR spectra confirm the presence of phytochemical functional groups such as –OH, –C=O, and aromatic rings on the metal surface, providing direct evidence of adsorption (Ferreira et al., 2004).

In the case of biomolecules, amino acids such as cysteine exhibit strong chemisorption due to sulfur atoms, while tryptophan interacts through both nitrogen atoms and aromatic π-electrons. These interactions explain their efficiencies of 75%–82%. Polymers and biopolymers, such as polyaniline and chitosan, provide additional barrier effects by forming adherent films. Yi, Liu, Jin, and Feng (2013) reported inhibition efficiencies above 85% for polyaniline in hydrochloric acid, attributing performance to the conjugated backbone and redox-active nature of the polymer. Similarly, Umoren and Solomon (2014) highlighted that polymeric inhibitors can be engineered for improved adsorption by introducing functional side groups.

The comparative analysis of green inhibitors reveals distinct advantages and limitations.

- **Plant extracts** consistently deliver the highest efficiencies, sometimes exceeding 90%. Their strength lies in the synergistic action of multiple phytochemicals. However, variability in chemical composition due to seasonality, geography, and extraction methods poses challenges to reproducibility (Schmitt, 2009).
- **Biomolecules** provide moderate but reliable inhibition with well-understood mechanisms. Their reproducibility is advantageous for standardization, although efficiencies rarely surpass those of plant extracts.
- **Polymers and biopolymers** offer unique advantages in durability and film adherence. For example, Benabdellah et al. (2007) demonstrated vinyl-based polymers achieving strong protection in phosphoric acid, while Ates and Ozyılmaz (2015) showed that nanoparticle-modified polycarbazole enhanced corrosion resistance in saline media.
- **Agricultural wastes** represent an economical and sustainable option, often reaching efficiencies above 80% while valorizing residues like fruit peels and bagasse. However, like plant extracts, they face variability issues that hinder industrial consistency (Yaro, Khadom, & Wael, 2013).

This comparative evidence suggests that while plant extracts dominate in laboratory performance, polymers and hybrid systems may provide greater industrial feasibility due to stability and tunability.

The experimental results confirm that green inhibitors can match or even surpass conventional synthetic inhibitors under laboratory conditions. Unlike chromates and phosphates, which are restricted for toxicity, natural inhibitors are biodegradable, renewable, and safer for ecosystems (Singh & Bockris, 1996). Economically, many are derived from low-cost raw materials such

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

as agricultural residues, making them accessible in developing countries where corrosion-related costs are disproportionately high. Their performance in acidic solutions makes them especially suitable for pickling, acid cleaning, and petroleum applications, where harsh environments demand effective but non-toxic solutions.

Despite their successes, experimental findings also highlight critical limitations. Variability in results is one of the most consistent challenges. Satapathy et al. (2009) noted that efficiencies varied depending on extract concentration and preparation, while Ferreira et al. (2004) showed that even single compounds like ascorbic acid could exhibit concentration-dependent behavior. Schmitt (2009) emphasized that the lack of standardized testing protocols prevents meaningful comparison across studies. Furthermore, most experiments are short-term, often conducted under static conditions. Real service environments—such as pipelines with turbulent flow, marine exposure, or reinforced concrete pore solutions—remain underexplored. This gap between laboratory and field performance continues to limit industrial adoption.

Inhibitor Source	**Active Constituents**	**Test Medium**	**Concentration (ppm)**	**Efficiency (%)**	**Supporting Technique(s)**
Neem leaves (*Azadirachta indica*)	Flavonoids, terpenoids	HCl (1 M)	800	90–95	Gravimetric, Polarization, SEM
Guava leaves (*Psidium guajava*)	Tannins, flavonoids	H_3PO_4 (1 M)	600	85–90	EIS, FTIR, SEM
Orange peel extract	Ascorbic acid, flavonoids	HCl (1 M)	1000	80–85	Gravimetric, FTIR
Apricot juice extract	Organic acids, sugars	H_3PO_4 (1 M)	700	75–80	Polarization, SEM
L-ascorbic acid (Vit C)	Hydroxyl, lactone groups	HCl (1 M)	500	80–85	FTIR, Polarization
Cysteine (amino acid)	–SH, –NH_2 groups	HCl (0.5 M)	400	78–82	EIS, FTIR

Chitosan biopolymer	–OH, –NH_2 groups	NaCl (3.5%)	1000	70–75	Gravimetric, SEM
Rice husk extract	Silica, polyphenols	HCl (1 M)	800	78–85	Gravimetric, EIS
Sugarcane bagasse extract	Polyphenols, lignin	H_2SO_4 (1 M)	600	80–83	Gravimetric, Polarization

Scalability is another concern. While apricot juice or guava leaf extracts may show high efficiencies in laboratory tests, producing these at industrial scale with consistent composition remains difficult. Regulatory validation, life-cycle assessments, and ecotoxicological testing are also underdeveloped areas that must be addressed for broader acceptance (Kalaivani, Arasu, & Rajendran, 2013; Umoren & Solomon, 2014).

Experimental research increasingly points to hybrid systems as a pathway forward. Ates and Ozyılmaz (2015) demonstrated that ZnO nanoparticle–modified polycarbazole improved barrier properties, while Qiu, Liu, Jin, Fang, Xie, and Robertson (2017) showed that graphene oxide enhanced polyaniline's corrosion resistance through improved stability and conductivity. These findings indicate that combining natural extracts with polymers, nanoparticles, or benign inorganic salts can enhance stability, address variability, and extend protection. Computational studies further support these strategies by predicting binding affinities and guiding experimental design (Ju, Kai, & Li, 2008).

Future research should prioritize standardized protocols, long-term durability studies, and scaling experiments. Integrating waste valorization with inhibitor production and adopting machine learning for molecular screening are also promising directions.

Overall, the experimental evidence demonstrates that green inhibitors are effective, versatile, and eco-friendly solutions for corrosion protection of iron and steel. Plant extracts deliver high efficiencies but face reproducibility challenges, biomolecules offer mechanistic clarity with moderate performance, and polymers provide durable and tunable options. Agricultural wastes add economic and environmental value but require standardization. Hybrid approaches that combine these categories hold the greatest promise for bridging laboratory success with industrial application. By addressing challenges of variability, standardization, and long-term stability, green inhibitors can move from experimental validation to large-scale adoption, advancing sustainable corrosion science.

Conclusion

The experimental study confirms that green inhibitors represent a practical and effective approach to mitigating the corrosion of iron and its alloys. Plant extracts such as neem, guava, and orange peel demonstrated inhibition efficiencies above 85% in acidic environments, largely due to the synergistic action of phytochemicals including flavonoids, tannins, and polyphenols. Biomolecules such as L-ascorbic acid and cysteine exhibited efficiencies between 70% and 85%, offering mechanistic clarity and reproducibility. Agricultural residues like rice husk and sugarcane bagasse extracts proved valuable in providing moderate to high inhibition while contributing to waste valorization. Electrochemical techniques confirmed that most green inhibitors act as mixed-type inhibitors, while SEM and FTIR analyses provided direct evidence of protective film formation and adsorption of active functional groups.

Despite their high efficiency in laboratory settings, challenges remain regarding variability in natural composition, dependence on extraction methods, and limited data on long-term stability under complex industrial conditions. The results underscore the need for standardized testing methodologies, durability assessments, and large-scale validation. Hybrid approaches—such as combining natural extracts with polymers, nanoparticles, or benign salts—show promise in enhancing film stability and addressing reproducibility issues.

In conclusion, this study provides robust experimental evidence that green inhibitors can serve as eco-friendly alternatives to synthetic inhibitors in corrosion control. Their biodegradability, abundance, and cost-effectiveness make them suitable for sustainable materials protection strategies. However, industrial adoption will require further research integrating experimental validation with computational modeling, life-cycle analysis, and field-scale trials. By bridging these gaps, green inhibitors have the potential to move beyond laboratory success and become reliable, scalable solutions for corrosion protection of iron and iron alloys.

References

Ates, M., & Ozyılmaz, A. T. (2015). The application of polycarbazole, polycarbazole/nanoclay and polycarbazole/Zn-nanoparticles as a corrosion inhibition for SS 304 in saltwater. *Progress in Organic Coatings, 84,* 50–58.

Benabdellah, M., Ousslim, A., Hammouti, B., Elidrissi, A., Aouniti, A., Dafali, A., Bekkouch, K., & Benkaddour, M. (2007). The effect of poly(vinyl caprolactone-co-vinyl pyridine) and poly(vinyl imidazol-co-vinyl pyridine) on the corrosion of steel in H_3PO_4 media. *Journal of Applied Electrochemistry, 37*(7), 819–826.

De Leon, A. C. C., Pernites, R. B., & Advincula, R. C. (2012). Superhydrophobic colloidally textured polythiophene film as superior anticorrosion coating. *ACS Applied Materials & Interfaces, 4*(6), 3169–3176.

Ferreira, E. S., Giacomelli, C., Giacomelli, F. C., & Spinelli, A. (2004). Evaluation of the inhibitor effect of L-ascorbic acid on the corrosion of mild steel. *Materials Chemistry and Physics, 83*(1), 129–134.

Fontana, M. G. (2015). *Corrosion engineering* (3rd ed.). McGraw-Hill.

Gerengi, H., & Sahin, H. I. (2011). *Schinopsis lorentzii* extract as a green corrosion inhibitor for low carbon steel in 1 M HCl solution. *Industrial & Engineering Chemistry Research, 51*(2), 780–787.

Ju, H., Kai, Z. P., & Li, Y. (2008). Aminic nitrogen-bearing polydentate Schiff base compounds as corrosion inhibitors for iron in acidic media: A quantum chemical calculation. *Corrosion Science, 50*(3), 865–871.

Kalaivani, R., Arasu, P. T., & Rajendran, S. (2013). Corrosion inhibition by polymers–A bird's eyeview. *European Chemical Bulletin, 2*(10), 807–815.

Mansfeld, F., Kendig, M. W., & Tsai, S. (1982). Recording and analysis of AC impedance data for corrosion studies. *Corrosion, 38*(11), 570–580.

Roberge, P. R. (2000). *Handbook of corrosion engineering*. McGraw-Hill.

Satapathy, A. K., Gunasekaran, G., Sahoo, S. C., Amit, K., & Rodrigues, P. V. (2009). Corrosion inhibition by *Justicia gendarussa* plant extract in hydrochloric acid solution. *Corrosion Science, 51*(12), 2848–2856.

Schmitt, G. (2009). Global needs for knowledge dissemination, research, and development in materials deterioration and corrosion control. *World Corrosion Organization, 38,* 1–48.

Singh, W. P., & Bockris, J. O. (1996). Toxicity issues of organic corrosion inhibitors: Applications of QSAR model. In *Corrosion 96*. NACE International.

Umoren, S. A., & Solomon, M. M. (2014). Recent developments on the use of polymers as corrosion inhibitors–A review. *The Open Materials Science Journal, 8*(1).

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Victoria, S. N., Prasad, R., & Manivannan, R. (2015). *Psidium guajava* leaf extract as green corrosion inhibitor for mild steel in phosphoric acid. *International Journal of Electrochemical Science, 10,* 2220–2238.

Yaro, A. S., Khadom, A. A., & Wael, R. K. (2013). Apricot juice as green corrosion inhibitor of mild steel in phosphoric acid. *Alexandria Engineering Journal, 52*(1), 129–135.

Yi, Y., Liu, G., Jin, Z., & Feng, D. (2013). The use of conducting polyaniline as corrosion inhibitor for mild steel in hydrochloric acid. *International Journal of Electrochemical Science, 8,* 3540–3550.