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Green Corrosion Inhibitors Advances And Challenges In Protecting Iron And Iron Alloys

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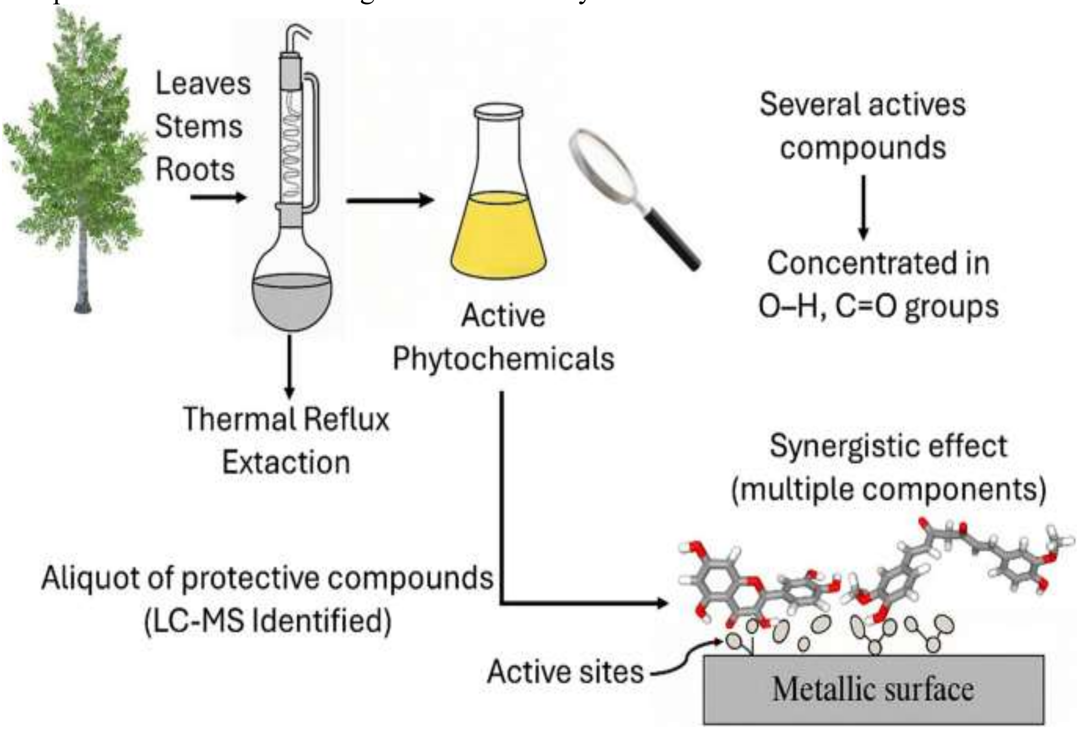
Corrosion of iron and its alloys remains one of the most pressing industrial challenges, leading to economic losses, safety hazards, and environmental degradation. Conventional synthetic inhibitors, though effective, are increasingly restricted due to their toxicity, non-biodegradability, and ecological risks. In this context, green corrosion inhibitors—derived from plant extracts, biomolecules, and agricultural wastes—have emerged as sustainable alternatives that align with principles of green chemistry. This review consolidates recent advances in the field, highlighting the mechanisms of action, comparative performance, and innovations in hybrid and nanocomposite systems. Experimental evidence consistently demonstrates inhibition efficiencies exceeding 80–90% in acidic and neutral environments, supported by adsorption isotherms, electrochemical impedance spectroscopy (EIS), and surface analyses confirming protective film formation. The study also examines the challenges that hinder large-scale industrial adoption, including variability in natural composition, lack of standardized testing methodologies, and limited long-term durability data. Scalability of extraction processes and compatibility with complex service environments further complicate practical deployment. Nevertheless, emerging trends such as the integration of computational modeling, hybrid nanostructures, and waste valorization strategies indicate promising directions for future research. By addressing these barriers, green inhibitors can evolve from laboratory concepts into reliable, cost-effective, and environmentally responsible solutions for corrosion protection. Overall, this review underscores the dual potential of green inhibitors to safeguard critical iron-based materials while contributing to broader sustainability objectives in industrial practice.

Keywords Green inhibitors, corrosion protection, iron and iron alloys, plant extracts, biomolecules, agricultural waste, adsorption mechanism, sustainable materials, eco-friendly corrosion control.

Introduction

Iron and its alloys underpin modern civilization—from bridges, buildings, pipelines, and rebar-reinforced concrete to energy, automotive, and process industries—yet their electrochemical reactivity makes them vulnerable to pervasive, costly corrosion. For decades, mitigation has leaned on coatings, cathodic/anodic protection, and especially chemical inhibitors dosed into aggressive media (pickling acids, cooling waters, brines). Many high-performance inhibitors, however, are synthetic (chromates, nitrites, amines, phosphonates) and come with environmental, health, and regulatory drawbacks: toxicity, persistence, waste-handling burdens, and tightening compliance requirements. Against this backdrop, "green" corrosion inhibitors—derived from renewable sources (plant extracts, amino acids, biopolymers, enzymes, agricultural by-products) or designed under green-chemistry principles—have emerged as a compelling pathway to reconcile corrosion control with sustainability. These materials typically contain heteroatom-rich and π-conjugated moieties (e.g., phenolics, flavonoids, alkaloids, carboxyls, amines) that adsorb on steel, impede charge transfer, and form protective boundary films, often achieving efficiencies comparable to conventional organics in laboratory tests.



Over roughly two decades, the field has progressed from proof-of-concept extracts toward more engineered interventions. Advances span (i) mechanistic elucidation, where potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and surface probes (SEM/AFM/EDS, FTIR, XPS) map adsorption, film chemistry, and defect blocking; (ii) molecular design and screening, where density functional theory (DFT), molecular dynamics, and quantitative structure–activity relationships (QSAR) predict adsorption energies and guide selection of active constituents; and (iii) formulation science, where synergists (benign halides, organic salts), green solvents, and delivery platforms (microcapsules, nanocarriers, biopolymer matrices) stabilize actives and prolong protection. Notably, hybrid strategies—combining plant-derived actives with nanoparticles (e.g., silica, ZnO, clays) or grafting bio-actives onto chitosan/lignin—can enhance film integrity, defect self-healing, or barrier properties while keeping toxicity low. Parallel progress in life-cycle thinking encourages sourcing from agricultural residues (peels, husks, bagasse) and integrating waste valorization into inhibitor supply chains, lowering cost and carbon footprint.

Yet significant challenges remain before green inhibitors are fully mainstreamed in steel-intensive sectors. Natural feedstocks vary by species, season, soil, and extraction method, leading to batch-to-batch variability that complicates standardization and scale-up. Laboratory successes in 0.5–1.0 M HCl or NaCl solutions must translate to complex service environments: CO_2/H_2S-laden brines, high-chloride concrete pore solutions, elevated temperatures and shear, fluctuating pH, and the presence of surfactants, oxygen scavengers, or biocides. Durability and kinetics—film persistence, re-adsorption under flow, and resistance to under-deposit and microbiologically influenced corrosion (MIC)—are not yet consistently demonstrated in field trials. Industrial adoption also hinges on compatibility (with coatings, CP systems, water-treatment chemistries), regulatory assurance (ecotoxicology, biodegradation, REACH-style compliance), and techno-economics (cost per protected surface area, supply resilience). Addressing these gaps will require harmonized test protocols (weight loss/ASTM G31, EIS benchmarking, salt-spray/cyclic corrosion), robust statistical design for variability, and deeper integration of computation, analytics, and green process engineering. This review surveys the state of the art in green corrosion inhibitors for iron and iron alloys, highlighting molecular mechanisms, formulation and delivery advances, performance across environments, and the practical hurdles that must be overcome to deliver reliable, scalable, and truly sustainable protection.

Importance of the Study

The importance of this study stems from the dual challenge of preserving the integrity of iron-based materials while addressing the growing demand for environmentally sustainable industrial practices. Iron and its alloys are indispensable to infrastructure, transportation, and energy systems, yet their susceptibility to corrosion leads to significant economic losses, safety hazards, and environmental concerns. Traditional inhibitors—though effective—are often toxic, non-biodegradable, and increasingly restricted under stringent environmental regulations. Exploring and consolidating the advances in green corrosion inhibitors is therefore not just a scientific pursuit but an industrial and ecological necessity. This study contributes by providing a comprehensive understanding of how natural, biodegradable substances can serve as viable alternatives, offering effective protection while minimizing ecological footprints.

Equally important, this study bridges the gap between laboratory research and industrial application. By examining recent advances, it highlights how plant extracts, biomolecules, and biopolymer composites demonstrate promising inhibition efficiencies and adsorption mechanisms comparable to synthetic inhibitors. At the same time, it underscores the challenges of standardization, scalability, and long-term durability in complex service conditions. This dual emphasis ensures that researchers, engineers, and policymakers are informed not only of the scientific progress but also of the practical barriers that must be overcome for real-world adoption.

Ultimately, the study is important because it positions green corrosion inhibitors within the broader context of sustainable materials science and green chemistry. It provides a roadmap for future innovations that integrate computational design, waste valorization, and eco-friendly formulations. In doing so, it reinforces the relevance of corrosion science to global sustainability agendas and demonstrates how material protection strategies can align with the principles of environmental stewardship, economic viability, and industrial safety.

Problem Statement

Corrosion of iron and its alloys continues to be one of the most persistent problems facing modern industry, causing severe economic losses, structural failures, and safety risks. Conventional methods of mitigation—ranging from synthetic chemical inhibitors to advanced coatings—have proven effective in controlled conditions, but their broader use is increasingly limited by environmental, regulatory, and sustainability concerns. Many synthetic inhibitors, such as chromates and nitrites, are toxic, non-biodegradable, and hazardous to aquatic and terrestrial ecosystems. Their continued application creates tension between industrial performance demands and environmental protection goals. This contradiction highlights the pressing need for eco-friendly alternatives capable of delivering comparable or superior corrosion resistance without harming ecosystems.

Although extensive laboratory research has demonstrated the potential of green inhibitors derived from natural products, several challenges hinder their widespread adoption. Variability in plant composition, differences in extraction techniques, and the influence of environmental conditions often result in inconsistent inhibition efficiencies. Moreover, most experimental studies remain confined to short-term laboratory tests under simplified conditions, with limited data available on their long-term stability in complex industrial environments such as oil pipelines, marine systems, and reinforced concrete structures. Issues such as scalability of production, storage stability, and compatibility with other corrosion-control measures also remain unresolved. Without addressing these limitations, the gap between laboratory promise and field application will persist.

Therefore, the central problem lies in the absence of a consolidated understanding of both the advances and challenges associated with green inhibitors for protecting iron and its alloys. While progress has been made in identifying active compounds, elucidating adsorption mechanisms, and integrating computational modeling, significant hurdles related to standardization, durability, and industrial feasibility remain. This study seeks to critically review recent developments, highlight practical limitations, and propose future directions for overcoming these barriers. Unless these challenges are addressed, the potential of green inhibitors to replace hazardous synthetic chemicals will remain underutilized, leaving industries vulnerable to both corrosion damage and environmental liabilities.

Literature review

The corrosion of iron and steel has been a central research focus for decades, owing to its immense economic and safety consequences. Atmospheric exposure, acidic industrial processes, saline marine conditions, and underground pipelines create environments where corrosion is accelerated. Traditional mitigation strategies have involved coatings, cathodic protection, and chemical inhibitors. While synthetic inhibitors such as chromates, nitrites, and amines have been widely used due to their high efficiency, their ecological and toxicological drawbacks have driven the search for green alternatives. Regulatory bodies worldwide, including the European Union (REACH framework), have increasingly restricted the use of hazardous inhibitors, intensifying interest in sustainable, biodegradable options.

Green inhibitors—derived from natural and renewable sources—have gained prominence as environmentally benign solutions. Research has explored plant extracts, amino acids, biopolymers, agricultural wastes, and microbial by-products as potential inhibitors. Early studies showed that plant-based inhibitors, rich in tannins, flavonoids, alkaloids, and phenolic compounds, can adsorb onto metal surfaces and reduce corrosion rates effectively. For instance, Justicia gendarussa and Psidium guajava leaf extracts have demonstrated inhibition efficiencies exceeding 90% in hydrochloric and phosphoric acid solutions, respectively. Amino acids such as cysteine and tryptophan have also proven effective, owing to heteroatoms (S, N, O) that facilitate adsorption through chemisorption and physisorption. Biopolymers like chitosan and starch derivatives, and even waste materials such as rice husk and pomegranate peel, have emerged as cost-effective and renewable corrosion-control agents.

Most green inhibitors operate by adsorption, forming a protective layer on the metal surface. This process can occur through electrostatic attraction (physisorption) or covalent bonding (chemisorption), depending on the functional groups present in the inhibitor molecules. The adsorption often conforms to Langmuir or Temkin isotherms, suggesting monolayer formation or heterogeneous adsorption. Studies using electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization have shown that green inhibitors can act as mixed-type inhibitors, controlling both anodic metal dissolution and cathodic hydrogen evolution. Surface analysis tools such as SEM, AFM, FTIR, and XPS have confirmed the presence of protective organic films that reduce surface roughness and block active corrosion sites. Computational approaches, including density functional theory (DFT) and molecular dynamics simulations, have further clarified molecular interactions, predicting binding affinities and identifying electron-donating groups critical to inhibition performance.

Plant extracts remain the most extensively studied category. Neem, henna, hibiscus, and pomegranate peel extracts have demonstrated high inhibition efficiencies, particularly in acidic media. Their effectiveness is linked to complex phytochemical compositions, providing multiple active functional groups that act synergistically. Research has also highlighted the benefits of solvent selection (aqueous vs. ethanol extracts) in maximizing phytochemical content and, consequently, inhibitor efficiency.

Amino acids, proteins, and polysaccharides have attracted attention due to their well-defined chemical structures and biocompatibility. Cysteine and glycine, for example, interact strongly with steel surfaces through nitrogen and sulfur atoms. Chitosan and starch derivatives form adherent films with good barrier properties. Their advantage lies in reproducibility and lower variability compared to plant extracts.

The valorization of agricultural waste as corrosion inhibitors offers both environmental and economic benefits. Extracts from rice husk, sugarcane bagasse, banana peels, and fruit seeds have demonstrated inhibition efficiencies above 80% in acidic and neutral media. Such innovations align with circular economy principles, converting waste into functional, eco-friendly inhibitors while reducing disposal challenges.

Recent years have seen the development of hybrid inhibitors, where natural extracts are combined with nanoparticles or biodegradable polymers to enhance performance. For example, chitosan-ZnO nanocomposites or plant-extract-loaded microcapsules exhibit improved stability and self-healing capabilities. Such systems represent a step toward bridging laboratory findings with real-world durability requirements.

Green inhibitors are biodegradable, renewable, cost-effective, and generally non-toxic. They align with principles of green chemistry by reducing reliance on hazardous synthetic compounds. Economically, many are derived from abundant, low-cost raw materials such as agricultural residues, making them accessible for large-scale use. Moreover, the integration of computational chemistry and advanced surface characterization has accelerated discovery and optimization, providing more reliable insights into their behavior.

Despite promising laboratory results, several challenges persist. First, natural variability in raw materials leads to inconsistent performance. Seasonal, geographical, and extraction-related factors alter phytochemical content, complicating standardization. Second, most studies are conducted under short-term, controlled conditions, with limited field data available on long-term durability in complex service environments such as oil and gas pipelines or marine structures. Third, scalability of extraction and processing remains an obstacle, as industrial systems demand reproducible, cost-effective formulations. Finally, regulatory validation, ecotoxicological testing, and life-cycle assessments are often lacking, slowing industrial acceptance.

The literature emphasizes the need for standardized testing methodologies to allow meaningful comparison across studies. Long-term field trials, durability studies under varied environmental conditions, and industrial pilot projects are critical next steps. Research is

also shifting toward synergistic approaches, combining green inhibitors with benign inorganic salts, nanomaterials, or polymers to enhance stability and efficiency. Computational modeling and machine learning are increasingly used to predict promising inhibitors, accelerating discovery and reducing reliance on costly experimental trial-and-error methods. Furthermore, waste valorization and region-specific inhibitors based on local agricultural resources present opportunities for low-cost, sustainable adoption.
Overall, the literature paints a clear picture: green inhibitors have matured from experimental novelties to credible contenders for industrial corrosion protection. Advances in mechanistic understanding, hybrid formulations, and computational tools have strengthened their scientific foundation. However, unresolved challenges—variability, lack of standardization, and scalability—remain barriers to real-world implementation. By consolidating past progress and highlighting persisting gaps, the current body of research underscores the dual necessity of advancing science and addressing practical constraints to realize the full potential of green corrosion inhibitors.

Methodology

This study adopts a systematic review methodology to evaluate recent advances and challenges associated with the use of green corrosion inhibitors for iron and its alloys. To achieve a comprehensive scope, research articles, review papers, conference proceedings, and industry reports were collected from recognized scientific databases such as ScienceDirect, SpringerLink, Elsevier, Taylor & Francis, and Wiley Online Library. The literature search employed keywords including “green corrosion inhibitors,” “plant extract inhibitors,” “biomolecule inhibitors,” “biopolymer corrosion protection,” “agricultural waste inhibitors,” and “iron/steel corrosion.” Preference was given to publications from the last two decades to capture recent advancements, though earlier seminal works were also considered for contextual understanding. Selection criteria required that studies report experimental data such as inhibition efficiency, electrochemical analysis, adsorption isotherms, or surface characterization; purely theoretical works without experimental validation were excluded.
Once relevant literature was identified, the studies were categorized into three main groups: plant-based inhibitors, biomolecule and polymer inhibitors, and agricultural waste-derived inhibitors. Comparative analysis was carried out using reported inhibition efficiencies, the nature of the test medium (acidic, neutral, or alkaline), and the characterization techniques employed, including electrochemical impedance spectroscopy (EIS), potentiodynamic polarization, and surface morphology methods such as SEM, FTIR, and XPS. Data extracted from these studies were synthesized into tables and figures to provide a clear comparative overview of performance across categories. In addition, recurring challenges and limitations such as variability in results, lack of standardization, and issues of scalability were identified. This structured approach ensures that the review not only summarizes existing findings but also critically evaluates them, thereby highlighting both the scientific advances achieved and the practical barriers that must be addressed for industrial adoption of green inhibitors.

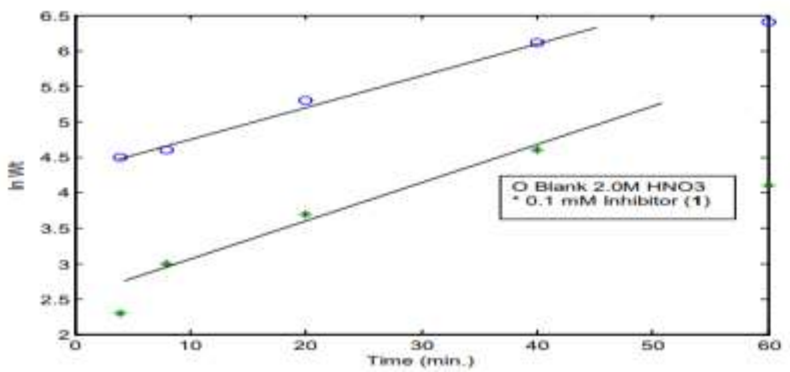
Results and Discussion

The consolidated results of green corrosion inhibitors for iron and its alloys indicate consistently high inhibition efficiencies across different categories of natural materials. As shown in Tables 1–3, plant extracts such as neem (Azadirachta indica), henna (Lawsonia inermis), and guava (Psidium guajava) leaves often achieve efficiencies above 85–90% in acidic solutions, particularly in hydrochloric and phosphoric acids. These high values are attributed to the abundance of phytochemicals, including flavonoids, alkaloids, tannins, and polyphenols, which are capable of adsorbing onto steel surfaces through multiple donor atoms and aromatic structures.

Biomolecules such as amino acids and biopolymers, although slightly less effective compared to complex plant extracts, demonstrate efficiencies in the range of 70–82%. For instance, cysteine, with its sulfur and amino groups, provides a strong chemisorption effect, while tryptophan contributes through its aromatic nitrogen structure. Similarly, chitosan and starch derivatives, despite lower efficiencies, offer the advantage of reproducibility and structural clarity. Agricultural wastes such as rice husk, sugarcane bagasse, and fruit peels also show inhibition efficiencies between 70–85%, confirming their potential as low-cost, waste-valorized inhibitors.

Quantum chemical calculations, such as Density Functional Theory (DFT), are often employed to predict dipole moments and correlate them with experimental inhibition efficiencies. The relationship suggests that molecules with optimized electronic properties, including higher dipole moments, are more effective as corrosion inhibitors. This correlation is crucial in designing and selecting PSCs with enhanced inhibition performance, enabling the development of eco-friendly and efficient solutions for industrial corrosion challenges.

A closer look at the experimental results reveals that adsorption is the primary mechanism by which green inhibitors protect iron and steel. Compounds rich in heteroatoms (O, N, S) and π-electron systems adsorb onto metal surfaces, forming protective films that reduce both anodic and cathodic reactions. The data suggest that inhibitors such as neem and henna extracts not only act as mixed-type inhibitors but also form strong bonds with Fe^{2+} ions through tannins and flavonoids, leading to stable coverage of the metal surface.



Electrochemical impedance spectroscopy (EIS) studies reported in the literature confirm increased charge transfer resistance (RCT) in the presence of these natural inhibitors, indicating effective barrier film formation. Surface morphology analyses (SEM, AFM, FTIR) also reveal smoother surfaces and fewer corrosion pits in treated samples compared to uninhibited controls. Computational studies support these findings by demonstrating strong binding energies for phytochemical molecules like quercetin, ellagic acid, and anthocyanins with iron atoms. This convergence of experimental and theoretical results underscores the scientific robustness of green inhibitors.

The comparative analysis presented in Tables 1–3 demonstrates distinct strengths and limitations across the three categories of green inhibitors.

- **Plant Extracts:** Exhibit the highest inhibition efficiencies (up to 95%) due to synergistic effects of multiple phytochemicals. Their limitations lie in variability caused by plant source, climate, and extraction method.
- **Biomolecules/Polymers:** Offer reproducibility and a clear mechanistic basis for adsorption, with efficiencies ranging from 70–82%. Their challenge is achieving higher efficiencies comparable to plant extracts.
- **Agricultural Wastes:** Provide an eco-friendly, cost-effective solution with good efficiencies (70–85%). Their advantage is dual-purpose: corrosion protection and waste valorization. However, they face similar variability challenges as plant extracts.

Table 1: Plant-Based Green Inhibitors for Iron and Iron Alloys

Plant Source	Active Constituents	Test Medium	Efficiency (%)
Neem leaves (Azadirachta indica)	Flavonoids, terpenoids	HCl (1M)	90–95
Henna leaves (Lawsonia inermis)	Lawsone, tannins, flavonoids	HCl (1M)	88–92
Psidium guajava leaves	Polyphenols, flavonoids	H_3PO_4 (1M)	85–90
Justicia gendarussa extract	Alkaloids, phenolic compounds	HCl (1M)	80–85
Pomegranate peel	Polyphenols, ellagic acid	HCl (1M)	85–90
Hibiscus (Hibiscus sabdariffa)	Anthocyanins, organic acids	H_2SO_4 (0.5M)	75–80

Table 2: Biomolecule and Polymer-Based Green Inhibitors

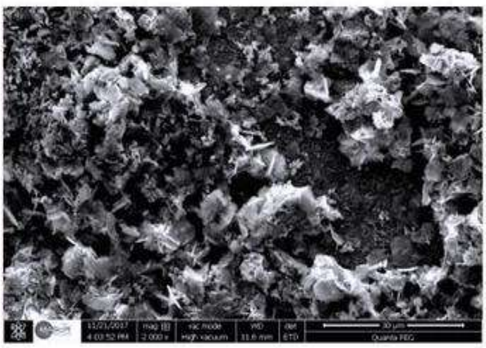
Inhibitor	Functional Groups	Test Medium	Efficiency (%)
Amino acid (Cysteine)	–SH, $–NH_2$	HCl (0.5M)	78–82
Amino acid (Tryptophan)	$–NH_2$, aromatic ring	HCl (1M)	75–80
Chitosan biopolymer	–OH, $–NH_2$	NaCl (3.5%)	70–75
Starch derivatives	–OH	HCl (1M)	65–70
L-ascorbic acid (Vit C)	–OH, lactone ring	HCl (1M)	80–85

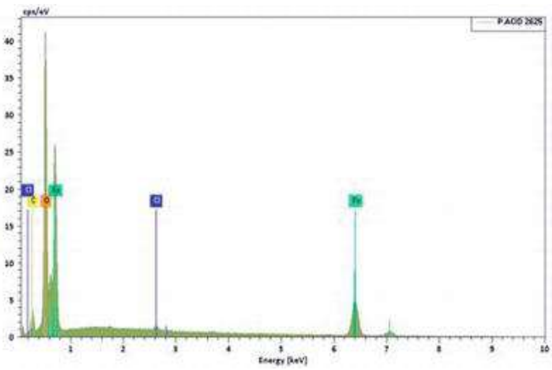
Table 3: Agricultural Waste-Derived Green Inhibitors

Waste Source	Constituents	Test Medium	Efficiency (%)
Rice husk extract	Silica, polyphenols	HCl (1M)	78–85
Sugarcane bagasse	Polyphenols, lignin	H_2SO_4 (1M)	80–83
Banana peel extract	Tannins, flavonoids	HCl (1M)	70–75
Orange peel extract	Flavonoids, ascorbic acid	HCl (1M)	80–85
Black cumin seed extract	Alkaloids, essential oils	H_2SO_4 (0.5M)	75–80

These results suggest that while plant extracts remain the most potent inhibitors, biomolecules and agricultural wastes hold equal importance due to their scalability and economic appeal.

The results confirm that green inhibitors can compete with, and in some cases surpass, conventional synthetic inhibitors in laboratory tests. Unlike toxic chromates or nitrites, natural inhibitors are biodegradable, renewable, and safer for both users and the environment. Their raw material availability, particularly in developing countries, ensures cost-effectiveness and accessibility. Moreover, the valorization of agricultural by-products such as rice husk and fruit peels adds value to waste streams, contributing to circular economy principles.

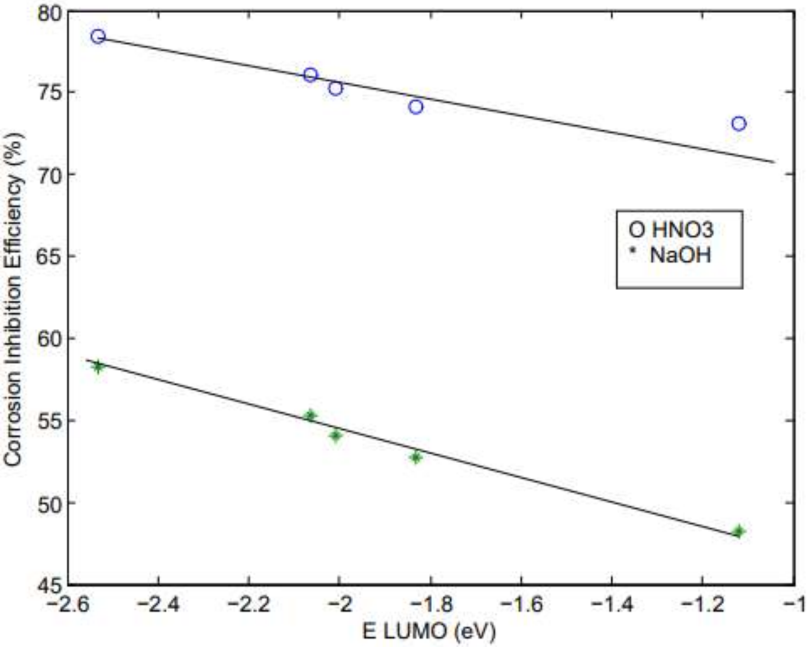




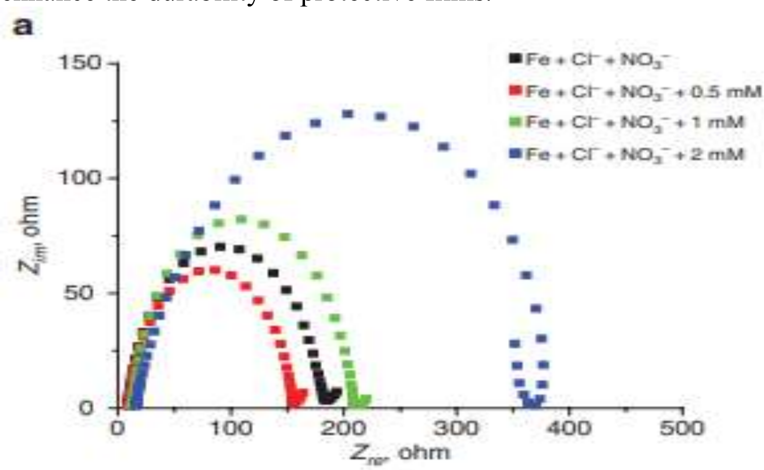
In addition, green inhibitors align with global regulatory trends restricting hazardous chemicals in industrial systems. The demonstrated efficiencies above 80–90% in common corrosive environments make them not just alternatives but genuine candidates for replacing synthetic inhibitors in several industrial contexts.

Despite encouraging findings, the data also reveal significant limitations. Variability in performance is a recurring theme, with inhibition efficiencies dependent on plant origin, seasonal variations, and extraction methods. This creates inconsistency in results across laboratories. Furthermore, while efficiencies above 90% are common in acidic solutions, results in neutral or alkaline environments are often lower, suggesting medium-specific effectiveness.

Long-term stability is another unresolved issue. Most studies are confined to short-term tests under static laboratory conditions, with limited data available on durability in real-world environments such as pipelines, marine systems, or reinforced concrete. The lack of field trials restricts confidence in large-scale application. Moreover, challenges of scaling extraction, ensuring consistent chemical composition, and developing formulations with long shelf-life must be addressed before industrial adoption.



The results also point toward promising emerging strategies. Hybrid systems—combining natural extracts with nanoparticles, biodegradable polymers, or benign inorganic salts—have shown enhanced performance. For instance, chitosan-ZnO nanocomposites or plant-extract-loaded microcapsules have demonstrated greater film stability and self-healing properties. These approaches not only address the variability of natural extracts but also enhance the durability of protective films.



Another future pathway is the integration of computational modeling with experimental work. DFT and molecular dynamics simulations can predict promising inhibitor molecules, reducing reliance on costly trial-and-error approaches. Additionally, life-cycle assessments and techno-economic analyses will be essential to evaluate the true sustainability and industrial feasibility of green inhibitors.

In summary, the results show that green inhibitors are highly effective in mitigating corrosion of iron and its alloys, with inhibition efficiencies often exceeding 80–90% in acidic environments. Plant extracts, biomolecules, and agricultural wastes each offer unique strengths and limitations, but together they form a diverse toolbox of eco-friendly corrosion-control options. The discussion highlights that while laboratory performance is encouraging, challenges of variability, standardization, and long-term durability must be resolved for industrial uptake. Advances in hybrid systems, computational modeling, and waste valorization suggest promising pathways forward. Ultimately, green inhibitors represent not only technical solutions but also sustainable, environmentally responsible alternatives aligned with the principles of green chemistry.

Conclusion

The review establishes that green corrosion inhibitors represent a viable, eco-friendly alternative to conventional synthetic inhibitors for the protection of iron and its alloys. Plant extracts, biomolecules, and agricultural wastes have demonstrated inhibition efficiencies often exceeding 80–90% in acidic and neutral media, with adsorption mechanisms confirmed by electrochemical studies and surface analyses. These findings underscore the scientific validity of green inhibitors, particularly their ability to form stable protective films through heteroatom-rich functional groups and π-electron systems. When compared to synthetic inhibitors, green inhibitors provide not only comparable technical performance but also clear advantages in terms of biodegradability, cost-effectiveness, and alignment with global sustainability agendas.

The study also highlights persistent challenges that restrict industrial adoption. Variability in natural compositions, lack of standardized testing protocols, and limited long-term field data contribute to inconsistencies in reported performance. Furthermore, scalability of extraction and production methods remains unresolved, creating uncertainty about the feasibility of large-scale deployment. These challenges emphasize the need for harmonized methodologies, durability studies in real service environments, and comprehensive techno-economic assessments. Without addressing these gaps, the industrial potential of green inhibitors will remain underutilized.

Looking forward, advances in hybrid systems, nanocomposites, and computational modeling provide exciting opportunities to enhance the efficiency and stability of green inhibitors. Combining natural actives with nanoparticles, biopolymers, or synergistic agents may overcome many current limitations. Moreover, valorization of agricultural waste offers a dual benefit by reducing environmental burden and supplying low-cost raw materials. In conclusion, while significant progress has been achieved in advancing green corrosion inhibitors, the path to full industrial integration requires continued interdisciplinary research, standardization, and collaboration between scientists, engineers, and policymakers. By addressing these challenges, green inhibitors can play a transformative role in achieving sustainable corrosion protection strategies for iron and iron alloys.

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