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A comprehensive review on green inhibitors for corrosion protection of iron and iron alloys

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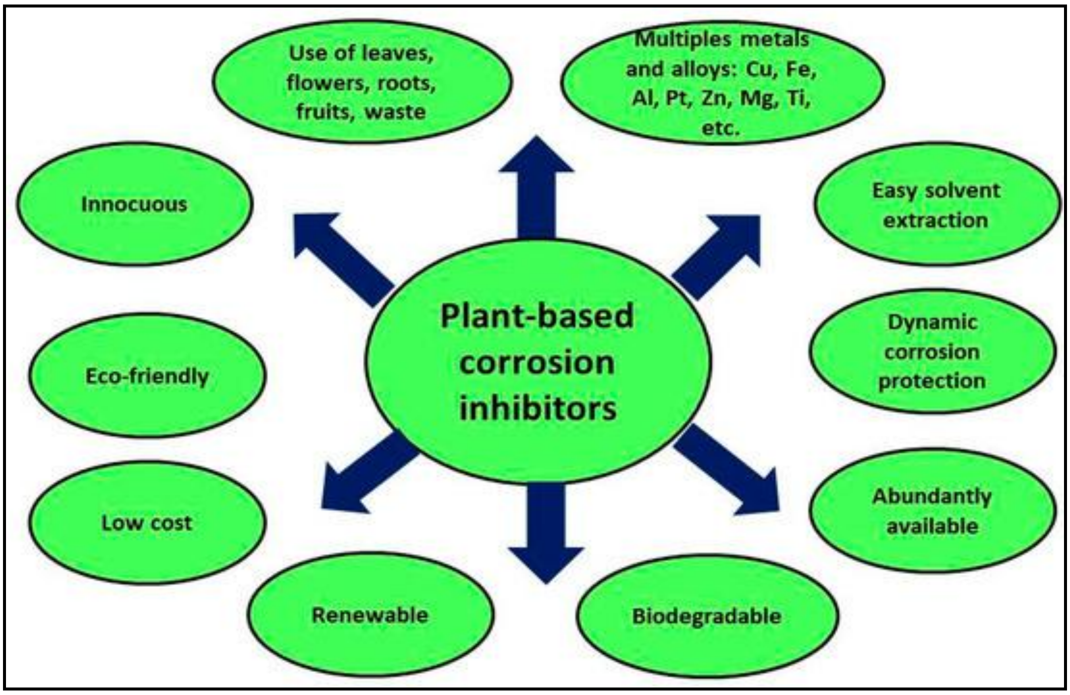
Abstract
Corrosion of iron and its alloys remains one of the most critical challenges in industrial, infrastructural, and environmental contexts. Conventional synthetic inhibitors, although widely used, present significant drawbacks due to their toxicity, high costs, and ecological risks, necessitating the exploration of sustainable alternatives. In recent years, green inhibitors—derived from plant extracts, biomolecules, and agricultural wastes—have emerged as effective and environmentally benign solutions. This review consolidates existing research on the mechanisms, efficiency, and applicability of natural corrosion inhibitors for iron and steel systems. Emphasis is placed on adsorption processes, protective film formation, and the influence of phytochemicals such as flavonoids, tannins, alkaloids, and amino acids. Reported inhibition efficiencies often exceed 80–90%, demonstrating strong potential for industrial application in acidic, neutral, and saline environments. The discussion further highlights the comparative advantages of green inhibitors over synthetic chemicals, including biodegradability, renewability, and alignment with sustainability principles. However, the review also identifies persistent challenges, such as variability in natural composition, limited stability under extreme conditions, and lack of standardized testing protocols. Advances in surface characterization, computational modeling, and synergistic formulations suggest promising pathways for optimizing the performance of green inhibitors. Overall, the findings affirm that green inhibitors offer not only a technical solution to corrosion but also contribute to global sustainability goals by promoting eco-friendly materials science. This review provides a critical foundation for future research and industrial adoption of green inhibitors in corrosion protection strategies.

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

Introductions

Corrosion has long been recognized as one of the most pressing industrial and environmental challenges, particularly for iron and its alloys, which are the backbone of infrastructure, construction, transportation, and countless engineering applications. The process of corrosion, primarily electrochemical in nature, leads to the gradual deterioration of metals when exposed to moisture, oxygen, and other aggressive species such as chlorides, sulfates, and acids. For iron and steel, corrosion manifests in the form of rust, which not only weakens structural integrity but also imposes significant economic burdens on maintenance, repair, and replacement. The World Corrosion Organization has repeatedly emphasized that corrosion accounts for a considerable percentage of global GDP losses annually, highlighting the urgent need for effective mitigation strategies. Conventional methods such as coatings, cathodic protection, and synthetic inhibitors have been employed extensively to combat corrosion; however, each comes with inherent limitations. Among these, chemical inhibitors—often organic or inorganic compounds—have been popular due to their ability to suppress corrosion by adsorbing onto the metal surface and forming a protective barrier. Yet, their widespread use has raised concerns about toxicity, non-biodegradability, and long-term ecological harm, thereby prompting a paradigm shift toward sustainable alternatives.

In recent decades, the pursuit of environmentally benign or "green" corrosion inhibitors has gained remarkable momentum as researchers strive to balance industrial performance with ecological safety. Green inhibitors, derived primarily from natural sources such as plant extracts, biomolecules, agricultural waste, and renewable organic compounds, offer a promising alternative to traditional inhibitors. Their effectiveness lies in the rich presence of alkaloids, tannins, flavonoids, amino acids, and other organic constituents, which facilitate



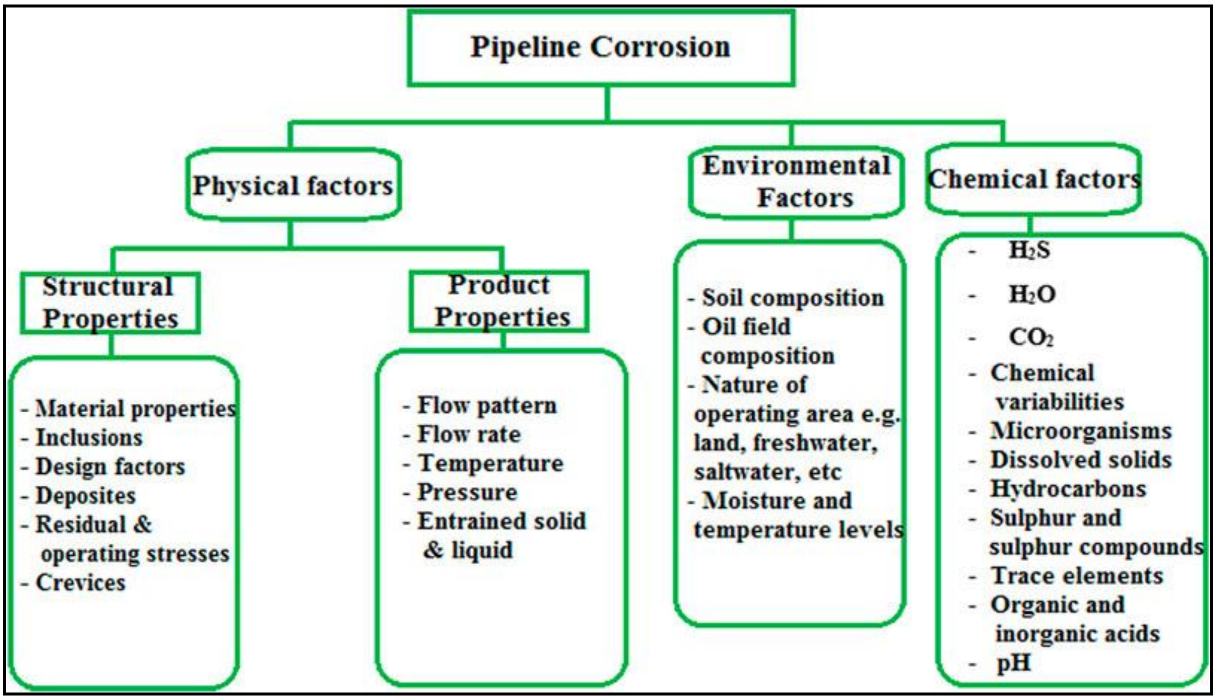
adsorption on metallic surfaces, thus hindering electrochemical reactions responsible for corrosion. Unlike synthetic inhibitors, these natural alternatives are biodegradable, cost-effective, renewable, and typically exhibit minimal or no toxicity. Furthermore, their use aligns with global efforts to minimize industrial pollution, adhere to stringent environmental regulations, and promote green chemistry principles. Research has demonstrated that plant-based inhibitors not only provide efficient corrosion resistance in various acidic, alkaline, and saline environments but also improve the overall surface morphology of metals, reducing pitting and localized attack. The increasing reliance on natural inhibitors is thus more than a technical innovation; it reflects a broader socio-environmental consciousness where sustainability becomes an integral factor in engineering decisions.

Despite the growing enthusiasm for green inhibitors, several critical aspects warrant comprehensive investigation before their large-scale industrial adoption. These include understanding the precise mechanisms of inhibition, optimizing extraction methods for active phytochemicals, standardizing concentration and dosage levels, and evaluating long-term stability under diverse environmental conditions. Moreover, the variability in plant species, geographical origins, and extraction techniques often leads to inconsistencies in inhibitor performance, making comparative studies and systematic reviews highly valuable. Advanced characterization techniques such as electrochemical impedance spectroscopy (EIS), potentiodynamic polarization, and surface analysis tools like SEM and FTIR have been instrumental in elucidating the interaction between inhibitor molecules and metal surfaces, yet more interdisciplinary approaches are needed to establish universal guidelines for practical applications. As industries worldwide seek to transition toward greener technologies, the integration of natural inhibitors in corrosion management represents a sustainable, scientifically rich, and economically viable pathway. This review, therefore, aims to consolidate existing knowledge, highlight significant breakthroughs, and identify future directions in the field of green inhibitors for the corrosion protection of iron and its alloys, ultimately contributing to the advancement of both material science and environmental stewardship.

Importance of the Study

The significance of this study lies in its ability to bridge the gap between effective corrosion protection and the urgent need for environmental sustainability. Iron and its alloys, being the most widely used engineering materials, are highly vulnerable to corrosion, leading to enormous economic and safety concerns worldwide. Traditional corrosion inhibitors, though effective, are often synthetic in origin and associated with toxicological risks, high costs of disposal, and environmental hazards. Their non-biodegradable nature poses long-term threats to ecosystems and public health. In this context, a comprehensive review of green inhibitors is critical, as it consolidates scattered research findings and provides clarity on how naturally derived compounds can effectively replace harmful synthetic inhibitors. This study is important because it highlights not just the technical feasibility of green inhibitors, but also their role in aligning industrial practices with the principles of green chemistry and sustainable development.

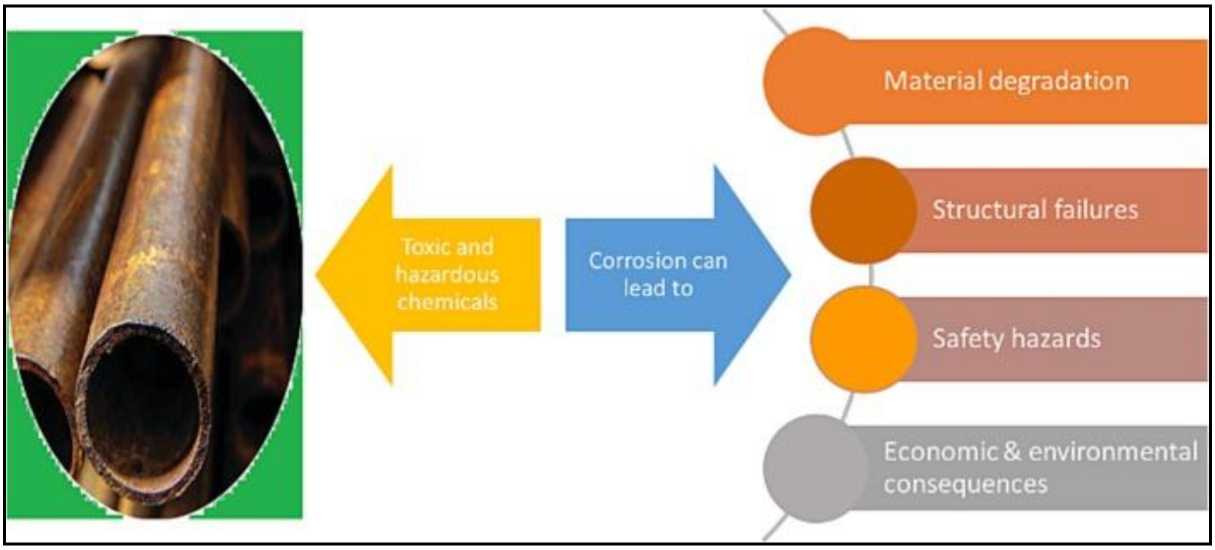
Furthermore, the review emphasizes the economic and industrial implications of adopting green inhibitors on a larger scale. Developing countries, where steel-based industries form the backbone of infrastructure and manufacturing, face the dual challenge of preventing material degradation while adhering to stricter environmental regulations. Green inhibitors, derived from locally available plants, agricultural by-products, and natural resources, present a cost-effective and easily accessible solution. Their adoption can significantly reduce the economic burden of corrosion-related damages and maintenance while promoting regional self-reliance in corrosion management practices. Additionally, understanding the importance of this study contributes to guiding industries and policymakers in adopting sustainable corrosion control strategies that are safe, scalable, and adaptable to diverse operational environments.



Finally, the study carries profound scientific importance by providing a roadmap for future research and innovation. Corrosion science is inherently multidisciplinary, intersecting chemistry, materials science, and environmental engineering. By exploring the molecular mechanisms of natural inhibitors and reviewing their application across different corrosive environments, this research offers valuable insights for designing more efficient, targeted, and standardized corrosion prevention systems. It underscores the potential of integrating modern characterization techniques with traditional knowledge of natural resources, thus fostering innovation in the field of eco-friendly materials. In sum, this study is important not only because it provides a greener alternative to conventional corrosion control methods but also because it contributes to global efforts toward environmental preservation, industrial safety, and scientific advancement.

Problem Statement

Corrosion of iron and its alloys remains a persistent and costly challenge, affecting industries, infrastructure, and national economies worldwide. While conventional corrosion inhibitors such as chromates, phosphates, and synthetic organic compounds have been extensively employed to mitigate this issue, their use raises serious environmental and health-related concerns. Many of these inhibitors are toxic, non-biodegradable, and hazardous to aquatic and terrestrial ecosystems, creating a conflict between industrial efficiency and ecological safety. Despite decades of research and the availability of numerous synthetic formulations, the problem of corrosion persists due to the unsustainable nature of existing solutions. This situation underscores the urgent need for alternative approaches that are both effective and environmentally responsible.



Although recent research has highlighted the potential of green inhibitors derived from plants, biomolecules, and renewable resources, several gaps continue to hinder their widespread adoption. Variability in natural sources, lack of standardization in extraction and application methods, and limited understanding of their long-term performance present significant challenges. Moreover, most studies have been limited to laboratory-scale experiments under controlled conditions, leaving questions about their scalability, consistency, and industrial applicability unresolved. Without comprehensive evaluations and systematic reviews, industries remain reluctant to replace conventional inhibitors with natural alternatives.

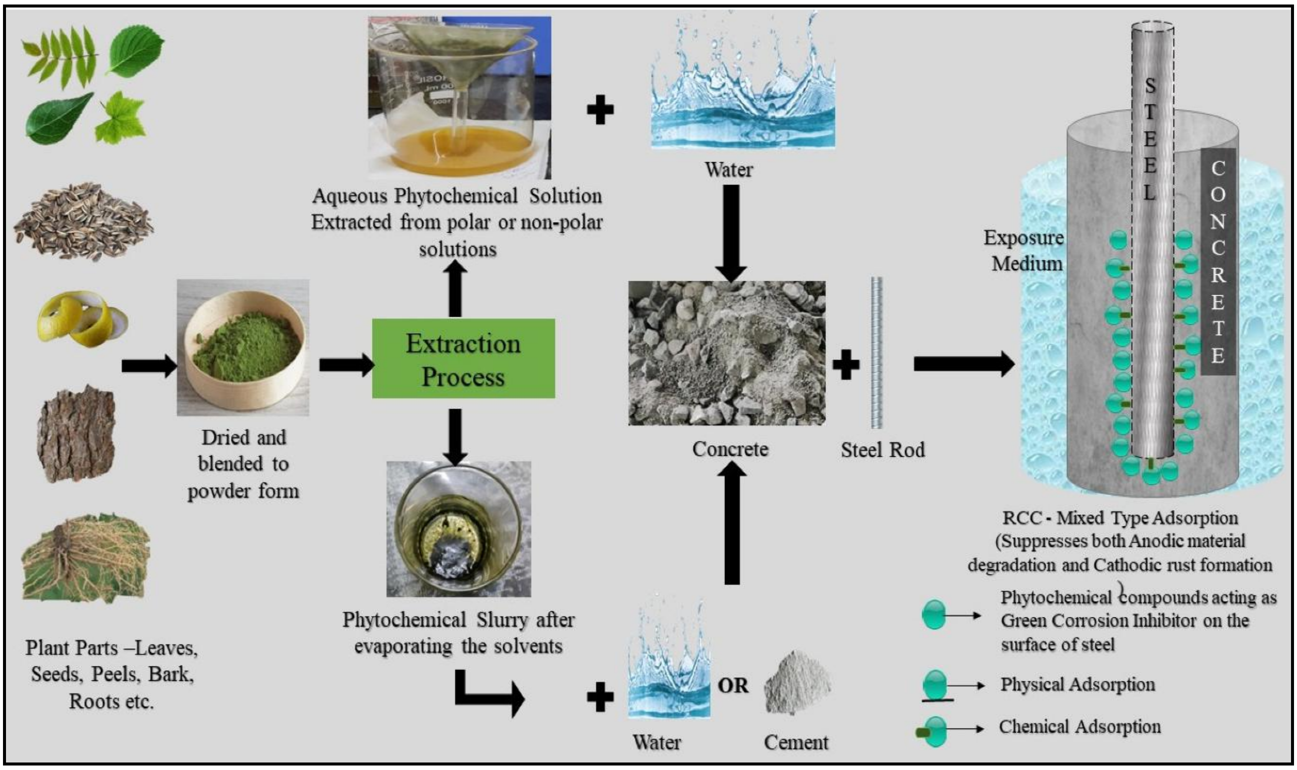
Therefore, the core problem addressed in this study is the lack of consolidated knowledge and critical evaluation of green inhibitors for corrosion protection of iron and iron alloys. A systematic review is necessary to analyse their effectiveness, identify their limitations, and explore pathways to optimize their industrial application. Unless such efforts are made, the corrosion of iron-based materials will continue to impose heavy financial, environmental, and safety burdens on society, while the promise of sustainable and eco-friendly corrosion protection remains underutilized.

Literature Review

The problem of corrosion has attracted extensive scholarly attention for decades due to its economic, technical, and environmental implications. For iron and its alloys, the susceptibility to rusting in the presence of oxygen and moisture has prompted engineers and scientists to develop protective strategies ranging from metallic coatings, cathodic protection, and synthetic inhibitors to advanced nanomaterials. Among these, corrosion inhibitors—chemical substances added in small quantities to aggressive media—have gained prominence because of their efficiency and ease of application. Early studies on inhibitors highlighted the effectiveness of inorganic salts such as chromates, phosphates, and nitrites in suppressing corrosion. Chromates, for example, were extensively used because of their strong passivating action on steel surfaces. However, numerous studies, including those by the World Health Organization, demonstrated their carcinogenic and ecotoxic effects, making them unsustainable in the long run. Synthetic organic inhibitors, usually containing heteroatoms such as nitrogen, sulfur, and oxygen, showed remarkable adsorption capabilities on metal surfaces, but their high toxicity and disposal challenges raised serious concerns. These limitations, repeatedly noted in corrosion science literature, became the driving force behind the search for eco-friendly alternatives, eventually leading to the emergence of "green inhibitors."

The term "green inhibitor" refers to naturally derived, biodegradable, and non-toxic substances capable of reducing corrosion rates. Over the past three decades, a substantial body of literature has explored the corrosion-inhibiting properties of plant extracts, biomolecules, and agricultural by-products. Plant-based inhibitors have gained the most attention due to their abundance of secondary metabolites such as alkaloids, flavonoids, tannins, terpenoids, and polyphenols, which are known for their ability to donate electrons and form protective films on metal surfaces. Early works in this domain, such as those by Raja and Sethuraman (2008), established that natural inhibitors could perform comparably to synthetic compounds while being renewable and environmentally benign. Since then, numerous investigations have documented the effectiveness of leaves, seeds, fruits, peels, bark, and roots as sources of potent phytochemicals that adhere to iron and steel surfaces, thereby hindering both anodic and cathodic reactions.

In addition to plants, researchers have experimented with biomolecules like amino acids, polysaccharides, and proteins, many of which contain functional groups that promote adsorption. Agricultural wastes, such as rice husk, sugarcane bagasse, and banana peels, have also been tested as cost-effective corrosion inhibitors. Such innovations underline the dual advantage of waste valorization and eco-friendly corrosion protection. Together, these studies show a clear paradigm shift in corrosion science: from reliance on synthetic chemicals toward nature-inspired solutions.



A central theme in the literature is the mechanism through which green inhibitors protect metal surfaces. Multiple electrochemical studies employing potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) have revealed that adsorption plays the most significant role. The phytochemicals or biomolecules in natural extracts adsorb onto the iron surface via physisorption (electrostatic interaction) or chemisorption (formation of covalent bonds). The Langmuir, Temkin, and Freundlich adsorption isotherms have been frequently used to describe the adsorption process. For example, several studies have shown that tannins and flavonoids, with their aromatic rings and polar functional groups, readily form complexes with Fe^{2+} ions, creating a protective barrier that reduces both anodic dissolution and cathodic hydrogen evolution.

Spectroscopic analyses, particularly Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM), have further confirmed the presence of protective organic films on corroded metal surfaces. These films not only block active sites but also modify the double-layer structure at the metal–electrolyte interface. Some researchers have noted synergistic effects when plant extracts are combined with small amounts of halide ions, leading to improved adsorption and inhibition efficiency. Overall, the literature suggests that the inhibition mechanism is multifaceted, involving adsorption, film formation, and sometimes the alteration of electrochemical kinetics.

A substantial portion of the literature focuses on case studies of individual plant extracts tested as corrosion inhibitors. Neem (*Azadirachta indica*) leaf extract has been reported to achieve inhibition efficiencies of up to 90% in acidic media due to its high concentration of flavonoids and terpenoids. Similarly, extracts of *Hibiscus sabdariffa*, *Lawsonia inermis* (henna), and *Ziziphus mauritiana* have demonstrated remarkable inhibition properties in hydrochloric acid solutions commonly used in pickling and descaling processes. Fruit-based inhibitors such as pomegranate peel and orange peel extracts are rich in polyphenolic compounds that enhance film-forming capabilities. Seeds such as those of black cumin and fenugreek have also been investigated, with results showing promising inhibition efficiencies.

Comparative studies highlight the diversity of phytochemical compositions and their corresponding performance. While some extracts act predominantly as anodic inhibitors, others exhibit mixed-type behavior, controlling both anodic and cathodic reactions. This variety reflects the inherent complexity of natural products and underscores the importance of systematic screening and optimization.

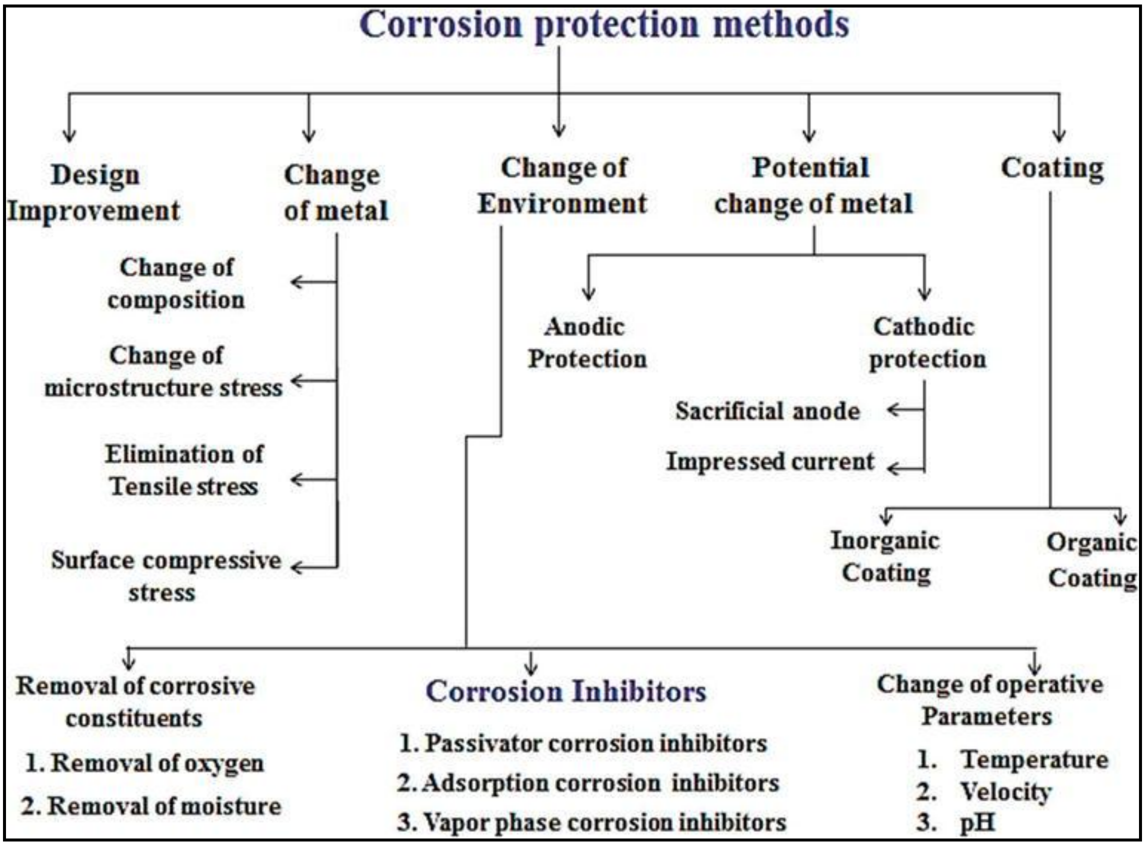
Beyond plants, biomolecules have also been explored extensively in the literature. Amino acids such as cysteine and tryptophan, which contain functional groups capable of binding to metal surfaces, have been shown to provide effective inhibition in acidic environments. Polysaccharides like starch, cellulose derivatives, and chitosan have been recognized for their ability to form protective, adherent films on metal substrates. Proteins and peptides, though less studied, have demonstrated potential as green inhibitors due to their high density of binding sites.

Agricultural waste materials represent another promising frontier. For example, rice husk extract has been tested in acidic chloride environments with encouraging results. Sugarcane bagasse, a widely available by-product, has also been reported to contain polyphenolic compounds suitable for corrosion inhibition. The utilization of such wastes aligns with circular economy principles, offering both environmental and economic benefits. Literature in this area demonstrates how waste valorization can simultaneously address issues of pollution, resource scarcity, and corrosion management.

While the literature establishes the efficacy of green inhibitors, it also highlights several limitations that need to be addressed. One recurring issue is variability in inhibitor performance due to differences in plant species, geographical origin, seasonal variation, and extraction methods. Such variability makes it difficult to standardize concentrations and develop universally applicable formulations. Another challenge is the limited stability of natural inhibitors under extreme temperature, pH, or salinity conditions. Many studies report good performance under laboratory conditions but lack evidence of long-term stability in real-world environments.

Additionally, most studies have been conducted at the laboratory scale, with few reports addressing the scalability of extraction and production processes. Industrial application requires inhibitors that are not only effective but also consistent, economical, and compatible with existing corrosion management systems. These gaps in the literature highlight the need for systematic reviews and interdisciplinary research to establish guidelines for standardization, optimization, and industrial adoption.

The existing body of literature points toward several future directions. First, greater emphasis needs to be placed on developing standardized methodologies for testing and comparing green inhibitors. Second, research should expand into studying synergistic combinations of natural extracts with small amounts of environmentally acceptable inorganic salts or nanoparticles to enhance performance. Third, long-term field studies are essential to validate laboratory findings and assess industrial feasibility. Finally, the development of commercial formulations, supported by life-cycle assessments and techno-economic analyses, will be crucial for widespread adoption. By addressing these aspects, future research can overcome current limitations and fully realize the potential of green inhibitors.



The literature on green inhibitors for corrosion protection of iron and its alloys reflects a clear trajectory from traditional, hazardous chemical inhibitors to sustainable, nature-derived alternatives. Extensive studies on plant extracts, biomolecules, and agricultural wastes have demonstrated that natural compounds can provide high inhibition efficiencies, often comparable to synthetic inhibitors. Advanced characterization and theoretical studies have further clarified inhibition mechanisms, highlighting the role of adsorption and film formation. Nevertheless, issues of variability, standardization, scalability, and long-term stability remain unresolved. Thus, the body of literature underscores both the promise and the challenges of adopting green inhibitors in industrial corrosion management. This review positions the present study as a timely and necessary contribution to consolidating knowledge, identifying gaps, and guiding future research toward eco-friendly and efficient corrosion protection strategies.

Conclusion

The review highlights that corrosion of iron and its alloys continues to be a critical challenge with significant economic, environmental, and safety implications. While conventional synthetic inhibitors have proven effective in reducing corrosion rates, their toxicity, non-biodegradability, and ecological risks have necessitated the exploration of sustainable alternatives. Green inhibitors, derived from plant extracts, biomolecules, and agricultural wastes, have emerged as promising candidates due to their biodegradability, abundance, and cost-effectiveness. Studies consistently report high inhibition efficiencies, often comparable to traditional chemical inhibitors, achieved through adsorption and protective film formation mechanisms. The natural compounds—rich in alkaloids, flavonoids, tannins, amino acids, and polysaccharides—demonstrate strong interactions with iron surfaces, thereby reducing both anodic and cathodic reactions.

Despite these advantages, challenges such as variability in natural composition, lack of standardized testing methods, and limited long-term field data remain barriers to large-scale adoption. The inconsistency in performance, influenced by factors like plant origin, extraction methods, and environmental conditions, highlights the need for greater standardization and reproducibility. Moreover, scaling up laboratory results to industrial applications requires comprehensive techno-economic analyses, stability assessments, and regulatory considerations. Emerging studies exploring synergistic approaches—combining natural extracts with nanoparticles, halides, or biodegradable polymers—offer exciting pathways to overcome current limitations and improve performance under diverse conditions.

In conclusion, green inhibitors represent a sustainable and scientifically viable alternative for corrosion protection of iron and iron alloys. Their adoption not only addresses technical needs but also aligns with global sustainability goals and environmental regulations. Continued interdisciplinary research, integrating experimental, computational, and industrial perspectives, will be essential to translate laboratory successes into real-world applications. This study underscores the potential of green inhibitors to transform corrosion science and contribute meaningfully to the future of eco-friendly engineering solutions.

References

1. Fontana MG. Corrosion Engineering. 3rd ed. New York: McGraw-Hill; 2015. p. 1-556.
2. NACE International. International Measures of Prevention, Application, and Economics of Corrosion

Technologies (IMPACT) Report. Houston: NACE International; 2018. Available from: http://impact.nace.org/economic-impact.asp
3. Schmitt G. Global needs for knowledge dissemination, research, and development in materials deterioration and corrosion control. World Corrosion Organization. 2009;38:1-48.
4. Singh WP, Bockris JO. Toxicity issues of organic corrosion inhibitors: Applications of QSAR model. Corrosion. 1996;52(2):174-180.
5. Mansfeld F, Kendig MW, Tsai S. Recording and analysis of AC impedance data for corrosion studies. Corrosion. 1982;38(11):570-580.
6. Anand B, Balasubramanian V. Study on corrosion inhibition of mild steel using natural product as corrosion inhibitor in acidic medium. Int J Electrochem Sci. 2011;6(9):3832-3835.
7. Negm NA, Morsy SM, Zaki MF, Mohamed AM. Gravimetric and electrochemical evaluation of environmentally friendly nonionic corrosion inhibitors for carbon steel in 1 M HCl. Corros Sci. 2012;65:94-103.
8. Yaro AS, Khadom AA, Wael RK. Apricot juice as green corrosion inhibitor of mild steel in phosphoric acid. Alex Eng J. 2013;52(1):129-135.
9. Ferreira ES, Giacomelli C, Giacomelli FC, Spinelli A. Evaluation of the inhibitor effect of L-ascorbic acid on the corrosion of mild steel. Mater Chem Phys. 2004;83(1):129-134.
10. Satapathy AK, Gunasekaran G, Sahoo SC, Kumar A, Rodrigues PV. Corrosion inhibition by Justicia gendarussa plant extract in hydrochloric acid solution. Corros Sci. 2009;51(12):2848-2856.
11. Gerengi H, Sahin HI. Schinopsis lorentzii extract as a green corrosion inhibitor for low carbon steel in 1 M HCl. Ind Eng Chem Res. 2011;51(2):780-787.
12. Victoria SN, Prasad R, Manivannan R. Psidium guajava leaf extract as green corrosion inhibitor for mild steel in phosphoric acid. Int J Electrochem Sci. 2015;10:2220-2238.
13. Umoren SA, Solomon MM. Recent developments on the use of polymers as corrosion inhibitors—a review. Open Mater Sci J. 2014;8:39-61.