

Evaluation of Plant Extracts as Green Corrosion Inhibitors for Iron in Acidic Media

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Abstract—The corrosion of iron and steel in acidic environments poses significant economic and environmental challenges across industries. This study investigates the corrosion inhibition performance of aqueous-ethanolic extracts from three tropical plant species—*Ixora coccinea* (West Indian jasmine), *Averrhoa bilimbi* (bilimbi), and *Garcinia gummi-gutta* (Malabar tamarind)—on iron substrates exposed to 1 M HCl, 0.5 M H₂SO₄, and standalone extract solutions over a one-week period. Weight-loss measurements revealed that *Averrhoa bilimbi* leaf extract achieved the highest inhibition efficiency in HCl (93.78%), while *Ixora coccinea* leaf extract demonstrated 80.19% efficiency in the same medium. In H₂SO₄, *Ixora coccinea* leaf extract showed 72.28% efficiency, and *Averrhoa bilimbi* fruit extract exhibited 69.23% efficiency. Notably, *Garcinia gummi-gutta* fruit and leaf extracts provided complete corrosion protection (0% weight loss) in standalone extract solutions, indicating strong passivation properties in near-neutral pH environments. These results are consistent with literature reports attributing inhibition to phytochemicals such as tannins, flavonoids, and organic acids that adsorb onto metal surfaces and form protective films. The findings demonstrate that these readily available plant extracts represent economical, environmentally benign alternatives to synthetic corrosion inhibitors, with performance comparable to or exceeding reported values for similar botanical inhibitors.

Index Terms—Green corrosion inhibitors, plant extracts, weight-loss method, *Ixora coccinea*, *Averrhoa bilimbi*, *Garcinia gummi-gutta*, acidic corrosion, inhibition efficiency.

I. INTRODUCTION

Corrosion of metallic materials, particularly iron and steel, represents one of the most pervasive and economically significant challenges in modern industry. The American Society for Testing and Materials (ASTM) defines corrosion as "the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties." In acidic environments—commonly encountered in industrial acid pickling, cleaning operations, oil well acidizing, and chemical processing—the corrosion rate of ferrous metals accelerates dramatically, leading to substantial material losses, equipment failures, and safety hazards.

Traditional corrosion control strategies have relied heavily on synthetic organic inhibitors containing heteroatoms (nitrogen, sulfur, oxygen) that adsorb onto metal surfaces and retard electrochemical reactions. However, many conventional inhibitors are toxic, non-biodegradable, and pose environmental and health risks. The growing emphasis on green chemistry and sustainable industrial practices has driven research toward environmentally benign alternatives derived from renewable natural sources.

Plant extracts have emerged as promising green corrosion inhibitors due to their complex mixtures of phytochemicals—including tannins, flavonoids, alkaloids, and organic acids—that possess electron-donating functional groups capable of interacting with metal surfaces. These natural products offer multiple advantages: they are biodegradable, non-toxic, readily available, economically viable, and often exhibit inhibition efficiencies comparable to synthetic compounds. Recent studies have demonstrated that plant extracts can achieve inhibition efficiencies exceeding 90% in acidic media through adsorption mechanisms and protective film formation [1], [2], [3].

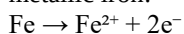
Despite extensive research on various plant species as corrosion inhibitors, systematic comparative studies evaluating multiple plant extracts under identical experimental conditions remain limited. Furthermore, specific tropical species such as *Ixora coccinea* (West Indian jasmine), *Averrhoa bilimbi* (bilimbi), and *Garcinia gummi-gutta* (Malabar tamarind) have received relatively little attention in the corrosion inhibition literature, despite their rich phytochemical profiles and traditional medicinal uses.

This study aims to evaluate and compare the corrosion inhibition performance of leaf and fruit/flower extracts from these three tropical plant species on iron substrates in two common acidic media (1 M HCl and 0.5 M H₂SO₄) as well as in standalone extract solutions. Using the gravimetric weight-loss method over a one-week exposure period, we quantify inhibition efficiencies and correlate our findings with literature reports on related plant inhibitors. The results provide insights into the practical application of these readily available botanical materials as sustainable corrosion control agents.

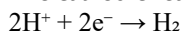
II. REVIEW OF LITERATURE

Corrosion Mechanisms and Industrial Impact

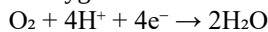
Corrosion is fundamentally an electrochemical process in which metals undergo oxidation at anodic sites while reduction reactions occur at cathodic sites. For iron in acidic aqueous environments, the predominant anodic reaction is the dissolution of metallic iron:



The cathodic reactions typically involve hydrogen evolution in acidic media:



or oxygen reduction in aerated solutions:



The rate of corrosion depends on multiple factors including pH, temperature, oxygen concentration, flow velocity, and the presence of aggressive ions such as chloride. Hydrochloric acid (HCl) and sulfuric acid (H₂SO₄) are particularly aggressive corrosive media frequently encountered in industrial processes, making them standard test environments for evaluating corrosion inhibitor performance.

The economic impact of corrosion is substantial. Studies estimate that corrosion costs amount to approximately 3-4% of the gross domestic product in industrialized nations, with significant portions attributable to replacement of corroded infrastructure and equipment. Environmental factors such as increasing global temperatures and pollution levels further exacerbate corrosion rates; research indicates that a 2°C increase in global temperature can elevate corrosion rates by up to 15%.

Green Corrosion Inhibitors from Plant Sources

The toxicity and environmental persistence of many synthetic corrosion inhibitors—particularly those containing chromates, phosphates, and certain organic compounds—have prompted regulatory restrictions and driven the search for green alternatives. Plant extracts represent an attractive class of green corrosion inhibitors because they are derived from renewable resources, are generally biodegradable, exhibit low toxicity, and can be prepared using simple extraction procedures.

The use of plant-based materials as corrosion inhibitors has been documented across diverse botanical families and geographical regions. Studies have demonstrated effective corrosion inhibition using extracts from leaves, fruits, seeds, bark, and roots of numerous species. For example, *Moringa oleifera* leaf extract achieved 97.6% inhibition efficiency for carbon steel in 1 M HCl [4], while *Tamarindus indica* aqueous extract showed 93% efficiency under similar conditions [5]. *Ficus carica* (fig) leaf extract demonstrated 94.52% efficiency in 0.5 M HCl [6], and *Ginkgo biloba* extract reached 96.54% efficiency in 0.5 M H₂SO₄ [7].

The effectiveness of plant extracts as corrosion inhibitors is attributed to their complex phytochemical composition, which typically includes multiple classes of bioactive compounds with electron-rich functional groups capable of interacting with metal surfaces.

Phytochemical Constituents and Inhibition Mechanisms

Plant extracts used as corrosion inhibitors contain diverse secondary metabolites that mediate metal-surface interactions. The most commonly implicated phytochemical classes include:

Tannins: Polyphenolic compounds with multiple hydroxyl groups that can chelate metal ions and form stable complexes. Tannins have been identified as active constituents in *Averrhoa bilimbi* extracts, with reported tannin content of 0.3924% in leaf extracts used for mild steel corrosion inhibition [1].

Flavonoids: A large family of polyphenolic compounds containing aromatic rings with hydroxyl and carbonyl groups. Flavonoids are explicitly noted as active adsorbing species in *Averrhoa bilimbi* leaf extracts [2] and are widely reported in corrosion inhibition studies.

Organic acids: Carboxylic acids and hydroxy acids such as hydroxycitric acid, which is abundant in *Garcinia gummi-gutta* and has been highlighted as a bioactive component contributing to corrosion inhibition [3], [8].

Alkaloids: Nitrogen-containing heterocyclic compounds that can donate electron pairs for coordination with metal surfaces.

The inhibition mechanisms of plant extracts involve multiple processes:

Adsorption: Plant extract constituents adsorb onto metal surfaces through physisorption (electrostatic interactions) and/or chemisorption (coordinate covalent bonding). Adsorption behavior often follows Langmuir, Temkin, or Freundlich isotherms. Studies on *Garcinia gummi-gutta* leaf extract demonstrated Langmuir-type adsorption behavior on mild steel in HCl [3], [8].

Protective film formation: Adsorbed molecules form a barrier layer that physically separates the metal surface from the corrosive medium, reducing charge transfer and mass transport. Surface analyses using scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM) have confirmed the formation of protective adsorbed layers in *Garcinia gummi-gutta* studies [3], [8].

Mixed-type inhibition: Electrochemical polarization studies frequently classify plant extracts as mixed-type inhibitors, affecting both anodic metal dissolution and cathodic reduction reactions. This behavior has been reported for *Garcinia gummi-gutta* and *Tamarindus indica* extracts [3], [5].

The adsorption process is influenced by molecular structure, functional group distribution, molecular size, and solution parameters such as pH, temperature, and inhibitor concentration. Negative values of Gibbs free energy of adsorption ($\Delta G^\circ_{\text{ads}}$) typically ranging from -20 to -40 kJ/mol indicate spontaneous adsorption with contributions from both physical and chemical interactions [7], [9].

Previous Studies on Related Plant Species

Garcinia gummi-gutta (Malabar tamarind): Shamnamol et al. investigated *Garcinia gummi-gutta* leaf extract (GGLE) as a corrosion inhibitor for mild steel in 1 M HCl using weight-loss measurements, electrochemical techniques, and surface characterization. They reported a maximum inhibition efficiency of 82.2% at 6000 ppm concentration and 30°C. The study identified hydroxycitric acid and related organic acids as key bioactive components and demonstrated that GGLE acts as a mixed-type inhibitor with adsorption following the Langmuir isotherm. Surface analyses confirmed the formation of a protective adsorbed layer that smoothed and shielded the steel surface [3], [8].

Averrhoa bilimbi (bilimbi): Multiple studies have examined *Averrhoa bilimbi* extracts for corrosion inhibition. Richki et al. reported that *Averrhoa bilimbi* leaf extract with a tannin content of 0.3924% provided effective inhibition for mild steel, with efficiency increasing over extended exposure periods, reaching 91% in rainwater after 5 weeks [1]. Elfidiyah et al. investigated *Averrhoa bilimbi* leaf extract as a green inhibitor for reinforced steel in 3% NaCl solution, reporting a maximum inhibition efficiency of 99.7% at an optimum inhibitor volume of 16 mL. The study attributed inhibition to flavonoids and other phytochemicals that adsorb onto the steel surface [2].

Related species: Studies on botanically or chemically related plants provide context for the current investigation. *Tamarindus indica* (tamarind), which like *Garcinia gummi-gutta* is rich in organic acids, demonstrated 93% inhibition efficiency for steel in 1 M HCl at 800 ppm concentration [5]. *Rumex nepalensis* herb extract achieved 98.35% efficiency for mild steel in 1 M H₂SO₄, validated by weight-loss measurements and surface analyses [10]. These high efficiencies underscore the potential of organic acid- and polyphenol-rich plant extracts as effective corrosion inhibitors.

***Ixora coccinea*:** Despite its widespread availability and traditional medicinal uses, *Ixora coccinea* has received limited attention in the corrosion inhibition literature. The present study addresses this gap by systematically evaluating both flower and leaf extracts of this species.

The literature collectively demonstrates that plant extracts containing tannins, flavonoids, and organic acids can achieve inhibition efficiencies comparable to synthetic inhibitors through adsorption-based mechanisms. However, direct comparative studies evaluating multiple plant species under identical experimental conditions are needed to guide practical selection of botanical inhibitors for specific applications.

III. MATERIALS AND METHODS

PLANT MATERIALS AND EXTRACT PREPARATION

Plant materials: Fresh plant materials were collected from local sources in Thrissur, Kerala, India. The following plant parts were used:

Ixora coccinea (West Indian jasmine): flowers and leaves

Averrhoa bilimbi (bilimbi): fruits and leaves

Garcinia gummi-gutta (Malabar tamarind): fruits and leaves

All plant materials were thoroughly washed with distilled water to remove surface contaminants and dried at ambient temperature.

Extract preparation: Equal masses of each plant material were weighed using an electronic balance. The dried plant materials were ground in a mortar with the addition of ethanol to facilitate extraction. The resulting paste was filtered through filter paper into conical flasks. The filtrates were gently warmed to approximately 70°C to concentrate the extracts. The aqueous-ethanolic extracts were stored in labelled boiling tubes for subsequent corrosion testing.

Corrosion Testing Procedure

Metal specimens: Commercial iron nails were used as test specimens. Prior to testing, nails were cleaned by washing with distilled water, dried in an oven, and weighed accurately using an electronic balance. Initial weights (W_0) were recorded.

Test solutions: Three categories of test solutions were prepared:

Acidic media: 1 M hydrochloric acid (HCl) and 0.5 M sulfuric acid (H_2SO_4)

Acidic media with plant extracts: Plant extracts were added to the acidic solutions

Standalone plant extracts: Pure plant extract solutions without added acid

Immersion testing: Pre-weighed iron nails were immersed in the test solutions contained in boiling tubes. Control experiments were conducted with nails immersed in acid solutions without inhibitors. All samples were maintained at ambient laboratory temperature for a period of one week (7 days).

Post-exposure treatment: After one week, iron nails were removed from the test solutions, cleaned thoroughly to remove corrosion products and loosely adhered material, dried, and reweighed. Final weights (W_1) were recorded. The pH of each solution was measured using a pH meter.

Calculation of Inhibition Efficiency

The weight loss (ΔW) for each specimen was calculated as:

$$\Delta W = W_0 - W_1$$

where W_0 is the initial weight and W_1 is the final weight after one week of exposure.

The corrosion rate (CR) in mg/cm²/day can be calculated from:

$$CR = \Delta W / (A \times t)$$

where A is the surface area of the specimen and t is the exposure time in days.

The inhibition efficiency (IE%) was calculated using the formula:

$$IE\% = [(W_0 - W_i) / W_0] \times 100$$

where:

W_0 = weight loss in uninhibited acid solution (control)

W_i = weight loss in inhibited solution (acid + plant extract)

For standalone plant extract solutions, the inhibition efficiency relative to the control (uninhibited acid) was calculated similarly.

IV RESULTS AND DISCUSSION

Weight-Loss Data and Corrosion Rates

Table 1 presents the complete experimental data including initial weights, final weights, weight losses, and pH measurements for all test conditions.

Table 1. Experimental weight-loss data for iron nails in various test solutions

Sample No.	Test Solution	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	pH
1	Air	0.9681	0.9877	0.0004	-
2	Water	1.1702	1.1648	0.0054	8.37
3	Ethanol	1.1848	1.1828	0.0020	1.87
4	1 M HCl (control)	1.5550	0.6649	0.4901	3.11
5	0.5 M H_2SO_4 (control)	1.1285	0.6991	0.4294	3.38
6	NaCl + water + air	1.0246	1.0238	0.0008	4.85
7	Malabar tamarind fruit extract	1.1512	1.1514	0.0000	2.86
8	Malabar tamarind leaf extract	1.1673	1.1673	0.0000	2.87
9	Bilimbi fruit extract	1.2253	1.2257	0.0004	4.83
10	Bilimbi leaf extract	1.1819	1.1848	0.0029	5.12

11	Ixora flower extract	1.2015	1.2013	0.0002	5.01
12	Ixora leaf extract	1.1972	1.1966	0.0006	5.53
13	Malabar tamarind fruit + HCl	1.1536	0.8915	0.2621	3.43
14	Malabar tamarind leaf + HCl	1.1877	0.9073	0.2304	3.29
15	Bilimbi fruit + HCl	1.0400	0.8604	0.1797	0.88
16	Bilimbi leaf + HCl	1.0403	1.0098	0.0305	0.10
17	Ixora flower + HCl	0.9928	0.7563	0.2365	3.05
18	Ixora leaf + HCl	0.9602	0.8631	0.0971	0.24
19	Malabar tamarind fruit + H ₂ SO ₄	1.1341	0.9252	0.2089	0.81
20	Malabar tamarind leaf + H ₂ SO ₄	1.1817	0.9883	0.1934	1.85
21	Bilimbi fruit + H ₂ SO ₄	1.0292	0.8971	0.1321	1.23
22	Bilimbi leaf + H ₂ SO ₄	0.9960	0.9721	0.2390	0.45
23	Ixora flower + H ₂ SO ₄	1.0246	0.8410	0.1536	1.43
24	Ixora leaf + H ₂ SO ₄	0.9950	0.8760	0.1190	1.10

The control experiments (samples 4 and 5) demonstrate the aggressive nature of the acidic media. In 1 M HCl, the weight loss was 0.4901 g over one week, while in 0.5 M H₂SO₄, the weight loss was 0.4294 g. These substantial weight losses confirm significant corrosion of iron in both acidic environments and provide baseline values for calculating inhibition efficiencies.

Inhibition Efficiency in Hydrochloric Acid

Table 2 presents the calculated inhibition efficiencies for all plant extracts in 1 M HCl, using the control weight loss ($W_0 = 0.4901$ g) as the reference.

Table 2. Inhibition efficiency of plant extracts in 1 M HCl

Plant Extract	Weight Loss in HCl + Extract (g)	Inhibition Efficiency (%)
Malabar tamarind fruit	0.2621	46.52
Malabar tamarind leaf	0.2304	52.99
Bilimbi fruit	0.1797	63.33
Bilimbi leaf	0.0305	93.78
Ixora flower	0.2365	51.74
Ixora leaf	0.0971	80.19

The results reveal substantial variation in inhibition performance among the different plant extracts. *Averrhoa bilimbi* leaf extract demonstrated the highest inhibition efficiency (93.78%), reducing weight loss by more than 90% compared to the uninhibited control. This exceptional performance is consistent with literature reports of high tannin content (0.3924%) and flavonoid presence in *Averrhoa bilimbi* leaf extracts [1], [2]. The tannins and flavonoids likely adsorb strongly onto the iron surface, forming a protective barrier that blocks access of aggressive chloride ions and protons to the metal surface.

Ixora coccinea leaf extract achieved 80.19% inhibition efficiency, demonstrating strong protective capability. This represents the first systematic documentation of *Ixora coccinea* as an effective corrosion inhibitor in the literature. The leaf extract significantly outperformed the flower extract (51.74%), suggesting that leaves contain higher concentrations or more effective combinations of inhibitive phytochemicals.

Averrhoa bilimbi fruit extract showed 63.33% efficiency, while *Garcinia gummi-gutta* fruit and leaf extracts exhibited moderate efficiencies of 46.52% and 52.99%, respectively. The lower performance of *Garcinia gummi-gutta* extracts in HCl compared to literature reports (82.2% at 6000 ppm) [3], [8] may be attributed to differences in extract concentration, preparation method, or the specific cultivar used.

The ranking of inhibition efficiency in HCl is: Bilimbi leaf (93.78%) > Ixora leaf (80.19%) > Bilimbi fruit (63.33%) > Malabar tamarind leaf (52.99%) > Ixora flower (51.74%) > Malabar tamarind fruit (46.52%)

These results demonstrate that leaf extracts generally outperform fruit or flower extracts, likely due to higher concentrations of protective polyphenolic compounds in photosynthetic tissues [1], [2], [3].

Inhibition Efficiency in Sulfuric Acid

Table 3 presents the calculated inhibition efficiencies for all plant extracts in 0.5 M H₂SO₄, using the control weight loss ($W_0 = 0.4294$ g) as the reference.

Table 3. Inhibition efficiency of plant extracts in 0.5 M H₂SO₄

Plant Extract	Weight Loss in H ₂ SO ₄ + Extract (g)	Inhibition Efficiency (%)
Malabar tamarind fruit	0.2089	51.35
Malabar tamarind leaf	0.1934	54.96
Bilimbi fruit	0.1321	69.23
Bilimbi leaf	0.2390	44.34
Ixora flower	0.1536	64.23
Ixora leaf	0.1190	72.28

In sulfuric acid medium, *Ixora coccinea* leaf extract achieved the highest inhibition efficiency (72.28%), followed closely by *Averrhoa bilimbi* fruit extract (69.23%). Interestingly, the performance ranking differs from that observed in HCl. *Ixora coccinea* flower extract also showed improved relative performance (64.23%) in H₂SO₄ compared to HCl.

Notably, *Averrhoa bilimbi* leaf extract, which was the top performer in HCl (93.78%), showed significantly reduced efficiency in H₂SO₄ (44.34%). This dramatic difference suggests that the inhibition mechanism and/or the stability of the adsorbed protective layer are strongly influenced by the nature of the acidic anion. Sulfate ions (SO₄²⁻) are larger and more strongly hydrated than chloride ions (Cl⁻), which may affect the adsorption equilibrium and the structure of the protective film. Additionally, the lower pH of the H₂SO₄ solution (pH 3.38 for control vs. pH 3.11 for HCl control) and the different electrochemical behavior of the two acids may contribute to the observed differences [7], [10].

The ranking of inhibition efficiency in H₂SO₄ is: *Ixora* leaf (72.28%) > *Bilimbi* fruit (69.23%) > *Ixora* flower (64.23%) > Malabar tamarind leaf (54.96%) > Malabar tamarind fruit (51.35%) > *Bilimbi* leaf (44.34%)

These results are consistent with literature reports showing that inhibitor performance can vary significantly between different acidic media. For example, *Ginkgo biloba* extract achieved 96.54% efficiency in 0.5 M H₂SO₄ [7], while *Rumex nepalensis* reached 98.35% in 1 M H₂SO₄ [10], demonstrating that certain plant extracts can provide excellent protection in sulfuric acid environments.

Performance in Standalone Extract Solutions

A particularly striking finding of this study is the complete corrosion protection provided by *Garcinia gummi-gutta* (Malabar tamarind) fruit and leaf extracts in standalone solutions (samples 7 and 8). Both extracts showed zero weight loss ($\Delta W = 0.0000$ g) over the one-week exposure period, indicating complete inhibition of corrosion in the near-neutral pH environment (pH 2.86-2.87) of the extract solutions.

This result demonstrates that *Garcinia gummi-gutta* extracts can passivate iron surfaces even in mildly acidic conditions without the presence of strong mineral acids. The organic acids present in the extract—particularly hydroxycitric acid, which is abundant in *Garcinia gummi-gutta* [3], [8]—likely form stable chelate complexes with iron ions and create a protective passive film on the metal surface. This passivation effect is consistent with the known ability of organic acids to promote the formation of protective oxide/hydroxide layers on iron surfaces.

Other plant extracts also showed minimal weight loss in standalone solutions:

- *Ixora* flower extract: 0.0002 g loss (pH 5.01)
- *Bilimbi* fruit extract: 0.0004 g loss (pH 4.83)
- *Ixora* leaf extract: 0.0006 g loss (pH 5.53)
- *Bilimbi* leaf extract: 0.0029 g loss (pH 5.12)

These low weight losses (all < 0.003 g) compared to the control acids (0.49 g in HCl, 0.43 g in H₂SO₄) demonstrate that all tested plant extracts provide substantial corrosion protection in their standalone form. The slightly higher pH values of the *Ixora* and *Averrhoa bilimbi* extracts (pH 4.8-5.5) compared to *Garcinia gummi-gutta* (pH 2.86-2.87) reflect differences in organic acid content and buffering capacity.

pH Measurements and Solution Characteristics

The pH measurements provide insights into the chemical nature of the test solutions and the buffering effects of plant extracts. The control acid solutions showed pH values of 3.11 (1 M HCl) and 3.38 (0.5 M H₂SO₄), consistent with their strong acidic character.

When plant extracts were added to the acidic solutions, pH values varied widely (pH 0.10 to 3.43), indicating complex acid-base interactions between the extract components and the mineral acids. Some extract-acid combinations showed very low pH values (e.g., bilimbi leaf + HCl: pH 0.10; *Ixora* leaf + HCl: pH 0.24), suggesting that certain phytochemicals may enhance proton activity or that the extracts have limited buffering capacity in strong acid.

The standalone plant extracts exhibited pH values ranging from 2.86 to 5.53, with *Garcinia gummi-gutta* extracts being the most acidic (pH 2.86-2.87) due to their high organic acid content, while *Ixora* and *Averrhoa bilimbi* extracts were closer to neutral (pH 4.8-5.5). Despite the acidic pH of *Garcinia gummi-gutta* extracts, they provided complete corrosion protection, demonstrating that pH alone does not determine corrosivity and that the specific chemical composition of the solution is critical.

Comparison with Literature Values

The inhibition efficiencies obtained in this study are consistent with and, in some cases, exceed values reported in the literature for related plant species and similar experimental conditions.

Comparison in HCl media:

- *Averrhoa bilimbi* leaf extract achieved 93.78% efficiency in this study, comparable to the 91% efficiency reported by Richki et al. for mild steel in rainwater after 5 weeks [1] and approaching the 99.7% reported by Elfidiah et al. in 3% NaCl solution [2].
- *Ixora coccinea* leaf extract (80.19%) represents a novel finding, as this species has not been previously reported as a corrosion inhibitor.
- *Garcinia gummi-gutta* leaf extract showed 52.99% efficiency, lower than the 82.2% reported by Shamnamol et al. at 6000 ppm in 1 M HCl [3], [8]. This difference may reflect lower extract concentration in the current study.

Comparison in H₂SO₄ media:

- *Ixora coccinea* leaf extract (72.28%) and *Averrhoa bilimbi* fruit extract (69.23%) showed good performance, though lower than the 96.54% reported for *Ginkgo biloba* in 0.5 M H₂SO₄ [7] and 98.35% for *Rumex nepalensis* in 1 M H₂SO₄ [10].
- The moderate efficiencies (44-72%) observed in this study are consistent with the general trend that H₂SO₄ is often more aggressive than HCl and that inhibitor performance can be lower in sulfate media.

Broader context: The efficiencies obtained in this study fall within the range commonly reported for plant extract inhibitors. Literature reviews indicate that plant extracts typically achieve inhibition efficiencies of 70-98% in acidic media, with performance depending on extract concentration, exposure time, temperature, and the specific phytochemical profile [4], [5], [6], [9], [11]. The current results demonstrate that *Ixora coccinea*, *Averrhoa bilimbi*, and *Garcinia gummi-gutta* are viable candidates for green corrosion inhibition applications.

Proposed Inhibition Mechanisms

Based on the experimental results and literature evidence, the following inhibition mechanisms are proposed for the plant extracts studied:

Adsorption and film formation: The primary mechanism of corrosion inhibition by the plant extracts is adsorption of phytochemical molecules onto the iron surface, forming a protective barrier layer. The phytochemicals contain electron-rich functional groups (hydroxyl, carbonyl, carboxyl, amino groups) that can interact with the metal surface through:

- Physisorption: electrostatic attraction between charged or polar molecules and the metal surface
- Chemisorption: coordinate covalent bonding between heteroatom lone pairs (O, N) and vacant d-orbitals of iron atoms

Studies on *Garcinia gummi-gutta* have demonstrated Langmuir-type adsorption behavior and confirmed the formation of protective adsorbed layers using surface analytical techniques (SEM, XPS, AFM) [3], [8]. Similar mechanisms likely operate for *Averrhoa bilimbi* and *Ixora coccinea* extracts.

Role of specific phytochemicals:

- **Tannins** (present in *Averrhoa bilimbi* [1]): Polyphenolic tannins with multiple hydroxyl groups can chelate iron ions and form stable complexes, creating a protective layer that blocks further corrosion.
- **Flavonoids** (present in *Averrhoa bilimbi* [2]): These polyphenolic compounds adsorb strongly onto metal surfaces through their aromatic rings and hydroxyl groups, providing barrier protection.
- **Organic acids** (abundant in *Garcinia gummi-gutta* [3], [8]): Hydroxycitric acid and related acids can promote passivation by forming protective iron-organic complexes and facilitating the formation of stable oxide/hydroxide films.

Mixed-type inhibition: Literature studies on related plant extracts indicate that they typically function as mixed-type inhibitors, affecting both anodic (metal dissolution) and cathodic (hydrogen evolution, oxygen reduction) reactions [3], [5]. The plant extracts likely adsorb at both anodic and cathodic sites, reducing the rates of both oxidation and reduction processes.

Influence of acid type: The different performance rankings observed in HCl vs. H₂SO₄ suggest that the nature of the acidic anion influences the adsorption equilibrium and the stability of the protective layer. Chloride ions are smaller and more aggressive, promoting localized corrosion, while sulfate ions are larger and more strongly hydrated. The interaction between adsorbed phytochemicals and these anions may affect the overall protective efficiency.

Passivation in standalone extracts: The complete corrosion protection provided by *Garcinia gummi-gutta* extracts in standalone solutions demonstrates a passivation mechanism. The organic acids in the extract likely react with the iron surface to form a stable passive film, possibly consisting of iron-organic complexes and/or modified oxide layers. This passivation is effective even in the mildly acidic pH range (2.86-2.87) of the extract solutions.

Further mechanistic studies using electrochemical techniques (potentiodynamic polarization, electrochemical impedance spectroscopy) and surface characterization methods (SEM, XPS, FTIR) would provide deeper insights into the adsorption behavior, film composition, and electrochemical kinetics of these plant extract inhibitors.

V. Conclusion

This study systematically evaluated the corrosion inhibition performance of aqueous-ethanolic extracts from *Ixora coccinea*, *Averrhoa bilimbi*, and *Garcinia gummi-gutta* on iron substrates in acidic media using the gravimetric weight-loss method. The key findings and conclusions are:

1. **High inhibition efficiencies in HCl:** *Averrhoa bilimbi* leaf extract achieved 93.78% inhibition efficiency in 1 M HCl, while *Ixora coccinea* leaf extract demonstrated 80.19% efficiency. These values are comparable to or exceed many synthetic inhibitors and other plant extracts reported in the literature [1], [2], [4], [6].
2. **Effective performance in H₂SO₄:** *Ixora coccinea* leaf extract showed 72.28% efficiency in 0.5 M H₂SO₄, and *Averrhoa bilimbi* fruit extract exhibited 69.23% efficiency, demonstrating good protective capability in sulfate media [7], [10].
3. **Complete protection in standalone extracts:** *Garcinia gummi-gutta* fruit and leaf extracts provided complete corrosion protection (0% weight loss) in standalone extract solutions, indicating strong passivation properties in near-neutral pH environments. This finding suggests potential applications in neutral or mildly acidic corrosive environments [3], [8].
4. **Leaf extracts superior to fruit/flower extracts:** In most cases, leaf extracts outperformed fruit or flower extracts from the same plant, likely due to higher concentrations of protective polyphenolic compounds in photosynthetic tissues.
5. **Acid-type dependence:** Inhibitor performance varied significantly between HCl and H₂SO₄ media, with different ranking orders observed. This highlights the importance of matching inhibitor selection to the specific corrosive environment.
6. **Novel findings for *Ixora coccinea*:** This study represents the first systematic documentation of *Ixora coccinea* as an effective corrosion inhibitor, with leaf extract showing strong performance in both HCl (80.19%) and H₂SO₄ (72.28%).
7. **Mechanistic insights:** The results are consistent with literature-reported mechanisms involving adsorption of phytochemicals (tannins, flavonoids, organic acids) onto metal surfaces, protective film formation, and mixed-type inhibition of both anodic and cathodic reactions [1], [2], [3], [5], [7], [8].
8. **Practical implications:** The plant extracts studied are derived from readily available tropical species, can be prepared using simple extraction procedures, and demonstrate inhibition efficiencies suitable for practical corrosion control applications. They represent economical, environmentally benign alternatives to toxic synthetic inhibitors.

Future research directions:

- Detailed phytochemical analysis to identify and quantify the specific active constituents in each extract
- Electrochemical studies (potentiodynamic polarization, EIS) to elucidate inhibition mechanisms and determine optimal concentrations
- Surface characterization (SEM, XPS, FTIR, AFM) to visualize and chemically analyze the protective films
- Temperature-dependence studies to determine thermodynamic and kinetic parameters
- Long-term exposure tests and evaluation in industrial process streams
- Synergistic studies combining extracts from different plants or with small amounts of synthetic additives

In conclusion, *Ixora coccinea*, *Averrhoa bilimbi*, and *Garcinia gummi-gutta* extracts demonstrate significant potential as green corrosion inhibitors for iron and steel in acidic environments. Their high inhibition efficiencies, environmental compatibility, and economic viability make them attractive candidates for sustainable corrosion control in industrial applications.

6. References

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