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A Review on the Corrosion Inhibition Efficacy of Bitter Leaf (*Vernonia amygdalina*) and Mango Leaf (*Mangifera indica*) Extracts

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Abstract
Corrosion of metallic infrastructure imposes substantial economic and environmental burdens, driving the search for sustainable alternatives to toxic synthetic corrosion inhibitors. This review systematically evaluates the utilization of bitter leaves (*Vernonia amygdalina*) and mango leaves (*Mangifera indica*) extracts as green corrosion inhibitors. The phytochemical compositions of these leaves are distinct: bitter leaves are rich in alkaloids, saponins, tannins, and flavonoids, while mango leaves contain predominantly mangiferin, gallotannins, flavonoids, and phenolic acids. Extraction methods—including maceration, Soxhlet, reflux, ultrasound-assisted, and microwave-assisted extraction—significantly influence the yield and composition of active compounds, with ethanol-water mixtures (70–80% ethanol) generally producing the most effective inhibitors. Experimental evaluation techniques commonly employed include weight loss measurements, potentiodynamic polarisation, electrochemical impedance spectroscopy, and surface characterisation (SEM, FTIR, XRD). For mild steel in 1 M hydrochloric acid, both extracts achieve inhibition efficiencies of 80–95% under optimized conditions (750–1500 ppm, 30–40°C, 24–72 hours). Mango leaves extract exhibits higher potency (requiring lower concentrations), superior thermal stability, better performance in neutral chloride media, stronger chemisorption, and greater batch-to-batch consistency, whereas bitter leaves extract remains a cost-effective option in regions where the plant is abundant. Inhibition mechanisms involve physisorption, chemisorption, chelation, site blocking, and double-layer alteration, with mango leaves demonstrating stronger chelation via gallotannin-iron complexation. Challenges include extract variability, storage stability, scalability, and lack of field validation. Future directions encompass formulation development, computational modeling, and industrial field trials.

Keywords: Green Corrosion Inhibitor, Bitter Leaves Extract, Mango Leaves Extract, Vernonia Amygdalina, Mangifera Indica, Mild Steel

Introduction

Corrosion is the gradual, time-dependent process of decay of metallic materials due to chemical or electrochemical reaction with the environment, which is ultimately responsible for failure and economic losses (Emmanuel, 2024; Enekwe et al., 2024). Corrosion costs approximately 3-5% of the annual GDP of industrialized nations in the form of repairs, replacements, reduced performance, loss of product, contamination, and safety hazards, with sectors such as oil and gas, petrochemicals, marine transport, power generation, and water treatment facilities facing some of the highest risks due to their use of metal components such as pipelines, storage tanks, heat exchangers, and reinforcement bars within their systems (Cherrada et al., 2024; Enekwe et al., 2024). The common environments in which corrosion occurs are acidic solutions (such as HCl and H_2SO_4 used for pickling metal parts), salt solutions (marine

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environments), and aqueous solutions with dissolved oxygen and carbon dioxide. Management of corrosion is therefore a key issue for material scientists, chemists, and industry personnel (Binda, 2024).

Recently, the extracts of bitter leaves (Vernonia amygdalina) and mango leaves (Mangifera indica) have received a great deal of interest due to their ability to act as corrosion inhibitors. Vernonia amygdalina is a shrub indigenous to the tropical regions of Africa, where it is consumed as a leaf vegetable and used in traditional medicine (Vijayaram et al., 2023). Its phytochemical screening shows it contains compounds such as sesquiterpene lactones, vernacularin, vernolide, vernodalol, with significant presence of flavanoids (luteolin, apigenin), saponins, alkaloids, phenolics and tannins. Multiple hydroxyl and carbonyl groups are found in the phytochemical constituents that are capable of anchoring to the surface of the metal as sites for chemisorption (Pinto et al., 2023). Mango leaves (Mangifera indica) on the other hand, contain compounds rich in mangiferin (a xanthonoid C-glucoside), gallotannins, ellagic acid, quercetin, kaempferol, among other phenolic acids. The structural and molecular composition of mangiferin gives it considerable ability to adsorb to the surface of iron and steel at various sites owing to its abundant hydroxyl and aromatic functionalities, thereby inhibiting corrosion (Shahrajabian & Sun, 2023a, 2023b).

The selection of bitter and mango leaves for this review is justified for several reasons. They are weeds and by-products of agriculture in developing nations; hence their cost is very cheap and readily available without competition for food crops. Bitter and mango leaf extracts have been reported to have inhibition efficiencies of over 80-90% in acidic medium, some of which compare favorably with commonly used synthetic inhibitors. Also, the chemical constitutions of bitter leaves (containing alkaloids, tannins, and saponins) and mango leaves (rich in mangiferin and gallotannins) can act synergistically. Although research into the inhibitory capacities of each of the leaves separately have been conducted, no review has been undertaken on the comparative analysis of their efficiency, adsorption characteristics and application potential. Thus, this review aims at summarizing, analyzing and discussing the available published literature on the use of bitter and mango leaves extracts as green corrosion inhibitors; it provides a summary of their phytochemical content, method of extraction and evaluation, inhibition efficiency at different experimental parameters, mode of adsorption and future industrial application prospects.

Methodology of Reviewed Studies

This review analysed peer-reviewed publications on the use of green extracts from bitter leaves (Vernonia amygdalina) and mango leaves (Mangifera indica) as corrosion inhibitors, published between 2022 and 2026. The search was carried out in the databases: Scopus, Web of Science, Google Scholar, PubMed and ScienceDirect using the search terms 'bitter leaves corrosion inhibitor', 'Vernonia amygdalina corrosion', 'mango leaves corrosion inhibitor', 'Mangifera indica corrosion inhibition', and 'green corrosion inhibitor plant extract'. Only papers published in the English language were considered, and a manual screening of reference lists identified further relevant publications. Included studies reported original experimental data about corrosion inhibition performance evaluated using the well-established techniques: weight loss method, electrochemical measurements and surface characterisation methods. Studies reporting only phytochemical compositions without corrosion inhibition tests, studies not mentioning the extraction solvent and duplicate papers providing no novel information were not included in the analysis. Of the ~180 records found in the database searches, 40 studies met the criteria and were fully reviewed. The information extracted was: botanical names of the plant, plant part studied, extraction method used, metal substrate analysed, corrosive medium, concentration of the inhibitor studied, experimental conditions, evaluation methods used, values of inhibition efficiency, thermodynamic and kinetic parameters, results of surface characterisation, and proposed mechanisms of inhibition. The data was thematically extracted and grouped into: phytochemical composition of extracts, methods of extraction, experimental evaluation techniques, inhibition performance (bitter leaves, mango leaves and comparative analysis), mechanisms of inhibition and challenges/limitations of the current research. If similar experiment conditions were applied, inhibition efficiency ranges were stated instead of specific values. A meta-analysis was not undertaken because of differences in study protocols; a narrative synthesis method was preferred. PRISMA guidelines were followed to perform this scoping review.

Phytochemical Composition of the Leaves

According the report of Zhou et al. (2026) and Ramalingam et al. (2026), alkaloids, saponins, condensed tannins, and flavonoids are the main component of bitter leaves; thus, providing nitrogen and oxygen-based electron donors to the both physisorption and chemisorption processes in mixed mode. On the other hand, mango leaves mainly contain mangiferin, hydrolysable gallotannins, flavonoids, and low concentrations of alkaloid and saponin; thus, providing the functional groups within the oxygen element alone for the chemisorption and chelation process. In that scenario,

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the strongly acidic condition will favor bitter leaves while at the elevated temperature and wider range of pH, mango leaves perform better due to C-glycosylated nature and extensive networks made by gallotannins (Pinto et al., 2023).

Phytochemical Composition of Bitter Leaves

The plant's inhibition efficiency totally depends on its phytochemical contents. Thus, their presence, concentration, molecular structure are essential for any extract's adsorption onto the surface of metal and formation of a protective film. Bitter Leaves (Vernonia amygdalina) are shrub belonging to the family Asteraceae that are commonly found throughout sub-Saharan Africa and have been widely studied for their vast quantity of secondary metabolites (Nwigwe & Nwoye, 2023; Okediran et al., 2023). The strong bitter flavor is due to the presence of sesquiterpene lactones and other polar phytochemicals. Through comprehensive analysis of leaves via TLC, HPLC, GC-MS, and FTIR, the four main class of compounds that have been identified are; alkaloids, saponins, tannins and flavonoids, plus small amounts of terprenoids, steroids, cardiac glycosides and phenolic acids, and all contribute in unique ways toward corrosion inhibition via electron donation, metal complexation, and film formation (Moiketsi et al., 2023).

Alkaloids are the predominant class of nitrogenous heterocycles found in bitter leaves in concentrations ranging from 1.2% to 3.5% of the dry leaf, although this figure can vary depending on factors such as seasonal and agricultural conditions. The chief alkaloids that have been identified are sesquiterpene lactones namely vernodalin, vernolide, vernodalol and hydroxyvernolide as well as stigmasterol-type alkaloids found in lower amounts (Pinto et al., 2023). The primary reason as to why alkaloids have corrosion inhibition properties lies in the presence of lone pairs of electrons on the nitrogen atoms, which readily form coordinate covalent bonds with vacant d-orbitals of transition metals, such as iron, via a process known as chemisorption. They are also rich in a conjugated pi-electron system present in the heterocyclic ring which helps in metal d-orbital back- donation, strengthening the adsorbed layer. Multi-point adsorption occurs due to the presence of hydroxyl and carbonyl functional groups which cause electron density delocalization over the entire molecule. It is known that fractions rich in alkaloids exhibit high inhibition efficiencies compared to crude extracts (Moiketsi et al., 2023).

Saponins form the second major class, constituting 2.5% to 5.8% of the dry leaf and bitter leaves are one of the richer plant sources of these compounds. Saponins are amphipathic glycosides that are comprised of an insoluble hydrophobic steroid-like aglycone moiety (sapogenin) bound by ether or ester linkages to one or more soluble hydrophilic oligosaccharide moieties (Dofuor et al., 2023). The most important saponins identified in bitter leaves include the steroidal saponins vernoniosides A1, A2, B1 and B2 as well as deltoide A and B; the linkage pattern of the oligosaccharides is complex. Their ability to inhibit corrosion comes from the fact that they are able to function as a surfactant thereby decreasing surface tension and reducing the influence of aggressive ions. The sugar groups contribute to the ability to form a hydrated film on the metal surface through hydrogen bonding to water and the aglycone, with its oxygen rich system, chemisorbs onto the metal through donation of electrons into the d-orbitals of the metal. The amphipathic nature allows for organized monolayer and/or aggregate (micelle) formation at the metal-electrolyte interface resulting in tight adsorption. The high foaming nature of these compounds helps in distribution of the inhibitor on the metal surface (Chowdhury et al., 2023; Okonkwo et al., 2022).

In the report of Ramalingam et al. (2026), tannins, present at 3.0-6.2% of dry leaf, have been identified as having a profound inhibitory effect on the corrosion of metals. High molecular weight, numerous phenolic hydroxyl groups; which can participate in metal complexation and/or hydrogen bonding are characteristic of these molecules. Tannins may be classified as hydrolysable or condensed. Condensed tannins (proanthocyanidins) are present in greater amounts than ellagitannins and gallotannins. Tannins form complexes with Fe+3 ions,passivating the surface of the metal (Mani et al., 2022). The ortho-dihydroxy functionality on the tannin molecule readily gets oxidized to ortho-quinone by Fe+3, thus reducing it to Fe+2 and forming a stable ferric-tannate coordination polymer on the metal surface, also known as tannin induced passivation. Tannins are also very rich in a multitude of hydrogen bond donors and acceptors resulting in strong physisorption. Steric hindrance from the bulky molecules also plays a significant role in blocking multiple corrosion sites. Flavonoids make up 1.8% to 4.5% of dry leaf. Some examples of flavonoids present include luteolin, apigenin, quercetin, kaempferol, myricetin and their respective glycosides. They possess planar structures, thus they lie flat on the metal surface enhancing corrosion inhibition; like tannins they possess a catechol group which is capable of forming complexes with Fe+3, have a higher density of conjugated pi electrons and electron withdrawing oxygen atom, and glycosylation ensures better water solubility and activity (Kumari et al., 2022).

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Phytochemical Composition of Mango Leaves

Mango leaves (Mangifera indica) belong to the family Anacardiaceae and are abundant but economically under-utilized plant resources in tropical and subtropical regions. While the mango fruit is economically important, its leaf is treated as agricultural waste and a traditional remedy (Bilgiç, 2022). Extensive phytochemical investigation revealed a unique group of bioactive secondary metabolites with very suitable structures for corrosion inhibition. The phytochemical composition is distinct from bitter leaves, consisting mainly of mangiferin (a unique xanthonoid C-glucoside in relatively large amount), various flavonoids (quercetin, kaempferol and their glycosides), hydrolyzable tannins (gallotannins and ellagitannins), phenolic acids (gallic, chlorogenic and ferulic acids) in moderate quantity, and small amounts of triterpenoids and phytosterols (Aghogho et al., 2025). Little or no alkaloids and saponins were detected, this shows that the inhibiting mechanism uses oxygen lone pair donors on the polyphenolic groups not on the nitrogenous heterocycles, properties important for the adsorption behavior, thermal stability and applicability of the electrolyte systems (Aghogho et al., 2025).

The most unique and concentrated phytochemical component is mangiferin (2-C-B-D-glucopyranosyl-1,3,6,7-tetrahydroxyxanthone, 0.5%-7.2% d. W., varies on cultivar, age, and harvest time), an aromatic, planar, tricyclic xanthone nucleus carrying four phenolic hydroxyls, and a glucose group attached via a C-C bond (C-glycosidic bond which is resistant to hydrolysis on acidic and thermal conditions compared to O-glycosides) (Guo et al., 2024). It possesses useful features in corrosion inhibition: planar system of the aromatic ring provides flat adsorption and large coverage, phenolic hydroxyls donate electrons on vacant d-orbitals of the surface atoms resulting in a chemisorption bond, and conjugated electron system and oxygen atoms in the aromatic ring stabilize the adsorbed complexes and back donation occur, in the case of the glucose unit increasing the water solubility and enabling hydrogen bonds with hydrated oxides on surface. Mangiferin alone was capable of reaching more than 90% inhibition efficiency at 200 ppm on 0.5 M HSO, indicating a good natural corrosion inhibitor in its pure form (Dofuor et al., 2023).

The second main component were flavonoids (1.5-4.8% d. W.) mainly quercetin, kaempferol, myricetin, apigenin and their O-glycosylated derivatives (isoquercitrin, hyperoside, astragalin) and also a novel C-glycosylated flavonoids as manghaslin and isomanghaslin. Quercetin is quite abundant and its catechol group can undergo redox process becoming ortho-quinone on oxidizing atmosphere forming passivating ferric-quercetin coordination polymer, that provides excellent inhibition in oxidizing acid solutions (Guo et al., 2024). Glycosylated derivatives improve water solubility and adsorption film forming, because of their ability to form uniform film without agglomerating. The aromatic ring systems enable π-stacking interactions among adsorbed molecules, forming dense, orderly packed monolayers that provide steric protection against penetrating corrosive ions. The flavonoid fraction also exhibits high efficiency in neutral and alkaline media, which is advantageous for cooling water systems and concrete protection environments (Ayad, 2022).

Tannins are the third component class (2.0–5.5% dry weight), preferably hydrolyzable gallotannins and ellagitannins, with no condensed tannins. Hydrolyzable tannins are polyesters of gallic acid with a glucose core, mostly bearing 5–10 galloyl residues. PGG (1,2,3,4,6-penta-O-galloyl-β-D-glucose) is the most abundant gallotannin. The inhibition mechanism is based on its unique ability to chelate Fe (III) ions and form insoluble cross-linked metal-organic networks on the metal surface (Aghogho et al., 2025). Gallic acid bearing three hydroxyl groups provides two chelation sites, which can simultaneously coordinate with metal atoms or ions. Stable three-dimensional protective films can be formed by chelating multiple iron atoms, a property widely used in conversion coating and rust converter formulations. Unlike condensed tannins from bitter leaves which form brittle films, hydrolyzable tannin films are more uniform, though more easily hydrolyzed in strongly alkaline or high-temperature media. PGG has a molecular weight of approximately 940 g/mol, allowing it to cover multiple adsorption sites and provide steric hindrance to aggressive ions (Dofuor et al., 2023).

Phenolic acids form the fourth major component class (0.8–2.5% dry weight), including gallic acid (most abundant, accounting for 30–50% of total phenolic acids), chlorogenic acid, ferulic acid, caffeic acid, p-coumaric acid, and protocatechuic acid (Ramalingam *et al.*, 2026). They contribute through metal chelation (gallic acid forms stable five-membered chelate rings with iron ions), filling gaps in the primary adsorbed film, ionic adsorption, and providing a hydrophobic layer. Triterpenoids and phytosterols are trace components (<0.5%), contributing a hydrophobic barrier film. Due to the absence of alkaloids and saponins, only oxygen-based functional groups are provided, making mango leaf extract particularly suitable for corrosion protection in neutral and marine environments (Islam *et al.*, 2026) . A comparison of the major components from the two leaf samples is summarized in Table 1.

Table 1: Differences in the phytochemical analysis of mango leaves and bitter leaves (García-González et al., 2025; Guo et al., 2024; Islam et al., 2026; Ogboro & Uko, 2025; Zhou et al., 2024)

Feature	Mango Leaves	Bitter Leaves
Dominant compound	Mangiferin (xanthonoid)	Sesquiterpene lactones + alkaloids
Alkaloids & saponins	Absent	Abundant
Tannin type	Hydrolyzable (gallotannins)	Condensed (proanthocyanidins)
Electron donors	Oxygen only	Oxygen and nitrogen
Best performance environment	Neutral, marine, wide pH range	Strongly acidic media
Thermal stability	Superior	Moderate
Consistency & shelf life	More consistent, longer shelf life	More variable, shorter shelf life

Preparation and Extraction Methods

Bitter and mango leaves are first washed and then oven dried at 30-50 C. The dried leaves are pulverized into fine powder. The efficiency of inhibition was observed to be greatest at the extraction temperature 70-80% ethanol. Standard methods of extraction include maceration at room temperature for 24-168 hours for volatile sensitive compounds (Ramalingam et al., 2026). With Soxhlet and reflux extraction for 4-12 hours higher yield can be achieved although there is a chance of degrading thermolabile components. Advanced ultrasound assisted extraction and microwave assisted extraction require extraction duration of only few minutes. The extracts after extraction are then subjected to filtration, concentration and then oven drying. Extracts should then be stored in refrigerator under dark condition. Mango leaves extract appears to be stable to heat during extraction because mangiferin is C-glycosylated while extract from bitter leaves should not be heated for a longer period as it contains alkaloids and saponins (Kumar et al., 2026).

Extraction Methods for Bitter Leaves and Mango Leaves

The corrosion inhibition mechanisms of bitter and mango leaves extracts are rooted in the adsorption of phytochemical molecules onto the metal surface, forming a protective barrier against the corrosive environment. The literature has elucidated several complementary mechanisms: physisorption via electrostatic interactions, chemisorption via electron donation, formation of metal-inhibitor chelates, blocking of active corrosion sites, and alteration of the electrical double layer (Islam et al., 2026).

As reported by Wang (2025), both extracts exhibit mixed physisorption and chemisorption mechanisms with differing contributions. Physisorption involves weak, reversible interactions (van der Waals forces, hydrogen bonding) with low adsorption enthalpies and decreasing inhibition at higher temperatures. Chemisorption involves coordinate covalent bonds between electron-rich centers (nitrogen or oxygen lone pairs) and vacant metal d-orbitals, with higher adsorption enthalpies and greater thermal stability. For bitter leaves, free energy of adsorption values of −25 to −35 kJ/mol indicate a mixed mechanism with significant physisorption, consistent with protonated alkaloids (electrostatic attraction) and saponins (hydrogen bonding). For mango leaves, values of −30 to −45 kJ/mol indicate stronger chemisorption due to abundant phenolic hydroxyl groups on mangiferin and gallotannins, explaining its superior thermal stability and lower concentration requirements (Vaishnav et al., 2025).

Chelate formation is particularly important for mango leaves due to its high gallotannin and mangiferin content. Gallotannins chelate ferric ions through ortho-dihydroxy groups, forming stable, cross-linked ferric-tannate coordination polymers (tannin-induced passivation). Mangiferin provides multiple bidentate chelation sites; DFT reveals binding energies of −150 to −200 kJ/mol. Bitter leaves contain both condensed and hydrolyzable tannins but form less extensively cross-linked complexes (Shahrajabian, 2025). PDP studies show that bitter leaves act as mixed-type inhibitors with slight cathodic predominance (corrosion potential shifts <85 mV). Mango leaves also show mixed-type inhibition but with larger shifts (up to 100–120 mV), varying from anodic predominance in chloride media to cathodic predominance in sulfate media. High-molecular-weight tannins and saponins are effective site blockers despite slower diffusion (Vaishnav et al., 2025).

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EIS reveals decreased double-layer capacitance with increasing concentration: from 200–400 to 40–100 μF/cm² for bitter leaves, and from 300–500 to 30–70 μF/cm² for mango leaves, indicating a more compact adsorbed layer for mango leaves. Charge transfer resistance increases from 50–200 to 500–2000 Ω·cm² for both extracts, confirming hindered electron transfer (Islam et al., 2026). Protonation is important for bitter leaves, whose alkaloids become protonated (cationic) in acidic media (pH < 2), electrostatically attracted to negatively charged cathodic sites. This explains higher efficiency in more acidic solutions. Mango leaves, lacking alkaloids, perform well across pH 1–10. In neutral/alkaline conditions, their phenolic –OH groups may deprotonate to phenolate anions, interacting with positively charged anodic sites (Schappo et al., 2025).

Film formation involves initial rapid adsorption (minutes to hours) onto high-energy sites, followed by slower reorganization (hours to days) involving lateral diffusion, intermolecular bonding, and chelation/cross-linking. For mango leaves, gallotannins slowly hydrolyze to release gallic acid, enhancing local protection in micro-crevices (Shahrajabian, 2025). For bitter leaves, saponins may form hemimicelles at high concentrations, reducing efficiency due to steric hindrance. In summary, mango leaves exhibit stronger chemisorption and chelation, while bitter leaves exhibit more pronounced protonation-dependent physisorption. Table 2 presents the summary of extraction methods, solvents, and processing parameters for bitter and mango leaves.

Table 2: Summary of Extraction Methods, Solvents, and Processing Parameters for Bitter and Mango Leaves (Islam *et al*., 2026; Ramalingam *et al*., 2026; Vaishnav *et al*., 2025).

Parameter	Details / Options	Key Advantages	Key Limitations / Considerations
Preparatory Steps	Washing (distilled water), drying (30–50°C, 24–72 hrs), grinding (0.2–1.0 mm particle size)	Removes contaminants; prevents thermal degradation; increases surface area for extraction	Drying >60°C degrades thermolabile compounds (flavonoids, tannins)
Solvent Selection	Water, methanol, ethanol (50–95%), acetone, or binary mixtures	Ethanol (70–80%) is optimal: balances polarity, low toxicity, good flavonoid/tannin extraction	Water extracts contain non-inhibitory components (sugars, salts); methanol is toxic; acetone is flammable and costly
Solvent-to-Solid Ratio	10:1 to 50:1 (mL solvent per g powder)	Higher ratios improve yield up to a point of diminishing returns	Excessive ratios increase cost and evaporation time
Maceration	Room temp (25–30°C), 24–168 hrs, intermittent stirring	Simple, inexpensive, preserves thermolabile compounds; yields >85% inhibition efficiency	Time-consuming; risk of microbial growth in aqueous solvents
Soxhlet Extraction	Continuous cycling with heated solvent, 4–12 hrs	High yield (18–25% dry weight); efficient for mangiferin (mango leaves)	Thermal degradation of sensitive compounds; not scalable; high solvent volume (200–500 mL)
Reflux Extraction	Boiling solvent with condenser, 2–6 hrs	Faster than maceration; simpler than Soxhlet	Thermal exposure may reduce alkaloid/flavonoid activity
Ultrasound-Assisted (UAE)	High-frequency sound (20–40 kHz), 20–40 min, 30–40°C	Fast; low solvent use; preserves thermolabile compounds (ice bath cooling)	Requires specialized equipment
Microwave-Assisted (MAE)	2.45 GHz radiation, 2–5 min	Extremely fast; low solvent use; high mangiferin yield	Localized overheating may degrade some compounds; specialized equipment needed

Parameter	Details / Options	Key Advantages	Key Limitations / Considerations
Post-Extraction Processing	Filtration → Concentration (rotary evaporator, 40–50°C) → Drying (vacuum oven or lyophilization) → Storage (4°C, airtight, dark)	Gravimetric standardization enables precise dosing; lyophilization best preserves thermolabile compounds	Crude liquid extracts introduce variability; lyophilization is expensive
Final Inhibitor Concentration	50–2000 ppm (mg/L) in corrosive medium (e.g., 1 M HCl, 0.5 M H_2SO_4, 3.5% NaCl)	Dried, standardized extracts preferred for reproducibility	Volume-based dosing (e.g., 10% v/v) less rigorous

Experimental Evaluation Techniques

Well-established experimental techniques are applied for measuring corrosion inhibition efficiencies of bitter and mango leaves extracts. These techniques are divided into: (1) gravimetric techniques (weight loss), (2) electrochemical techniques (potentiodynamic polarization, electrochemical impedance spectroscopy, and linear polarization resistance), and (3) surface characterization techniques (scanning electron microscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, and atomic force microscopy). The majority of studies used weight loss and electrochemical methods in addition to surface analyses and theoretical calculations (García-González et al., 2025; Schappo et al., 2025).

Weight Loss Method

The weight loss method is the simplest and oldest reported method. A cleaned metal coupon (usually mild steel) after grinding, polishing, degreasing, washing, and drying is weighed to constant weight before immersion into corrosive solution (acid or saline) with or without different inhibitor concentrations for 6–168 hours at 25–80°C. The corroded coupons are cleaned, reweighed, and inhibition efficiency is evaluated from corrosion rates. For bitter leaf extract, inhibition efficiency reaches 75–92% with 500–1500 ppm in 1 M HCl, while mango leaf extract achieves 70–95% with 800 ppm in 1 M H_2SO_4. Advantages include low cost, ease of implementation, and simple setup. The major drawback is being time-consuming and unable to provide kinetic data at different time intervals (Schappo et al., 2025).

Potentiodynamic Polarization

This method provides quick qualitative data on corrosion kinetics through analysis of a potential sweep recorded between −0.5 and +0.5 V relative to open circuit potential. Using a three-electrode system (reference, working, and counter electrodes), polarization is scanned from cathodic to anodic region or vice versa. Cathodic and anodic Tafel slopes and corrosion current density are extrapolated from Tafel polarization curves, and inhibition efficiency is determined. Bitter leaf extract is a mixed-type inhibitor with slight cathodic control, while mango leaf extract shows occasional anodic control. The advantage is quick corrosion kinetics data, but disadvantages include potential electrode surface modification and artifacts from redox-active phytochemicals (Ogboro & Uko, 2025; Ohunene et al., 2025).

Electrochemical Impedance Spectroscopy

According to Di et al. (2025), this technique provides comprehensive data on metal-electrolyte interfaces in a non-destructive manner, where a small amplitude AC perturbation signal is applied across a wide frequency range. Impedance data are represented as Nyquist and Bode plots and fitted to an equivalent circuit model (solution resistance, double-layer capacitance, and charge transfer resistance). Inhibition efficiency is evaluated from increased charge transfer resistance and decreased double-layer capacitance. For both extracts, the Nyquist semicircle diameter increases with inhibitor concentration, while double-layer capacitance decreases, indicating adsorption and protective film formation. EIS provides detailed interfacial information and is non-destructive, but requires more complex data interpretation and more expensive equipment.

Linear Polarization Resistance

This is a faster screening technique involving application of a small over-potential and measurement of corresponding current density. Polarization resistance is determined, which has an inverse relationship with corrosion current. Inhibition efficiency is calculated by comparing polarization resistances. This technique is not often reported alone because it requires knowledge of Tafel slope values, which is not always true for plant extracts (García-González et al., 2025; Islam et al., 2026).

Surface Characterization Techniques

Scanning electron microscopy images show uninhibited and inhibited surface morphologies. Uninhibited metal shows pits and cracks, while the inhibited surface shows a smooth surface with a finely dispersed protective film. The film of bitter leaves extract is uniform compact and adheres to the grains and micro-cracks. The smooth surface of mango leaves extract is expected due to the adsorption of mangiferin gallotannin. EDX spectra, combined with the SEM images show elemental analyses of treated and uninhibited surfaces. Oxygen concentration on treated bitter leaves is reduced and carbon and nitrogen is enhanced, while oxygen concentration is reduced and carbon concentration is increased and oxygen concentration remains on treated mango leaves. Also, the concentration of chloride in the saline medium decreases on treated surfaces (Alam et al., 2025; Calefi et al., 2025).

FTIR spectra identify functional groups responsible for the inhibition effect. In the case of bitter leaves, peaks corresponding to hydroxyl, carbonyl, aromatic ring, C-N, and C-O were observed. In addition, the intensities of hydroxyl, carbonyl and C-N peaks shifted on treated surfaces, indicating their chemical interaction with the metal surface. Similarly for mango leaves, the dominant peaks for hydroxyl, xanthone carbonyl, aromatic rings, glycosidic bonds also shifted after adsorption which is attributed to chemisorption. X-ray diffraction analysis provides the structural nature of the surface layer. The intensities of iron oxide on the surfaces decreased in the presence of the inhibitors which indicate that the inhibitive layer formed does not allow the formation of oxide on the metal surface. The AFM profile shows the topography of the surface. For inhibited surface the root-mean square roughness is much lower than that on uninhibited surface, meaning the inhibition layer is smooth (Aghogho et al., 2025; Zhou et al., 2024).

Computational Methods

Quantum chemical parameters (HOMO and LUMO energy values, dipole moment value, hardness, softness and fraction of electron transferred) are computed by density functional theory. The high HOMO energy value observed for compounds of bitter leaves implies good electron-donating characteristics of compounds (Olawale et al., 2024). For mango leaves, the fraction of electron transferred for mangiferin is above 3.67 eV, this shows that adsorption is spontaneous chemi-adsorption. The adsorption process was monitored using molecular dynamics simulations and it was observed that the inhibitors lie parallel to the surface of the iron. All compounds showed negative adsorption energies and also indicate spontaneous and firm chemi-adsorption that also helps to cover most of the iron surface area (Monday et al., 2024; Ohunene et al., 2024). Hence, the various corrosion performance techniques of corrosion inhibitor are depicted in Figure 1.

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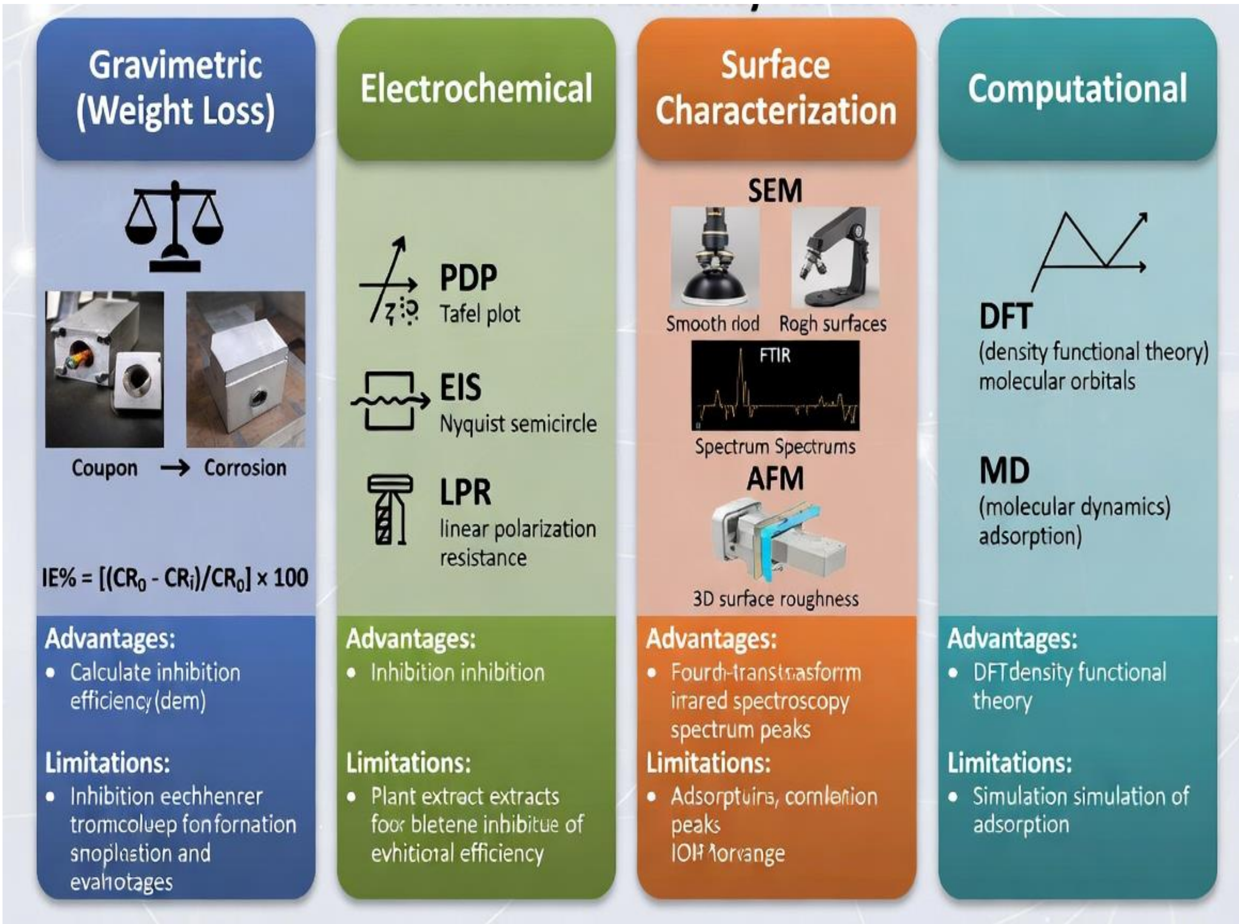

Figure 1: Corrosion evaluation techniques (Monday et al., 2024; Ohunene et al., 2024).

Mechanisms of Inhibition for Bitter Leaves and Mango Leaves Extracts

The mechanism of corrosion inhibition by bitter and mango leaf extracts lies in adsorption of phytochemical molecules to the metal surface and formation of a protective layer against the corrosive environment. Several simultaneous mechanisms have been cited: physical adsorption involving electrostatic interaction, chemisorption involving charge sharing or electron transfer, formation of metal-inhibitor chelates, inhibition of active corrosion sites, and perturbation of the electrical double layer (Enekwe et al., 2024; Guo et al., 2024).

Physisorption versus Chemisorption

Both extracts follow mixed physisorption and chemisorption mechanisms with different degrees of contribution. Physisorption involves weak, reversible interactions (electrostatic, van der Waals forces) with low adsorption enthalpies, and inhibition decreases with temperature. Chemisorption involves coordinate covalent bonds between electron-rich centers (N, O) and empty d-orbitals of metal, with high adsorption enthalpies and great thermal stability. For bitter leaves, free energy of adsorption values of 25–35 kJ/mol indicate a mixed mechanism where physisorption is dominant, consistent with protonated alkaloids (electrostatic interaction) and saponins (hydrogen bonding). For mango leaves, values of 30–45 kJ/mol indicate stronger chemisorption due to abundant phenolic hydroxyl groups on mangiferin and gallotannins, supporting better thermal stability and lower concentration requirements (Cherrada et al., 2024; Emmanuel, 2024).

Role of Functional Groups

Specific functional groups were characterized by FTIR and DFT studies. For bitter leaves, functional groups include nitrogen atoms of alkaloids (forming Fe–N bonds), –OH groups (Fe–O bonds), carbonyl groups, and glycosidic oxygen atoms. FTIR shows shifts in N–H, C–N, O–H, and C=O frequencies upon adsorption, confirming participation of heteroatoms. For mango leaves, functional groups are phenolic –OH (four on mangiferin, up to ten on gallotannins),

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carbonyl oxygen of xanthone, and ether oxygens. FTIR shows only shifts in O–H and C=O peaks, confirming oxygen-based chemisorption only (Cherrada et al., 2024; Emmanuel, 2024).

Chelate Formation and Site Blocking

Mango leaf extract, the dominant one is chelation. Gallotannins and mangiferin present in abundance coordinate with the ferric ions via the o-dihydroxy group of the molecule to form the inseparable cross-linked Fe gallotannins and Fe-mangiferin complexes. Binding energy ofmangiferin on Fe (110) of 150-200 kJ/mol shown from DFT binding energies suggests strong binding. Although hydrolyzable and condensed tannins are present in bitter leaves their complex coordination is less cross-linked than that of the mango leaves (Vijayaram et al., 2023). The PDP analysis shows both of them as mixed type inhibitors; the former show little cathodic trend (shift of corrosion potential<85mV), latter showed variable results according to the medium used (shift of corrosion potential can be 100-120mV); anodic in chloride media, cathodic in sulfate media. The increase in size of the tannin molecule of the mango leaf contributes to its ability to block greater surface area, which gives a higher surface coverage at lower concentration. High molecular weight tannins and saponins acts as site blocking molecules though with slow diffusion rate (Shahrajabian & Sun, 2023b).

Electrical Double Layer Alteration and Protonation

EIS analysis shows reduction in double-layer capacitance with increasing concentration: from 200–400 to 40–100 $\mu F/cm^2$ for bitter leaves, and from 300–500 to 30–70 $\mu F/cm^2$ for mango leaves, indicating a more compact adsorbed layer for mango leaves. Charge transfer resistance increased from 50–200 to 500–2000 $\Omega \cdot cm^2$ for both extracts, signifying hindered charge transfer. Protonation is crucial for bitter leaf extracts: in acidic solution, alkaloids become protonated and positively charged, electrostatically attracted to negative cathodic sites, increasing efficiency at lower pH. Mango leaf extract shows effective inhibition over a wide pH range (1–10). At alkaline pH, phenolic –OH groups deprotonate to phenolate ions, attracted to positive anodic sites (Vaishnav et al., 2025).

Synergistic Effects and Molecular Orientation

Synergism of both extracts and mixing with halide salts results in even better efficiency. Co-mixture provides a protective layer combining nitrogen-based chemisorption of bitter leaves with oxygen-based chemisorption/chelation of mango leaves, forming a more stable, compact, desorption-resistant layer. Mixing with iodide ions (KI) yields even higher efficiency (78% to 96% at 500 ppm mango leaf extract in 1 M HCl with 5–10 mM KI), due to preferential adsorption of halide ions creating a negative film that induces electrostatic attraction on inhibitor molecules. MD simulations reveal that active molecules adsorb flat onto the metal surface, maximizing contact and surface coverage per molecule through π-π interactions. Mangiferin shows near-parallel adsorption to Fe(110), allowing four –OH groups and carbonyl oxygen to form coordinative bonds. Vernodalin shows similar planar adsorption, indicating tightly bound film formation. Both extracts provide nearly complete surface coverage at 1000–1500 ppm (García-González et al., 2025; Schappo et al., 2025).

Film Formation Over Time

Film formation occurs in two stages: immediate strong physisorption on highest energy sites, followed by a slow process (hours to days) involving diffusion of inhibitors, intermolecular bonding, and formation of coordinative bonds and complexes. Slow hydrolysis of gallotannins in mango leaves is responsible for increased localized protection within micro-crevices. High concentration of saponins in bitter leaves can cause micellization, reducing inhibitory efficiency due to steric hindrance. In conclusion, mango leaves exhibit stronger chemisorption and chelation, while bitter leaves are stronger with respect to pH-dependent physisorption mechanism (Alam et al., 2025; Zhou et al., 2024).

Challenges and Future Directions

Green corrosion inhibitors such as bitter leaves and mango leaves which possess many phytoconstituents can be effectively utilized for inhibiting the corrosion. Bitter leaves possess alkaloids, saponins, and tannins while the compounds which dominate the mango leaf are mangiferin and gallotannins and the former has the most inhibition efficiency even in strong acid conditions, the later has good performance and stability in the neutral and marine environment due to high thermal stability and excellent performance. For the mild steel, it gives efficiency of about 75-95% for both the extract while mango leaves have better uniformity and stability, bitter leaves are cost-effective and will perform well in the place where the bitter leaves grow. It has been noticed that the combination of these both extract works more efficient than its individual use with efficiency greater than 95% (Nwigwe & Nwoye, 2023; Vijayaram et al., 2023).

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Challenges

As reported by Subbiah et al. (2026), some major challenges need to be overcome before bitter and mango leaf extracts can be implemented on a commercial basis, moving beyond lab scale studies. Technical issues represent one of the most important hurdles. Phyto-chemicals contained within the plant material inherently vary due to factors such as species/cultivar, origin, soil type, climate, time of year and age of the leaf. Inevitably this affects efficiency of corrosion inhibition and batch-to-batch performance may vary from 75-92% for bitter leaves and 86-93% for mango leaves under identical conditions. These values may result in over or under protection when implemented by end users who may be interested in uniform predictable performance (Chowdhury et al., 2023). Long term stability during storage can also represent a significant issue. For bitter leaves extraction losses of between 20-25% after 12 months were measured and attributed to oxidation of phenolic components, hydrolysis of ester-linked gallotannins and saponins, and potential microbial degradation. Another significant issue can involve scalability of the extraction methods. Maceration, commonly used in lab studies, is clearly too inefficient for large-scale operation, Soxhlet extraction uses far too much solvent for commercial applications, and newer techniques such as microwave and ultrasonic extraction need specialized equipment and associated costs to overcome a significant challenge in terms of scalability from the laboratory to industrial volumes (Bilgiç, 2022). A final, major hurdle is that very little has been published concerning these types of extracts when exposed to real, dynamic, multicomponent industrial environments rather than static laboratory conditions and field tests. Both extracts have not undergone sufficient environmental and toxicological evaluation to comply with regulatory requirements and full techno-economic evaluations considering the value chain of activities, from harvesting to dosing, are largely non-existent. Standard quality control procedures, such as defined marker compounds and associated criteria and standards are not available and would be needed for approval and marketing (Ramalingam et al., 2026; Xia et al., 2025).

Discussion and Future Directions

Future research should establish standardized quality control methods, including the identification of marker compounds showing a good correlation to inhibition performance such as total mangiferin for mango leaves, total alkaloids or flavonoids for bitter leaves. High-inhibiting cultivars grown under controlled agronomic conditions or using biotechnological methods such as plant cell culture, would be suitable to guarantee comparable phytochemical compositions. Methods to improve storage stability should be explored (addition of antioxidants, blanketing with inert gases, encapsulation within matrices such as cyclodextrins or bio-degradable polymers, two-part formulations) and their compatibility with industrial processes tested. Optimized scaled-up extraction processes using R.S.M with a view to use water as the only solvent and continuous processes to ensure good economic feasibility; development of practical formulations (concentrated liquids, powders, granules or tablet forms) and formulation methods such as encapsulation for controlled release were required to suit an industrial market (Schappo *e*t al., 2025). Evaluation of inhibitor performance under realistic flow conditions in flow loops or with a rotating cylinder electrode, followed by long term trials under realistic industrial conditions (cooling water systems, oil & gas pipelines, marine corrosion site) were essential; thorough environmental and toxicological testing following recognized guidelines including acute and chronic aquatic toxicity tests, biodegradability tests, human toxicity tests (all required for Safety Data Sheets, SDS, and registration/approval processes) were critical. Synergism between different components, use of computational modelling to support discovery and formulation (DFT, MD, ML). Formulations composed of blends of bitter and mango leaf extracts with additional synergistic components (iodide salts or low concentrations of synthetic inhibitors) would likely constitute a most promising direction, offering over 95% efficiency at total concentrations less than 600 ppm when used alone and effective under diverse conditions (mixed acids, neutral chloride environments and high-temperature conditions. The challenges and future direction of using natural source of inhibition such as mango and bitter leaves are presented in the Figure 2.

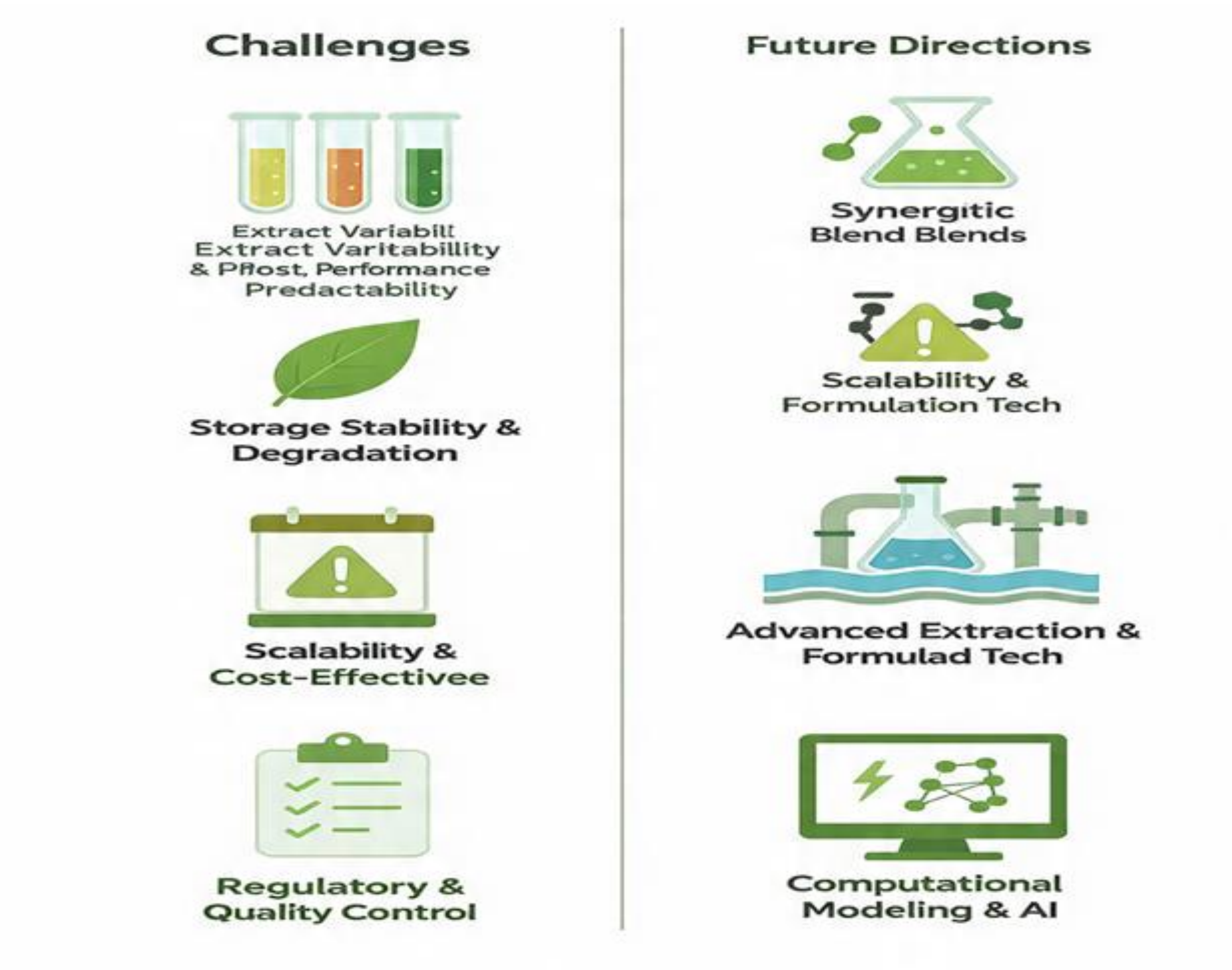

Figure 2: Challenges and future directions for mango and bitter leaves as corrosion inhibition (Alam *et al*., 2025; Binda, 2024)

Conclusion

The reviewed articles strongly established that both bitter leaves (*Vernonia amygdalina*) and mango leaves (*Mangifera indica*) extracts are efficient green corrosion inhibitors for a number of metals especially for mild steel in different corrosive media like acidic and saline environment due to their phytochemicals-flavanoids, tannins, saponins, alkaloids and polyphenols-which gets adsorbs on the surface of the metals forming a protective layer over the metal surface, blocking the active sites and reducing corrosion. Bitter leaves extraction had an efficiency of more than 85% in the optimum conditions while that of mango leaves was found to be 80-90% mainly in hydrochloric acid media. Both bitter and mango leaves extract followed Langmuir isotherm adsorption characteristics indicating the adsorption of a single layer. The inhibitor efficiency increases with the extract concentration while it decreases with increase in temperature. Mango leaves is more thermo-stable compared to bitter leaves extract while bitter leaves are more widely available in tropical regions at lower cost. Although there is evidence for good inhibition efficiency by both the extracts in the laboratory setup, there are still practical hurdles such as extract stability, testing procedure standardizations and application on industrial scale that need to be overcome. Future studies need to be concentrated on combining both the extracts for improved synergistic performance, and performing long-term field test for the extracted inhibitors and computer simulations for optimum molecular interaction. In summary, Bitter leaves and mango leaves extracts are cheapest, ecofriendly and cost-effective substitutes for the currently used synthetic corrosion inhibitors.

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