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REVIEW ARTICLE

SUSTAINABLE CORROSION PROTECTION OF STEEL USING PLANT EXTRACTS: A REVIEW OF NEEM, CASHEW, AND *ZIZIPHUS*-DERIVED INHIBITORS

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ABSTRACT

The increasing demand for environmentally benign corrosion protection methods has led to the exploration of plant-based (green) corrosion inhibitors over toxic and non-renewable synthetic chemicals. This study presents a comprehensive review of empirical studies reported on the application of plant extracts to prevent corrosion of mild and carbon steels in acidic and saline media. Special emphasis is placed on the extracts from Azadirachta indica (neem), Anacardium occidentale (cashew) and Ziziphus species because of their availability, richness in phytochemicals and proven inhibitory performance. A critical review of published studies utilising gravimetric, electrochemical, surface analytical and computational techniques was performed. The results suggest that inhibition efficiencies higher than 80-90% are generally achievable under optimised conditions and adsorption of phytochemicals such as polyphenols, alkaloids, tannins, flavonoids and phenolic lipids is the dominant mechanism. Most of the extracts are mixed type inhibitors following Langmuir, Temkin or Freundlich adsorption isotherms with physisorption and chemisorption processes. Despite their efficacy challenges exist regarding extract stability, standardisation and long-term performance. In general, the review confirms the huge potential of neem, cashew and Ziziphus based inhibitors for sustainable corrosion control in industrial applications.

1.0 Introduction

The use of plant-derived substances as natural corrosion inhibitors for mild steel dates to the 1960s, when tannins and their derivatives were first applied to protect metals such as steel and iron from corrosion (Panchal, *et al.*, 2021). Over time, several reviews have examined the effectiveness of plant-based inhibitors across various environments and conditions (Abdel-Karim and El-Shamy, 2022; El–Maksoud, 2008; Panchal, *et al.*, 2021). Early investigations demonstrated that plant materials such as tobacco stems, twigs, and leaves possess strong anticorrosive properties in highly acidic pickling environments (El Hosary, *et al.*, 1972).

Subsequent studies in the early 1980s extended this understanding to include extracts from black pepper, castor seed, *Acacia* gum, and lignin, which were found to provide excellent protection for steel in acidic solutions (Buchweishaija, 2009). Research by Buchweishaija (2009) and Saleh *et al.* (1982) further evaluated the corrosion inhibition potential of aqueous extracts obtained from *Opuntia ficus indica*, *Aloe eru* leaves, orange peels, mango, and pomegranate. Using gravimetric and polarization methods, these studies revealed that all the plant extracts offered superior inhibition performance in hydrochloric acid compared to sulfuric acid media.

Eddy and Ebenso (2008) assessed the effectiveness of ethanol extracts from *Musa sapientum* (banana) peels on mild steel corrosion in sulfuric acid using gasometric and thermometric techniques. Their results showed that inhibition efficiency increased with higher inhibitor concentration, longer immersion time, elevated temperature, and higher pH levels. Similarly, Buchweishaija (2009) examined the corrosion protection capability of aqueous extracts from *Eucalyptus* leaves in 1 M HCl using mass loss and galvanostatic polarization measurements.

The results showed that the inhibition efficiency increased with increasing of the extract concentration and decreased with decreasing the temperature. The extract behaved as a mixed type inhibitor with a major effect on the cathodic reaction. Furthermore, a study on alkaloids from pomegranate indicated that these compounds were effective in the reduction of mild steel corrosion in sulphuric acid especially at lower temperatures.

Valdez-Salas *et al.* (2021) evaluated *Azadirachta indica* (neem) leaf extract as a green corrosion inhibitor for carbon steel embedded in concrete exposed to chloride (simulated marine) environments. Using long-term exposure tests and electrochemical monitoring, the authors reported that aqueous neem extracts provided sustained corrosion protection (up to ~95% reduction in corrosion tendency over extended exposures under their test conditions) without adversely affecting concrete integrity; the protective action was attributed to adsorption of tannins, terpenoids and other heteroatom-containing phytochemicals that formed a surface film and impeded chloride-induced corrosion processes.

Yee *et al.* (2020) investigated pomelo (*Citrus maxima*) peel extract as a green inhibitor in both simulated seawater (3.5% NaCl) and in dilute hydrochloric acid (0.1 M HCl). Their immersion and electrochemical studies found that an optimal pomelo-peel formulation reduced corrosion rates significantly (reported optimum inhibition efficiencies ≈ 71–75% depending on medium), and that inhibition in saline media was somewhat lower than in the acidic medium; mechanistic analyses (FTIR, PDP, EIS) supported adsorption of polyphenolic/polysaccharide components on the steel surface and Langmuir-type behaviour.

Ashassi-Sorkhabi *et al.* (2015) examined pomegranate (*Punica granatum*) peel extract as an inexpensive green inhibitor for mild steel in hydrochloric acid solutions. Using weight-loss, potentiodynamic polarization and impedance techniques, the authors demonstrated concentration-dependent inhibition with efficiencies rising as extract dose increased; the data indicated that polyphenolic constituents were the active species, adsorption followed common isotherms (e.g., Langmuir/Temkin), and the extract acted primarily as a mixed-type inhibitor in their HCl tests. Odewunmi *et al.* (2015) studied watermelon waste products (peel, seed and rind fractions) as green corrosion inhibitors for mild steel in 1.0 M HCl. The study reported substantial inhibition efficiencies (dependent on fraction and concentration) and found that the active components (amino acids, sugars, and polyphenols) adsorbed onto the metal surface to reduce anodic dissolution and cathodic reaction rates.

The study conducted by the Mamudu *et al.* (2024) focused on investigating a novel method of employing *Dillenia suffruticosa* leaf extract (DSLE) as a corrosion inhibitor for mild steel (MS) immersed in molar hydrochloric acid. Phytochemical constituents believed to contribute to corrosion inhibition were isolated using ethanol extraction with a Soxhlet apparatus. Morphological and chemical changes on the steel surface have been observed using techniques such as scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR). The results revealed that DSLE showed a significant corrosion protection and the efficiency of inhibition was dependent on the extract concentration with the highest value of 81.4% obtained at 1000 mg/L. Electrochemical polarisation studies revealed that the extract acted as a mixed type of inhibitor that retarded both anodic and cathodic reactions in the corrosion process. Other forms of green organic compounds which act as corrosion inhibitors and show excellent properties in protecting metal surfaces are derivatives of chitosan (El-Haddad, *et al*., 2019), hybridisation of neem leaf, bitter leaf and moringa leaf (Aji, *et al*., 2016), Leptadenia hastata (Yadiya) leaves extracts (Maina, *et al*., 2021; Maina, *et al*., 2022), Polyalthia longifolia leaves extract (Zubairu, *et al*., 2021) and many others.

Several studies have investigated neem, cashew and Ziziphus derived extracts individually as green corrosion inhibitors for steel. However, there is a dearth of existing review that has systematically synthesised empirical findings across all three plant genera using a transparent. Thus, the present study aims at filling this gap through a systematic review of empirical studies on the use of neem, cashew and Ziziphus extracts as corrosion inhibitors of steel and iron substrates. The specific objectives are to (i) synthesise and compare reported inhibition efficiencies and mechanisms of the three plant genera, (ii) determine dominant phytochemical classes and adsorption behaviours that are responsible for inhibition, and (iii) highlight recurring operational bottlenecks that limit industrial application. This review is limited to empirical peer-reviewed studies (2000–2025) that quantify the corrosion inhibition performance of neem, cashew and Ziziphus extracts on steel or iron substrates; plant extracts from other genera are not included unless used for baseline comparison, non-metallic substrates, or purely theoretical and opinion-based works. Therefore, the reported ranges of efficiency should be understood to be representative of the performance under the conditions of each of the studies and not values that can be reproduced in general.

2. Methodology

The study was conducted by using literature review approach on empirical studies exploring plant-based corrosion inhibitors for mild steel, carbon steel and related alloys. Relevant peer-reviewed journal articles, review papers, and conference proceedings were identified by searching major scientific databases, such as Scopus and Google Scholar. The steps of study identification, screening, eligibility and inclusion were described using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework Figure 1.

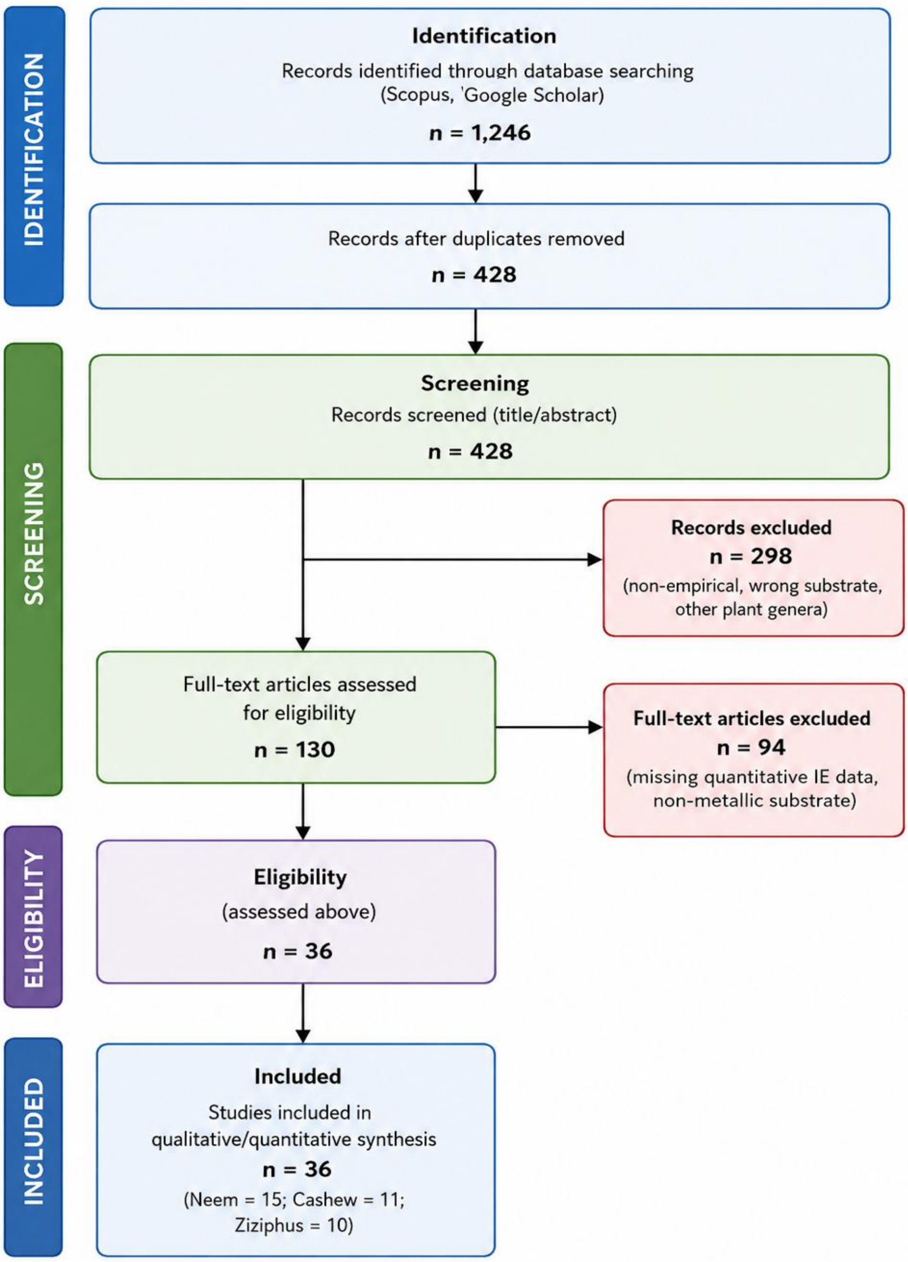

Figure 1: PRISMA flow diagram of study identification, screening, eligibility, and inclusion.

2.1 Study Selection Criteria

To ensure transparency and reproducibility of the review process, explicit inclusion and exclusion criteria were defined, as summarized in Table 1.

2.2 Search Strategy

The following Boolean search strings were applied, with minor syntax adaptations for field-tag conventions, across Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar:

Scopus: TITLE-ABS-KEY((“mild steel” OR “carbon steel” OR “steel” OR “iron”) AND ("corrosion inhibitor*” OR “corrosion protection”) AND (“neem” OR “Azadirachta indica” OR “cashew” OR “Anacardium occidentale” OR “Ziziphus”))

Google Scholar: (“mild steel” OR “carbon steel” OR “iron”) (“corrosion inhibitor”) (“neem” OR “cashew” OR “Ziziphus”) (“weight loss” OR “PDP” OR “EIS” OR “DFT” OR “MD”)

Table 1: Inclusion and exclusion criteria for study selection

Inclusion Criteria	Exclusion Criteria
Peer-reviewed empirical studies published between 2000–2025, with preference given to studies published within the last five years	Non-empirical or opinion pieces (e.g., editorials, commentaries)
Studies using steel or iron substrates	Studies using non-metallic substrates
Studies testing neem (*Azadirachta indica*), cashew (*Anacardium occidentale*), or Ziziphus extracts as corrosion inhibitors	Green inhibitors derived from plant genera other than neem, cashew, or Ziziphus (unless used strictly for baseline comparative context)
Studies reporting quantitative metrics (e.g., weight loss, potentiodynamic polarization (PDP), electrochemical impedance spectroscopy (EIS), surface analysis, DFT/MD simulations)	Studies lacking quantitative inhibition efficiency metrics

3. Results and Discussion

3.1 Empirical Studies on Neem Extract as Corrosion Inhibitor

Several experimental studies had investigated *Azadirachta indica* (neem) extracts as green corrosion inhibitors for carbon/mild steel and related alloys in both acidic and saline/microbially active environments. Early and widely cited experimental work showed that aqueous and organic extracts of neem leaves reduced the corrosion rate of carbon/mild steel in hydrochloric and sulfuric acid media (Nahlé, *et al*., 2010). In that study the inhibition efficiency rose with extract concentration and reached values on the order of ~80–87% at gram-per-litre level concentrations at near-room temperatures, although efficiency was sensitive to temperature. Subsequent work extended neem testing to more complex service environments: Bhola *et al.* (2014) demonstrated that neem leaf extract reduced microbiologically influenced corrosion (MIC) of API-5L X80 line pipe steel exposed to sulphate-reducing bacteria (SRB) consortia in hypersaline media, achieving roughly a ~50% reduction in biocorrosion metrics under their conditions. More recent experimental–computational studies had also reported high inhibition (around 80–90%) for neem extracts in aggressive HCl media and have combined experimental electrochemistry with DFT/MD modelling to probe adsorption and active sites (Kumar, *et al.*, 2022; Sharma, *et al*., 2015). Applied work assessing neem as an inhibitor in reinforced-concrete/chloride-exposed systems had shown promising sustained protection compared with controls in simulated saline environments (Valdez-Salas, *et al*., 2021).

Electrochemical approaches used across the neem-inhibitor literature were standard and complementary. Gravimetric (weight-loss) measurements remained the baseline for corrosion rate determination and temperature/Arrhenius analysis (Nahlé, *et al*., 2010), while potentiodynamic polarization and electrochemical impedance spectroscopy provided mechanistic insight by quantifying corrosion current reductions and increases in charge-transfer resistance when neem extracts are present (Kumar, *et al*., 2022). In microbiologically influenced corrosion settings, electrochemical monitoring was combined with microbiological assays to show reduced biocorrosion activity when neem was applied (Bhola, *et al*., 2014). The observed efficiencies are strongly modulated by temperature and medium. The increase in polarisation resistance and decrease in Icorr with increase in neem concentration have been observed consistently by the methods.

Weight loss, electrochemical and surface characterisation techniques were used to investigate the corrosion inhibition efficiency of neem leaf powder on thermo-mechanically treated steel in 1 M HCl and 1 M NaCl solutions. The results show that the neem extract at the highest concentration significantly reduce the corrosion rate with inhibition efficiencies of 93.26% and 85.94% in the acidic and saline media respectively. Tafel polarisation and EIS results indicated mixed type inhibition behaviour. GC–MS and FTIR analyses were used to identify the phytochemicals and functional groups that contributed to the adsorption on the steel surface (Ahmed & Mohan, 2024). The inhibitive effect of neem leaf extract as an eco-friendly corrosion inhibitor for mild steel in alkaline medium containing 1 wt% Ca(OH)2 and 0.5 wt% NaCl was studied by weight loss, EIS and adsorption isotherm techniques (Baitule and Manivannan, 2025). The results showed that NLE was effective in reducing corrosion, with the maximum inhibition efficiency being about 78%. However, the efficiency decreased by increasing the time of immersion. The Frumkin isotherm was fitted showing spontaneous physisorption. SEM, FTIR, XPS and XRD surface analyses confirmed the formation of a protective inhibitor film and functional groups such as NH2 responsible for adsorption were identified and the disappearance of FeCl2 peaks confirmed the corrosion suppression. Besides the biodegradability, low cost and environmental friendliness, the study also pointed out the advantages of neem for corrosion control.

Surface-analytical results corroborated electrochemical conclusions. SEM/EDS imaging typically displayed smoother, less-damaged metal surfaces and reduced oxide/scale on neem-treated samples; FT-IR spectra of adsorbed films or recovered residues showed characteristic organic bands (O–H, C=O, aromatic C=C) that pointed to polyphenols, terpenoids and other oxygenated phytochemicals as the film-forming species (Valdez-Salas, *et al*., 2021). In reinforced concrete tests the neem-treated rebars showed electrochemical indicators of very low corrosion risk over long exposure times and concrete integrity metrics were not affected.

Published inhibition efficiencies reported for neem extracts span roughly ~50% to ~90% depending on medium, concentration and test conditions: Nahlé *et al.* (2010) reported ~80–87% at ~2.0 $g{\cdot}L^{-1}$ in 1.0 M HCl at ambient/near-ambient temperatures; Kumar *et al.* (2022) reported a peak around ~89% in aggressive HCl tests when combining electrochemical and computational corroboration; Bhola *et al.* (2014) found ~50% reduction in MIC metrics in SRB tests (MIC used different endpoints so percentages were not directly comparable to HCl pickling tests); and Valdez-Salas *et al.* (2021) reported very high long-term protection for rebars in simulated chloride ingress tests (≈95% based on half-cell potential criteria after 182 days under their protocol).

Phytochemical analyses and computations indicated the active classes in neem extracts were limonoids (e.g., azadirachtin and related triterpenoids), flavonoids, tannins and other oxygen-containing polyfunctional molecules. These moieties provided lone pairs/π-electrons (O, sometimes N) that coordinated or strongly adsorbed onto Fe sites; computational studies (DFT/MD) pointed to favourable adsorption energies for certain limonoid/flavonoid moieties and support Langmuir/Temkin adsorption behaviour reported in experiments (Sharma, *et al*., 2015; Kumar, *et al*., 2022). Table 2 provides a summary of related studies for neem as corrosion inhibitor.

Cashew (*Anacardium occidentale* L.) and its industrial by-products most notably cashew nutshell liquid (CNSL) had been investigated extensively as green corrosion inhibitors because they are rich in alkylphenols (cardanol, cardol, anacardic acids), tannins and other polyphenolics that adsorb on metal surfaces and reduce electrochemical attack. Philip *et al.* (2001) examined CNSL as an inhibitor for carbon steel in CO_2-saturated 3% NaCl at 30 °C using AC impedance and potentiodynamic polarization. They reported that 300 ppm of CNSL reduced the corrosion rate by >92%, establishing early evidence that the phenolic constituents of CNSL can provide strong surface adsorption and electrochemical inhibition in chloride/CO_2 environments.

Furtado *et al.* (2019) evaluated CNSL and its distillation residue as inhibitors for API P110 carbon steel in 15% HCl (an aggressive acidizing fluid used in well-stimulation). Using mass-loss, potentiodynamic polarization, linear polarization resistance and EIS across 298–353 K, they found formulations based on CNSL/residue achieving very high inhibition (reported up to ≈99%) at certain compositions and temperatures. The study combined FT-IR, H-NMR and TGA for chemical characterization and used DFT to rationalize active functional groups showing that alkylphenols (cardanol/cardol/anacardic fractions) were principally responsible for adsorption and film formation under acidizing conditions (Furtado *et al*., 2019). This work is important because it demonstrated CNSL can perform even in extremely aggressive HCl at elevated temperatures when properly formulated.

Mohammed and Sobri (2018) reported on cashew nut (kernel) extracts as inhibitors for carbon steel in 1.0 M HCl using weight-loss experiments. They observed a maximum inhibition efficiency of ≈86% after 3 days at 12 $g{\cdot}L^{-1}$, but efficiency fell (≈72.9%) after 12 days, indicating loss of protection with prolonged immersion. Adsorption data in that study fitted a Temkin isotherm and the calculated $\Delta G°$ (~−17.4 $kJ{\cdot}mol^{-1}$) indicated predominately spontaneous physisorption with some exothermic character highlighting the common limitation of crude plant extracts: good short-term performance but reduced long-term stability.

Table 2: Neem as corrosion inhibitor

Study	Metal / alloy	Corrosive medium	Extract type / prep	Concentration range (as reported)	Reported max IE (approx.)	Key techniques used	Adsorption isotherm / mechanism (as reported)
(Oguzie, 2006)	Mild steel	1 M H_2SO_4; 2 M HCl	Aqueous neem extract (maceration)	% w/v varied (paper reports multiple doses)	91–96% (high extract doses in H_2SO_4/HCl)	Gas-volumetric weight loss; kinetics	Freundlich / chemical adsorption dominant; high IE at higher conc.
(Valek and Martínez, 2007)	Copper (relevant for comparison)	0.5 M H_2SO_4	Aqueous neem leaf extract	not large (experimental units)	≈90% for copper	PDP, weight loss	Adsorption / film formation — supports neem's general adsorption behaviour
(Nahlé, *et al.*, 2010)	Carbon steel	1.0 M HCl	Aqueous neem leaf extract (UAE / maceration)	0.02–2.00 $g \cdot L^{-1}$	~80–87% at 2.0 $g \cdot L^{-1}$ (RT)	Weight-loss, PDP, temperature study	Adsorption (surface coverage increases with conc.); temp affects physio/chemisorption
(Okafor and Ebenso, 2010)	Mild steel	HCl / H_2SO_4 acidic media	Various neem extracts (leaves, seeds, roots)	reported several $g \cdot L^{-1}$ / % w/v	Up to ~85–95% depending on part used	Weight loss, gasometrical; some electrochemical	Chemical adsorption proposed; seeds often more active than leaves
(Bhola, *et al.*, 2014)	API-5L X80 pipeline steel (carbon steel)	Hypersaline, SRB (MIC) conditions	Aqueous neem leaf extract	ppm to % (study-specific)	≈50% reduction in MIC metrics; up to ~80% in abiotic controls	Electrochemical monitoring, polarization, impedance, microbiology, surface analysis	Mixed action: adsorption + biocidal/anti-biofilm effects
(Sharma, *et al.*, 2015)	Various metals (compilation)	Various acidic/saline media	Survey of aqueous/ethanolic neem extracts	N/A	Reported range across studies: ~50–90%	Meta-analysis of WL, PDP, EIS studies	Authors conclude mixed adsorption models (Langmuir/Temkin /Freundlich)

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(Valdez-Salas, *et al.*, 2021)	Carbon steel (reinforcing bars)	Simulated saline concrete (chloride ingress)	Aqueous neem leaf macerate (applied in concrete)	applied doses per concrete protocol	Long-term reduction in corrosion tendency — reported ~95% (half-cell potential criteria over 182 days)	Half-cell potential monitoring, chloride tests, concrete integrity	Adsorption/film formation on rebar; effective in concrete matrix
(Kumar, *et al.*, 2022)	Mild steel	High-molarity HCl	Ethanol/aqueous neem extract; experimental + DFT/MD	up to g·L⁻¹ (study units)	≈89% (peak reported)	Gravimetry, PDP, EIS, SEM; DFT & MD simulations	Langmuir / Temkin fits; mixed physisorption/chemisorption;
(Parthipan, *et al.* (2017)	Carbon steel API-5LX / pipeline steels	Hypersaline / MIC conditions (mixed bacterial strains; SRB)	Aqueous neem leaf extract	~150 ppm minimum inhibitory conc. for several strains reported	IE: abiotic ≈81%; mixed consortia ≈72%; large reduction in corrosion rates vs untreated	Weight loss, PDP, EIS, FT-IR, microbiological assays, SEM/XRD	Adsorption + antimicrobial (biofilm suppression) mechanism
(Desai, 2015)	Mild steel	1.0 M HCl	Neem preparations (leaf-based)	up to ~1.25% v/v in some reports	Variable (often 60–85% depending on temp & conc.)	Weight loss (gravimetric)	Langmuir / Freundlich reported in different tests; mixed inhibitor type
(Meza-Castellar, *et al.*, 2017)	Carbon steel & aluminium	3.5% NaCl (simulated seawater)	Aqueous neem leaf powder / macerate	% v/v (e.g., 5%)	~78% (carbon steel in NaCl at 5% extract)	Weight-loss, corrosion rate analysis	Adsorption / film formation; better performance on steel than on aluminium
(Okpala, *et al.*, 2022)	Medium carbon steel	0.5–1.0 M H_2SO_4	Aqueous/ethanolic neem leaf extracts (Soxhlet / maceration)	1–5% v/v (ppm units converted by authors)	70–88% depending on conc./temp	Weight loss, PDP, SEM, FT-IR	Adsorption; IE increases with conc. and immersion time

PDP – Potentiodynamic Polarization, EIS – Electrochemical Impedance Spectroscopy, SEM – Scanning Electron Microscopy, FTIR – Fourier Transform Infrared Spectroscopy, XRD – X-ray Diffraction, RT – Room Temperature, IE – Inhibition Efficiency, ppm – Parts Per Millio

Ezzat *et al.* (2024) approached the thermal-stability problem by green-synthesizing silver nanoparticles (AgNPs) using cashew leaf extract (CLE) as the reducing/stabilizing agent, and testing CLE-AgNPs as inhibitors for mild steel in ASTM D1141 simulated seawater. The CLE-AgNPs showed ~90.5% IE at 40 °C and ≈90% at 80 °C, indicating greatly improved thermal and biochemical stability compared with typical crude extracts; electrochemical (PDP, EIS) and surface (SEM, AFM, FTIR) analyses supported a mixed-type inhibition mechanism and a protective film formation on steel. This demonstrates that nanoparticle formulations derived from cashew extracts can substantially extend applicability into higher-temperature marine environments. Pino *et al.* (2024) investigated the tribocorrosion and corrosion behaviour of CNSL on several alloys (mild steel AISI 1012, stainless steel AISI 420, Al-6061). Their multi-method study (electrochemistry, immersion tests, tribological measurements) found that CNSL not only reduced corrosion current for stainless steel and aluminium but also provided lubricating properties that reduced wear — positioning CNSL as a multifunctional tribocorrosion mitigator in applications subject to combined wear and corrosion. This highlighted the potential of CNSL beyond pure corrosion inhibition.

Other work had examined cashew-derived gums and modified CNSL derivatives. Edoga, *et al.* (2014) reported that cashew gum increased inhibition efficiency with concentration for mild steel in 0.1 M H_2SO_4 and that adsorption followed a Langmuir isotherm. Modified CNSL derivatives have also shown promise in laboratory acidic tests (literature reviews and experimental reports), confirming that chemistry-based modification or formulation of CNSL often enhances thermal stability and adsorption strength versus crude extracts.

Enabulele *et al*. (2023) explored the use of non-edible cashew nutshell as a sustainable source of corrosion inhibitors for seawater on thermo-mechanically treated (TMT) steel. The methanolic extracts of the cashew nutshell were found to contain phytochemicals such as saponins, phenols and terpenoids and were tested for their corrosion inhibition performance. The extract efficiency was evaluated by gravimetric, spectroscopic and electrochemical methods supported by scanning electron microscopy (SEM). The results showed that the extract gave significant corrosion protection with inhibition efficiency over 75% at concentration of 500 ppm and 30 °C for up to 15 days. Spectroscopic analyses (UV–Vis and FTIR) revealed that inhibition mainly occurs through an adsorptive mechanism, where there are interactions between oxygen atoms and aromatic rings present in the constituents of the extract. However, efficiency decreased slightly on increase of temperature and the results of SEM and FTIR confirmed the adsorption of the components of the extract on the surface of the steel. Finally, the study proved that cashew nutshell extract could be used as an environmentally friendly and efficient corrosion inhibitor for TMT steel in marine environments.

Together with other cashew fractions CNSL is empirically among the most effective plant derived inhibitors. High IEs (often > 80-90%) can be achieved in chloride/CO2 and strongly acidic (HCl) media where CNSL is properly formulated. The remaining challenges are standardisation of extraction/formulation methods, enhancement of long-term stability in continuous service and deeper molecule level identification of the most active constituents. Some empirical studies reporting on cashew extracts as corrosion inhibitors are summarised in Table 3.

3.3 Empirical Studies on Ziziphus Species as Corrosion Inhibitors

Mauro *et al.* (2021) evaluated an aqueous extract of *Ziziphus joazeiro* stem bark and a high-molecular-weight fraction (HMWF) as inhibitors for mild steel in 1.0 M HCl. Gravimetric, potentiodynamic polarization and electrochemical impedance spectroscopy showed that inhibition efficiency increased with inhibitor concentration (100–800 mg·L^{-1}), reaching gravimetric IEs ≈ 85–93% and impedance IEs up to ≈94.7% for the HMWF. Surface analyses (SEM, XPS) and LC-HRMS characterization supported formation of an adsorbed protective film and identified molecular constituents responsible for adsorption; the authors concluded that saponin-like and other high-molecular-weight components were central to the observed mixed-type inhibition.

Shivakumar and Mohana (2012) studied *Ziziphus mauritiana* leaf extracts on mild steel corrosion in 0.5 M H_2SO_4 and 0.5 M HCl using weight-loss, polarization and EIS methods. They reported good inhibition in both acids with inhibition decreasing as temperature rose; polarization data indicated mixed-type behaviour and impedance showed that charge-transfer resistance increased with extract concentration. Thermodynamic parameters were calculated, and SEM was used to examine the protective adsorbed film, leading the authors to propose an adsorption-based inhibition mechanism predominantly governed by physical adsorption of flavonoids and phenolics.

Table 3: Studies on cashew extracts as corrosion inhibitor

Study	Cashew part/form	Metal / Alloy	Corrosive medium	Concentration / range	Reported max IE (%)	Techniques used	Adsorption isotherm / Key finding
(Philip, *et al.*, 2001)	CNSL	Carbon steel (SAE 1008)	3% NaCl saturated with CO_2, 30 °C	10–300 ppm	>92% at 300 ppm	AC impedance, PDP	Strong adsorption by phenolic components; effective in CO_2/Cl^- environment
(Furtado, *et al.*, 2019)	CNSL and distillation residue (R)	API P110 carbon steel	15% HCl (acidizing fluid), 298–353 K	Various organic formulations	≈99% (best formulations at elevated T)	Mass loss, PDP, LPR, EIS; FTIR, ¹H-NMR, TGA; DFT	High IE maintained at elevated T; alkylphenols (cardanol/cardol) drive adsorption/film formation
(Mohammed and Sobri, 2018)	Cashew nut (kernel) extract	Carbon steel	1.0 M HCl	4–12 $g·L^{-1}$; immersion up to 12 days	86% (3 days, 12 $g·L^{-1}$); 72.9% (12 days)	Weight loss	Temkin isotherm; $\Delta G°ads \approx -17.4$ $kJ·mol^{-1}$ → mainly physisorption; decline over time noted
(Ezzat, *et al.*, 2024)	Cashew leaf extract → green AgNPs (CLE-AgNPs)	Mild steel	Simulated seawater (ASTM D1141)	0.1–0.3 $g·L^{-1}$ (AgNPs)	90.5% (40 °C); 90.0% (80 °C)	PDP, EIS, SEM, AFM, FTIR	CLE-AgNPs give thermal stability; mixed-type inhibition; reduced surface roughness
(Pino, *et al.*, 2024)	CNSL (raw/extracted)	AISI 1012, AISI 420, AA6061	Various (chloride-containing acids; tribocorrosion tests)	Not specified (concentration-dependent)	Variable by alloy; positive inhibition trends	Electrochemical, immersion, tribological tests, SEM	CNSL provides corrosion inhibition + lubricating effects — multifunctional tribocorrosion mitigation
(Pino, *et al.*, 2024)	Cashew gum (exudate)	Mild steel	0.1 M H_2SO_4	Variable	Concentration-dependent increases	Gravimetric (weight loss)	Langmuir isotherm; physisorption dominant

Al-Turkustani *et al.* (2010) investigated aqueous and alcoholic extracts of *Ziziphus spina-christi* against mild-steel corrosion in 1.0 M H_2SO_4 (10% EtOH) using hydrogen-evolution, weight-loss, PDP and EIS. Their results showed that the extracts reduced corrosion by retarding both anodic and cathodic reactions (mixed inhibition) and that adsorption obeyed a Langmuir isotherm. Charge transfer is what causes inhibition, while higher concentration of extract increases the protection according to the authors.

Natarajan and Zahir (2021) have produced a biomass-derived product using Ziziphus spina-christi as a protective agent to protect aluminum and other metals in acidic media. In the publication Chemosphere, they used gravimetric studies, PDP, and EIS to mathematically analyse the dynamic of the protective process on the thermodynamic and surface levels. The outcomes showed that the inhibition depends on the concentration which complies with Langmuir adsorption theory and confirmed the practical implementation of the process as exothermic. The researchers introduced and explained the plant as a promising biomass for creating inhibitors in terms of sustainable and scalable feedstock.

Shahryari and Gheisari (2023) investigated the synergistic effects of adding Zn2+ and studied the role of Ziziphus spina-christi leaf extract in NaCl (saline) medium. The electrochemical tests showed higher performance of mild steel protection in 3.5% NaCl solution due to the combination of Zn2+ and the extract than with the extract used separately. The mechanism of the process was deduced based on the behaviour of the adsorbed layer being more stable in the presence of the zinc cations thus allowing the formation of the protection coating in saline environment being more effective.

Table 4 provides overview of some studies that investigated the use of Ziziphus species as green inhibitors.

Table 4: Use of Ziziphus species for inhibition

Study	***Ziziphus* species & part**	**Metal / alloy**	**Corrosive medium**	**Techniques**	**Reported max IE (%)**	**Key point**
(Jmiai, *et al.*, 2018)	*Zizyphus lotus* (pulp / shell)	Copper	1.0 M HCl (natural seawater tests discussed)	Weight loss, PDP, EIS, AAS, SEM	~90–93% (reported for some conditions)	Pulp/shell extracts markedly reduced copper corrosion in acidic chloride media; FTIR/SEM confirmed adsorption film formation.
(Dubey, *et al.*, 2016)	*Ziziphus jujuba* (stem, fruit)	Mild steel	1.0 M HCl (303–333 K)	Weight loss, thermodynamic analysis	Stem ≈78.1%; Fruit ≈68.6%	IE increased with concentration, decreased with temperature; adsorption followed Langmuir isotherm, suggesting physisorption.
(Natarajan and Zahir, 2021)	*Ziziphus lotus* (leaves/pulp)	Copper	Natural seawater & acidic media	Weight loss, polarization, SEM	~93% (reported for some seawater conditions)	Z. lotus extracts lowered corrosion currents and reduced surface damage on copper in seawater tests.
(Shahryari and Gheisari, 2023)	*Ziziphus jujuba* (leaves)	Mild steel	0.5 M H_2SO_4	Weight loss, PDP	~>90% reported in some conditions	Alcoholic/acid extracts showed high inhibition and temperature-resistant behaviour in the reported experiments.

4. Conclusion

The present review confirms the efficiency of neem, cashew and Ziziphus derived extracts as green corrosion inhibitors for steel in acidic and saline media, several formulations showing inhibition efficiencies between 85-99%. Polyphenols, flavonoids, tannins, alkylphenols (cashew: cardanol/cardol) and terpenoids/limonoids (in neem) are the major active phytochemical classes common to the three genera. They adsorb onto the steel surface via lone-pair and π-electron interactions to form protective films. Most of the inhibitors are mixed-type and obey Langmuir, Temkin or Freundlich isotherms, indicating the combination of physisorption and chemisorption. Besides these efficiencies, three operational bottlenecks tend to re-emerge, i.e., thermal instability, with protection frequently declining at elevated temperatures unless nanoparticle or hybrid formulations are employed; degradation of inhibition over prolonged immersion time, with crude extracts often losing efficiency beyond a few days; and the absence of standardised extraction, concentration and testing protocols, limiting cross-study comparability. Future work should involve trials of the industrial scale-up under real service conditions, more use of computational DFT/MD screening to select and optimise the most active molecular building blocks, and further development of nanoparticle-enhanced and hybrid formulations for improved thermal and long-term stability. Bridging these gaps is vital for the transition of neem, cashew and Ziziphus based inhibitors from laboratory scale demonstrations to real-time industrial corrosion-control applications.

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