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Evaluation of Corrosion Inhibition Properties of Natural Organic Compounds on Mild Steel

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Abstract

Corrosion of mild steel in acidic media is a persistent problem in pickling, cleaning, oil-and-gas, chemical-processing and maintenance operations. The environmental and toxicological limitations of many conventional inhibitors have encouraged the evaluation of naturally occurring organic molecules as sustainable surface-protective agents. This methodology paper presents a comparative framework for evaluating tannic acid, gallic acid, quercetin and L-ascorbic acid as model natural organic corrosion inhibitors for mild steel in 1 M hydrochloric acid. The protocol integrates gravimetric weight-loss measurements, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), adsorption-isotherm analysis, Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). Inhibitor concentrations of 100-500 mg L−1 and temperatures of 298-328 K are proposed, with triplicate measurements and matched solvent controls. Corrosion rate, inhibition efficiency, charge-transfer resistance, double-layer capacitance and corrosion-current density are used as primary response variables. A transparent illustrative dataset demonstrates the statistical and mechanistic interpretation expected from the framework: increasing inhibitor concentration should reduce mass loss and corrosion-current density, increase charge-transfer resistance and promote surface-film formation. Tannic acid and quercetin are expected to show strong adsorption because of multiple aromatic rings and oxygen-containing donor sites, whereas gallic and ascorbic acids provide smaller but highly polar adsorption structures. The methodology provides a reproducible basis for screening natural organic compounds before scale-up to industrial corrosion-control applications.

Introduction

Mild steel is widely used because of its low cost, mechanical strength and ease of fabrication, but it is vulnerable to aggressive acidic solutions employed during descaling, acid pickling and chemical cleaning. In hydrochloric acid, anodic iron dissolution and cathodic hydrogen evolution proceed rapidly unless a protective barrier is introduced. Organic inhibitors work primarily by adsorption: electron-rich heteroatoms, π systems and polar functional groups interact with the metal/solution interface and reduce the number of active corrosion sites. Plant-derived substances and isolated phytochemicals have therefore become important candidates for environmentally compatible corrosion control [1-3].

Natural organic compounds are attractive because many contain phenolic hydroxyl groups, conjugated aromatic rings and oxygen-rich functional groups capable of donating electron

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density or participating in Fe-organic surface complexes. Tannic acid and gallic acid are polyphenolic compounds; quercetin is a flavonoid with a larger conjugated framework; and L-ascorbic acid is a naturally occurring antioxidant that can modify electrochemical reactions at steel interfaces. Earlier work demonstrated synergistic inhibition by tannic and gallic acids on mild steel [4], theoretical and electrochemical benefits associated with quercetin [5,6], and measurable inhibition by ascorbic acid in steel systems [7,8].

The main methodological challenge is that inhibition efficiency can appear different when assessed by mass loss, polarization or impedance because each technique probes a different time scale and corrosion response. In addition, inhibitor solubility, temperature, surface preparation and adsorption equilibrium strongly affect the outcome. Consequently, a reliable evaluation must combine independent methods, control the test environment and interpret electrochemical results together with adsorption and surface evidence. The objective of this paper is to establish such a comparative protocol for natural organic compounds on mild steel and to define the calculations, quality controls and decision criteria needed for reproducible inhibitor screening.

Literature Review

Green corrosion-inhibitor research has moved from simple plant-extract screening toward integrated electrochemical, surface and computational investigations. Reviews published through 2022 emphasize that fruit, vegetable and botanical extracts contain alkaloids, tannins, flavonoids, phenolics and related oxygen- or nitrogen-bearing molecules that can adsorb on metallic surfaces and impede charge transfer [1,3]. Sonneratia caseolaris leaf extract, for example, produced high inhibition in 1 M HCl when assessed by weight loss and electrochemical techniques, supporting the value of natural organic constituents in acid corrosion control [2].

Studies on individual polyphenolic molecules are especially relevant to a controlled comparative methodology. Obot and Madhankumar [4] showed that tannic acid inhibited mild-steel corrosion and that adding gallic acid enhanced the protective effect, while adsorption behavior and EIS supported film formation at the interface. Quercetin has also attracted interest because its aromatic and hydroxyl-rich structure can interact strongly with iron surfaces. Dehghani et al. [5] combined electrochemical, surface, density-functional-theory and molecular-simulation approaches to explain quercetin-assisted protection of mild steel, while Baildya et al. [6] demonstrated theoretically that quercetin and related structures possess favorable electronic characteristics for adsorption on Fe surfaces.

Ascorbic acid represents a different class of natural molecule: it is smaller, water-soluble and redox-active. Ferreira et al. [7] evaluated L-ascorbic acid on mild steel using electrochemical methods, and Argiz et al. [8] later examined it as a green inhibitor for steel reinforcement in chloride-contaminated cement mortar. These studies indicate that naturally occurring molecules can influence both anodic and cathodic processes, but their effectiveness depends strongly on medium chemistry and dosage.

The broader plant-extract literature also identifies experimental practices that improve reliability. Mango-leaf extract studies combined electrochemical data with molecular dynamics and quantum calculations [9]; lemon-balm extract was examined through similarly integrated experimental and computational methods [10]. Glycyrrhiza glabra extract produced substantial protection in 1 M HCl and was characterized using multiple scales of analysis [11], whereas sunflower-seed-hull extract demonstrated that agricultural waste can serve as a low-cost inhibitor source [12]. Longan seed and peel investigations linked corrosion behavior with both experimental and theoretical evidence [13], while Ziziphus joazeiro stem-bark extract [14] and white-tea extract [15] reinforced the importance of concentration-dependent adsorption and surface-film formation. Taken together, the literature supports a multi-technique protocol that compares standardized natural molecules under identical conditions rather than relying on a single extract or single measurement method.

Methodology

1. Materials and experimental design

Commercial mild steel coupons are proposed with an approximate composition typical of low-carbon steel (Fe balance, C ≤0.20 wt%, Mn ≤1.0 wt%, with minor Si, P and S). Coupons of approximately 20 × 20 × 1 mm are mechanically polished using successive SiC papers (320-1200 grit), rinsed with distilled water, degreased with acetone, dried and weighed to ±0.1 mg. Fresh 1 M HCl is prepared from analytical-grade acid and deionized water. Four natural organic compounds—tannic acid (TA), gallic acid (GA), quercetin (QT) and L-ascorbic acid (AA)—are

tested at 100, 200, 300, 400 and 500 mg L−1. Quercetin is first dissolved in a minimal ethanol volume and diluted into acid so that ethanol remains ≤1% v/v; an identical ethanol concentration is added to the corresponding blank.

A randomized factorial screening design is used for inhibitor identity and concentration at 298 K. The temperature effect is then studied at 298, 308, 318 and 328 K for the blank and a selected high-performance concentration. All gravimetric and electrochemical measurements are conducted in triplicate. Glassware is acid-cleaned and rinsed thoroughly, while solutions are freshly prepared to minimize oxidation or degradation of the natural compounds. The design is intentionally standardized so that differences in inhibition efficiency arise principally from inhibitor chemistry and concentration rather than coupon history or uncontrolled solution conditions.

Figure 1. Experimental workflow for evaluating corrosion inhibition properties of natural organic compounds on mild steel.

Table 1. Comparative properties and roles of the selected natural organic inhibitors.

Inhibitor	Natural class / key groups	Proposed concentration	Expected interfacial role
Tannic acid (TA)	Polyphenol; multiple phenolic –OH and aromatic rings	100-500 mg L−1	Multidentate adsorption and Fe-tannate-type protective film
Gallic acid (GA)	Phenolic acid; 3 –OH + –COOH	100-500 mg L−1	Polar adsorption; may enhance polyphenol packing
Quercetin (QT)	Flavonoid; conjugated aromatic system + carbonyl/–OH	100-500 mg L−1	Strong π-electron and oxygen-donor interaction with Fe surface
L-Ascorbic acid (AA)	Natural antioxidant; enediol/lactone oxygen sites	100-500 mg L−1	Adsorption/redox modification of anodic and cathodic reactions

2. Gravimetric measurements

For weight-loss measurements, each coupon is immersed in 100 mL of uninhibited or inhibited 1 M HCl for 6 h at 298 K. After immersion, corrosion products are removed consistently, the coupon is rinsed, dried and reweighed. The mass loss Δm is recorded and converted to corrosion rate. For a coupon area A, exposure time t and steel density ρ, the corrosion rate can be expressed as $CR = K\Delta m/(A\ t\ \rho)$, where K is the unit-conversion constant. Inhibition efficiency from mass loss is calculated as $\eta WL(\%) = [(CR0 - CRi)/CR0] \times 100$, where CR0 and CRi are corrosion rates in the blank and inhibited solutions, respectively. Surface coverage is approximated as $\theta = \eta WL/100$. This approach supplies an integrated corrosion response over several hours and serves as an independent check on electrochemical measurements.

3. Electrochemical measurements

Electrochemical tests are performed in a conventional three-electrode cell using mild steel as the working electrode, a platinum counter electrode and Ag/AgCl (or saturated calomel) as the reference electrode. The exposed steel area is fixed at 1 cm^2. After 30-45 min open-circuit stabilization, EIS is collected over approximately 100 kHz to 10 mHz using a 10-mV sinusoidal perturbation. Nyquist data are fitted to an Rs-(Rct||CPE) equivalent circuit. Inhibition efficiency is calculated from charge-transfer resistance as $\eta EIS(\%) = [(Rct,i - Rct,0)/Rct,i] \times 100$. The effective double-layer capacitance is expected to decrease when organic molecules replace interfacial water and form a thicker, lower-dielectric adsorption layer.

Potentiodynamic polarization is conducted from about −250 to +250 mV relative to the stabilized open-circuit potential at a scan rate near 0.5-1.0 mV s−1. Tafel extrapolation provides corrosion potential (Ecorr), corrosion-current density (icorr), and anodic/cathodic slopes. Polarization inhibition efficiency is $\eta PDP(\%) = [(icorr,0 - icorr,i)/icorr,0] \times 100$. If Ecorr shifts by less than roughly 85 mV relative to the blank while both

anodic and cathodic branches are affected, the compound is interpreted as a mixed-type inhibitor rather than a purely anodic or cathodic inhibitor.

4. Adsorption, spectroscopic and surface analysis

Adsorption behavior is evaluated using Langmuir, Temkin and Freundlich relationships, with the model giving the highest physically reasonable fit and coefficient of determination selected for interpretation. For Langmuir behavior, C/θ is plotted against C. Apparent adsorption equilibrium constants may be used to estimate standard free energy of adsorption, while temperature-dependent corrosion rates permit Arrhenius analysis of activation energy. FTIR spectra of inhibitors before exposure and surface films recovered after immersion are compared for shifts in O–H, C=O and aromatic bands. SEM images are acquired for freshly polished steel, blank-corroded steel and optimally inhibited steel. A smoother inhibited surface with fewer pits, together with higher Rct and lower icorr, is regarded as convergent evidence for protective adsorption.

5. Statistical treatment and quality assurance

Triplicate results are reported as mean ± standard deviation. One-way or two-way ANOVA is used to evaluate concentration and inhibitor effects, followed by an appropriate post-hoc test at $p < 0.05$. Relative standard deviation should preferably remain below 5% for replicate electrochemical and weight-loss measurements. Instrument calibration, fresh solution preparation, matched solvent blanks, identical coupon preparation and repeated blank controls are included as quality-assurance steps. A compound is considered a strong screening candidate when high inhibition efficiency is reproduced by at least two independent techniques and is supported by surface evidence rather than by a single favorable measurement.

Results

Because this paper defines a methodology rather than reporting newly performed laboratory experiments, the numerical values below are an internally consistent demonstration dataset used only to show how the proposed analysis should be reported. They must be replaced by measured laboratory values before the paper is presented as original experimental research.

The demonstration dataset shows the expected concentration-dependent behavior of adsorbing organic inhibitors. For the blank, the corrosion current is high and the charge-transfer resistance is low. Increasing inhibitor concentration reduces the active area for iron dissolution and hydrogen evolution, producing a lower gravimetric corrosion rate and lower icorr together with a larger Rct. At 500 mg L−1, tannic acid gives the strongest model response, followed by quercetin, gallic acid and ascorbic acid. This ranking is chemically plausible because larger polyphenolic/conjugated structures offer more adsorption sites and greater surface coverage, consistent with trends reported for tannic/gallic systems and quercetin-based inhibition [4-6].

Table 2. Illustrative comparative performance at 500 mg L−1 in 1 M HCl (methodology-demonstration data).

System	CR (mm y−1)	ηWL (%)	icorr (μA cm−2)	ηPDP (%)	Rct (Ω cm^2)	ηEIS (%)
Blank	2.36	—	815	—	44	—
Tannic acid	0.18	92.4	60	92.6	590	92.5
Quercetin	0.23	90.3	74	90.9	505	91.3
Gallic acid	0.34	85.6	119	85.4	315	86.0
L-Ascorbic acid	0.46	80.5	160	80.4	225	80.4

Agreement among ηWL, ηPDP and ηEIS in Table 2 is the principal validity check. A difference of only a few percentage points among the techniques would indicate that the inhibitor ranking is not an artifact of one measurement method. For tannic acid, the model increases in Rct from 44 to 590 Ω cm^2 and the reduction of icorr from 815 to 60 μA cm−2 correspond to approximately 92% inhibition by both electrochemical calculations. The expected depressed semicircle in the Nyquist plot would enlarge as inhibitor concentration increases,

whereas the fitted interfacial capacitance would decline. Such behavior is consistent with adsorption-driven replacement of water/chloride species by organic molecules at the steel surface.

A Langmuir-type plot with a coefficient of determination near unity would suggest that the first approximation of monolayer surface coverage is useful, although real organic adsorption can involve lateral interactions, multiple active components and heterogeneous steel sites. The TA-GA literature specifically reports enhanced interfacial protection and a Langmuir-like adsorption response [4]. For quercetin, conjugation and multiple hydroxyl groups can support electron donation and surface interaction [5,6]. The ascorbic-acid response is expected to be more sensitive to solution chemistry and oxidation state [7,8]. SEM should therefore show severe roughening and pits on blank-exposed steel, while inhibited surfaces should retain more of the polishing texture and exhibit a more continuous organic/iron-containing film.

Conclusion and Discussion

The proposed framework provides a systematic method for evaluating natural organic compounds as corrosion inhibitors for mild steel in acidic service. Its central strength is methodological triangulation: weight loss measures cumulative metal loss, polarization quantifies corrosion kinetics, EIS probes the interfacial barrier, adsorption models describe surface coverage, and FTIR/SEM provide chemical and morphological evidence. Using these techniques under standardized conditions reduces the risk of assigning inhibitor performance from a single measurement. The literature up to 2022 supports the expectation that natural polyphenols, flavonoids, antioxidants and plant-derived organic constituents can reduce mild-steel corrosion through adsorption and film formation [1-3,9-15]. Tannic acid, gallic acid and quercetin are particularly useful model compounds because their structures contain multiple oxygen donor sites and aromatic systems, whereas L-ascorbic acid provides a contrasting small redox-active molecule. The demonstration analysis predicts concentration-dependent inhibition and mixed-type electrochemical behavior, but these numerical values are not presented as experimental observations. Actual publication-quality conclusions should be based on measured replicate data, statistical significance, surface characterization and transparent reporting of specimen composition, inhibitor purity and solution preparation. For future work, the protocol can be extended to inhibitor mixtures, plant extracts standardized by chromatographic analysis, saline or CO2-containing environments, longer immersion periods and elevated temperatures. Biodegradability, toxicity, cost and compatibility with downstream industrial processes should be evaluated alongside inhibition efficiency. This combination of electrochemical performance, surface evidence and sustainability criteria can help identify natural organic compounds that are not merely effective in short laboratory tests but are practical candidates for greener corrosion-control technologies.

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