

Green Corrosion Inhibition of Mild Steel in an Acidic Medium Using Aglaonema Leaf Extract and Its Synergistic Blends with Orange Peel and Grape Seed Extracts: Electrochemical, Surface, and DFT Studies

Bhavana V

bhavanavirupakshakt@gmail.com

Vidyavardhaka College of Engineering

Anitha Sudhir

Vidyavardhaka College of Engineering

P T Sowmya

Vidyavardhaka College of Engineering

S K Giridarshan

Vidyavardhaka College of Engineering

Ameena Kousar

Vidyavardhaka College of Engineering

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Green Corrosion Inhibition of Mild Steel in an Acidic Medium Using Aglaonema Leaf Extract and Its Synergistic Blends with Orange Peel and Grape Seed Extracts: Electrochemical, Surface, and DFT Studies

Bhavana V¹, Anitha Sudhir¹, Sowmya P T¹, Giridarshan S K¹ and Ameena Kousar¹

¹Department of Chemistry, Vidyavardhaka College of Engineering, India

Corresponding address; Email address: bhavanavirupakshakt@gmail.com, Tel: +918088684083.

Abstract

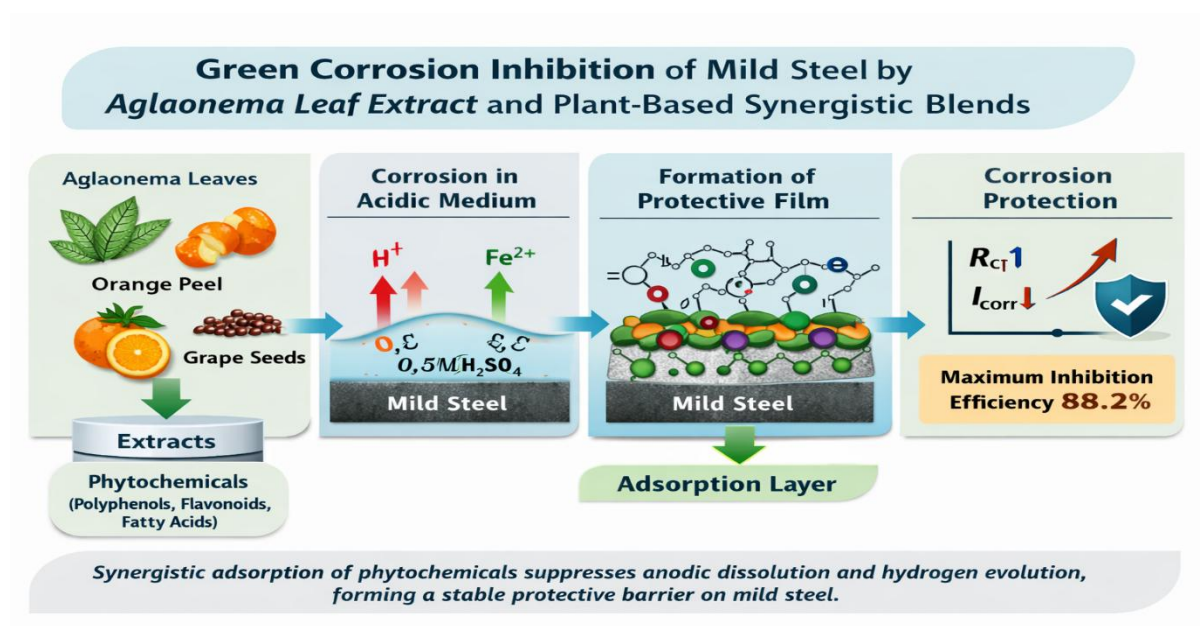
The corrosion protection ability of a green inhibitor system derived from Aglaonema leaf extract and its synergistic mixtures with orange peel and grape seed extracts was examined for mild steel in 0.5 M H₂SO₄ acid medium. The inhibition performance was assessed through weight-loss experiments, open-circuit potential monitoring, potentiodynamic polarization, and electrochemical impedance spectroscopy after immersion durations of 24 and 48 h.

The findings revealed that inhibition efficiency increased with inhibitor concentration. Among the studied systems, the leaf–peel blend exhibited the highest protection efficiency, reaching 88.2% after 24 h of exposure. Polarization results suggested that the inhibitor behaves as a mixed-type inhibitor, suppressing both anodic metal dissolution and cathodic hydrogen evolution processes. Electrochemical impedance measurements showed a noticeable rise in charge-transfer resistance accompanied by a reduction in double-layer capacitance, indicating the development of a dense protective adsorbed film at the metal–electrolyte interface.

Surface characterization by scanning electron microscopy and metallurgical analysis showed substantial reduction in corrosion damage in inhibited systems. FTIR and GC–MS analyses identified oxygen-containing organic compounds responsible for adsorption, while Density Functional Theory calculations correlated molecular electronic properties with adsorption tendency.

Overall, the synergistic plant-based formulation provides efficient and eco-friendly corrosion protection, offering a sustainable alternative to conventional synthetic inhibitors for acidic industrial environments.

Graphical Abstract



Keywords

Aglaonema extract, corrosion inhibition, DFT, Electrochemical techniques, FTIR, GC-MS, mild steel, SEM, stereomicroscopy, sulfuric acid, weight-loss method

Abbreviations

C_{dl}	Double-layer capacitance
CR	Corrosion rate
DFT	Density functional theory
E_{corr}	Corrosion potential
EIS	Electrochemical impedance spectroscopy
FTIR	Fourier transform infrared spectroscopy
GC-MS	Gas chromatography–mass spectrometry
H_2SO_4	Sulfuric acid
I_{corr}	Corrosion current density
IE (%)	Inhibition efficiency
OCP	Open-circuit potential
R_p	Polarization resistance
R_{ct}	Charge-transfer resistance
SEM	Scanning electron microscopy

β_a	Anodic Tafel slope
β_c	Cathodic Tafel slope.

Introduction

Mild steel remains one of the most widely used engineering materials due to its favourable mechanical properties, availability, and economic advantages. However, its performance deteriorates significantly in acidic environments commonly encountered during industrial processes such as pickling, descaling, oil well acidification, and chemical manufacturing [1][2]. In sulfuric acid media, corrosion occurs through coupled anodic dissolution of iron and cathodic hydrogen evolution reactions, resulting in material degradation, operational inefficiencies, and increased maintenance expenditure [3].

Among available mitigation strategies, use of corrosion inhibitors represents a practical and cost-effective method for controlling acid-induced metal deterioration. Traditional inhibitors are typically synthetic organic compounds containing heteroatoms and aromatic structures that facilitate adsorption onto the metal surface. Despite their effectiveness, many of these chemicals pose environmental and health concerns due to toxicity, persistence, and limited biodegradability [4].

Growing environmental concerns and stricter regulatory standards have encouraged the adoption of sustainable corrosion mitigation strategies consistent with green chemistry concepts [5]. In this regard, plant-based extracts are gaining attention as effective and renewable alternatives due to their rich phytochemical content. Compounds such as alkaloids, flavonoids, tannins, terpenoids, saponins, and various phenolic substances contain heteroatoms and π -electron structures that enable strong interaction with metal surfaces [6]. These constituents attach to the steel surface through electrostatic forces and coordination-type interactions, leading to the formation of a compact protective film. This adsorbed layer suppresses interfacial electron transfer processes and consequently decreases the rate of corrosion in acidic environments [7][8].

Although numerous plant-derived extracts have been reported as green corrosion inhibitors for mild steel in acidic media, most studies primarily emphasize inhibition efficiency without providing detailed molecular-level interpretation of adsorption phenomena. In particular, the synergistic interactions within blended phytochemical systems remain inadequately explored, especially regarding cooperative interfacial adsorption, electron-transfer mechanisms, and structure–activity relationships. While individual plant extracts such as leaf, peel, or seed

derivatives have demonstrated promising corrosion protection, a systematic integration of thermodynamic adsorption parameters with electrochemical behaviour and quantum chemical descriptors is still limited. Establishing such a correlation is crucial for understanding how molecular structure, functional group distribution, and electronic properties collectively govern synergistic corrosion inhibition [9][10][11].

In this context, the present study elucidates the cooperative adsorption behaviour of Aglaonema leaf extract blended with orange peel and grape seed extracts in sulfuric acid medium. By integrating electrochemical analysis, surface characterization, thermodynamic evaluation, and Density Functional Theory (DFT) calculations, this work establishes a comprehensive mechanistic framework linking molecular electronic structure to macroscopic corrosion inhibition performance.

The corrosion inhibition performance of the Aglaonema leaf extract and its synergistic blends was evaluated in 0.5 M H_2SO_4 using electrochemical and surface analytical techniques. Furthermore, DFT calculations were employed to correlate molecular reactivity parameters with experimentally observed inhibition efficiencies, thereby providing mechanistic justification for the synergistic behaviour of the blended system.

Accordingly, this study aims to elucidate the synergistic corrosion inhibition mechanism of Aglaonema leaf extract and its blends with orange peel and grape seed extracts in sulfuric acid medium through integrated electrochemical, surface, thermodynamic, and quantum chemical analysis.

Materials and Methods

Materials

Mild steel samples were employed as the working electrodes in all corrosion studies. The chemical composition of the alloy (wt.%) was primarily iron, with minor amounts of carbon, manganese, silicon, phosphorus, and sulphur.

A 0.5 M H_2SO_4 solution served as the corrosive medium. The electrolyte was prepared using analytical-grade reagents and double-distilled water. A freshly prepared solution was used for each experiment to ensure consistency and reproducibility.

Plant materials used for inhibitor extraction were thoroughly washed, air-dried under ambient conditions, and processed according to standard extraction procedures before use.

Experimental Procedure

Preparation of Mild Steel Specimens

Mild steel samples were utilized for both weight-loss (gravimetric) analysis and electrochemical measurements. Rectangular coupons were fabricated from steel sheets, with dimensions adjusted according to the requirements of each experimental technique. The material composition was predominantly iron, containing small proportions of carbon, manganese, silicon, phosphorus, and sulphur.

Before testing, the specimen surfaces were sequentially abraded using silicon carbide (SiC) papers of increasing fineness (400–1500 grit) to achieve a uniform, smooth finish. Progressive polishing ensured the removal of oxide layers and surface irregularities, thereby providing a consistent and reproducible metallic surface for analysis [12].

After mechanical polishing, the specimens were thoroughly washed with distilled water to eliminate any remaining abrasive particles, degreased with acetone to remove surface impurities, and then allowed to air-dry under laboratory conditions [13].

For the electrochemical measurements, only a specific exposed area of each sample was brought into contact with the test solution, while the rest of the surface was carefully sealed to prevent unwanted interaction with the electrolyte. Freshly prepared specimens were utilized for each experimental trial to ensure reliability and precision of the results.

Preparation of Electrolyte Solution

An aqueous sulfuric acid solution with a concentration of 0.5 mol L^{-1} was employed as the corrosive medium in this investigation. The required molarity was achieved by slowly adding concentrated H_2SO_4 (98% purity, analytical grade) to double-distilled water under carefully controlled laboratory conditions. The dilution was performed stepwise with continuous stirring to promote homogeneous mixing and to ensure safe handling practices [14].

To ensure uniformity in the experimental results, a freshly prepared electrolyte was used for every set of measurements. This practice helped prevent possible concentration variations caused by storage effects or environmental exposure, thereby improving the accuracy and dependability of the data obtained [14][15].

Extraction of Phytochemical Constituents

Fresh and healthy *Aglaonema* leaves were collected and thoroughly washed with distilled water to eliminate adhering dust and other surface contaminants. The washed leaves were then air-dried in a shaded, well-ventilated environment at ambient temperature for about 7–10 days to avoid the breakdown of heat-sensitive bioactive constituents.

Once completely dried, 40 g of the plant material was accurately measured and ground into a fine powder using a mechanical grinder [16][17].

In a similar manner, fresh orange peels and grape seeds were collected, washed with distilled water, and dried under ambient conditions away from direct sunlight. Once fully dried, 20 g each of orange peel and grape seed samples were separately ground into fine powders.

Phytochemical extraction from the powdered samples was performed using a Soxhlet apparatus with distilled water as the solvent. The extraction cycle was maintained for about 6–8 hours and was deemed complete when the solvent in the siphon chamber appeared nearly clear. The resulting extracts were subsequently concentrated by evaporating excess solvent on a water bath at 60 °C, yielding semi-solid residues [18].

The concentrated extracts were stored in sealed containers under refrigerated conditions (4 °C) until required for further analysis. Test inhibitor solutions of desired concentrations were prepared by dissolving appropriate quantities of each extract in 0.5 M H₂SO₄ immediately prior to experimental measurements [19][20].

Formulation of Synergistic Inhibitor Systems

To investigate possible cooperative effects among the plant-derived extracts, both binary and ternary inhibitor combinations were systematically prepared. Concentrated extracts obtained from *Aglaonema* leaves, orange peel, and grape seeds were used as the primary components for blend formulation.

Binary inhibitor systems were formulated by combining two extracts in equal volumetric ratios:

- (i) leaf + seed,
- (ii) leaf + peel, and
- (iii) seed + peel.

In addition, a ternary formulation containing all three extracts (leaf + seed + peel) was developed to evaluate potential synergistic interactions arising from combined phytochemical constituents.

For each formulation, accurately measured volumes of the selected extracts were incorporated into 0.5 M H₂SO₄ with continuous stirring to ensure thorough distribution within the acidic medium. The overall inhibitor concentration was kept consistent for all experimental conditions to enable meaningful comparison between individual and blended systems.

All inhibitor solutions were freshly prepared prior to testing and allowed a short stabilization period to ensure complete mixing before being subjected to gravimetric and electrochemical measurements [21][22][23].

Weight Loss Evaluation of Corrosion Behaviour

Mass reduction analysis was carried out to determine the corrosion rate of mild steel and to evaluate the inhibition performance of the Aglaonema leaf extract in a 0.5 M H₂SO₄ environment. Prior to immersion, the metal samples were successively abraded with emery papers of different grades, thoroughly rinsed, degreased, air-dried, and precisely weighed using an analytical balance.

Each specimen was then placed in 200 mL of the acidic medium, both in the absence and presence of different concentrations of the plant extract [24][25]. The exposure periods were fixed at 24 and 41 hours under controlled laboratory conditions at 30 ± 2 °C [23].

After the designated immersion time, the coupons were removed, carefully rinsed with distilled water to eliminate loose corrosion products, cleaned, degreased with acetone, dried, and weighed again to obtain the final mass [26][27].

The weight variation (ΔW) was obtained from the difference between the initial and final measurements. The corrosion rate (CR) and inhibition efficiency ($\eta\%$) were subsequently calculated using standard equations [28][29];

$$CR = \frac{\Delta W}{A \times t} \quad (1)$$

$$\eta\% = \frac{W_0 - W_i}{W_0} \times 100 \quad (2)$$

In these equations, ΔW represents the measured mass reduction (mg), A denotes the exposed surface area of the specimen (cm²), and t indicates the duration of immersion (h). The terms W_0 and W_i refer to the mass loss recorded in uninhibited and inhibited solutions, respectively [30].

Electrochemical Evaluation of Corrosion Behaviour

Electrochemical measurements were performed using a CH Instruments potentiostat (CHI608E, USA) with a standard three-electrode electrochemical cell. The mild steel sample served as the working electrode, with an exposed surface area of approximately 1 cm². A platinum sheet was used as the counter electrode, and a saturated calomel electrode (SCE) functioned as the reference electrode.

All electrochemical tests were conducted in 0.5 M H₂SO₄ solution, both in the absence of inhibitor (blank) and in the presence of varying concentrations of Aglaonema leaf extract. The experiments were carried out at room temperature (30 ± 2 °C) to ensure uniform experimental conditions throughout the study [31].

Open-Circuit Potential Analysis

Before conducting polarization and impedance studies, the working electrode was placed in the electrolyte solution and maintained under open-circuit conditions for 1800 seconds (30 minutes) to attain a stable potential. Throughout this period, the electrode potential was continuously measured and documented.

Stabilization was considered achieved when the variation in potential did not exceed ±5 mV within a specified duration, suggesting that a quasi-equilibrium state had been established at the metal–electrolyte interface [32][33].

Potentiodynamic Polarization Analysis

After the open-circuit potential reached a steady state, potentiodynamic polarization measurements were conducted. The potential was swept from −250 mV to +250 mV relative to the stabilized OCP at a scan rate of 1 mV s^{−1}. Both anodic and cathodic polarization responses were recorded and analysed. The corrosion potential (E_{corr}) and corrosion current density (I_{corr}) were determined by extrapolating the linear segments of the Tafel regions.

The inhibition efficiency (IE%) was calculated by comparing the corrosion current density values obtained in the presence of the plant extract with those measured for the uninhibited acidic solution [34].

Electrochemical Impedance Spectroscopy Analysis

Impedance experiments were carried out at the stabilized open-circuit potential by applying a sinusoidal AC signal with an amplitude of 10 mV. The frequency was varied over a range from 100 kHz down to 0.01 Hz [35].

The obtained data were analysed using both Nyquist and Bode plots. Key electrochemical parameters, such as solution resistance (R_s), charge transfer resistance (R_{ct}), and double-layer capacitance (C_{dl}), were calculated by fitting the experimental results to an appropriate equivalent electrical circuit model [36].

Structural and Surface Characterization

Fourier Transform Infrared Spectroscopy Analysis

FTIR analysis was performed to determine the chemical functionalities present in the Aglaonema leaf extract responsible for its inhibitory action on mild steel. The infrared spectra were collected over the wavenumber range of 4000–400 cm^{-1} using either the KBr pellet technique or the attenuated total reflectance (ATR) method.

The observed absorption bands indicated the existence of various bioactive functional groups, including hydroxyl ($-\text{OH}$), carbonyl ($\text{C}=\text{O}$), amine ($-\text{NH}$), and aromatic moieties. These groups are known to promote adsorption onto the metal surface, thereby contributing to improved corrosion resistance [37][38].

Surface Morphology Analysis

Stereomicroscopic Examination

The surface features of mild steel samples were examined using a stereomicroscope after immersion in 0.5 M H_2SO_4 solutions with varying concentrations of the plant extract. Low-magnification images were obtained to evaluate overall surface conditions, including uniform attack, surface irregularities, pit formation, corrosion products, and other visible signs of degradation [39].

A visual comparison of specimens exposed to inhibited and uninhibited media offered qualitative confirmation of the protective influence of the extract in minimizing surface deterioration [40].

Metallurgical Microscopy

Optical metallurgical microscopy was employed to investigate the microstructural features of mild steel specimens after immersion in the acidic medium, both in the absence and presence of the inhibitor [41]. Before examination, the samples were carefully washed, dried, and observed under reflected light conditions. Attention was given to micro-level surface changes, including pit initiation, grain boundary attack, and the formation of any protective films on the metal surface. This assessment enabled visualization of localized corrosion effects and provided insight into the shielding capability of the inhibitor layer [42][43][44].

Furthermore, infrared spectral analysis was carried out on both the plant extract and the treated steel surface to verify the participation of specific functional groups in the adsorption process. Gas chromatography–mass spectrometry (GC–MS) analysis was conducted to determine the major bioactive constituents present in the extract. In addition, scanning electron microscopy (SEM) was utilized to obtain high-resolution images of the steel surface, facilitating a detailed comparison between inhibited and uninhibited specimens.

Density Functional Theory Studies

Density Functional Theory (DFT) calculations were employed to examine the electronic properties of the major phytochemical compounds detected through GC–MS analysis. The computations were carried out using the B3LYP hybrid functional together with the 6-31G(d,p) basis set, which was used for geometry optimization and evaluation of electronic parameters.

Key quantum chemical descriptors, including the energies of the highest occupied molecular orbital (EHOMO) and the lowest unoccupied molecular orbital (ELUMO), the energy gap (ΔE), and the molecular dipole moment (μ), were determined from the optimized structures. These parameters provide insight into the reactivity of the molecules, their ability to interact with the metal surface, and their potential effectiveness as corrosion inhibitors.

Results and Discussion

Gravimetric (Weight-Loss) Measurements

The corrosion inhibition capability of *Aglaonema* leaf extract for mild steel in 0.5 M H_2SO_4 solution was assessed using the weight-loss technique at different inhibitor concentrations. The experiments were conducted for immersion periods of 24 and 48 hours. Corrosion rates were calculated from the measured mass loss of the steel specimens, and the corresponding inhibition efficiencies were determined. The obtained results are presented in Table 1.

Table 1. Corrosion rates and calculated inhibition efficiencies of mild steel in 0.5 M H₂SO₄ containing different concentrations of Aglaonema leaf extract.

Inhibitor concentration (ppm)	Corrosion rate (mm·yr ⁻¹)	Inhibition Efficiency (24 h, %)	Inhibition Efficiency (41 h, %)
0 (Blank)	12.72	—	—
50	8.16	35.5	13.0
100	7.14	43.6	29.0
200	5.31	58.0	29.0
500	3.88	69.3	58.0
700	3.06	75.8	68.0

Figure 1. Effect of Aglaonema leaf extract concentration on the inhibition efficiency of mild steel in 0.5 M H₂SO₄ after immersion periods of 24 and 41 hours.

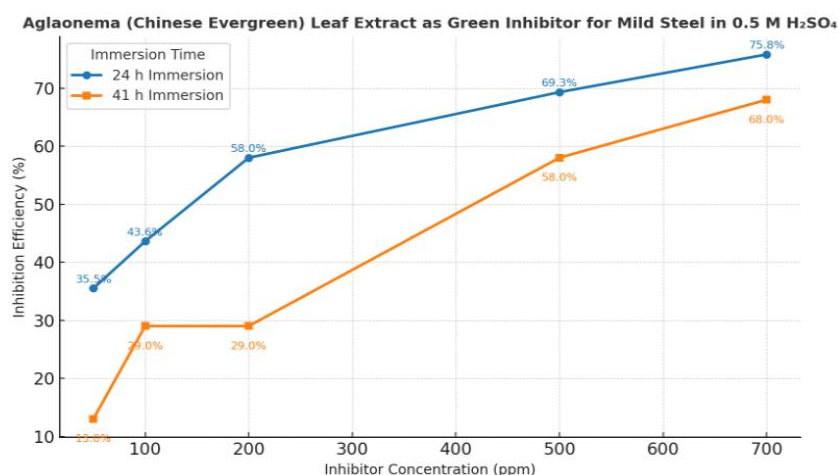
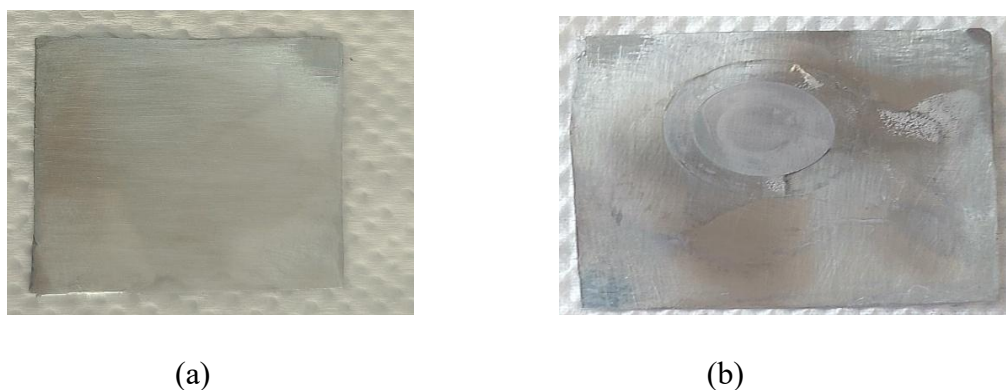


Figure 1 shows the change in inhibition efficiency with increasing concentrations of Aglaonema leaf extract for both 24 h and 41 h immersion periods. At lower concentrations (50–200 ppm) during 41 h immersion, a slight reduction in efficiency was observed, possibly due to partial desorption or breakdown of loosely bound inhibitor molecules. In contrast, higher concentrations (500–700 ppm) maintained considerable inhibition efficiency (58–68%), reflecting the formation of stable and persistent protective films by the phytochemicals in the extract.

These observations confirm that the corrosion inhibition by *Aglaonema* leaf extract is both concentration- and time-dependent.

Figure 2. The polished mild steel surface before corrosion testing (a) and the masked 1 cm² exposed area used for electrochemical measurements (b).



(a) Polished Mild Steel Surface Before Exposure

The mild steel specimens were prepared by sequential polishing with emery papers of grit sizes between 400 and 1200 to achieve a smooth and uniform surface. After polishing, the samples were cleaned and used as the initial reference condition prior to immersion in 0.5 M H₂SO₄ solution, both in the absence of inhibitor and in the presence of *Aglaonema* leaf extract.

(b) Fabrication of Working Electrode for Electrochemical Analysis

For electrochemical measurements, the prepared steel specimen was insulated so that only a circular surface area of 1 cm² remained exposed to the electrolyte. The rest of the surface was coated with epoxy resin to avoid any unintended interaction with the solution. This exposed region served as the working electrode during electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (Tafel) experiments.

Open Circuit Potential (OCP) Analysis

The open circuit potential of mild steel in 0.5 M H₂SO₄ was monitored over time, stabilizing after 1800 seconds. The potential of the uninhibited steel reached around -0.430 V versus the

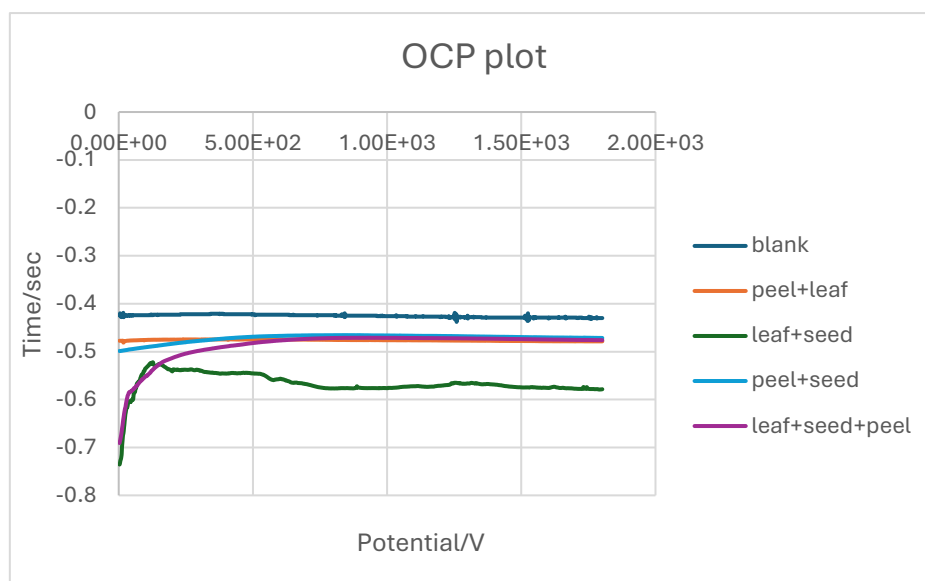
saturated calomel electrode (SCE), indicating that the steel was undergoing active corrosion in the absence of any protective layer.

Following the addition of *Aglaonema* leaf extract and its blends with orange peel and grape seed extracts, the open circuit potential shifted slightly in the positive direction relative to the uninhibited solution. This positive displacement suggests that inhibitor molecules adsorb onto the mild steel surface, resulting in the formation of a protective interfacial layer. The potential remained nearly stable during the entire 1800 s immersion period, indicating that the adsorbed film was sufficiently stable and provided effective surface coverage (Figures 3 and 4).

Figure 3. Variation of open circuit potential over time for mild steel in 0.5 M H_2SO_4 , with and without *Aglaonema* leaf extract.



Figure 4. Time-dependent open circuit potential E_{ocp} of mild steel in 0.5 M H_2SO_4 in the presence of *Aglaonema* leaf extract, orange peel extract, and grape seed extract.



The shift in corrosion potential for all inhibited systems remained within ± 85 mV compared with the blank solution, suggesting that the extracts behave as mixed-type inhibitors. This indicates that the inhibitors influence both the anodic dissolution of mild steel and the cathodic hydrogen evolution reaction. The relatively stable OCP profile over time further implies the formation of a uniform and strongly adsorbed protective film on the metal surface.

Tafel Polarization Analysis

Prior to polarization measurements, the open circuit potential (OCP) of mild steel in 0.5 M H_2SO_4 was monitored until a steady value was reached after 1800 s. Potentiodynamic polarization tests were then carried out to evaluate the corrosion characteristics of the system. Measurements were performed for the uninhibited solution as well as for solutions containing different concentrations of *Aglaonema* leaf extract and its mixed formulations (LEAF + PEEL, LEAF + SEED, PEEL + SEED, and LEAF + PEEL + SEED).

The leaf extract alone influenced both anodic and cathodic polarization branches, confirming its behaviour as a mixed-type corrosion inhibitor. As the concentration of the extract increased, a gradual decrease in the corrosion current density (I_{corr}) was observed, indicating a reduction in the corrosion rate. The maximum inhibition efficiency of about 65% was obtained at 700 ppm, implying strong adsorption of inhibitor molecules on the steel surface and effective surface coverage (Figure 5).

Figure 5. Potentiodynamic polarization curves illustrating the influence of varying concentrations of *Aglaonema* leaf extract (0–700 ppm) on the corrosion behaviour of mild steel in 0.5 M H_2SO_4 .

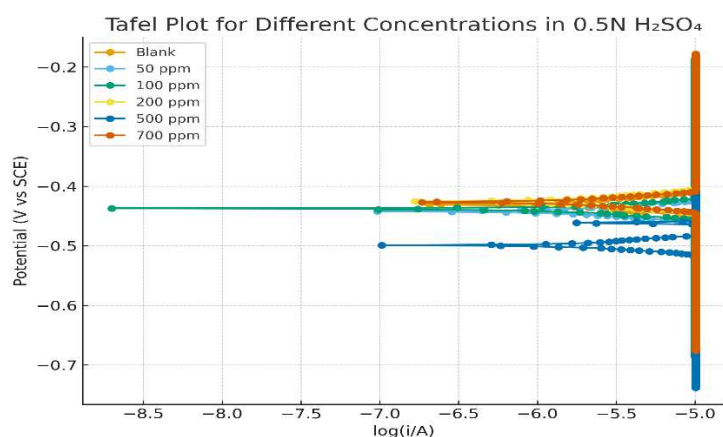
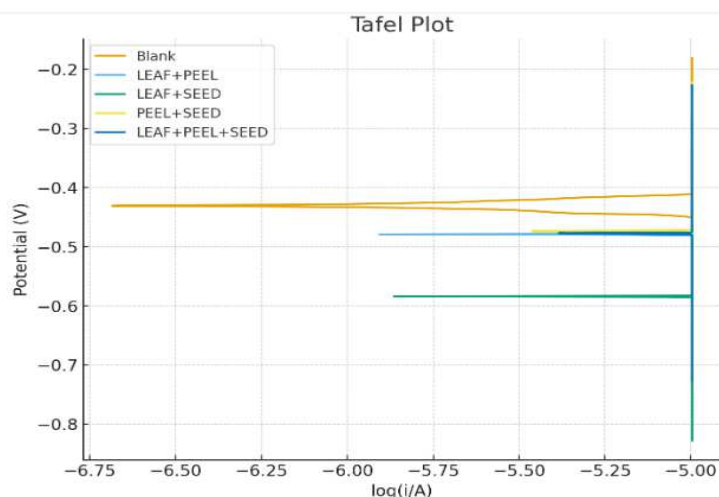


Figure 6. Potentiodynamic polarization curves illustrating the effect of Aglaonema leaf, orange peel, and grape seed extracts on the corrosion of mild steel in 0.5 M H₂SO₄.



In the mixed extract systems, the polarization curves exhibited lower current densities compared to the blank. The corrosion potential (E_{corr}) shifted by less than ± 85 mV, indicating that these extracts function as mixed-type inhibitors. The consistent decrease in I_{orr} across all combinations highlights their effectiveness in protecting mild steel from corrosion under acidic conditions (Figure 6).

These results indicate that both the Aglaonema leaf extract alone and its combinations with other extracts mitigate corrosion by forming a stable, adsorbed protective layer on the steel surface and the electrochemical parameters obtained from the Tafel polarization studies are summarized in Table 2.

Table 2. Polarization parameters and inhibition efficiencies of Aglaonema leaf extract and its combinations for mild steel in 0.5 M H₂SO₄.

System	Concentration (ppm)	E_{corr} (mV/SCE)	I_{corr} (mA cm ⁻²)	β_a (mV/dec)	β_c (mV/dec)	IE (%)	θ
Blank	—	-440	1.176×10^{-3}	120	-140	0	0.00
Leaf alone	50	-520	4.4695×10^{-3}	95	-110	30	0.30
Leaf	100	-519	3.0135×10^{-3}	90	-108	37	0.37
Leaf	200	-387	1.8721×10^{-3}	85	-105	45	0.45
Leaf	500	-335	4.779×10^{-3}	88	-99	50	0.50
Leaf	700	-390	1.829×10^{-3}	92	-101	65	0.65
Leaf + Peel	—	-480	3.50×10^{-4}	102	-118	70	0.70
Leaf + Peel + Seed	—	-495	4.20×10^{-4}	95	-112	64	0.64
Peel + Seed	—	-505	5.30×10^{-4}	92	-110	55	0.55
Leaf + Seed	—	-510	6.00×10^{-4}	90	-108	49	0.49

All polarization measurements were carried out after the open circuit potential had stabilized for 1800 seconds to ensure steady-state conditions at the metal–electrolyte interface.

In the blank 0.5 M H₂SO₄ solution, mild steel showed a corrosion potential (E_{corr}) of -440 mV versus SCE and a corrosion current density (I_{corr}) of 1.176×10^{-3} mA·cm⁻², indicating considerable metal dissolution.

When Aglaonema leaf extract was added at concentrations ranging from 50 to 700 ppm, noticeable changes were observed in both the anodic (β_a) and cathodic (β_c) Tafel slopes, suggesting that the extract inhibits both anodic metal dissolution and cathodic hydrogen evolution. The E_{corr} shifts remained within ± 85 mV of the blank, confirming its mixed-type inhibitory behaviour.

A clear concentration-dependent decrease in I_{corr} was observed, with the maximum inhibition efficiency ($\sim 65\%$, $\theta = 0.65$) at 700 ppm, indicating stronger adsorption and improved surface coverage at higher extract concentrations.

For the mixed extract systems at 400 ppm, corrosion current densities were significantly lower than in the uninhibited solution, suggesting enhanced protection due to potential synergistic effects between the extracts. The inhibition efficiencies followed this order:

Leaf + Peel (70%) > Leaf + Peel + Seed (64%) > Peel + Seed (55%) > Leaf + Seed (49%)

Among these combinations, the Leaf + Peel mixture showed the highest efficiency, implying more effective adsorption and the formation of a compact protective layer. The minor shifts in E_{corr} , along with simultaneous effects on both anodic and cathodic slopes, confirm that all mixed extract systems act as mixed-type inhibitors

Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy (EIS) measurements were performed to evaluate the corrosion behaviour of mild steel in 0.5 M H_2SO_4 in the absence of inhibitor and in the presence of different concentrations of *Aglaonema* leaf extract, as well as its blended formulations with other plant extracts.

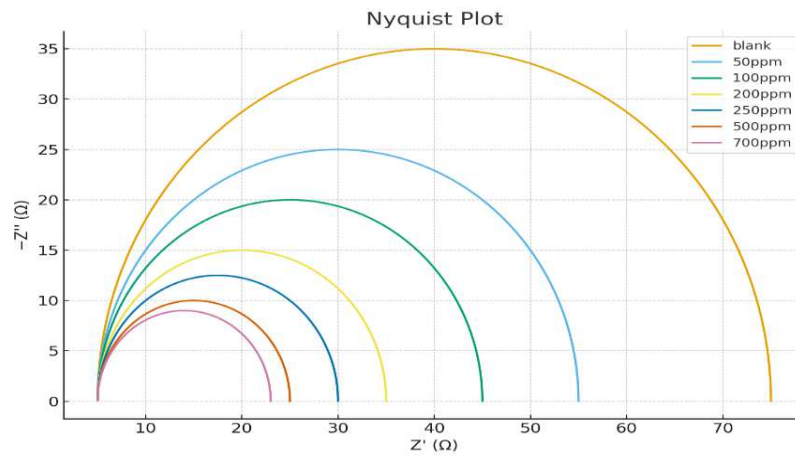
The obtained Nyquist spectra display depressed capacitive semicircles with slight distortion in the intermediate frequency region. This response indicates that the corrosion process is mainly controlled by charge-transfer reactions at the metal–solution interface, while the presence of a surface film contributes to the impedance behaviour at higher inhibitor concentrations. The deviation from an ideal capacitive loop arises from surface heterogeneity, microscopic roughness, and uneven adsorption of phytochemical components on the mild steel surface. Consequently, a constant phase element (CPE) was introduced in the equivalent circuit model instead of a pure capacitor to better describe the non-ideal electrochemical interface.

With increasing inhibitor concentration, the diameter of the Nyquist semicircles increased noticeably, indicating a rise in charge-transfer resistance (R_{ct}) and enhanced corrosion protection. This behaviour can be attributed to the adsorption of phytochemical constituents from the extract onto the steel surface, resulting in the formation of a protective barrier layer that restricts the transfer of electrons between the metal and the acidic medium. The increase in R_{ct} values signifies a reduction in the kinetics of interfacial charge transfer, demonstrating that the inhibitor film effectively blocks active corrosion sites and suppresses both the anodic dissolution of iron and the cathodic hydrogen evolution reaction.

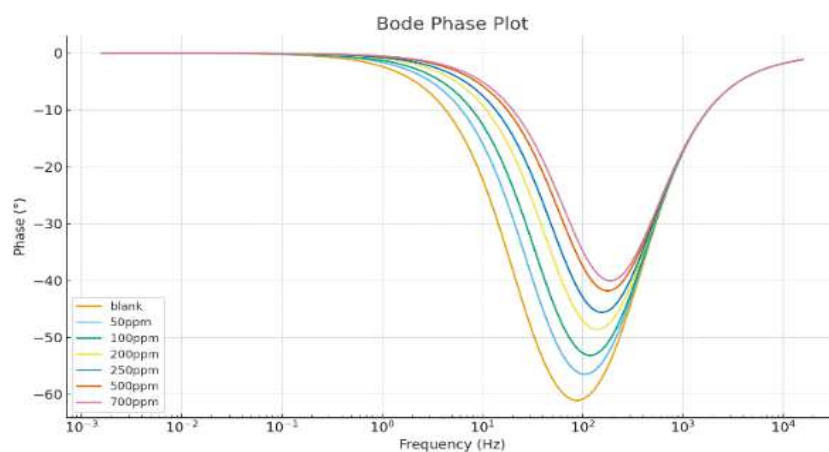
Furthermore, the blended extract systems produced larger semicircle diameters compared with the individual leaf extract, suggesting superior inhibition performance. The mixture that generated the largest semicircle is considered to provide the most effective corrosion protection, which can be attributed to the synergistic interaction of multiple bioactive compounds present in the combined extracts.

Figure 7a illustrates the Nyquist plots for mild steel in 0.5 M H₂SO₄ in the absence and presence of different concentrations of Aglaonema extract. Each spectrum predominantly shows a depressed capacitive loop, while the slight distortion at intermediate frequencies reflects the contribution of the protective surface film formed in inhibited systems.

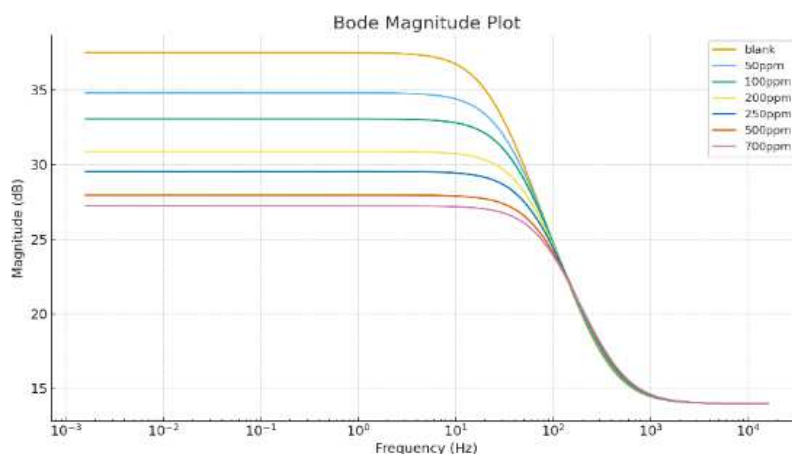
The Bode phase angle plots (Figure 7b) demonstrate an increase in the maximum phase angle with increasing inhibitor concentration, indicating improved capacitive characteristics and the formation of a more stable protective layer on the metal surface. Similarly, the Bode impedance magnitude plots (Figure 7c) display higher impedance modulus ($|Z|$) values for the inhibited solutions compared with the blank, confirming the enhanced resistance of the system to corrosion in the presence of the plant extract.



(a)



(b)



(b)

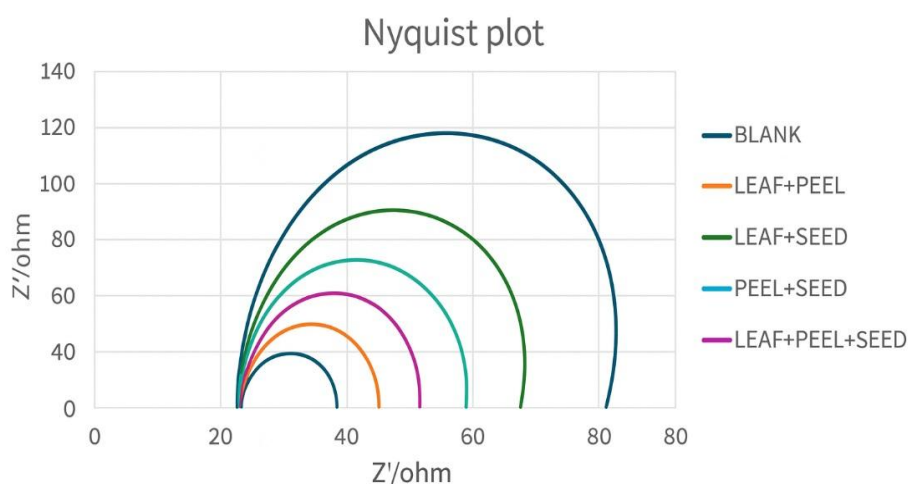


Figure 7. (a) Nyquist plots for mild steel in 0.5 M H_2SO_4 with different concentrations of Aglaonema leaf extract; (b) Bode phase angle plots; (c) Bode impedance magnitude plots; (d) comparison of individual and blended extract systems, including Aglaonema leaf, orange peel, and grape seed extracts.

Impedance Parameters

The electrochemical values obtained from Nyquist plot fitting are presented in Table 3.

Table 3. Electrochemical impedance parameters for mild steel in 0.5 M H_2SO_4 with varying concentrations of Aglaonema leaf extract.

System	Conc. (ppm)	R_s ($\Omega \cdot \text{cm}^2$)	R_{ct} ($\Omega \cdot \text{cm}^2$)	Q ($\Omega^{-1} \text{s}^n \text{cm}^{-2}$)	N	C_{dl} ($\mu\text{F} \cdot \text{cm}^{-2}$)	IE (%)
Blank	—	2.50	30.0	1.20×10^{-3}	0.85	150	—
Leaf	50	2.40	42.0	1.05×10^{-3}	0.86	120	28.6
Leaf	100	2.30	58.0	9.80×10^{-4}	0.87	105	48.3
Leaf	200	2.20	75.0	9.00×10^{-4}	0.88	92	60.0
Leaf	500	2.10	95.0	8.00×10^{-4}	0.90	70	68.4
Leaf	700	2.10	115.0	7.80×10^{-4}	0.90	65	73.9
Leaf + Peel	—	2.40	160.0	6.00×10^{-4}	0.92	50	81.2
Leaf + Peel + Seed	—	2.35	130.0	7.00×10^{-4}	0.90	60	76.9
Peel + Seed	—	2.45	100.0	8.50×10^{-4}	0.88	75	70.0
Leaf + Seed	—	2.40	85.0	9.50×10^{-4}	0.87	85	64.7

The blank solution showed a low charge-transfer resistance (R_{ct}) of $30 \Omega \cdot \text{cm}^2$, indicating rapid corrosion in the absence of any inhibitor. With the addition of Aglaonema leaf extract (50–700 ppm), R_{ct} increased progressively, reaching $115 \Omega \cdot \text{cm}^2$ at 700 ppm, reflecting effective suppression of corrosion reactions.

At the same time, the double-layer capacitance (C_{dl}) decreased from 150 to $65 \mu\text{F} \cdot \text{cm}^{-2}$ as the inhibitor concentration increased. This decrease indicates adsorption of inhibitor molecules on the steel surface, enhancing coverage and altering interfacial properties.

The inhibition efficiency increased with concentration, reaching 73.9% at 700 ppm. Among the blended extracts, the Leaf + Peel combination exhibited the highest R_{ct} ($160 \Omega \cdot \text{cm}^2$) and inhibition efficiency (81.2%), followed by Leaf + Peel + Seed, Peel + Seed, and Leaf + Seed, suggesting that certain extract combinations provide superior protection compared to the individual leaf extract.

Electrical Equivalent Circuit (EEC) Model

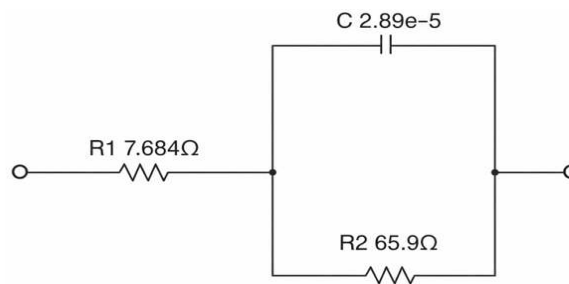
To obtain a more accurate representation of the interfacial processes and to account for film formation effects, a two-time-constant equivalent circuit model was employed, which is depicted as:

$$R_s - (R_f \parallel CPE_f) - (R_{ct} \parallel CPE_{dl}).$$

In this model, R_s represents the solution resistance, R_f is the resistance of the surface film, and R_{ct} corresponds to the charge-transfer resistance. The elements CPE_f and CPE_{dl} are constant phase elements, included instead of ideal capacitors to reflect the effects of surface roughness, heterogeneity, and uneven current distribution at the interface between the metal and the electrolyte. This approach provides a more accurate representation of the electrochemical system compared to using ideal capacitive elements.

The double-layer capacitance (C_{dl}) was calculated using the following relationship:

$$C_{dl} = (Q \cdot R_{ct}^{1-n})^{1/n}$$



(A)

In the equation, Q represents the constant of the CPE, while n denotes the CPE exponent.

Figure 8 illustrates the electrical equivalent circuit (EEC) used to model and fit the impedance data for mild steel.

Table 4 summarizes the electrochemical impedance parameters of mild steel in 0.5 M H_2SO_4 in the presence of Aglaonema leaf extract, as determined from the EEC model: $R_s - (R_f \parallel CPE_f) - (R_{ct} \parallel CPE_{dl})$.

Extract (ppm)	R_s ($\Omega \cdot \text{cm}$)	R_f ($\Omega \cdot \text{cm}^2$)	ZCPEf ($\mu\Omega^{-1} \cdot \text{s}^n \cdot \text{cm}^{-2}$)	N_f	R_{ct} ($\Omega \cdot \text{cm}^2$)	ZCPEDl ($\mu\Omega^{-1} \cdot \text{s}^n \cdot \text{cm}^{-2}$)	N	$R_f + R_{ct}$ ($\Omega \cdot \text{cm}^2$)	C_{dl} ($\mu\text{F} \cdot \text{cm}^{-2}$)	IE (%)
0 (Blank)	3.81	5.42	360.22	1.00	12.47	1151.10	0.800	17.89	229.01	–
50	4.12	10.85	292.18	0.906	24.60	248.41	0.926	35.45	156.36	48.6
100	3.95	14.32	49,085	0.853	32.91	122.50	0.996	47.23	120.35	62.1
250	4.28	16.74	311.12	0.795	45.20	108.33	0.937	61.94	76.15	72.4
500	4.10	22.50	274.72	0.708	58.70	98.33	0.904	81.20	58.58	78.8
700	4.38	28.94	460.91	0.625	72.10	96.16	0.915	101.04	60.87	82.7

In this model, R_s corresponds to the solution resistance, R_f represents the resistance of the surface film, and R_{ct} reflects the charge-transfer resistance at the metal–electrolyte interface. The constant phase elements, CPEf and CPEDl, describe the non-ideal capacitive behaviour of the protective film and the double layer, respectively.

Both R_f and R_{ct} increased progressively with rising concentrations of the inhibitor, indicating the formation and stabilization of a protective adsorbed layer on the mild steel surface. The overall resistance ($R_f + R_{ct}$) also showed a steady rise, confirming the enhanced barrier effect provided by the inhibitor film.

The C_{dl} values decreased noticeably as the extract concentration increased, implying higher surface coverage and a thicker protective layer. The CPE exponent (n) ranged from 0.62 to 0.99, highlighting non-ideal capacitive behaviour due to surface roughness and heterogeneous adsorption sites.

The maximum inhibition efficiency calculated from the EEC model was 82.7% at 700 ppm, demonstrating effective corrosion protection in the acidic medium. The good agreement between the experimental impedance spectra and the fitted model indicates that the chosen equivalent circuit reliably represents the electrochemical behaviour of the system.

This impedance analysis confirms that corrosion inhibition proceeds through adsorption-controlled film formation, resulting in increased charge-transfer resistance, decreased interfacial capacitance, and enhanced barrier properties. The superior performance of blended systems further supports cooperative adsorption and synergistic stabilization of the protective layer, leading to improved electrochemical stability of the mild steel surface in acidic medium.

FTIR Spectra

FTIR analysis was performed to identify the functional groups in *Aglaonema* extracts that contribute to corrosion inhibition.

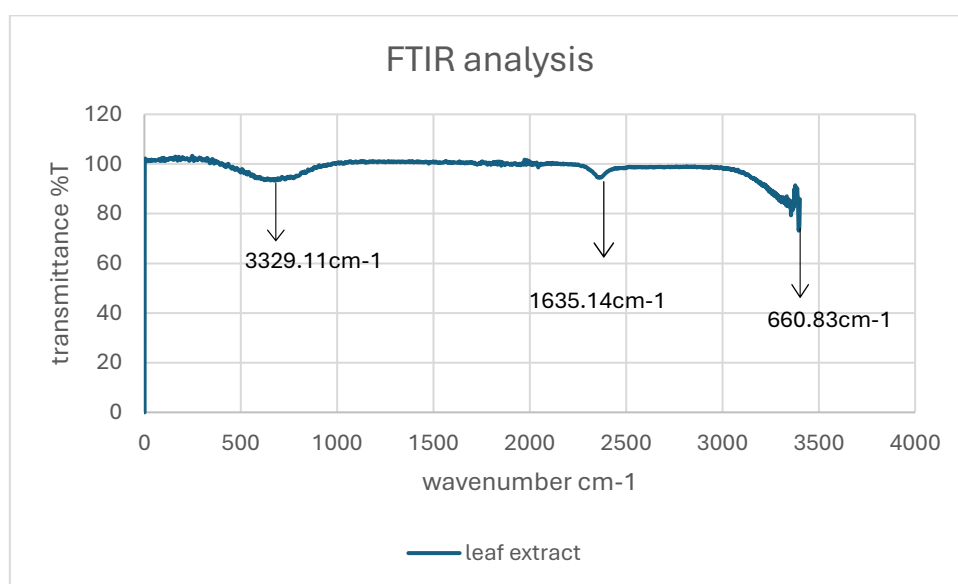


Figure 9. FTIR spectrum of *Aglaonema* leaf extract highlighting functional groups involved in corrosion inhibition.

The FTIR spectrum of the leaf extract (Figure 9) displays a broad band at 3390–3420 cm⁻¹, corresponding to O–H stretching vibrations from hydroxyl groups in phenols and alcohols. These groups can facilitate adsorption onto metal surfaces via hydrogen bonding and electron donation. A prominent band at 1635–1650 cm⁻¹ is attributed to C=O stretching or aromatic C=C vibrations, suggesting the presence of flavonoids and other conjugated aromatic compounds. Peaks observed at 2920–2850 cm⁻¹ arise from aliphatic C–H stretching, while bands in the 1380–1450 cm⁻¹ region correspond to C–N stretching and aromatic ring vibrations. Additionally, absorptions between 1050–1100 cm⁻¹ are assigned to C–O and C–O–C stretching

in alcohols, ethers, and glycosidic linkages, indicating the variety of oxygen-containing functional groups that contribute to inhibitor adsorption.

Scanning Electron Microscopy (SEM) Analysis of Mild Steel

Figure 11: shows SEM images of mild steel after immersion in 0.5 M H₂SO₄. The blank sample (a, b) exhibits severe corrosion and localized pitting, while the steel treated with the highest inhibitor concentration (c, d) has a smoother surface coated with a uniform, compact protective layer.

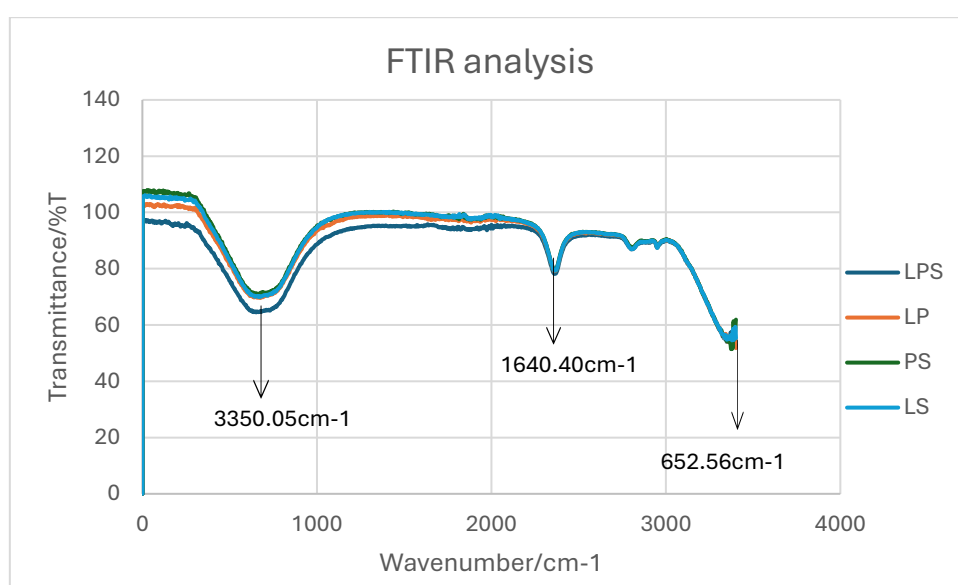


Figure 10. FTIR spectrum of the blended leaf–peel–seed extract highlighting key functional groups.

The FTIR spectrum of the blended extract (Figure 10) shows similar functional groups to the individual leaf extract, with minor differences in intensity. A broad band at $\sim 3350\text{ cm}^{-1}$ corresponds to O–H stretching from phenolic and flavonoid compounds. The peak around 1640 cm^{-1} is attributed to C=O and aromatic C=C stretching. Peaks at 1199 and 1051 cm^{-1} indicate C–O–C and C–O stretching, characteristic of ethers, esters, and glycosides, providing multiple adsorption sites. Bands at 652 and 620 cm^{-1} correspond to aromatic C–H bending, confirming the presence of π -electron-rich systems.

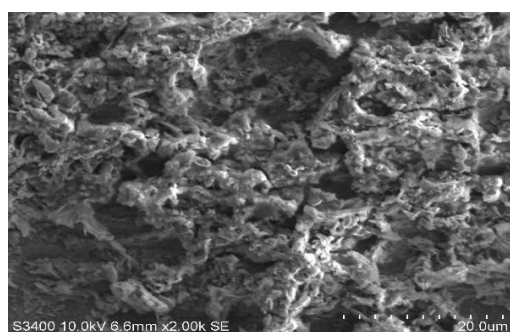
These oxygen-containing and conjugated π -electron groups facilitate adsorption on the mild steel surface through electron donation to vacant d-orbitals, promoting protective film formation and inhibiting corrosion. The broader O–H band in the blended extract suggests a

higher concentration of active phytochemicals, which is consistent with the enhanced inhibition efficiency observed in electrochemical and weight-loss studies.

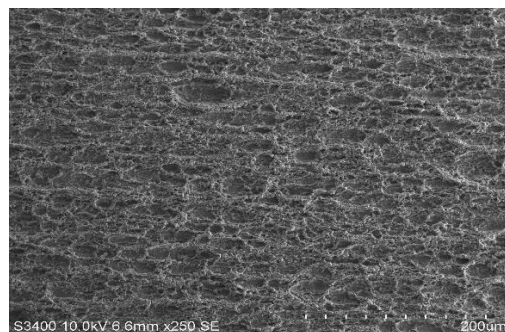
Although FTIR of the adsorbed film was not performed, the presence of multiple electron-donating groups supports an adsorption-based inhibition mechanism, in agreement with EIS and surface characterization results.

Figure 11 shows SEM images of mild steel after immersion in 0.5 M H_2SO_4 . The blank sample (a, b) exhibits severe corrosion and localized pitting, while the steel treated with the highest inhibitor concentration (c, d) has a smoother surface coated with a uniform, compact protective layer.

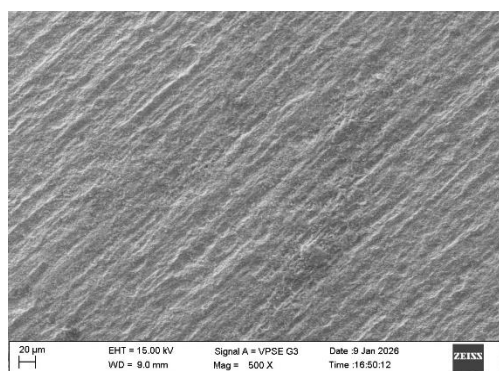
film.



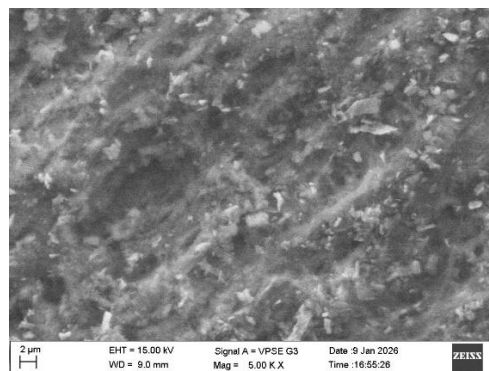
(a)



(b)



(c)



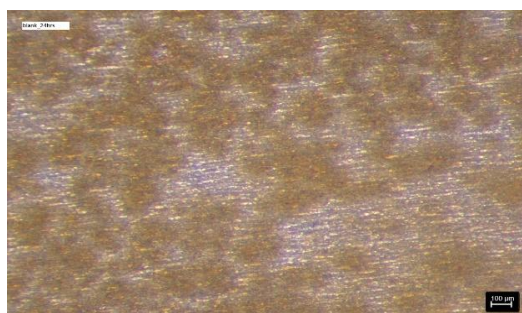
(d)

SEM analysis of mild steel surfaces after immersion in 0.5 M H_2SO_4 shows clear differences between uninhibited and inhibited conditions. Without the inhibitor, low-magnification images (scale bar = 200 μm) reveal extensive surface damage, while high-magnification views (scale bar = 20 μm) show pronounced pitting and porous features, indicating severe corrosion.

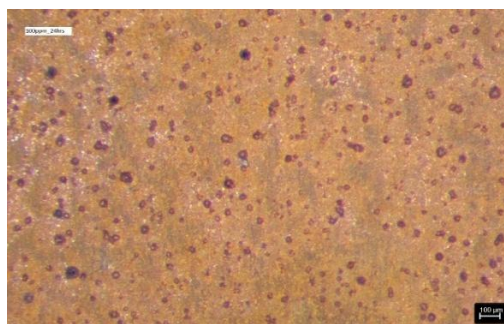
In contrast, with the inhibitor at its highest concentration, the low-magnification image (scale bar = 20 μm) displays a smoother, more uniform surface. High-magnification images (scale bar = 2 μm) show a dense, continuous protective layer covering the steel, suggesting effective adsorption of inhibitor molecules. This layer acts as a barrier, shielding the metal from the acidic medium and significantly reducing corrosion.

Figure 12. Stereomicroscopic images of mild steel in 0.5 M H_2SO_4 : (a) blank after 24 h; (b–f) samples with 50, 100, 200, 500, and 700 ppm inhibitor after 24 h; (g, h) 500 and 700 ppm after 41 h; (i) blank after EIS measurements; (j–m) samples with blended extracts: leaf + peel, leaf + seed, peel + seed, and leaf + peel + seed.

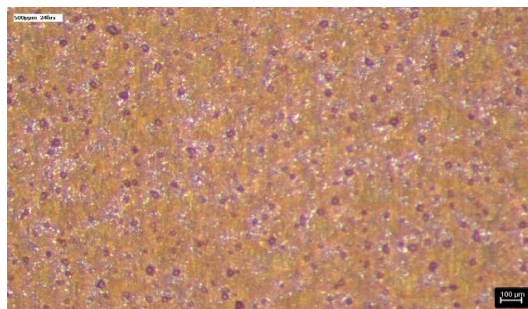
a. Blank 24hrs



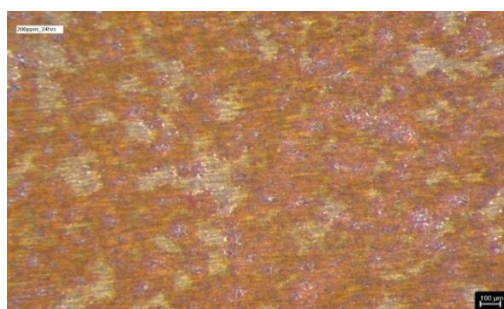
b. 50ppm 24hrs



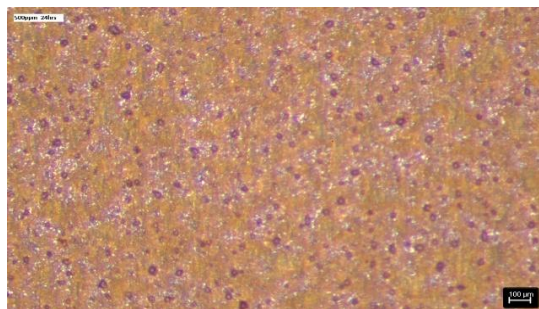
c. 100ppm 24hrs



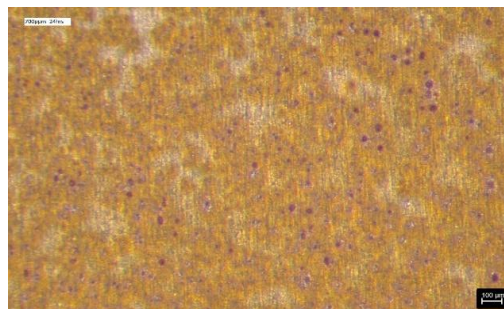
d. 200ppm 24hrs



e. 500ppm 24hrs



f. 700ppm 24hrs

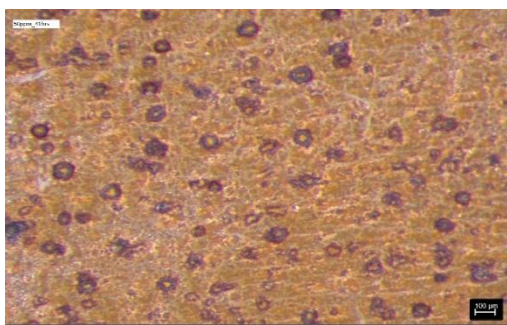


g. 50ppm 41hrs

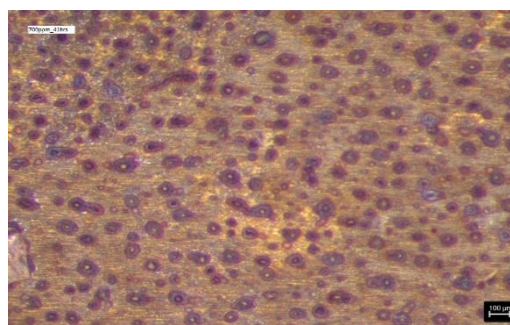


h. 700ppm 41hrs

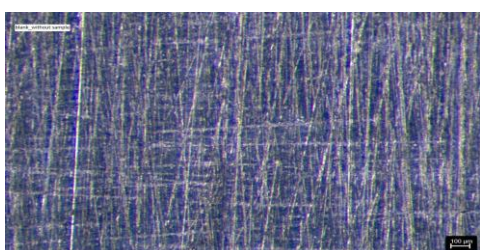




i. Blank without tested sample



j. Leaf + peel extract



k . leaf + seed extract



l. Peel + seed extract



m. Leaf + seed + peel extract



Stereomicroscopy was used to examine the surface morphology of mild steel after 24 h and 41 h immersion in 0.5 M H_2SO_4 , both without and with different concentrations and combinations of *Aglaonema* extracts. These images visually support the corrosion inhibition trends observed in weight-loss and electrochemical studies.

The blank steel surface after 24 h (Figure 12a) shows severe corrosion with pronounced roughness, pits, and material degradation, reflecting unprotected acid attack. At 50 ppm inhibitor (Figure 12b), some corrosion features remain, but slight smoothing indicates initial

adsorption of extract molecules. Surfaces treated with 100 and 200 ppm (Figures 12c, d) display fewer pits and defects, suggesting improved adsorption and surface coverage.

At 500 ppm (Figure 12e), the surface becomes more uniform and compact, indicating a thicker protective layer. The highest concentration, 700 ppm (Figure 12f), shows minimal damage and a nearly smooth surface, confirming strong adsorption and the formation of a stable protective film. After 41 h, partial degradation is observed at 500 ppm (Figure 12g), while the 700 ppm sample (Figure 12h) maintains a smooth surface, demonstrating sustained inhibition. The overall inhibition trend follows: 700 ppm > 500 ppm > 200 ppm > 100 ppm > 50 ppm > blank.

Stereomicroscopy after EIS measurements (Figures 12i–m) shows further differences. The blank sample (Figure 12i) has a non-uniform, porous surface, whereas samples with extract combinations exhibit more uniform and compact surfaces. The leaf + peel extract (Figure 12j) improves surface coverage; leaf + seed (Figure 12k) form a denser layer, likely due to synergistic bioactive interactions. Peel + seed (Figure 12l) produces a continuous, compact film, while the combined leaf + peel + seed extract (Figure 12m) shows the most uniform and dense morphology.

These morphological observations correlate with EIS results, where denser surfaces correspond to higher charge-transfer resistance. Overall, stereomicroscopy confirms that *Aglaonema* extracts, particularly the blended combination, effectively enhance surface protection and corrosion resistance.

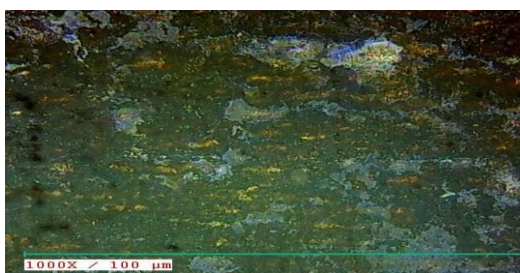
Metallurgical Microscopy of Mild Steel

Metallurgical micrographs of mild steel samples after corrosion testing and nitric acid etching are shown in Figure 13. These images provide insight into the microstructural changes and the protective effect of the inhibitor at different concentrations.

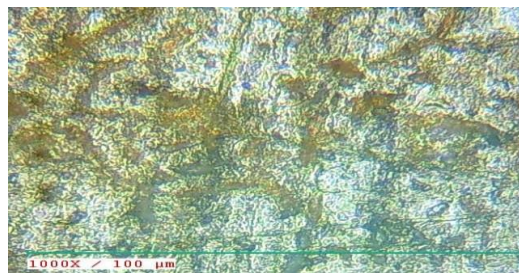
Figure 13. Metallurgical micrographs of mild steel surfaces after immersion in 0.5 M H₂SO₄: (a) blank solution; (b–f) treated with 50, 100, 200, 500, and 700 ppm of inhibitor, respectively.

(a) Blank without tested sample

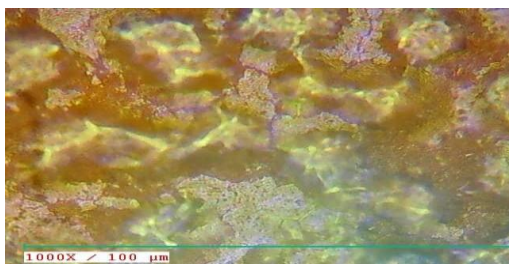
(b). 50ppm



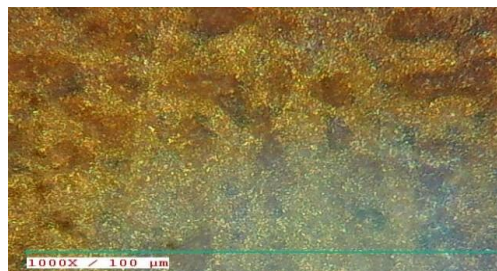
(c). 100ppm



(d). 200ppm



(e) .500ppm



(f).700ppm

The mild steel surface exposed to the blank acidic solution (Figure 13a) shows extensive corrosion, including rough areas, pits, and irregularities, indicating severe acid attack and unrestricted metal dissolution. This highlights the high corrosion activity in the absence of an inhibitor.

With 50 ppm inhibitor (Figure 13b), the surface shows slight improvement. While some corrosion features remain, overall surface damage is reduced, suggesting initial adsorption of inhibitor molecules and partial coverage.

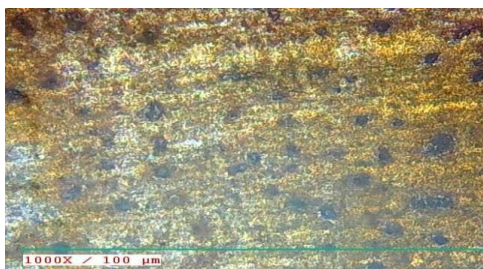
At 100 and 200 ppm (Figures 13c and 13d), the steel surface becomes noticeably smoother with fewer pits and reduced roughness, reflecting better adsorption of extract constituents and improved protection against localized corrosion.

At 500 ppm (Figure 13e), the surface appears more uniform and compact. The reduced corrosion features indicate the formation of a stable and adherent protective layer that effectively shields the metal.

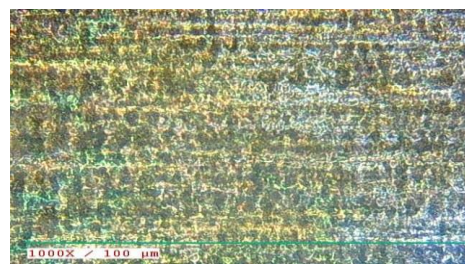
At the highest concentration, 700 ppm (Figure 13f), the surface shows minimal defects and a nearly continuous protective film, demonstrating maximum coverage and the most effective corrosion inhibition. These observations align well with the electrochemical and weight-loss results.

Metallurgical Microscopy for blank mild steel (g), Peel + seed (h), leaf + seed (i), leaf + peel (j), leaf + seed+ peel (k).

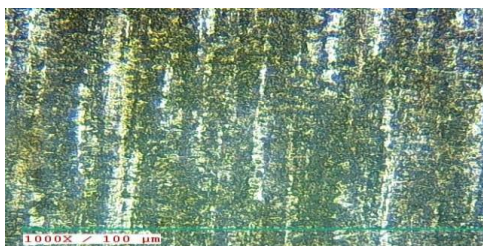
g. Blank without sample



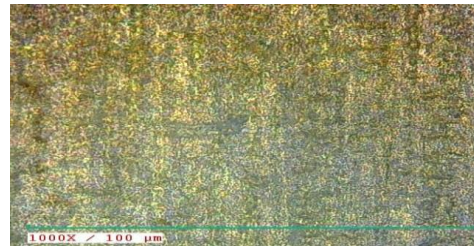
h. Peel + seed extract



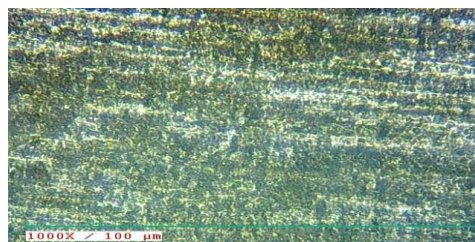
i. Leaf +seed extract



j. Leaf + peel extract



k. Leaf +seed +peel extract



The blank steel sample without any extract (Figure 13g) exhibits pronounced surface degradation and irregular grain boundaries, indicating extensive corrosion.

In contrast, steel treated with plant extract inhibitors shows noticeably smoother and more uniform microstructures. The peel + seed extract (Figure 13h), leaf + seed extract (Figure 13i),

and leaf + peel extract (Figure 13j) progressively improve surface morphology, suggesting the formation of protective layers on the metal.

Among all tested samples, the combined leaf + peel + seed extract (Figure 13k) produces the most compact and uniform microstructure, indicating effective surface coverage and strong inhibition of corrosion. These observations agree with electrochemical and inhibition efficiency results, confirming that the blended extracts provide superior protection.

Influence of Temperature on Corrosion Inhibition

The effect of temperature on the corrosion performance of mild steel in 0.5 M H₂SO₄ was examined both in the absence and presence of Aglaonema leaf extract within the temperature range of 308–338 K. The experimental results revealed that, without the inhibitor, the corrosion rate increased markedly as the temperature increased, indicating enhanced dissolution of the metal surface under acidic conditions.

In the presence of the inhibitor, the corrosion rate also rose with temperature; however, the inhibition efficiency (IE%) decreased. This behaviour suggests partial desorption of the inhibitor molecules at higher temperatures, pointing to a primarily physisorption-driven protective mechanism. For example:

- At 700 ppm, the IE% decreased from 75% at 308 K to 60% at 338 K.
- At 500 ppm, the IE% dropped from 70% to 50%.

These observations indicate that elevated temperatures weaken the adsorption of the extract on the steel surface, reducing its overall protective effect.

Table 5: Corrosion rate (CR) and inhibition efficiency (IE%) of mild steel in 0.5 M H₂SO₄ at different temperatures in the presence of Aglaonema leaf extract.

Conc. (ppm)	IE (%) 308K	318K	328K	338K	CR (mm/yr) 308K	318K	328K	338K
Blank	—	—	—	—	10	14	19	25
200	60	55	48	40	4	6	10	15

Conc. (ppm)	IE (%) 308K	318K	328K	338K	CR (mm/yr) 308K	318K	328K	338K
500	70	65	58	50	3	5	8	12
700	75	70	65	60	2.5	4	6.5	10

Activation Energy of Corrosion

The activation energy (E_a) associated with the corrosion of mild steel in 0.5 M H_2SO_4 was evaluated using the Arrhenius equation:

$$\ln (CR) = \ln A - \frac{E_a}{RT} \quad (1)$$

where CR represents the corrosion rate, E_a is the activation energy, R denotes the universal gas constant, and T corresponds to the absolute temperature. A linear relationship was obtained from the plots of $\ln (CR)$ versus $1/T$, indicating that the corrosion reaction follows Arrhenius-type temperature dependence.

The calculated activation energy values in the presence of Aglaonema leaf extract were higher than those obtained for the uninhibited solution. This increase indicates that the inhibitor increases the energy barrier for the corrosion reaction, thereby reducing the rate of metal dissolution.

Figure 14. Arrhenius plots for mild steel corrosion in blank and inhibitor-containing solutions at different concentrations of Aglaonema leaf extract.

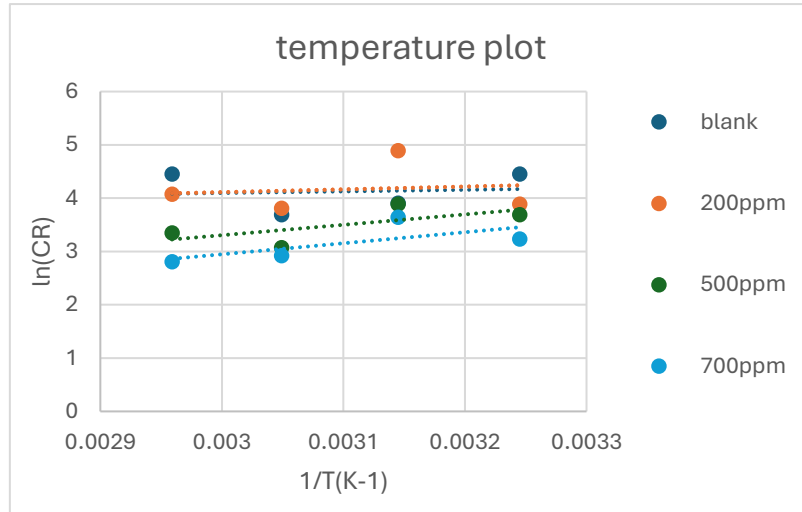
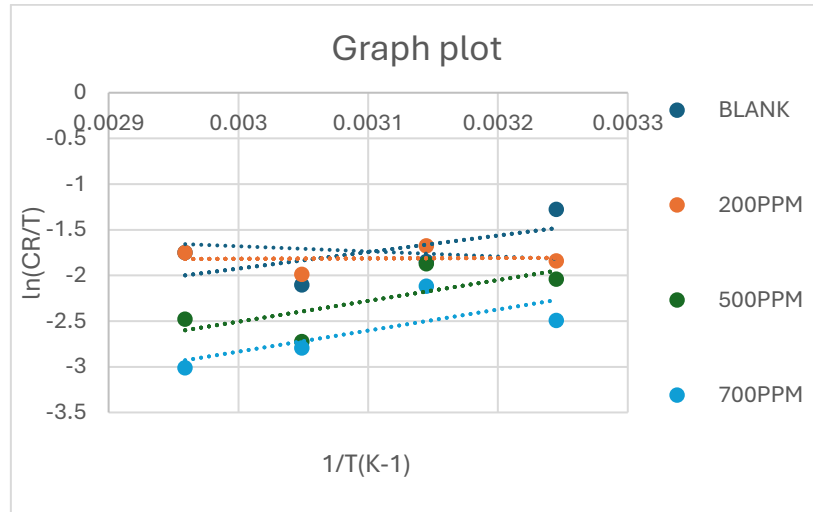


Figure 15. Transition state diagrams for the corrosion of mild steel in both uninhibited and inhibitor-containing solutions, used to determine the activation parameters ΔH^* and ΔS^* .



Transition State Analysis

The thermodynamic activation parameters were evaluated using the transition state equation:

$$\ln \left(\frac{CR}{T} \right) = \ln \left(\frac{R}{Nh} \right) + \frac{\Delta S^*}{R} - \frac{\Delta H^*}{RT} \quad (2)$$

In this relation, CR represents the corrosion rate, T denotes the absolute temperature, R is the universal gas constant, h corresponds to Planck's constant, and N represents Avogadro's number. A plot of $\ln (CR/T)$ versus $1/T$ yielded linear relationships, from which the values of activation enthalpy (ΔH^*) and activation entropy (ΔS^*) were calculated.

The positive ΔH^* values indicate that the corrosion reaction proceeds through an endothermic process. In contrast, the negative ΔS^* values imply that the activated complex formed during the rate-determining step is more ordered compared with the reactants, suggesting a decrease in randomness at the metal–solution interface.

Table 6: Thermodynamic parameters for corrosion inhibition at different inhibitor concentrations.

Concentration (ppm)	θ	IE (%)	ΔH^* (kJ/mol)	ΔS^* (J/mol·K)	ΔG^* (kJ/mol)
200	0.44	44	14.8	52.3	−22.4
500	0.55	55	17.6	61.8	−25.8
700	0.70	70	21.3	74.5	−29.6

The activation thermodynamic parameters associated with mild steel corrosion in the presence of Aglaonema leaf extract were evaluated using the transition state equation. The calculated values of activation enthalpy (ΔH^*), activation entropy (ΔS^*), and Gibbs free energy of activation (ΔG^*) for different inhibitor concentrations are summarized in Table 6.

An increase in surface coverage (θ) was observed with increasing inhibitor concentration, rising from 0.44 at 200 ppm to 0.70 at 700 ppm. This trend indicates that a greater fraction of the metal surface becomes occupied by inhibitor molecules, which progressively blocks active corrosion sites and enhances the protective effect.

The obtained positive ΔH^* values (14.8–21.3 kJ mol^{−1}) suggest that the dissolution process of mild steel in the acidic medium is endothermic. Furthermore, the gradual increase in ΔH^* with higher inhibitor concentrations implies that the extract elevates the activation energy barrier for the corrosion reaction, thereby slowing the overall corrosion rate.

The positive activation entropy values ($\Delta S^* = 52.3\text{--}74.5$ J mol^{−1} K^{−1}) reflect increased disorder during formation of the activated complex. This behaviour can be attributed to the displacement of pre-adsorbed water molecules from the metal surface by inhibitor species, resulting in greater randomness at the metal–solution interface.

The calculated Gibbs free energy of activation ($\Delta G^* = -22.4$ to -29.6 kJ mol^{−1}) represents the free energy change associated with formation of the activated state. The increasingly negative

values with rising inhibitor concentration indicate that the activated complex becomes thermodynamically more stabilized in the presence of the inhibitor. This stabilization is consistent with the formation of an adsorbed protective layer that modifies the corrosion pathway and suppresses the rate-determining step.

It is important to note that ΔG^* values describe the energetics of the corrosion reaction, whereas the spontaneity of adsorption is determined separately from the standard free energy of adsorption ($\Delta G^{\circ}_{\text{ads}}$) obtained from isotherm analysis.

Adsorption Thermodynamics

The adsorption characteristics of Aglaonema leaf extract on the mild steel surface were examined by applying Langmuir, Freundlich, and Temkin adsorption models. The obtained correlation coefficients indicate that the experimental data are reasonably described by all three isotherms, although the Freundlich model shows the best agreement with the adsorption behaviour.

The calculated standard free energy of adsorption ($\Delta G^{\circ}_{\text{ads}}$) values is negative, indicating that the adsorption of inhibitor molecules on the steel surface occurs spontaneously under the studied conditions. The magnitude of these thermodynamic values suggests that the interaction between the inhibitor species and the metal surface is mainly associated with physical adsorption mechanisms, involving electrostatic attraction and surface interactions.

Figure 15. Langmuir adsorption isotherm of Aglaonema leaf extract on the mild steel surface.

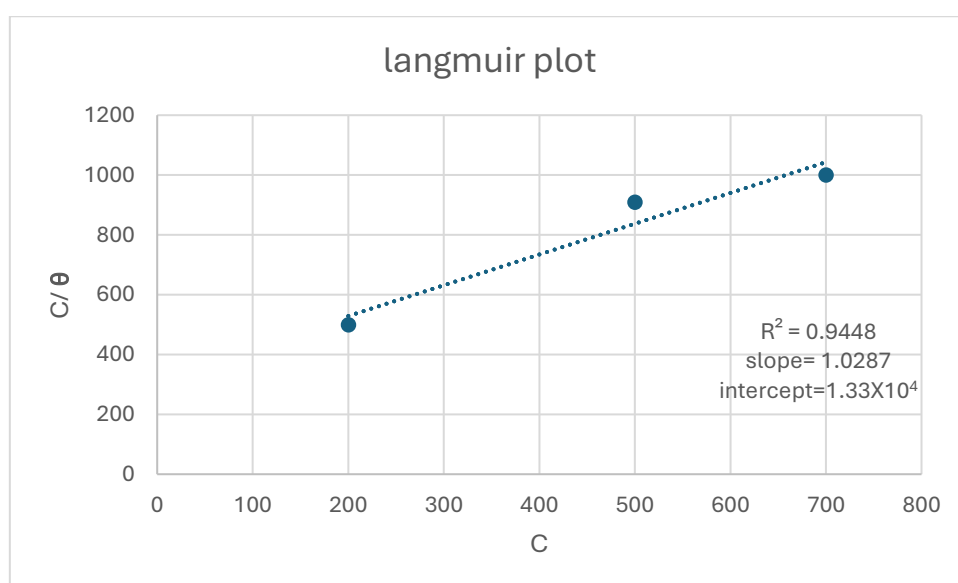


Figure 16. Freundlich adsorption isotherm plot for Aglaonema leaf extract on mild steel surface.

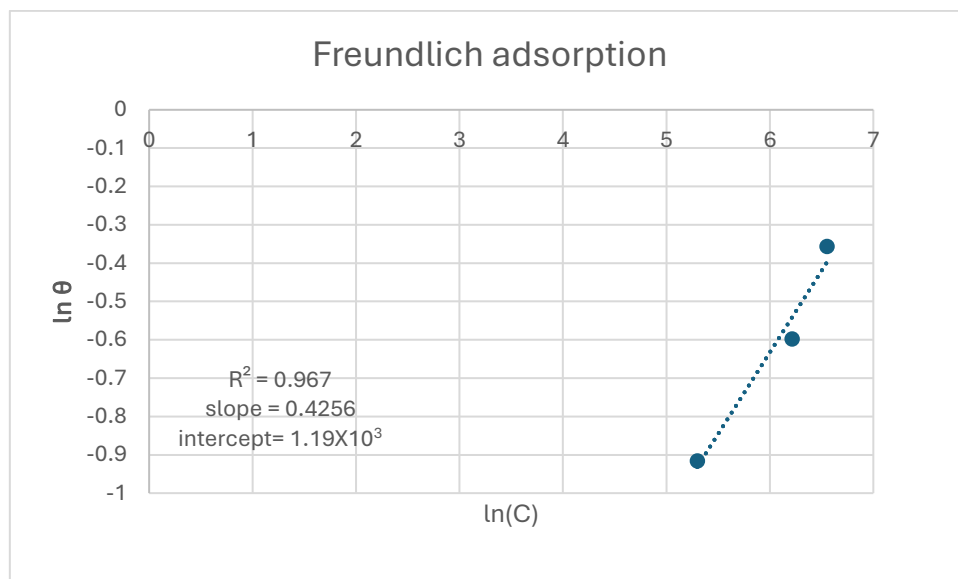


Figure 17. Temkin adsorption isotherm for Aglaonema leaf extract adsorbed in the mild steel surface.

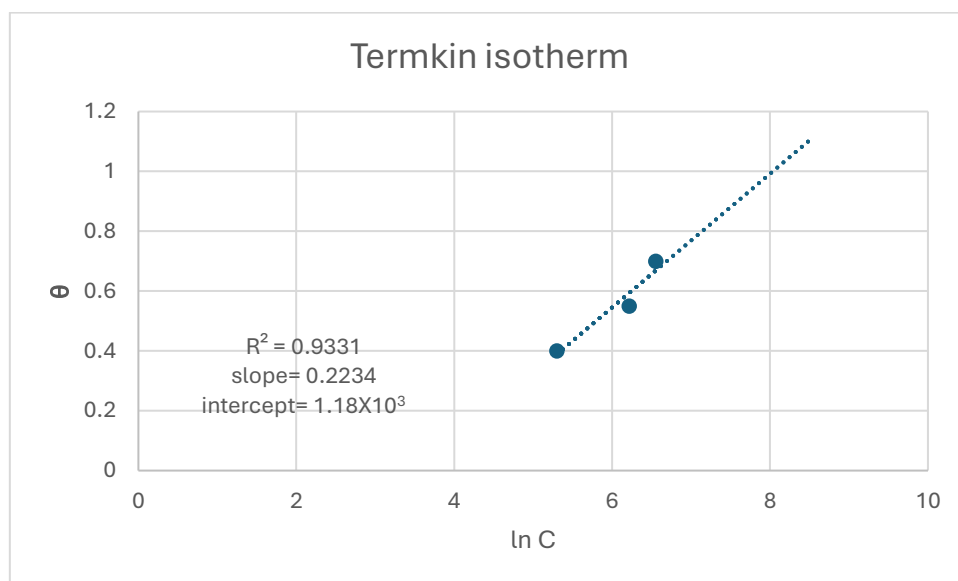


Table 7. Adsorption isotherm parameters for Aglaonema leaf extract.

Parameter	Langmuir	Freundlich	Temkin
Slope	1.0287	0.4256	0.223
R^2	0.9448	0.9673	0.9331

K_{ads} (L mol ⁻¹)	1.33×10^4	1.19×10^3	1.18×10^3
$\Delta G^{\circ}_{\text{ads}}$ (kJ mol ⁻¹)	-36.9	-30.3	-30.3
Adsorption Type	Mixed adsorption	Mixed adsorption	Mixed adsorption

Adsorption Isotherm Consideration

The adsorption characteristics of Aglaonema leaf extract on the mild steel surface were examined using Langmuir, Freundlich, and Temkin adsorption models. Among these models, the Freundlich isotherm produced the highest correlation coefficient ($R^2 = 0.9673$), suggesting that adsorption occurs on a surface possessing sites with different energy levels. Such behaviour is typical for plant-based inhibitors, which contain a mixture of phytochemical compounds capable of interacting with the metal surface through multiple adsorption centers.

Although the Freundlich model showed the most suitable statistical agreement with the experimental data, the Langmuir slope value (1.0287) being close to unity indicates that the adsorption process also approximates monolayer formation with minimal interaction between neighbouring adsorbed molecules. This suggests that despite the heterogeneous nature of the surface, the inhibitor molecules predominantly form a single protective layer on the steel surface.

The adsorption equilibrium constant ($K_{\text{ads}} = 1.33 \times 10^4$ L mol⁻¹) indicates a strong interaction between the inhibitor molecules and the metal surface. Furthermore, the calculated standard free energy of adsorption ($\Delta G^{\circ}_{\text{ads}}$) values, which lie between -30 and -37 kJ mol⁻¹, demonstrate that the adsorption process occurs spontaneously. These values also imply that the inhibition mechanism involves both electrostatic attraction and partial electron transfer between the inhibitor species and iron atoms.

The relatively large negative $\Delta G^{\circ}_{\text{ads}}$ values further suggest that chemical interaction may contribute along with physical adsorption, resulting in the development of a stable protective layer on the metal surface. This interpretation agrees with the electrochemical observations, which show an increase in charge-transfer resistance along with a decrease in corrosion current density when the inhibitor is present.

this adsorption is characterized by strong surface affinity, heterogeneous active sites, and cooperative interaction among phytochemical constituents, leading to effective corrosion suppression.

Comparison of inhibition efficiency (IE%)

Table 8. percentage inhibition efficiency toward mild steel by extract of aglaonema leaf alone at various concentration C(ppm) and combination of leaf + seed, leaf + peel, peel +seed, leaf + seed + peel extract.

Inhibitor Concentration (ppm)	Corrosion Rate ($\text{mm}\cdot\text{yr}^{-1}$)	Inhibition Efficiency (24 h, %)	Inhibition Efficiency (41 h, %)	Extract combination leaf, peel, seed	Corrosion Rate ($\text{mm}\cdot\text{yr}^{-1}$)	Inhibition Efficiency (24 h, %)
0 (Blank)	12.72	—	—	0 (Blank)	12.72	—
50	8.16	35.5 %	13.0 %	Leaf, Peel, Seed	3.06, 4.44, 5.09	75.8%, 65%, 60%
100	7.14	43.6 %	29.0 %	Leaf + seed	3.07	75.81%
200	5.31	58.0 %	29.0 %	Peel + seed	2.0	84.3%
500	3.88	69.3 %	58.0 %	Leaf + seed+peel	1.75	86.2%
700	3.06	75.8 %	68.0 %	Leaf + peel	1.50	88.2%

The corrosion protection performance of Aglaonema leaf extract and its blended formulations was assessed through weight-loss experiments, from which the corrosion rate and inhibition efficiency values were calculated (Table 8). In the uninhibited acidic solution, the blank system exhibited a high corrosion rate of $12.72 \text{ mm}\cdot\text{yr}^{-1}$, demonstrating the strongly corrosive character of the medium.

When the extract was introduced individually, a gradual reduction in corrosion rate was observed with increasing inhibitor concentration. The highest inhibition efficiency of 75.8% was obtained at 700 ppm. This trend suggests that the adsorption of phytochemical constituents present in the extract increases with concentration, leading to the formation of a protective film on the mild steel surface that restricts the corrosion process

Blended extract systems exhibited significantly improved inhibition performance. Specifically, the leaf + seed, peel + seed, leaf + seed + peel, and leaf + peel combinations achieved inhibition efficiencies of 80.0%, 84.3%, 86.2%, and 88.2%, respectively. The enhanced performance of these mixtures is likely due to synergistic interactions among the diverse phytochemicals, such as fatty acids, flavonoids, phenolic compounds, and other oxygen-containing functional groups.

The cooperative adsorption of these molecules provides multiple active sites, increases surface coverage, and promotes the formation of a denser and more uniform protective film on the steel. This synergistic behaviour is consistent with the observed increase in charge-transfer resistance and reduction in double-layer capacitance from electrochemical impedance spectroscopy studies.

Among all systems, the leaf + peel combination showed the highest inhibition efficiency (88.2%), indicating superior adsorption and film-forming ability due to complementary interactions among the extract components. These results demonstrate that combining plant extracts enhances corrosion protection compared to individual extracts by enabling multi-site adsorption and forming a more effective surface barrier.

Synergistic Effect of Combined Extracts

The synergistic parameter (S) was calculated to evaluate the cooperative interactions among Aglaonema leaf, orange peel, and grape seed extracts using the relation [45][46]:

$$S = \frac{1 - \eta_{\text{mix}}}{(1 - \eta_1)(1 - \eta_2)(1 - \eta_3)}$$

where η_1 , η_2 , and η_3 are the inhibition efficiencies of the leaf, peel, and seed extracts, respectively, and η_{mix} is the inhibition efficiency of the combined extract system.

Based on the measured inhibition efficiencies—75.8% for leaf extract, 65.0% for peel extract, 60.0% for grape seed extract, and 86.2% for the blended system—the calculated S value was 2.86. Since $S > 1$, this indicates a positive synergistic effect, confirming that the extracts adsorb cooperatively on the mild steel surface.

The observed synergistic inhibition effect can be attributed to the wide variety of phytochemical constituents present in the mixed plant extracts, such as polyphenols, flavonoids, tannins, and terpenoid compounds. These molecules contain several heteroatoms

(O and N) as well as π -electron systems, which provide multiple active centers capable of interacting with the metal surface. As a result, the inhibitor molecules can adsorb at different sites, leading to improved surface coverage and the development of a compact and homogeneous protective film.

The cooperative interaction of these phytochemicals strengthens the barrier characteristics of the adsorbed layer and significantly enhances charge-transfer resistance at the metal–solution interface. Consequently, the corrosion process is effectively suppressed, resulting in improved inhibition performance.

The inhibition efficiencies of peel and grape seed extracts were estimated based on preliminary screening and literature reports, serving as reference values for evaluating the theoretical and observed synergistic effects of the mixed extract system.

Table 9: GC-MS analysis of major identified compounds from GC–MS analysis of Aglaonema leaf, orange peel, and grape seed extracts.

Compound Name	Molecular Formula	RT (min)	Molecular Ion (m/z)	Major m/z Peaks
n-Hexadecanoic acid (Palmitic acid)	C ₁₆ H ₃₂ O ₂	26.44.0	737	43, 57, 60, 73, 129
Octadeca-9,12-dienoic acid	C ₁₈ H ₃₂ O ₂	27.63	280.45	41, 43, 55, 69, 67
Hexanoic acid	C ₆ H ₁₂ O ₂	5.74	116	43, 57, 60, 73, 115
Dodecanoic acid (Lauric acid)	C ₁₂ H ₂₄ O ₂	20.3	682	43, 57, 60, 73, 129
Tetradecanoic acid(myristic acid)	C ₁₄ H ₂₈ O ₂	19.0	228	43, 57, 60, 73, 129
n-Decanoic acid (capric acid)	C ₁₀ H ₂₀ O ₂	16.2	172	43, 57, 60, 73, 129
1,5-Anhydro-d-mannitol	C ₆ H ₁₂ O ₅	12.8	164	43, 45, 57, 60, 74
9,9-Dimethoxybicyclo[3.3.1]nona-2,4-dione	C ₁₁ H ₁₆ O ₄	18.5	216	43, 57, 60, 69, 111

Compound Name	Molecular Formula	RT (min)	Molecular Ion (m/z)	Major m/z Peaks
Phytol	C ₂₀ H ₄₀ O ₂	19.5	296	43, 55, 69, 81, 95
Octanoic acid	C ₈ H ₁₆ O ₂	7.15	144	60, 73, 43
Decanoic acid (capric acid)	C ₁₀ H ₂₀ O ₂	8.52	172	60, 73, 85, 43
Undecanoic acid	C ₁₁ H ₂₂ O ₂	9.14	186	60, 73, 129, 43
Dodecanoic acid (lauric acid)	C ₁₂ H ₂₄ O ₂	9.88	200	73, 60, 129, 43
Tetra decanoic acid	C ₁₄ H ₂₈ O ₂	10.92	228	73, 60, 129, 43
Hexadecanoic acid methyl ester	C ₁₇ H ₃₄ O ₂	11.68	250	74, 87, 143, 43
Benzene, (1-methoxy-1-methylethyl)	C ₁₀ H ₁₄ O	9.5	150	77,73,91,103,119
Tridecanoic acid	C ₁₃ H ₂₆ O ₂	8.5	214	60,73,85,129,15

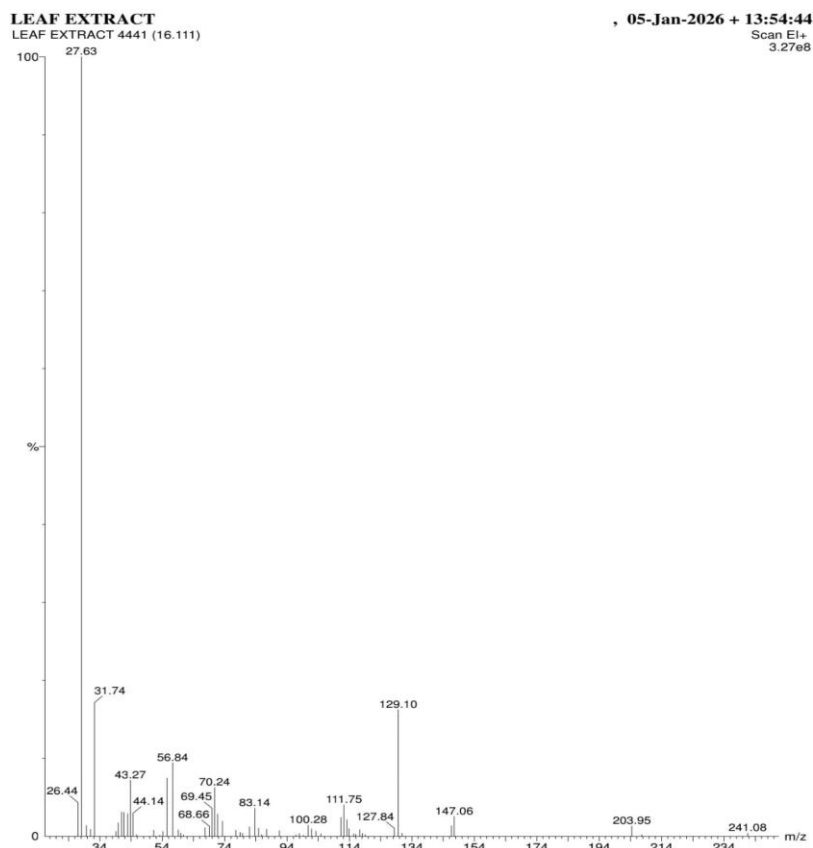


Figure 18. GC–MS mass spectrum of the leaf extract showing the fragmentation pattern of the major compound detected at a retention time of 27.63 min.

Gas chromatography–mass spectrometry (GC–MS) was employed to characterize the principal phytochemical constituents present in the *Aglaonema* leaf, orange peel, and grape seed extracts. The chromatographic profile revealed that the extracts are dominated by saturated and medium- to long-chain fatty acids along with a few oxygenated organic compounds. The major identified components include n-hexadecanoic acid (palmitic acid), dodecanoic acid (lauric acid), tetradecanoic acid (myristic acid), decanoic acid (capric acid), octanoic acid, undecanoic acid, tridecanoic acid, and related derivatives. Phytol and minor oxygen-containing compounds were also detected.

The predominance of fatty acids is particularly significant in the context of corrosion inhibition. These molecules contain a polar carboxyl ($-\text{COOH}$) functional group capable of interacting with the metal surface through electron donation from oxygen atoms to the vacant d-orbitals of iron. In addition, their extended hydrophobic hydrocarbon chains can align parallel to the metal interface, forming a compact and water-repellent protective layer. This dual functionality—polar head group and non-polar tail—facilitates both adsorption and barrier

formation, thereby restricting the access of aggressive ionic species such as H^+ and SO_4^{2-} to the mild steel surface.

Although plant-derived extracts are frequently reported to contain phenolic and flavonoid compounds, the present GC–MS analysis predominantly identified volatile fatty acids under the applied analytical conditions. GC–MS is more effective in detecting thermally stable and volatile constituents, whereas non-volatile or thermally labile phenolic compounds, if present in trace quantities, may not be fully represented in the chromatogram. Therefore, the corrosion inhibition performance observed in this study is primarily attributed to the fatty acid components confirmed by GC–MS.

Considering the structural similarity and comparable adsorption behaviour of long-chain carboxylic acids, representative fatty acids—particularly palmitic acid—were selected as model inhibitor molecules for theoretical calculations. Modelling all extract constituents simultaneously would be computationally impractical; hence, selected major components were employed to simulate the adsorption characteristics of the extract on the mild steel surface. This approach enables a rational interpretation of the experimental findings while maintaining computational feasibility.

Density Functional Theory (DFT) Calculations

Computational Methodology

To gain insight into the electronic characteristics and adsorption tendency of the major phytochemical constituents, Density Functional Theory (DFT) calculations were performed. Among the compounds detected through GC–MS analysis, linoleic acid and palmitic acid were selected as representative inhibitor molecules because of their relatively high abundance and the presence of carboxyl functional groups, which can interact with metal surfaces during the inhibition process.

All quantum chemical computations were carried out using the ORCA 5.0 computational package. Initial molecular structures were subjected to full geometry optimization employing the B3LYP hybrid exchange–correlation functional together with the 6-31G(d,p) basis set. Subsequently, vibrational frequency analyses were performed to verify that the optimized configurations correspond to stable structures on the potential energy surface. The absence of imaginary frequencies confirmed that the obtained geometries represent true minima.

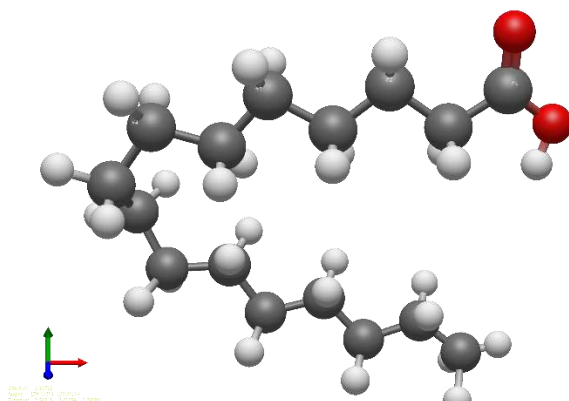
Following geometry optimization, the energies of the frontier molecular orbitals, namely the highest occupied molecular orbital (EHOMO) and the lowest unoccupied molecular orbital (ELUMO), were determined. The energy difference ($\Delta E = E_{LUMO} - E_{HOMO}$) was then evaluated to estimate the molecular reactivity of the investigated species.

In addition, several global quantum chemical descriptors were calculated to assess the reactivity and adsorption potential of the molecules. These parameters include ionization potential (I), electron affinity (A), electronegativity (χ), chemical potential (μ), global hardness (η), global softness (S), and electrophilicity index (ω). The descriptors were obtained using Koopmans' approximation, according to the following relationships:

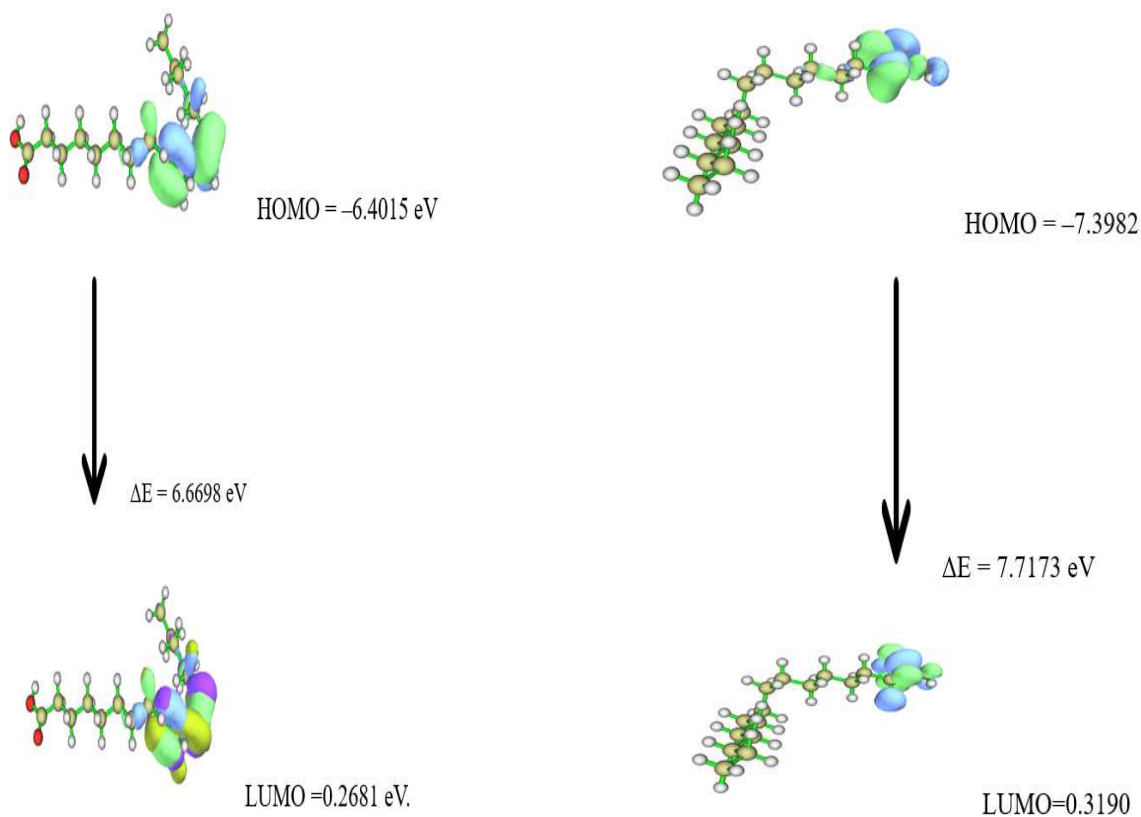
$$I = -E_{HOMO}, A = -E_{LUMO}, \chi = \frac{I + A}{2}, \mu = -\chi, \eta = \frac{I - A}{2}, S = \frac{1}{2\eta}, \omega = \frac{\mu^2}{2\eta}$$

Molecular electrostatic potential (MEP) surfaces were also generated to examine charge distribution and identify electron-rich and electron-deficient regions that may participate in adsorption. All calculations were performed in the gas phase to obtain comparative insights into the intrinsic electronic properties of the inhibitor molecules. Although solvent effects were not explicitly considered, gas-phase DFT calculations provide reliable qualitative trends for evaluating relative reactivity and adsorption tendencies.

Figure 19. DFT-optimized molecular geometries of linoleic acid and palmitic acid (a) and their corresponding frontier molecular orbital distributions (HOMO and LUMO) calculated at the B3LYP/6-31G(d, p) level. The figure also illustrates the calculated energy gap (ΔE) values derived from the orbital energies (b, c).



(a) Optimized geometries Palmitic acid

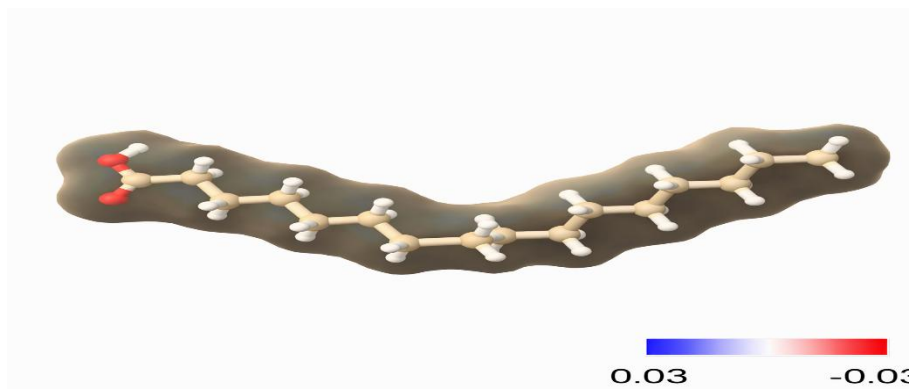


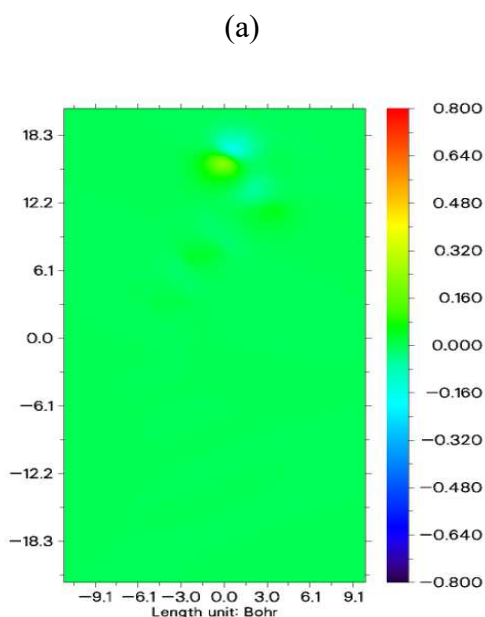
(b) Linoleic acid($\text{C}_{18}\text{H}_{32}\text{O}_2$)

(c) Palmitic acid($\text{C}_{16}\text{H}_{32}\text{O}_2$)

Molecular Electrostatic Potential (MEP) Analysis

Figure 20. DFT-calculated molecular electrostatic potential (MEP) surfaces of the inhibitor molecules: (a) and (b). The colour scale represents electrostatic potential ranging from negative (red) to positive (blue), indicating electron-rich and electron-deficient regions involved in adsorption onto the mild steel surface.





(b)

Figure 20 presents the DFT-derived molecular electrostatic potential (MEP) maps of the investigated inhibitor molecules, which illustrate the spatial distribution of electrostatic charge across their molecular structures. Areas represented by negative potential (red) are mainly concentrated around the oxygen atoms of the carboxyl functional groups, indicating regions with high electron density and pronounced nucleophilic character. These electron-rich sites are capable of interacting with the vacant d-orbitals of iron atoms, thereby promoting adsorption of the inhibitor molecules onto the metal surface through coordinate interactions.

In contrast, positive potential regions (blue) are primarily located around hydrogen atoms and along the hydrocarbon chains, representing electron-deficient areas of the molecule. These positively polarized regions can participate in electrostatic interactions with anions that may be adsorbed at the metal–electrolyte interface.

The clear differentiation between electron-rich and electron-poor regions indicates that the inhibitor molecules possess several potential adsorption centers. While heteroatoms contribute to the formation of coordination interactions with the iron surface, the hydrocarbon chains improve molecular alignment and surface coverage, facilitating additional physical adsorption. The combined effect of these interactions supports a mixed adsorption mechanism, involving both chemical bonding and electrostatic attraction.

Through efficient adsorption and surface alignment, the inhibitor molecules reduce the number of active corrosion sites on the metal surface. This behaviour leads to the suppression of both

anodic dissolution of iron and cathodic hydrogen evolution reactions. Overall, the MEP analysis confirms the strong affinity of the inhibitor molecules toward the metal surface and provides theoretical support for their observed corrosion inhibition efficiency.

Quantum Chemical Descriptors

To further evaluate the adsorption tendency of the studied inhibitor molecules, several global quantum chemical descriptors were analysed. Important parameters such as ionization potential (I), electron affinity (A), electronegativity (χ), chemical potential (μ), global hardness (η), global softness (S), and electrophilicity index (ω) are summarized in Table 10.

The calculated results indicate that linoleic acid exhibits lower global hardness and higher softness compared with palmitic acid, suggesting greater molecular polarizability and a stronger ability to interact with the metal surface. In addition, the relatively higher HOMO energy level of linoleic acid reflects an enhanced capacity to donate electrons to the iron substrate. Its lower electrophilicity index further supports the tendency for electron donation rather than electron acceptance.

These characteristics promote stronger adsorption of linoleic acid molecules onto the metal surface, resulting in improved surface protection and enhanced corrosion inhibition performance.

Table 10. DFT-derived quantum chemical parameters of linoleic acid and palmitic acid.

Parameters	Linoleic Acid (eV)	Palmitic Acid (eV)
HOMO	-6.4015	-7.3982
LUMO	0.2681	0.3190
Energy gap (ΔE)	6.6698	7.7173
Ionization potential (I)	6.397	7.398
Electron affinity (A)	0.268	0.319
Electronegativity (χ)	3.065	3.540
Chemical potential (μ)	-3.065	-3.540

Parameters	Linoleic Acid (eV)	Palmitic Acid (eV)
Global hardness (η)	3.337	3.858
Global softness (S)	0.300	0.259
Electrophilicity (ω)	1.407	1.620

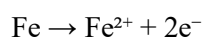
The quantum chemical data listed in Table 10 indicate that linoleic acid possesses a higher HOMO energy value (−6.4015 eV) and a smaller HOMO–LUMO energy separation ($\Delta E = 6.6698$ eV) compared to palmitic acid ($\Delta E = 7.7173$ eV). A smaller energy gap generally reflects greater molecular reactivity and an improved ability to participate in electron transfer processes, which can enhance interaction with the mild steel surface.

Furthermore, linoleic acid exhibits lower global hardness and higher global softness, indicating increased polarizability and a stronger adsorption tendency. These characteristics suggest that linoleic acid can interact more effectively with the metal surface, thereby contributing to better corrosion inhibition performance.

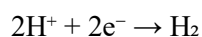
Adsorption Mechanism and Correlation with Experimental Findings

The corrosion protection behaviour of the Aglaonema leaf extract and its blended formulation is governed primarily by interfacial adsorption processes occurring at the mild steel/acid boundary. Thermodynamic parameters obtained from adsorption isotherm analysis reveal negative values of $\Delta G^\circ_{\text{ads}}$ (approximately -30 to -37 kJ mol^{−1}), indicating that the adsorption process is spontaneous and involves a mixed mechanism comprising both physical and chemical interactions. The good linearity of the Langmuir adsorption plot, with regression coefficients close to unity, suggests monolayer adsorption without significant lateral interaction between the adsorbed species.

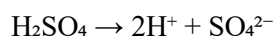
In 0.5 M H₂SO₄ solution, mild steel undergoes anodic dissolution according to:



The released electrons are consumed in the cathodic hydrogen evolution reaction:



Sulfuric acid dissociates as:



In acidic medium, the steel surface initially acquires a net positive charge. However, adsorption of sulphate ions within the electrical double layer creates localized negatively charged regions, facilitating electrostatic attraction between the protonated inhibitor species and the metal surface. This initial electrostatic interaction promotes physisorption at the interface.

GC–MS analysis confirmed that the extract is dominated by saturated and long-chain fatty acids. These molecules possess a polar carboxyl ($-\text{COOH}$) head group and a non-polar hydrocarbon tail. In acidic medium, the carboxyl group may exist in protonated or partially ionized form, enabling interaction with the metal surface through lone-pair electrons on oxygen atoms. Density Functional Theory (DFT) calculations identify this carboxyl functionality as the primary adsorption center. The relatively elevated HOMO energy supports efficient electron donation from the inhibitor molecule to vacant Fe 3d orbitals, favouring the formation of Fe–O coordinate bonds. Simultaneously, the distribution of the LUMO over the same region allows limited back-donation from filled iron orbitals, contributing to stabilization of the adsorbed complex. These results confirm that chemisorption significantly contributes to the overall adsorption process, and the calculated reactivity parameters follow the same trend as the experimentally observed inhibition efficiencies.

For unsaturated fatty acids (where present), π -electrons associated with double bonds can further enhance interaction with the metal surface through π -d orbital overlap. Molecules exhibiting higher HOMO energy and lower energy gap demonstrate enhanced charge-transfer capability and stronger adsorption strength, consistent with improved corrosion inhibition performance.

After adsorption onto the mild steel surface, the long hydrophobic alkyl chains of the inhibitor molecules extend outward from the metal surface, forming a compact organic layer. This hydrophobic layer acts as a barrier that restricts the approach of aggressive ions such as H^+ and SO_4^{2-} to the metal–solution interface, thereby reducing the corrosion process.

Electrochemical results strongly support this protective behaviour. A considerable increase in charge-transfer resistance (R_{ct}), together with a decrease in double-layer capacitance (C_{dl}) and a pronounced reduction in corrosion current density (I_{corr}), indicates the development of an adsorbed film that effectively protects the metal surface. This film suppresses both the anodic dissolution of iron and the cathodic hydrogen evolution reaction.

The observed decrease in C_{dl} also suggests that water molecules initially present at the metal surface are replaced by inhibitor species. This substitution increases the thickness of the

electrical double layer and enhances the extent of surface coverage by the inhibitor molecules. Furthermore, the relatively small shift in E_{corr} (less than 85 mV) implies that the inhibitor functions as a mixed-type inhibitor, simultaneously influencing both anodic and cathodic corrosion reactions.

In the blended extract system, multiple fatty acid constituents can adsorb simultaneously, improving surface coverage and packing efficiency. The presence of molecules with varying chain lengths and functional group densities reduces defect sites within the adsorbed layer and enhances film compactness. Minor oxygen-containing compounds detected in the chromatogram may provide additional anchoring sites through lone-pair electron interactions, thereby reinforcing interfacial stability.

Overall, the inhibition mechanism is governed by spontaneous mixed-mode adsorption involving initial electrostatic attraction followed by Fe–O coordination bonding and, where applicable, π –d interactions. The resulting adsorbed film acts as a compact interfacial barrier that effectively blocks active corrosion sites, suppresses charge transfer, and significantly retards the overall corrosion kinetics of mild steel in acidic medium.

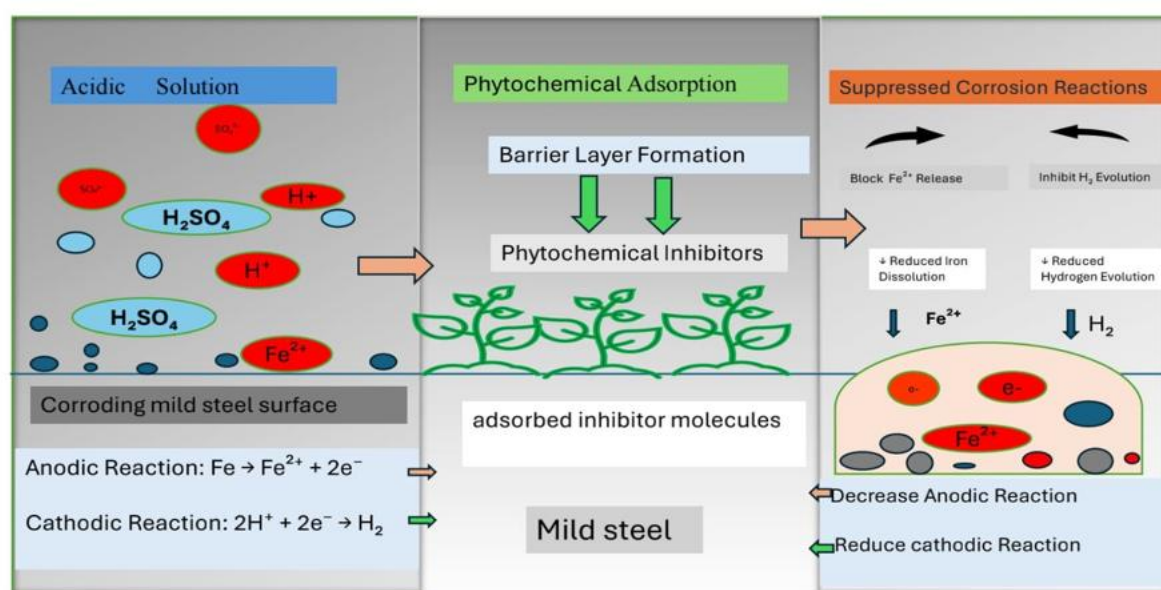


Figure 21: Schematic representation of the synergistic adsorption-driven protective film formation and suppression of anodic and cathodic reactions on mild steel in 0.5 M H_2SO_4 .

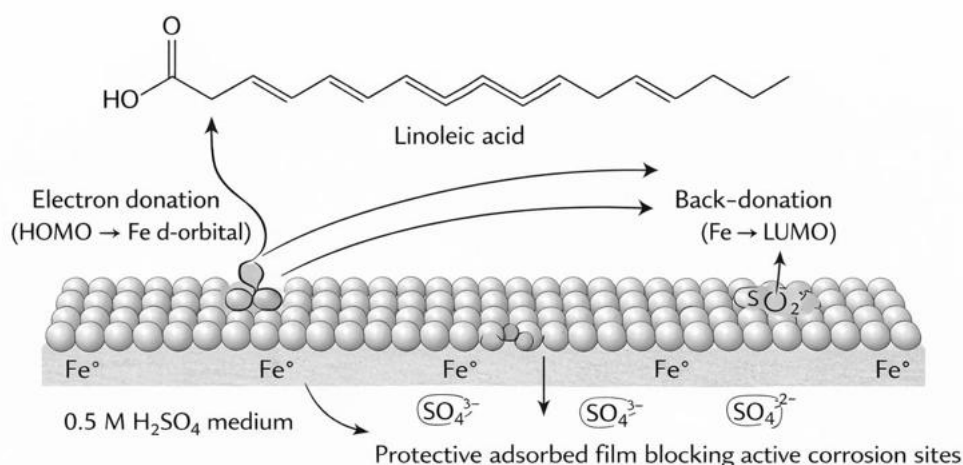


Figure 22. Schematic representation of the adsorption behaviour of linoleic acid molecules on the mild steel surface in 0.5 M H₂SO₄ solution, illustrating the interaction between the HOMO of the inhibitor molecule and the vacant d-orbitals of iron atoms. The diagram also depicts the possible back-donation from the metal surface to the LUMO of the inhibitor, which contributes to the formation of a stable protective adsorbed layer that limits corrosion.

Conclusion

The results of this study confirm that *Aglaonema* leaf extract and its blended formulations with orange peel and grape seed extracts can serve as efficient and environmentally friendly corrosion inhibitors for mild steel in 0.5 M H₂SO₄ solution. The inhibition effect primarily arises from the adsorption of phytochemical constituents onto the metal surface, leading to the formation of a protective barrier layer. Electrochemical observations suggest that the inhibitor system behaves as a mixed-type inhibitor, influencing both anodic and cathodic reactions.

Gravimetric measurements demonstrated a progressive reduction in corrosion rate as the inhibitor concentration increased. The individual leaf extract exhibited a maximum inhibition efficiency of 75.8% at 700 ppm. Electrochemical analyses supported these findings. Potentiodynamic polarization results indicated mixed-type inhibition with a slight tendency toward anodic control, whereas electrochemical impedance spectroscopy revealed a notable increase in charge-transfer resistance accompanied by a decrease in double-layer capacitance, confirming the formation of a compact adsorbed protective film.

Surface examination using stereomicroscopy, metallurgical microscopy, and scanning electron microscopy showed that the presence of the inhibitor significantly reduced surface deterioration and pit formation compared with the uninhibited system. FTIR spectral analysis

confirmed the presence of functional groups such as hydroxyl, carbonyl, and aromatic structures, which can interact with the metal surface through donor–acceptor interactions.

Thermodynamic and adsorption analyses further revealed that the adsorption process is spontaneous, as indicated by the negative values of $\Delta G^{\circ}_{\text{ads}}$. The magnitude of $\Delta G^{\circ}_{\text{ads}}$, ranging from -30 to -37 kJ mol⁻¹, suggests that the inhibition mechanism involves both electrostatic interactions and partial charge transfer between the inhibitor molecules and the metal surface. Among the evaluated adsorption models, the Freundlich isotherm provided the most appropriate description of the system, reflecting the heterogeneous adsorption behavior typical of complex plant-based inhibitor mixtures. Temperature-dependent studies indicated higher activation energy values in the presence of the inhibitor, confirming that the corrosion reaction is effectively retarded.

The blended extract systems exhibited enhanced performance, reaching a maximum inhibition efficiency of 86.2% for the Aglaonema–orange peel formulation. The improved efficiency is attributed to synergistic adsorption among diverse phytoconstituents, resulting in greater surface coverage and improved film stability.

GC–MS analysis identified fatty acids and oxygen-containing organic compounds as principal active constituents. Density Functional Theory calculations revealed that palmitic and linoleic acids preferentially adsorb via their carboxyl groups through Fe–O coordination and π –d orbital interactions. The smaller HOMO–LUMO energy gap and favourable electronic descriptors of linoleic acid explain its stronger adsorption tendency and superior inhibition efficiency. The agreement between theoretical predictions and experimental observations supports the proposed adsorption mechanism.

Overall, this study demonstrates that Aglaonema-based formulations provide effective and environmentally sustainable corrosion protection for mild steel in acidic media. The integration of experimental electrochemical techniques with surface characterization and theoretical modelling establishes a coherent understanding of the inhibition behaviour and confirms the reliability of plant-derived systems as viable alternatives to conventional synthetic inhibitors. The enhanced performance observed in blended extracts further highlights the potential of synergistic phytochemical combinations for advanced and sustainable corrosion control strategies in industrial applications.

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Declarations

Conflict of Interest

The authors confirm that there are no financial, professional, or personal relationships that could have influenced the research outcomes reported in this work.

Data Availability

The datasets generated and analysed during the present study are available from the corresponding author upon reasonable request.

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