

Interfacial Corrosion Protection of ST37 Steel by *Borassus flabellifer* Husk Extract in 1 M HCl: Effect of Inhibitor Concentration

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Abstract

In this study, the corrosion inhibition performance of *Borassus flabellifer* fruit husk extract was evaluated for ST37 steel in 1 M HCl at inhibitor concentrations of 50–250 ppm using weight-loss, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), FTIR, SEM–EDX, and atomic force microscopy (AFM). The extract exhibited its highest inhibition efficiency of 88.40% at 100 ppm. At this concentration, the corrosion current density decreased from 479.12 to 121.86 $\mu\text{A cm}^{-2}$, the corrosion rate decreased from 5.62 to 1.43 mm year⁻¹, and the charge-transfer resistance increased from 41.72 to 190 $\Omega \text{ cm}^2$. Polarization measurements indicated mixed-type inhibition with anodic predominance. Surface characterization showed reduced corrosion-induced degradation and lower surface roughness at 100 ppm, with R_a and R_q values of 68.28 and 88.15 nm, respectively. FTIR analysis identified oxygen-containing and aromatic functional groups that may contribute to interfacial adsorption. Overall, the electrochemical and surface-characterization results support a proposed adsorption-assisted inhibition mechanism involving the formation of a protective interfacial layer that reduces corrosion of ST37 steel in acidic media.

Keywords: *Borassus flabellifer*; ST37 steel; corrosion inhibition; electrochemical impedance spectroscopy; adsorption

1. Introduction

Acid pickling is an important surface-treatment process in steel manufacturing, particularly for removing oxide scale and other surface contaminants prior to subsequent processing [1,2]. Hydrochloric acid (HCl) is widely employed as a pickling medium because of its effective dissolution of iron oxides and relatively low operating cost [3–5]. However, the aggressive nature of HCl is not limited to the oxide layer [6]. Once the scale has been removed, the exposed steel substrate becomes susceptible to anodic dissolution of iron accompanied by cathodic hydrogen evolution [5,7]. Prolonged exposure can consequently cause unnecessary metal loss and progressive deterioration of the steel surface [8–10]. Therefore, effective pickling requires not only adequate oxide removal but also control of substrate corrosion at the steel–acid interface.

Corrosion inhibitors are commonly introduced into acidic solutions to suppress the dissolution of exposed steel surfaces [11–13]. protective action is primarily associated with adsorption onto the metal surface [14], where inhibitor molecules can form a barrier that reduces direct interaction between the corrosive medium and the steel [15,16]. Thus, the extent of surface protection depends strongly on the interaction between inhibitor molecules and the metal-electrolyte interface, which can influence the electrochemical processes responsible for corrosion [17,18]. Although conventional inhibitors can provide effective protection, concerns regarding toxicity, environmental persistence, and waste management have driven the search for more environmentally compatible alternatives derived from renewable resources [19,20].

Plant-derived extracts have consequently emerged as potential alternatives because they contain diverse secondary metabolites capable of interacting with metallic surfaces [21,22]. Phenolic compounds, flavonoids, tannins, alkaloids, and saponins possess heteroatoms and electron-rich structures that can facilitate adsorption onto metal surfaces and contribute to the formation of protective layers [17,23]. Their effectiveness in acidic environments has been demonstrated for a range of plant species. For example, *Trochodendron aralioides* extract achieved a maximum inhibition efficiency of 96.42% for mild steel in 1 M HCl at 250 ppm, with electrochemical and surface analyses indicating the formation of a protective layer on the steel surface [24]. *Moringa oleifera* fruit extract likewise inhibited mild-steel corrosion in HCl, with its

adsorption behaviour described by the Langmuir isotherm [25]. Dardagan fruit extract achieved inhibition efficiencies of approximately 92% after 1 h and 97% after 6 h in 1 M HCl, while SEM and AFM revealed marked differences in the morphology and roughness of inhibited and uninhibited steel surfaces [26]. Taken together, these studies demonstrate that plant-derived compounds can modify both the electrochemical corrosion process and the physical condition of the metal surface. However, their protective performance depends strongly on the nature of the extract, inhibitor concentration, and experimental conditions.

The use of plant-based residues as corrosion inhibitors provides an additional route for transforming underutilized biomass into functional materials for surface protection [27,28]. *Borassus flabellifer* (lontar) is a tropical palm whose fruit is covered by an outer husk that represents a relatively underutilized biomass resource [29]. Previous phytochemical investigations of *Borassus flabellifer* fruit and its fibrous tissues have identified several classes of secondary metabolites, including alkaloids, flavonoids, tannins, saponins, phenolic compounds, terpenoids, and glycosides [30,31]. These constituents possess functional groups that may interact with the steel surface and contribute to the formation of an adsorbed protective layer at the steel-HCl interface [32]. Accordingly, the corrosion-inhibiting role of these constituents is closely associated with their interaction with the steel-electrolyte interface, particularly their adsorption and its influence on electrochemical behaviour and surface condition.

Despite the phytochemical profile reported for *Borassus flabellifer*, its capacity to provide interfacial corrosion protection for ST37 steel in HCl remains poorly understood. In particular, the influence of inhibitor concentration on corrosion kinetics, interfacial charge transfer, adsorption behaviour, and surface degradation has yet to be adequately clarified [33,34]. This is important because increasing inhibitor concentration does not necessarily translate into a proportional increase in corrosion protection [35]. Changes in concentration may alter surface coverage and the arrangement of adsorbed inhibitor species at the steel-solution interface, thereby influencing both the electrochemical response and the condition of the protected surface [36]. A systematic concentration-dependent investigation is therefore needed to clarify how *Borassus flabellifer* fruit husk extract interacts with the steel surface and how this interaction contributes to corrosion protection in acidic media.

Accordingly, this study examines the interfacial corrosion protection of ST37 steel by *Borassus flabellifer* fruit husk extract in 1 M HCl as a function of inhibitor concentration. Tafel polarization and electrochemical impedance spectroscopy (EIS) were employed to characterize the corrosion kinetics and charge-transfer behaviour at the ST37-HCl electrolyte interface. Changes in surface morphology and elemental composition were examined using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX) and atomic force microscopy (AFM), while phytochemical screening and Fourier-transform infrared spectroscopy (FTIR) were used to characterize the extract. Adsorption analysis was further applied to examine the interaction between inhibitor species and the steel surface. By linking inhibitor concentration with electrochemical behaviour, adsorption characteristics, and surface morphology, this study clarifies the role of *Borassus flabellifer* fruit husk extract in modifying the steel-HCl interface and evaluates its effectiveness as a plant-derived corrosion inhibitor for ST37 steel under acidic pickling conditions.

2. Experimental and Methods

2.1. Materials and Reagents

Fresh *Borassus flabellifer* fruit husks were collected from a local market in Balikpapan, East Kalimantan, Indonesia. Hydrochloric acid (HCl, 32%), ethanol (96% (v/v)), distilled water, Dragendorff's reagent, and sodium hydroxide (NaOH, ≥98%) were purchased from Merck, Germany. HCl was diluted with distilled water to prepare the 1 M HCl solution, while NaOH was prepared as a 1% (w/v) solution. ST37 steel specimens with dimensions of 20 mm × 20 mm × 2 mm were obtained from a local market in Balikpapan, East Kalimantan, Indonesia.

2.2 Apparatus

The instruments used in this study included a CS100 potentiostat (Corrtest, China) for electrochemical measurements, including Tafel polarization and electrochemical impedance spectroscopy (EIS). Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX, Phenom ProX, Thermo Scientific, USA) was used to characterize the surface morphology and elemental composition of the ST37 steel specimens and operated at an

accelerating voltage of 10-15 kV. Fourier-transform infrared spectroscopy (FTIR, Alpha II, Bruker, USA) was employed to identify the functional groups present in the *Borassus flabellifer* fruit husk extract over the wavenumber range of 200-4000 cm^{-1} using an ATR-ZnSe module. Atomic force microscopy (AFM, Bruker, Germany) was used to characterize the surface topography and roughness of the steel specimens. Optical emission spectroscopy (OES, Thermo Scientific, USA) was employed to determine the elemental composition of the ST37 steel.

2.3 Preparation of *Borassus flabellifer* Fruit Husk Extract

Fresh *Borassus flabellifer* fruit husks were collected from a local market in Balikpapan, East Kalimantan, Indonesia, washed thoroughly with running water, cut into small pieces, and dried in a hot-air oven at 70 °C for 8 h. The dried material was ground into a fine powder and extracted by maceration in 96% (v/v) ethanol at room temperature for 21 days. The resulting mixture was filtered, and the filtrate was concentrated under reduced pressure using a rotary vacuum evaporator at 40-50 °C. The concentrated extract was collected and stored in amber glass containers until further use [37]. Subsequently, the extract was subjected to phytochemical screening for flavonoids, tannins, and alkaloids, followed by FTIR analysis to characterize its functional groups [38,39].

2.4 Electrochemical Measurements

Electrochemical measurements were conducted in 1 M HCl containing *Borassus flabellifer* fruit husk extract at concentrations of 50, 100, 150, 200, and 250 ppm, using a Corrtest CS100 potentiostat connected to a conventional three-electrode cell. ST37 steel with an exposed surface area of 4.8 cm^2 was used as the working electrode, with Ag/AgCl and platinum serving as the reference and counter electrodes, respectively. A schematic illustration of the electrochemical cell configuration is presented in Fig. 1. Prior to each measurement, the working electrode was immersed in the test solution for 15 min under open-circuit conditions to allow stabilization of the steel-electrolyte interface. Electrochemical impedance spectroscopy (EIS) was then performed at the stabilized open-circuit potential (OCP) using a sinusoidal perturbation of 10 mV over a frequency range of 100 kHz-10 mHz, followed by potentiodynamic polarization at

a scan rate of 1 mV s^{-1} . The resulting electrochemical parameters were used to assess the corrosion behaviour and inhibition efficiency of the *Borassus flabellifer* fruit husk extract.

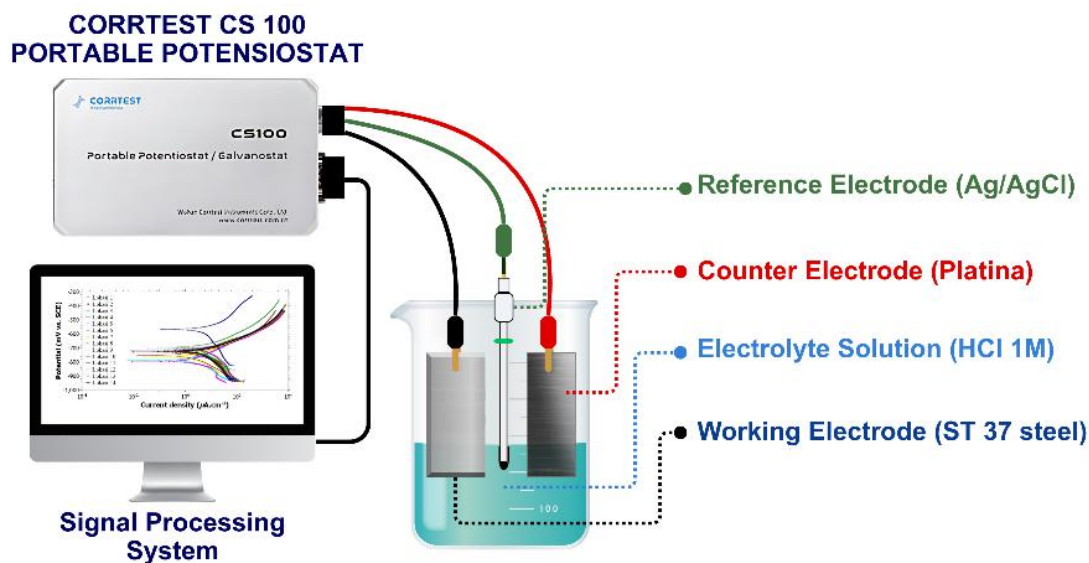


Fig 1. Schematic illustration of the three-electrode electrochemical cell used for corrosion measurements.

3. Results and Discussion

3.1 Chemical Characterization of *Borassus flabellifer* Fruit Husk Extract

3.1.1 Phytochemical Screening

The phytochemical screening results of *Borassus flabellifer* fruit husk extract are presented in Fig. S1, with the corresponding observations and identification summarized in Table S1. Flavonoids, tannins, and alkaloids were detected in the extract. The flavonoid test produced a yellow precipitate following the addition of 1% NaOH and HCl, while the tannin test showed colour fading after the addition of 1% lead acetate. The alkaloid test resulted in an orange coloration upon treatment with 1% HCl and Dragendorff reagent. These positive reactions confirmed the presence of flavonoids, tannins, and alkaloids in the extract.

3.1.2 FTIR Analysis of *Borassus flabellifer* Fruit Husk Extract

The FTIR spectrum of the *Borassus flabellifer* fruit husk extract (Fig. 2) displayed distinct absorption bands at 3320.76 , 2979.67 , 1640.70 , 1043.68 , and 846.92 cm^{-1} . The broad band

centered at 3320.76 cm^{-1} corresponds to O-H stretching, whereas the band at 2979.67 cm^{-1} is associated with aliphatic C-H stretching. A band at 1640.70 cm^{-1} was observed in the region characteristic of C=C stretching. The strong absorption at 1043.68 cm^{-1} can be assigned to C-O stretching, while the band at 846.92 cm^{-1} is attributable to out-of-plane C-H bending in substituted aromatic structures [40,41]. These oxygen- and carbon-containing functional groups may facilitate interactions between the extract constituents and the steel surface through adsorption [42,43].

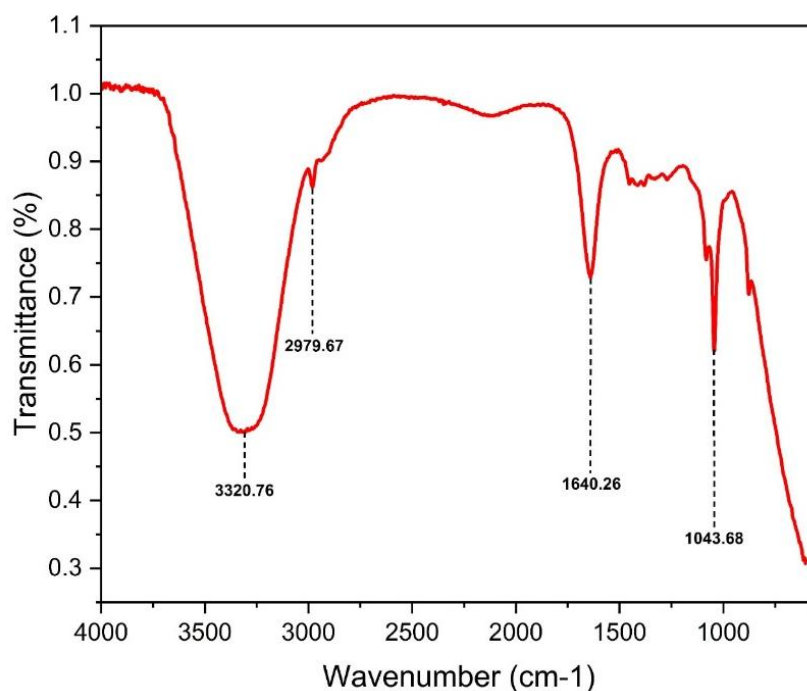


Fig 2. FTIR spectrum of *Borassus flabellifer* fruit husk extract

3.2 Weight Loss Measurement

The weight loss (WL) and inhibition efficiency (IE) were calculated using Eqs. (1) and (2), respectively:

$$WL = W_i - W_f \quad (1)$$

$$IE(\%) = \frac{WL_0 - WL_i}{WL_0} \times 100 \quad (2)$$

where W_i and W_f are the initial and final weights of the ST37 specimens, respectively, while WL_0 and WL_i represent the weight loss in the blank and inhibited solutions, respectively. The weight loss and inhibition efficiency results are presented in Table S2. The blank specimens showed weight losses of 0.067-0.082 g, which decreased to 0.002-0.025 g upon addition of the extract. The average IE increased from 73.23% at 50 ppm to 88.40% at 100 ppm, then decreased to 87.06%, 77.69%, and 81.25% at 150, 200, and 250 ppm, respectively (Fig. S2). Thus, the highest IE of 88.40% was obtained at 100 ppm, indicating that further increasing the extract concentration did not improve corrosion protection.

3.3 Electrochemical Corrosion Behaviour

3.3.1 Open Circuit Potential Analysis

The OCP response of ST37 steel in 1 M HCl is presented in Fig. 3. In the uninhibited electrolyte, the potential was initially recorded at approximately -0.427 V and gradually shifted to -0.425 to -0.426 V with immersion. In the presence of 100 ppm *Borassus flabellifer* fruit husk extract, the initial potential was considerably more positive at approximately -0.393 V and stabilized near -0.395 to -0.396 V. The inhibitor-containing system therefore exhibited a positive potential displacement of approximately 30 mV relative to the uninhibited condition throughout the measurement. This shift reflects a change in the electrochemical state of the steel-electrolyte interface induced by the presence of the extract [44]. The subsequent stabilization of both OCP profiles indicates that the interfacial conditions approached a quasi-steady state before the polarization and EIS measurements.

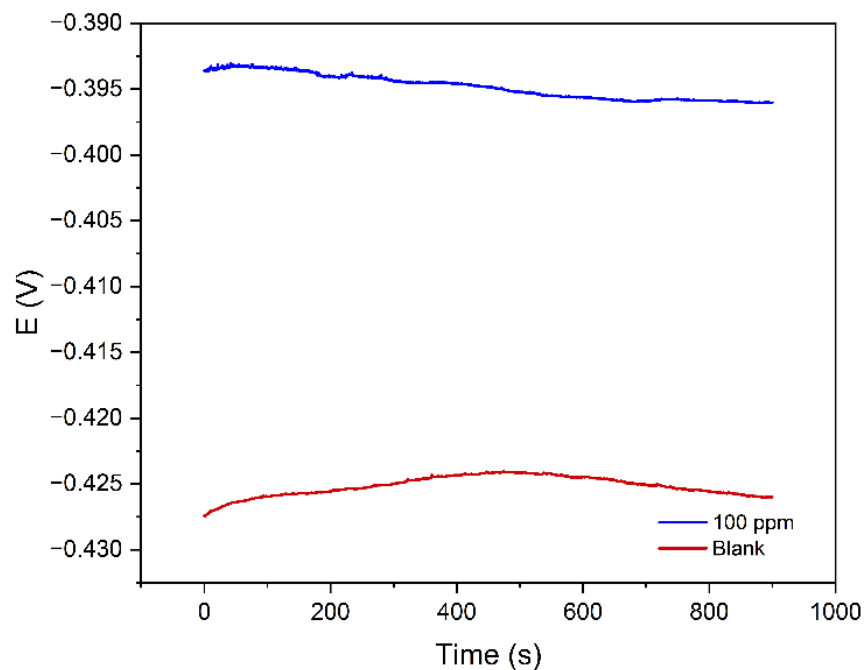


Fig 3. Open-circuit potential (OCP) evolution of ST37 steel in 1 M HCl without inhibitor and with 100 ppm *Borassus flabellifer* fruit husk extract

3.3.2 Potentiodynamic Polarization Analysis

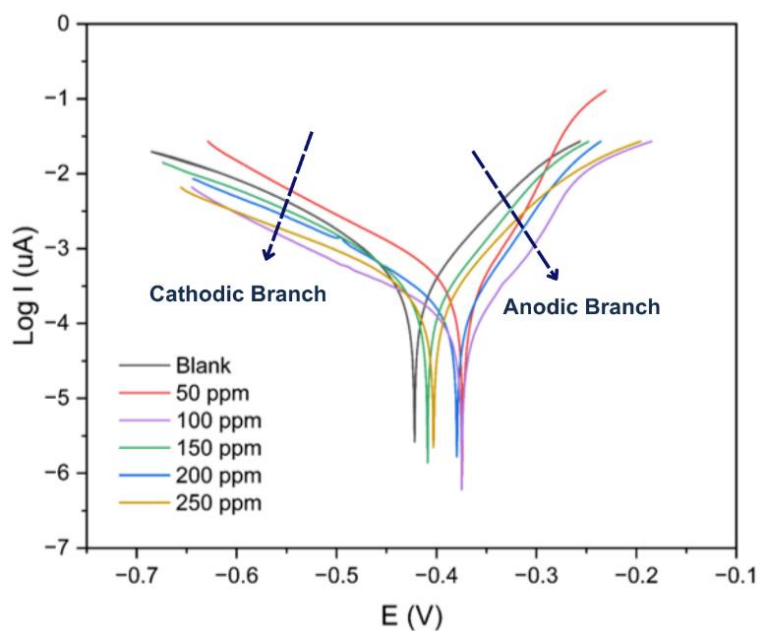


Fig 4. Potentiodynamic polarization curves of ST37 steel in 1 M HCl without and with different concentrations of *Borassus flabellifer* fruit husk extract.

The addition of *Borassus flabellifer* fruit husk extract markedly reduced the corrosion current density (i_{corr}) of ST37 steel in 1 M HCl, although the inhibition response varied with inhibitor concentration, as shown by the polarization curves in Fig. 4 and the corresponding parameters in Table 1. The blank exhibited an i_{corr} of 479.12 $\mu\text{A cm}^{-2}$ and a corrosion rate of 5.62 mm year⁻¹. At 100 ppm, these values decreased to 121.86 $\mu\text{A cm}^{-2}$ and 1.43 mm year⁻¹, respectively, corresponding to the highest inhibition efficiency of 74.6%. The inhibition efficiency increased from 51.8% at 50 ppm to 74.6% at 100 ppm, but declined at higher concentrations, reaching 34.8%, 60.7%, and 34.0% at 150, 200, and 250 ppm, respectively. This non-monotonic response demonstrates that the corrosion-inhibition performance was strongly dependent on inhibitor concentration, with 100 ppm providing the most effective protection among the investigated conditions. The inhibition efficiency was calculated using:

$$IE\% = \left(1 - \frac{i_i}{i_0}\right) \times 100\% \quad (3)$$

where $i_{corr,blank}$ and $i_{corr,inh}$ denote the corrosion current densities of the blank and inhibited systems, respectively. As summarized in Table 2, the corrosion potential (E_{corr}) shifted from -0.42195 V for the blank to values between -0.37420 and -0.40896 V following inhibitor addition. All shifts remained within ± 85 mV relative to the blank, indicating that the extract acts as a mixed-type inhibitor [45]. The changes in both anodic and cathodic branches of the curves in Fig. 4 further indicate that the extract affects both iron dissolution and hydrogen evolution, while the predominantly positive shift in E_{corr} suggests a somewhat greater influence on the anodic reaction [44,46,47]. Overall, the polarization results in Fig. 4 and Table 2 identify 100 ppm as the optimum concentration and demonstrate a pronounced concentration dependence of the extract's corrosion-inhibition performance.

Table 1. Tafel polarization parameters of ST37 steel in 1 M HCl containing different concentrations of *Borassus flabellifer* fruit husk extract

Concentrations (ppm)	β_a (mV.dec ⁻¹)	$-\beta_c$ (mV.dec ⁻¹)	I_{corr} ($\mu A\ cm^{-2}$)	E_{corr} (V)	CR (mm year ⁻¹)	%IE
Blank	92.039	150.59	479.12	-0.42195	5.62	-
50	50.83	121.65	231.35	-0.3742	2.71	51.8
100	74.25	163.62	121.86	-0.37464	1.43	74.6
150	81.23	151.1	312.75	-0.40896	3.67	34.8
200	64.56	153.25	188.67	-0.37951	2.21	60.7
250	99.30	198.93	316.57	-0.40298	3.7138	34

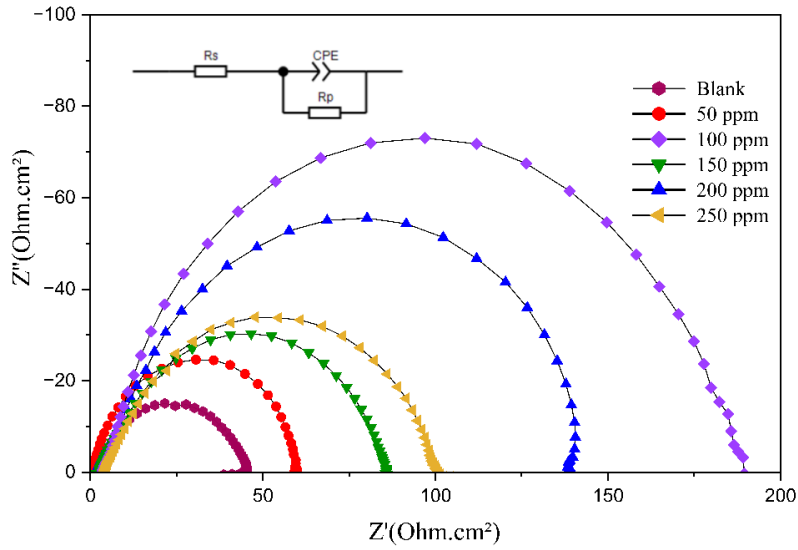
3.3.3 Electrochemical Impedance Spectroscopy Analysis

The EIS response of ST37 steel changed markedly with the addition of *Borassus flabellifer* fruit husk extract, as reflected by the Nyquist and Bode spectra in Fig. 5. The inhibited systems exhibited larger capacitive responses than the blank, indicating increased resistance to interfacial charge transfer. The corresponding impedance parameters are listed in Table 2. The charge-transfer resistance (R_{ct}) increased from 41.72 $\Omega\ cm^2$ for the uninhibited steel to 60.84, 190.00, 84.17, 145.00, and 98.53 $\Omega\ cm^2$ at 50, 100, 150, 200, and 250 ppm, respectively. The highest R_{ct} was obtained at 100 ppm, representing an approximately 4.6-fold increase relative to the blank and corresponding to the highest EIS-based inhibition efficiency of 78.1%. This pronounced increase in R_{ct} indicates that the presence of the extract substantially hindered charge transfer at the steel-electrolyte interface [48]. The EIS-based inhibition efficiency was calculated according to:

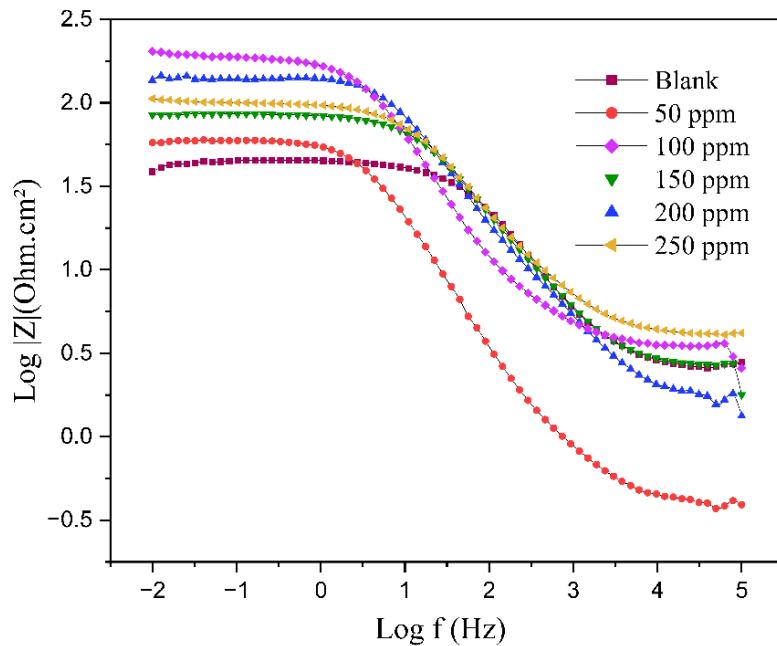
$$IE\% = \left(1 - \frac{R_{ct,blank}}{R_{ct,inhibitor}} \right) \times 100\% \quad (4)$$

where $R_{ct,blank}$ and $R_{ct,inh}$ represent the charge-transfer resistance of the uninhibited and inhibited systems, respectively.

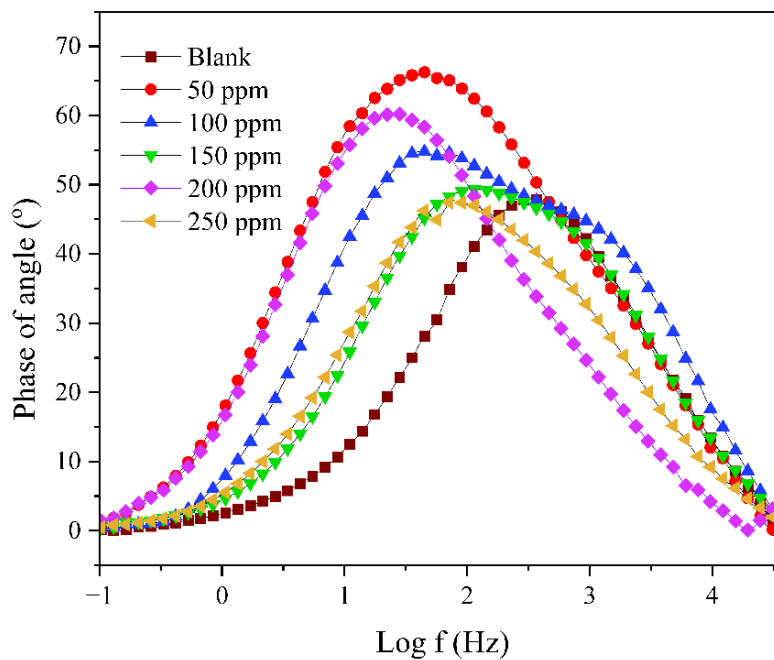
The concentration-dependent variation in R_{ct} reveals a non-monotonic inhibition response (Table 2). After reaching its maximum at 100 ppm, R_{ct} decreased at 150 ppm, increased again at 200 ppm, and subsequently decreased at 250 ppm. This trend is consistent with the polarization results, which also identified 100 ppm as the optimum concentration. The R_s values showed no systematic variation across the investigated concentrations, indicating that the impedance response was primarily associated with changes at the steel-electrolyte interface rather than substantial changes in bulk solution resistance [49].



(a)



(b)



(c)

Fig. 5. Electrochemical impedance spectroscopy results for ST37 steel in 1 M HCl containing different concentrations of *Borassus flabellifer* fruit husk extract: (a) Nyquist plot, (b) Bode impedance modulus plot, and (c) Bode phase-angle plot.

The variation in R_{ct} with inhibitor concentration confirms a non-monotonic inhibition response (Table 2). The R_{ct} increased from 41.72 $\Omega \text{ cm}^2$ for the blank to 190.00 $\Omega \text{ cm}^2$ at 100 ppm, corresponding to the highest EIS-derived inhibition efficiency of 78.1%, before decreasing at higher concentrations. This trend agrees with the polarization results, which also identified 100 ppm as the optimum concentration. The R_s values showed no systematic variation (0.42-4.10 $\Omega \text{ cm}^2$), indicating that the observed impedance changes were primarily associated with the steel-electrolyte interface rather than the bulk solution. The Bode impedance modulus spectra in Fig. 5(b) showed the highest low-frequency $|Z|$ at 100 ppm, consistent with its maximum R_{ct} . The phase-angle spectra in Fig. 5(c) exhibited a single dominant maximum for all systems, indicating a similar principal electrochemical time constant. Overall, the EIS response demonstrates enhanced resistance to interfacial charge transfer in the presence of the extract, with the strongest effect observed at 100 ppm.

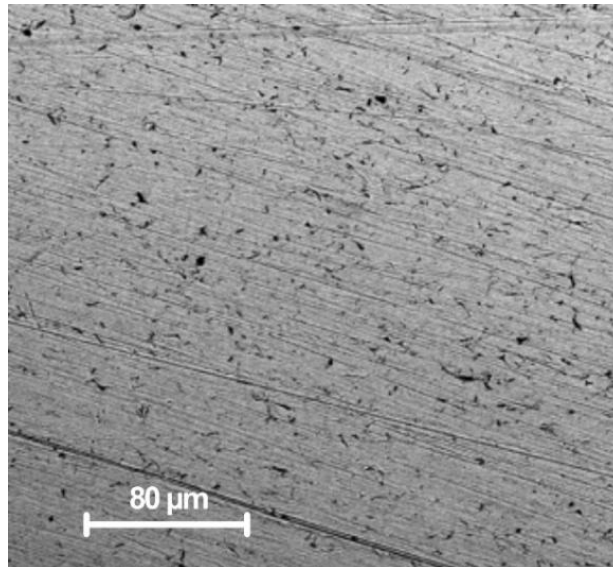
Table 2. Electrochemical impedance parameters of ST37 steel in 1 M HCl containing different concentrations of *Borassus flabellifer* fruit husk extract.

Concentrations (ppm)	R_s ($\Omega \cdot \text{cm}^2$)	R_{ct} ($\Omega \cdot \text{cm}^2$)	%IE
Blank	2.64	41.72	-
50	0.4238	60.84	31.5
100	3.58	190	78.1
150	2.575	84.17	50.5
200	1.703	145	71.3
250	4.099	98.53	57.7

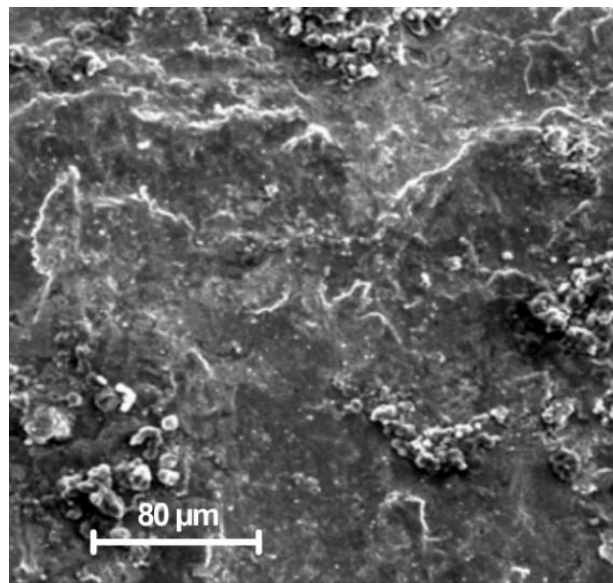
3.4 Surface Morphology and Elemental Composition

The bare ST37 surface was relatively smooth, with visible polishing marks (Fig. 6a). After immersion in 1 M HCl, the surface became markedly rougher and exhibited localized damage (Fig. 6b). In contrast, the surface exposed to 100 ppm *Borassus flabellifer* extract appeared to be covered by a relatively continuous and uniform layer, with fewer exposed defects (Fig. 6c). The corresponding SEM observations at the other extract concentrations are presented in Figs. S3-

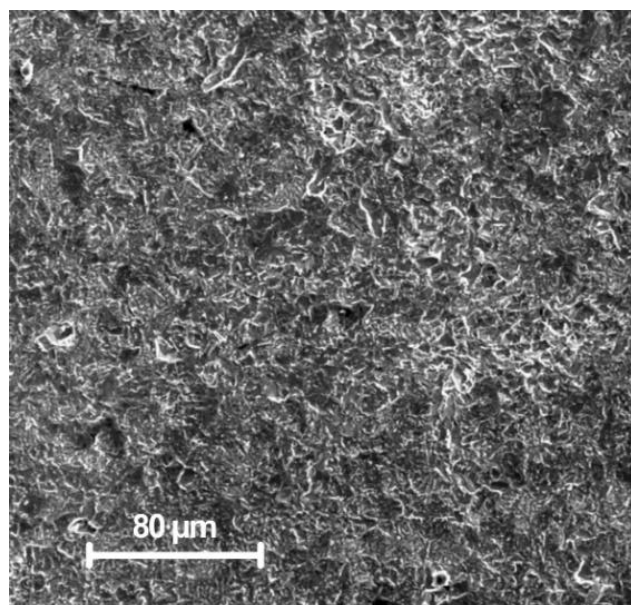
S6. This surface coverage suggests the formation of a protective layer by the extract, which limits direct contact between the acidic solution and the steel surface.



(a)



(b)



(c)

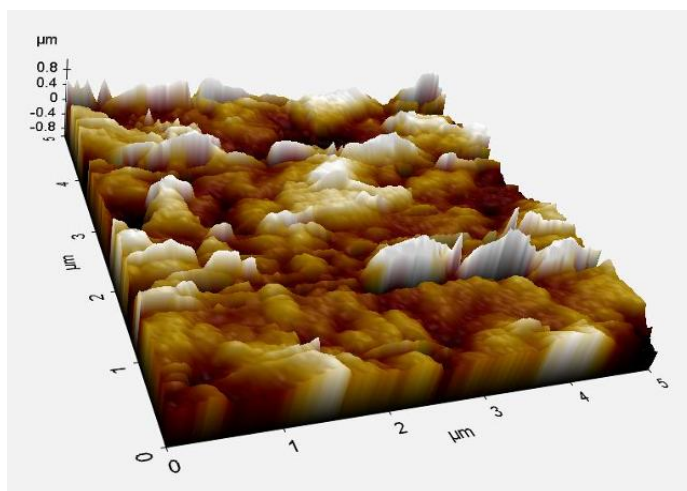
Fig. 6. SEM micrographs of ST37 steel surfaces: (a) bare steel, (b) after immersion in 1 M HCl, and (c) after immersion in 1 M HCl containing 100 ppm *Borassus flabellifer* extract.

The EDX results further support these observations. The Fe content decreased from 98.75 wt.% for the bare steel to 81.74 wt.% after immersion in uninhibited HCl, accompanied by an increase in O to 16.13 wt.%. With the addition of the extract, the Fe content increased to 90.11, 96.77, 90.22, 86.83, and 84.21 wt.% at 50, 100, 150, 200, and 250 ppm, respectively. The highest Fe content was obtained at 100 ppm, indicating the greatest preservation of the steel surface at this concentration. The corresponding O contents were 6.45, 1.45, 7.06, 10.83, and 1.17 wt.%, respectively. Although the O content at 250 ppm was slightly lower than that at 100 ppm, its Fe content was substantially lower. Overall, the EDX results support 100 ppm as the optimum concentration for surface protection, consistent with the electrochemical and weight-loss results. The summarized EDX elemental compositions are provided in Table S3.

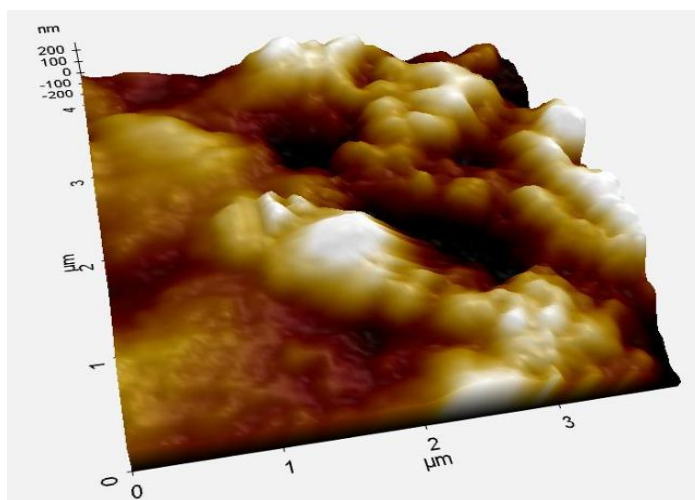
3.5 Surface Roughness Analysis

The AFM images in Fig. 7 show a highly heterogeneous surface with pronounced height variations for the blank specimen, whereas the surface exposed to 100 ppm *Borassus flabellifer* extract was considerably more uniform. The corresponding surface roughness parameters for all

extract concentrations are summarized in Table 4. The blank (Fig. 7a) exhibited R_a (arithmetic mean roughness), R_q (root mean square roughness), R_{pv} (maximum peak-to-valley height), and R_z (average maximum height of the surface profile) values of 156, 206, 2100, and 1770 nm, respectively. At 100 ppm, these values decreased markedly to 68.28, 88.15, 558.11, and 552.61 nm, respectively, corresponding to reductions of approximately 56.2%, 57.2%, 73.4%, and 68.8% relative to the blank (Table 4). The corresponding AFM observations at the other extract concentrations are presented in Fig. S7.



(a)



(b)

Fig 7. Three-dimensional AFM surface topography of ST37 steel: (a) blank 1 M HCl and (b) steel after immersion in 1 M HCl containing 100 ppm *Borassus flabellifer* fruit husk extract.

As shown in Table 4, increasing the extract concentration above 100 ppm resulted in higher roughness values. At 150 ppm, R_a , R_q , R_{pv} , and R_z increased to 91.40, 125.76, 1550.90, and 1470.53 nm, respectively. At 200 ppm, the corresponding values were 75.91, 95.79, 838.97, and 753.16 nm, while further increasing the concentration to 250 ppm resulted in values of 127, 174, 1582, and 1425 nm, respectively. The lowest values for all roughness parameters were obtained at 100 ppm (Table 4), indicating the greatest reduction in surface roughness at this concentration.

Table 4. Surface roughness parameters of ST37 steel after immersion in 1 M HCl containing different concentrations of *Borassus flabellifer* fruit husk extract.

Concentrations (ppm)	Ra (nm)	Rq(nm)	Rpv (nm)	Rz (nm)
Blank	156	206	2100	1770
50	143.53	188.90	1644.35	1491.35
100	68.28	88.15	558.11	552.61
150	91.40	125.76	1550.90	1470.527
200	75.91	95.79	838.97	753.16
250	127	174	1582	1425

3.6 Adsorption Behavior

To evaluate the adsorption behavior of *Borassus flabellifer* fruit husk extract on the ST37 steel surface, the experimental data were fitted using four commonly employed adsorption isotherm models: Langmuir, Freundlich, Temkin, and Frumkin [50]. The corresponding linearized plots are presented in Fig. 8.

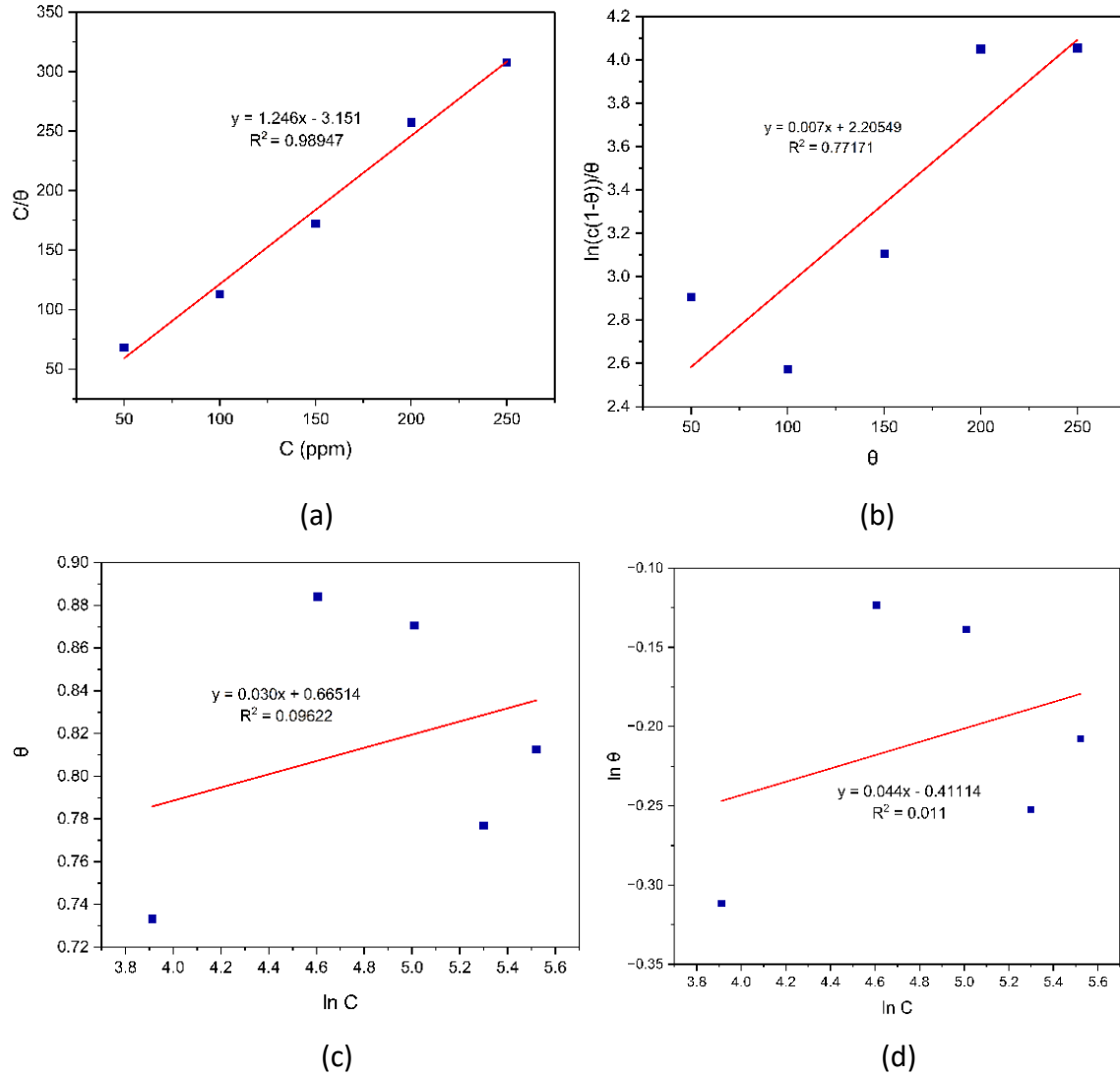


Fig. 8. Linearized adsorption isotherm plots for *Borassus flabellifer* fruit husk extract on ST37 steel in 1 M HCl: (a) Langmuir, (b) Freundlich, (c) Temkin, and (d) Frumkin models.

Langmuir isotherm

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \quad (5)$$

where C is the inhibitor concentration, θ is the surface coverage, and K_{ads} is the adsorption equilibrium constant.

Freundlich isotherm

$$\theta = K_{ads} C^n \quad (6)$$

where n represents the adsorption intensity associated with surface heterogeneity.

Temkin isotherm

$$e^{-2a\theta} = K_{ads} C \quad (7)$$

where a is the molecular interaction parameter describing the interactions between adjacent adsorbed species.

Frumkin isotherm

$$\ln \frac{c(1-\theta)}{\theta} = -2a\theta - \ln K_{ads} \quad (8)$$

where a is the interaction parameter that accounts for lateral interactions between adsorbed molecules.

Among the investigated models, the Langmuir isotherm exhibited the highest coefficient of determination ($R^2 = 0.98947$), indicating the closest fit to the experimental adsorption data. Thus, the Langmuir model provides the best empirical description of the concentration-dependent surface coverage under the present conditions [22,51,52]. However, the R^2 value alone does not establish ideal monolayer adsorption. The Freundlich, Temkin, and Frumkin models showed lower R^2 values, indicating poorer agreement with the experimental data. The adsorption equilibrium constant and standard Gibbs free energy of adsorption were further considered using the Langmuir relationship and:

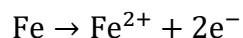
$$\Delta G_{ads}^\circ = -RT \ln(55.5 K_{ads}) \quad (9)$$

where R is the gas constant, T is the absolute temperature, and K_{ads} is the adsorption equilibrium constant. However, the linearized Langmuir plot exhibited a negative intercept. Because the intercept corresponds to $1/K_{ads}$, this result yields a physically meaningless negative K_{ads} . Consequently, a valid K_{ads} and the corresponding ΔG_{ads}° could not be determined reliably.

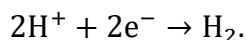
Therefore, the adsorption analysis was interpreted primarily based on the relative R^2 values rather than thermodynamic adsorption parameters.

3.7 Corrosion Inhibition Mechanism

The corrosion inhibition of ST37 steel by *Borassus flabellifer* fruit husk extract is proposed to involve adsorption of extract constituents at the steel-solution interface, thereby reducing the exposure of the metal surface to corrosive species [53]. In 1 M HCl, anodic iron dissolution occurs as:



coupled with cathodic hydrogen evolution:



The O-H ($\sim 3320\text{ cm}^{-1}$), C=C ($\sim 1640\text{ cm}^{-1}$), and C-O ($\sim 1043\text{ cm}^{-1}$) bands identified by FTIR, together with the detected flavonoids, tannins, and alkaloids, indicate the presence of oxygen-containing and aromatic constituents capable of interacting with the steel surface [40,41]. Such interactions may involve heteroatom- and π -electron-containing groups through electrostatic and donor–acceptor interactions [10,54]. However, specific Fe-O or metal– π bonding cannot be established from the present characterization.

The proposed surface protection is consistent with the electrochemical and morphological results. The optimum concentration of 100 ppm produced the highest R_{ct} and lowest i_{corr} , while SEM-EDX and AFM showed reduced surface degradation and the lowest surface roughness at the same concentration. The Langmuir model also provided the highest R^2 (0.98947), supporting the relevance of surface coverage, although the negative intercept prevented reliable determination of K_{ads} and ΔG_{ads}° . Thus, the adsorption mode cannot be conclusively assigned from the present data. Overall, the results support the proposed adsorption-assisted inhibition mechanism shown in Fig. 9, in which extract constituents form a protective interfacial layer that limits corrosion reactions.

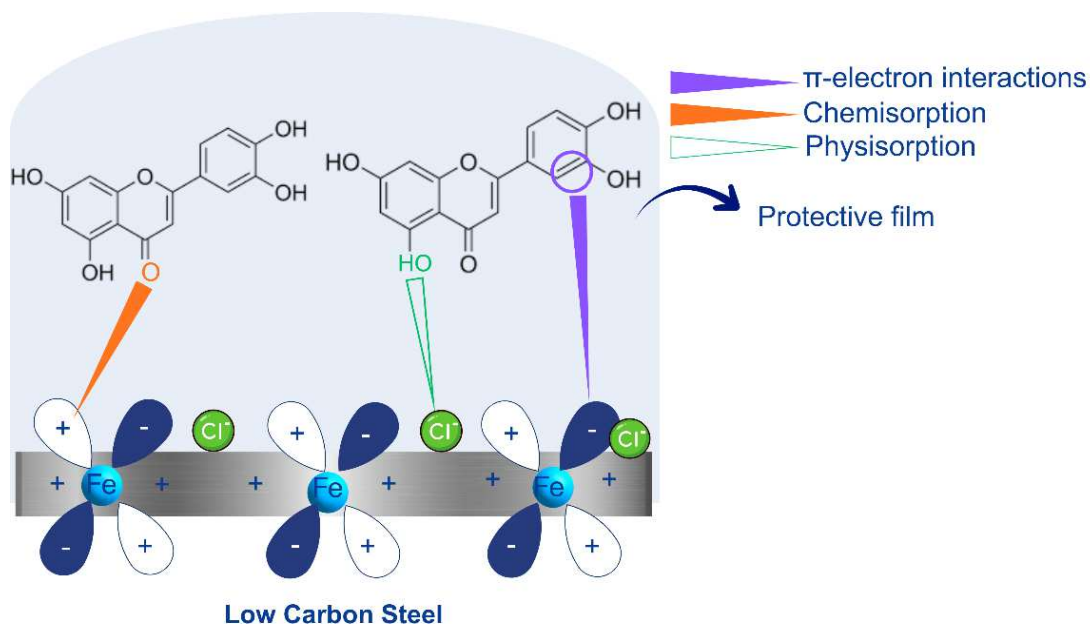


Fig 9. Proposed corrosion inhibition mechanism of *Borassus flabellifer* fruit husk extract on ST37 steel in 1 M HCl, illustrating adsorption of extract constituents at the steel/solution interface and the resulting protective surface layer.

4. Conclusion

Borassus flabellifer fruit husk extract effectively inhibited the corrosion of ST37 steel in 1 M HCl, with the optimum performance obtained at 100 ppm. At this concentration, the surface exhibited the lowest roughness ($R_a = 68.28$ nm; $R_q = 88.15$ nm) and a more uniform morphology. Electrochemical measurements indicated mixed-type inhibition with anodic predominance, while FTIR identified oxygen-containing and aromatic functional groups that may contribute to adsorption at the steel-solution interface. The maximum inhibition efficiency reached 88.40% from weight-loss measurements, accompanied by reductions in i_{corr} from 479.12 to 121.86 $\mu\text{A cm}^{-2}$ and corrosion rate from 5.62 to 1.43 mm year⁻², together with an increase in R_{ct} from 41.72 to 190 Ωcm^{-2} . Overall, the agreement among weight-loss, polarization, EIS, and surface-characterization results supports an adsorption-assisted inhibition mechanism, in which extract constituents form a protective interfacial layer that reduces corrosion of ST37 steel in 1 M HCl.

CRedit authorship contribution statement

Yunita Triana: Conceptualization, Supervision, Project administration, Writing - review & editing. Thiananda Citra Julianty: Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing - original draft. Aflihud Wildan: Investigation, Validation. Andromeda Dwi Laksono, Keysi Devain Destiny, Yosua Anjupaian Situmeang: Project Administration. Kartika Anoraga Madurani, Masato Tominaga: Supervision, Resources

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data supporting the findings of this study are available in the Supplementary Information.

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