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A Green and Sustainable Approach for Corrosion Inhibition of Carbon Steel in HCl Solution by *Abelmoschus Esculentus* Peduncle Extract

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Abstract

The corrosion of carbon steel in hydrochloric acid (HCl) is a major economic and safety problem in industrial processes such as pickling and descaling. This research investigates the use of peduncle extract from *Abelmoschus esculentus* (okra) as a green, ecological corrosion inhibitor. A structured literature review indicates that okra extracts, particularly mucilage, can achieve high inhibition efficiencies (up to 96%) by adsorbing onto carbon steel surfaces, predominantly following the Langmuir adsorption isotherm. Experimentally, weight loss measurements were performed on carbon steel in 1 M HCl with varying concentrations of okra peduncle extract (1–3) g at 20–60 °C. Results showed high inhibition efficiency (up to 98.4% at 40 °C for 3 g extract), which was concentration-dependent and exhibited a slight decrease at 60°C (90.7%). Thermodynamic analysis indicated a spontaneous physisorption process. The synthesized evidence confirms that *Abelmoschus esculentus* peduncle extract is a potent, sustainable, and economically viable alternative to traditional synthetic corrosion inhibitors.

Keywords: Corrosion Inhibition; Carbon Steel; Abelmoschus esculentus; Green Inhibitor; HCl; Adsorption Isotherm; Weight Loss.

1. Introduction

Corrosion of carbon steel in acidic media is a pervasive industrial problem with global economic losses estimated in the billions of dollars annually [1, 2]. Hydrochloric acid (HCl) is widely used in processes like pickling, descaling, and oil well acidizing, leading to aggressive attack on steel infrastructure [3, 4]. Traditional synthetic inhibitors, such as chromates and aromatic amines, often contain toxic components, raising significant environmental and health concerns despite their high efficiency [5]. The shift towards "green chemistry" has spurred research into plant-based corrosion inhibitors [6], which are biodegradable, non-toxic, renewable, and affordable [7]. These natural extracts contain phytochemicals like alkaloids, flavonoids, tannins, and polysaccharides. Their heteroatoms (O, N, S) and π-electrons enable adsorption onto metal surfaces, forming protective films [8].

Abelmoschus esculentus (L.) Moench (okra) is a promising candidate for green corrosion inhibition. Native to tropical regions, okra is rich in bioactive compounds, especially a mucilaginous substance composed of high-molecular-weight polysaccharides (e.g., galactose, rhamnose, galacturonic acid) known for excellent film-forming and adhesive properties [9, 10]. A structured literature review was conducted for *Abelmoschus esculentus* corrosion inhibitor. This review revealed numerous studies reporting inhibition efficacy from moderate (49%) to very high (96%) [11-13]. The form of the extract significantly influences performance, with mucilage powder showing the highest efficiency (96%), followed by aqueous extract (91.2%) and gel filtrate (88.4%).

The adsorption of okra phytochemicals on carbon steel predominantly follows the Langmuir adsorption isotherm, suggesting monolayer coverage on a homogeneous surface [6, 11, 14]. The mechanism is consistently described as mixed physisorption and chemisorption. Physisorption involves electrostatic attraction between protonated inhibitor molecules and the chloride-covered, positively charged steel surface. Chemisorption involves coordinate covalent bonding between heteroatoms (O, N) in the extract and vacant d-orbitals of iron atoms. Potentiodynamic polarization tests confirm that okra extracts act as mixed-type inhibitors, retarding both anodic metal dissolution and cathodic hydrogen evolution reactions [11, 15]. Electrochemical impedance spectroscopy (EIS) shows an increase in charge transfer resistance (Rct) and a decrease in double-layer capacitance (Cdl), indicating the formation of a protective barrier. Surface characterization by scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) provides visual and chemical evidence of adsorbed inhibitor films rich in hydroxyl, carbonyl, and amino functional groups [11, 16].

While previous studies have established okra's potential, most focus on fruit or mucilage extracts over short immersion times.

The novelty of this work lies in the first use of okra *peduncle* (the dried stalk) extract in a comprehensive weight-loss study, including long-term immersion (up to 339 hours) at room temperature and performance evaluation at elevated temperatures to simulate industrial conditions. This study combines a systematic analysis of existing literature with original experimental research to provide a holistic evaluation. The objectives are to: (1) synthesize global research on the inhibition efficiency and mechanisms of okra extracts; (2) experimentally investigate the inhibition effect of okra peduncle extract using weight loss techniques; (3) analyze the effects of concentration, temperature, and adsorption behavior; and (4) discuss practical implications and future directions for industrial application.

2. Experimental Methodology

2.1. Materials Preparation

Carbon steel coupons (composition: C 0.060%, Mn 0.185%, P 0.012%, S 0.02%, Fe balance) with dimensions of 4.13 cm × 2.05 cm × 0.08 cm were polished, washed with deionized water and acetone, and dried. A 1 M HCl solution was prepared from analytical-grade 37% HCl and double-distilled water.

Dried peduncles (The peduncle refers to the dried stalk bearing the okra fruit, which is rich in mucilaginous polysaccharides) of *Abelmoschus esculentus* were collected (Figure 1). They were dried at 60 °C for 48 hours, ground to a fine powder (particle size < 150 µm), and stored in a desiccator. The aqueous extract was prepared by macerating a specific mass of the powder in 50 mL of distilled water for 24 hours at room temperature. The mixture was filtered, and the filtrate was used as the stock inhibitor solution. Extracts were prepared fresh for each experiment and stored in airtight containers at 4 °C when not in use. Inhibitor concentrations of 1, 2, and 3 g of dry powder per 50 mL of 1 M HCl were tested.

Figure 1. Dried peduncles of *Abelmoschus esculentus* peduncles used for extract preparation.

2.2. Chemical Analysis by FTIR

The functional groups present in the *Abelmoschus esculentus* peduncle powder were identified using Fourier transform infrared spectroscopy (FT-IR Shimadzu Spectrophotometer). The powdered extract was mixed with potassium bromide (KBr) and pressed into pellets for analysis. The spectrum was recorded in the range of 4000 to 600 cm^{-1}.

2.3 Weight Loss Measurements

Duplicate carbon steel coupons were immersed in uninhibited and inhibited solutions. At 20 °C, immersion times extended up to 339 hours to study long-term behavior. To simulate industrial pickling conditions, tests at 40 °C and 60 °C were conducted for a shorter duration of 3 hours. After immersion, coupons were cleaned according to standard ASTM procedures, dried, and weighed accurately. The corrosion rate (CR), inhibition efficiency (IE%), and surface coverage (θ) were calculated using Equations 1–3. All reported values are the average of duplicate measurements, and standard deviations are provided.

$$Corrosion\ Rate\ (CR) = \frac{K\Delta W}{AT} \quad (1)$$

where ΔW is the mass loss (g), A is the surface area (cm^2), T is the immersion time (hours), and K is a constant (8.76×10^4 for CR in mm/yr).

$$\text{inhibition efficiency}\ (IE\%) = \frac{CR_{blank} - CR}{CR_{blank}} \times 100 \quad (2)$$

$$\text{surface coverage}\ (\theta) = \left(\frac{CR_{blank} - CR}{CR_{blank}}\right) \quad (3)$$

The adsorption behavior was modeled using the Langmuir isotherm (Equation 4). The standard free energy of adsorption (ΔG^{o}_{ads}) was calculated from the equilibrium constant (K_{ads}) derived from the isotherm (Equation 5).

$$\frac{C}{\theta} = \frac{1}{K} + C \quad (4)$$

$$K = \frac{1}{55.5} exp\left(-\frac{\Delta G^{\circ}_{ads}}{RT}\right) \quad (5)$$

where C is the inhibitor concentration (g/L), R is the universal gas constant (8.314 J/mol. K), and T is the absolute temperature (K).

3. Results and Discussion

3.1. FTIR for *Abelmoschus esculentus*

The FTIR spectrum (Figure 2) confirms the presence of bioactive compounds in the okra peduncle powder responsible for corrosion inhibition. A broad, strong peak around 3200–3400 cm^{-1} is characteristic of O–H stretching vibrations, indicating a high content of hydroxyl groups from polysaccharides and adsorbed water. The intense peak between 1000 and 1100 cm^{-1} corresponds to C–O and C–O–C stretching vibrations of glycosidic linkages in polysaccharides like pectin. A peak near 1600–1650 cm^{-1} is attributed to C=O stretching of carbonyl groups in galacturonic acid (pectin) and possibly in flavonoids. Smaller peaks in the 800–900 cm⁻¹ region suggest aromatic C–H bending, confirming the presence of phenolic compounds or flavonoids. The identified functional groups (hydroxyl, carbonyl) support the proposed inhibition mechanism, enabling adsorption onto the carbon steel surface via hydrogen bonding and coordination with iron atoms [16].

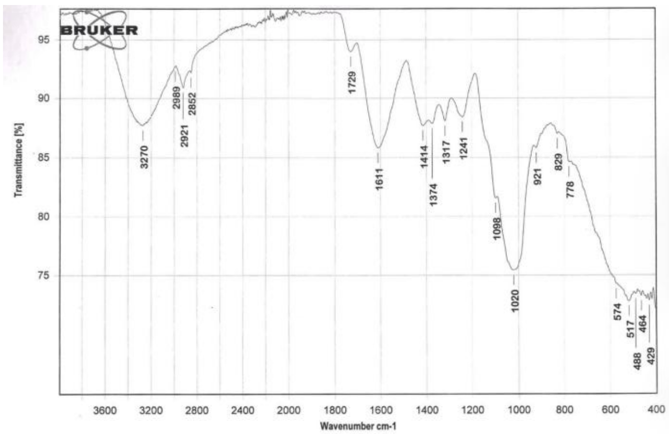

Figure 2. FTIR spectrum of *Abelmoschus esculentus* peduncle powder.

3.2 Effect of Inhibitor Concentration at 20 °C

The effect of concentration was first analyzed based on 3-hours immersion data to establish a baseline, with long-term data discussed separately. Weight loss decreased significantly with increasing inhibitor concentration. The corrosion rate dropped from 2.3917 mm/yr for the blank to 0.9567 mm/yr with 3 g of extract (Figure 4). Consequently, the inhibition efficiency increased with concentration, reaching 60% at 3 g (Table 2, Figure 5). This trend validates the adsorption of inhibitor molecules onto the steel surface, reducing the area available for corrosive attack [17, 18]. Standard deviations from duplicate measurements are included in the tables.

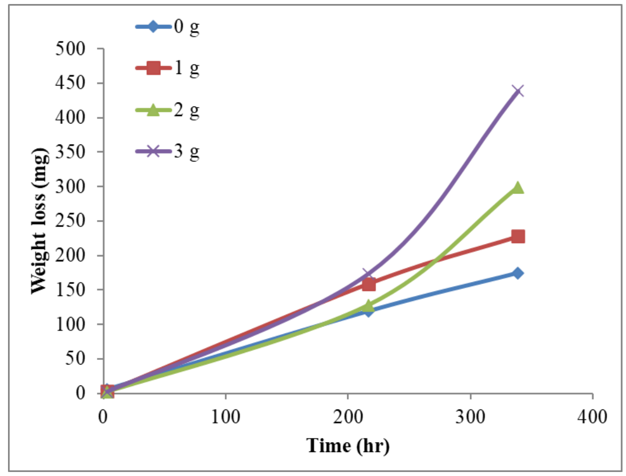

Figure 3. Weight loss vs. time for carbon steel in 1.0 M HCl in the absence and presence of different concentrations of *Abelmoschus esculentus* peduncle extract at 20 °C. Error bars represent standard deviation.

Table 1. Weight loss data for carbon steel in 1 M HCl at 20°C (mean ± SD, n=2).

Condition	Initial Weight (g)	Weight after 3h (g)	Weight after 216.5h (g)	Weight after 338.8h (g)
Blank	6.6463 ± 0.0021	6.6408 ± 0.0018	6.5274 ± 0.0032	6.4719 ± 0.0041
1g Okra	6.3673 ± 0.0015	6.3648 ± 0.0012	6.2082 ± 0.0028	6.1395 ± 0.0033
2g Okra	6.6624 ± 0.0023	6.6600 ± 0.0019	6.5342 ± 0.0035	6.3631 ± 0.0050
3g Okra	6.6606 ± 0.0018	6.6584 ± 0.0015	6.4870 ± 0.0030	6.2218 ± 0.0042

Table 2. Inhibition parameters at 20°C for 3h immersion (mean ± SD, n=2).

Conc. (g/50ml)	CR (mm/yr)	IE (%)	θ
0 (Blank)	2.3917 ± 0.052	--	--
1	1.0871 ± 0.031	54.5 ± 1.5	0.545 ± 0.015
2	1.0436 ± 0.028	56.4 ± 1.2	0.564 ± 0.012
3	0.9567 ± 0.025	60.0 ± 1.1	0.600 ± 0.011

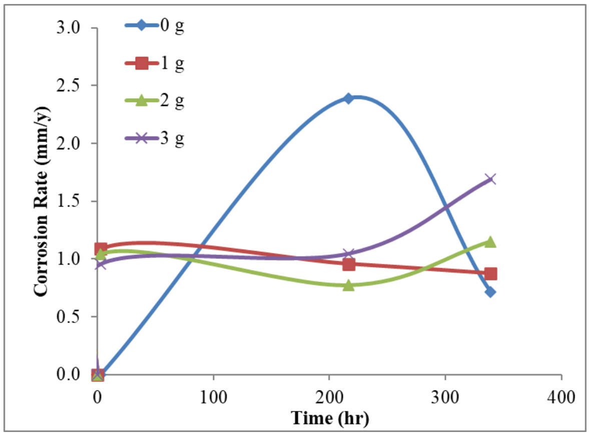

Figure 4. Corrosion rate for carbon steel in 1.0 M HCl in the absence and presence of different concentrations of *Abelmoschus esculentus* peduncle extract at 20 °C (3h immersion). Error bars represent standard deviation.

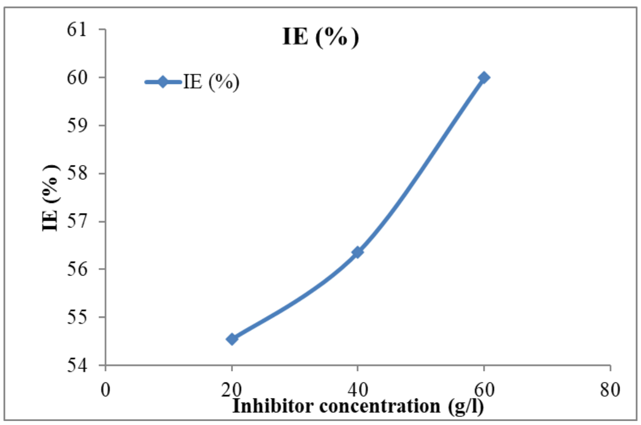

Figure 5. Inhibition efficiency vs. concentration of *Abelmoschus esculentus* peduncle extract for carbon steel in 1.0 M HCl at 20 °C (3h immersion).

3.2. Adsorption Isotherm

3.2.1 Adsorption Isotherm and Thermodynamic Parameters

A plot of C/θ versus C yielded a straight line with a slope close to unity and a high correlation coefficient (R^2 = 0.999), confirming that the adsorption of the okra peduncle extract follows the Langmuir adsorption isotherm (Figure 6). The Langmuir model assumes monolayer adsorption onto a homogeneous surface with no interaction between adsorbed molecules. From the intercept, the equilibrium constant (K_{ads}) was calculated. The standard free energy of adsorption (ΔG°ads) was subsequently determined to be -17.2 kJ/mol using Equation 5. The negative value confirms the spontaneity of the adsorption process. The magnitude of ΔG°ads (less than -20 kJ/mol) is typically associated with physisorption, dominated by electrostatic interactions between the inhibitor and the charged metal surface [19]. The calculated parameters are summarized in Table 3.

Table 3: Langmuir adsorption isotherm parameters for okra peduncle extract on carbon steel in 1 M HCl at 20°C.

Parameter	Value
Slope	1.02
Intercept ($1/K_{ads}$)	0.83 L/g
K_{ads}	1.20 L/g
R^2	0.999
ΔG°_{ads}	-17.2 kJ/mol

3.3. Effect of Temperature

The corrosion rate increased with temperature for both uninhibited and inhibited solutions, consistent with Arrhenius theory. However, inhibition efficiency showed a complex trend. At 40 °C, efficiency was exceptionally high, reaching 98.4% for the 3 g extract (Table 4). This enhancement with temperature may indicate a shift towards a more dominant chemisorption mechanism. At 60 °C, efficiency remained high but decreased slightly to 90.7% for the 3 g extract (Table 5). This slight decrease may be attributed to partial desorption or thermal degradation of some phytochemical components in the extract. An anomalous increase in corrosion rate for the 2 g extract at 60 °C compared to the 1 g extract was observed (Table 5). This may result from non-uniform adsorption, concentration-dependent aggregation of inhibitor molecules, or experimental variability. Further replication is recommended to confirm the reproducibility of this trend. Future surface analysis (e.g., SEM-EDX) would be valuable to visually confirm the protective layer formation and investigate such anomalies. The high-temperature performance, particularly at 40 °C, suggests potential suitability for industrial pickling applications, though factors like flow dynamics and solution impurities warrant further study in a pilot-scale context [20, 21].

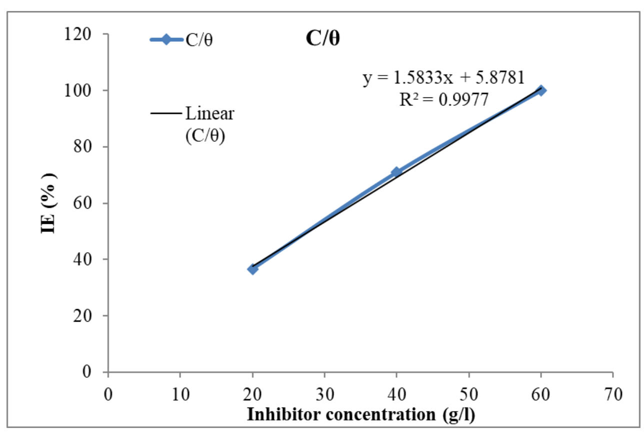

Figure 6. Langmuir adsorption isotherm plot for carbon steel in 1.0 M HCl with different concentrations of *Abelmoschus esculentus* peduncle extract at 20 °C.

Table 4: Effect of temperature at 40°C for 3h immersion (mean ± SD, n=2).

Condition	CR (mm/yr)	IE (%)	θ
Blank	22.3946 ± 0.87	--	--
1g Okra	2.3917 ± 0.12	89.3 ± 0.5	0.893 ± 0.005
2g Okra	0.9567 ± 0.08	95.7 ± 0.4	0.957 ± 0.004
3g Okra	0.3479 ± 0.05	98.4 ± 0.2	0.984 ± 0.002

Table 5. Effect of temperature at 60°C for 3h immersion (mean ± SD, n=2).

Condition	CR (mm/yr)	IE (%)	θ
Blank	80.9251 ± 2.15	--	--
1g Okra	10.7407 ± 0.45	86.7 ± 0.6	0.867 ± 0.006
2g Okra	16.3937 ± 0.75	79.7 ± 0.9	0.797 ± 0.009
3g Okra	7.5229 ± 0.38	90.7 ± 0.5	0.907 ± 0.005

4. Conclusions

This integrated study demonstrates the significant potential of *Abelmoschus esculentus* peduncle extract as a green corrosion inhibitor for carbon steel in HCl environments. Empirical results align with literature findings, showing high inhibition efficiencies (up to 98.4% at 40 °C for a 3 g extract) that are concentration-dependent. The inhibition action is attributed to the adsorption of phytochemicals onto the steel surface, forming a protective film that follows the Langmuir monolayer model. Thermodynamic analysis ($\Delta G°_{ads}$ = -17.2 kJ/mol) indicates a spontaneous physisorption process. The inhibitor performs well across a temperature range, with notable efficiency at elevated temperatures (40–60 °C), which is crucial for industrial applications like pickling. Under optimal conditions (3 g extract, 40 °C), inhibition efficiency reached 98.4%. Compared to synthetic inhibitors like benzotriazole (95% efficiency), okra extract offers comparable performance with a superior environmental profile, as okra is Generally Recognized as Safe (GRAS) and its components are biodegradable. Limitations of this weight-loss study include the lack of electrochemical validation and direct surface morphology evidence. Future work should include electrochemical techniques (EIS, polarization), long-term stability tests, surface analysis (SEM, AFM), formal eco-toxicity assessments, and pilot-scale industrial trials to facilitate commercial adoption.

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Abbreviations

CR: Corrosion	CR: Corrosion Rate
IE%:	IE%: Inhibition Efficiency
θ: Surface	θ: Surface Coverage
ΔG°ads:	ΔG°ads: Standard Free Energy of
Kads:	Kads: Equilibrium Constant for
Rct: Charge	Rct: Charge Transfer Resistance
Cdl: Double	Cdl: Double Layer Capacitance

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Conceptualization: B.J.N. and A.K.H.; Data curation: L.G. and S.A.M.; Formal analysis: B.J.N. and A.K.H.; Investigation: L.G. and S.A.M.; Supervision: L.G.; Writing-original draft: L.G. and B.J.N.; Writing— review and editing: L.G. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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