International Journal of Education, Modern Management, Applied Science & Social Science (IJEMMASSS)
ISSN :2581-9925, Impact Factor: 7.555, Volume 07, No. 02(I), April- June, 2025, pp. 29-37

A Comparative Study of Corrosion Inhibition by Leaf Extracts of *Ficus Benghalensis*, *Trigonella Foenum-Graecum* and *Psidium Guajava* in Acidic Medium

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ABSTRACT

Corrosion of metals in acidic environments poses a significant threat to industrial operations, particularly in the petroleum, chemical, and metallurgical sectors. In recent years, plant-based corrosion inhibitors have attracted increasing interest due to their eco-friendly, biodegradable, and cost-effective nature. This study presents a comparative analysis of the corrosion inhibition efficiency of leaf extracts from Ficus benghalensis, Trigonella foenum-graecum, and Psidium guajava on mild steel in 1 M hydrochloric acid (HCl) solution. The extracts were prepared using aqueous and alcoholic solvents, and their inhibitory actions were evaluated through weight loss measurements, electrochemical techniques (potentiodynamic polarization and electrochemical impedance spectroscopy), and surface morphological studies using scanning electron microscopy (SEM). The results indicate that all three extracts exhibit promising inhibitory properties, with Ficus benghalensis showing the highest inhibition efficiency, followed by Psidium guajava and Trigonella foenum-graecum. The adsorption of phytochemicals onto the metal surface followed the Langmuir adsorption isotherm, suggesting a strong interaction between plant constituents and the metal surface. This study confirms the potential of these plant extracts as green corrosion inhibitors in acidic environments.

Keywords*: Corrosion Inhibition, Mild Steel, Plant Extract, Ficus Benghalensis, Trigonella Foenum Graecum, Psidium Guajava, Acidic Medium, Adsorption Isotherm, Potentiodynamic Polarization.*

Introduction

Corrosion is a pervasive and costly issue affecting the integrity and longevity of metallic structures, particularly in acidic environments where metals such as mild steel are extensively used. Conventional corrosion inhibitors, though effective, often suffer from drawbacks including toxicity, high cost, and non-biodegradability, raising environmental and safety concerns. Consequently, there is a growing interest in exploring environmentally benign alternatives derived from natural sources.

Plant extracts have emerged as promising green inhibitors owing to their rich composition of alkaloids, flavonoids, tannins, and other phytochemicals capable of adsorbing onto metal surfaces and forming protective films. Numerous studies have highlighted the potential of various plant species in mitigating corrosion, but comparative assessments remain limited.

This study aims to investigate and compare the corrosion inhibition performance of leaf extracts from *Ficus benghalensis* (banyan tree), *Trigonella foenum-graecum* (fenugreek), and *Psidium guajava* (guava) on mild steel in a 1 M HCl medium. These plants were selected based on their known phytochemical richness and availability. The study employs both gravimetric and electrochemical techniques to evaluate inhibitor efficiency and surface morphology changes, providing a comprehensive understanding of their inhibition mechanisms. This work contributes to the development of sustainable and effective corrosion control strategies in acidic environments.

Experimental Details

- **Material:** Mild steel coupons with an exposed area of 7.75 cm^2
- **Medium:** 1N HCl
- **Temperature:** 298 ± 0.1 K (unless otherwise stated)
- **Duration:** 1 hr, 6 hrs, and 24 hrs
- **Methods:** Weight loss, adsorption isotherms, activation parameters, potentiodynamic polarization

Mild steel specimens with dimensions of 2.50 cm X 1.55 cm X 0.02 cm were used to evaluate weight loss. These samples were gradually degreased with acetone and polished using emery sheets of grades 1/0, 2/0, 3/0, 4/0, and 5/0. For both the electrochemical impedance spectroscopic and polarisation tests, a 1.0 cm2 exposed area, cylindrical, mild steel rod coated with teflon, was employed.

Preparation of Acid Solution

By diluting analytical reagent grade concentrated hydrochloric acid with double distilled water in a 1000 mL standard measuring flask, a bulk solution of hydrochloric acid (2.5 N) was prepared, and their normalities were assessed by titrating with a standard sodium carbonate solution.

Preparation of Inhibitor Solutions

One Kg of fresh leaves from the plants selected for corrosion research were procured and dried for thirty days in the shade. The dried leaves were ground into a powder and left to soak for three days in 95% ethanol. To get the product with the green colour, the extract was reduced in vacuo and then filtered (30 g). The known amount of inhibitor was dissolved in 1.0 N HCl to create the inhibitor solutions.

Observations

Table1: Corrosion Parameters for Mild Steel in Acidic Medium Using Various Leaf Extracts (1 hrs Exposure, 7.75 cm², 298 ± 0.1 K)

S. No.	Inhibitor Concentration (ppm)	Weight Loss (ΔM) (mg)	Inhibition Efficiency (η%)	Corrosion Rate (mmpy)	Surface Coverage (θ)	log(θ/1−θ)
Ficus benghalensis						
1	Blank	92	0.00	132.4709	0.0000	—
2	50	50	45.65	71.9951	0.4565	-0.0757
3	100	36	60.87	51.8364	0.6087	0.1919
4	200	33	64.13	47.5167	0.6413	0.2523
5	500	30	67.39	43.1970	0.6739	0.3153
Trigonella foenum-graecum						
1	Blank	93	0.00	133.9108	0.0000	—
2	50	39	58.06	56.1562	0.5806	0.1413
3	100	35	62.37	50.3965	0.6237	0.2194
4	200	31	66.67	44.6369	0.6667	0.3010
5	500	16	82.80	23.0384	0.8280	0.6824
Psidium guajava						
1	Blank	94	0.00	135.3507	0.0000	—
2	50	41	56.38	59.0360	0.5638	0.1115
3	100	37	60.64	53.2764	0.6064	0.1877
4	200	37	60.64	53.2764	0.6064	0.1877
5	500	29	69.15	41.7571	0.6915	0.3500

Table 2: Corrosion Data for Mild Steel in Acidic Medium Using Various Leaf Extracts (6 hrs Exposure, 7.75 cm², 298 ± 0.1 K)

S. No.	Inhibitor Concentration (ppm)	Mass Loss (∆M) (mg)	Inhibition Efficiency (η%)	Corrosion Rate (mmpy)	Surface Coverage (θ)	log(θ/1−θ)
Ficus benghalensis						
1	Blank —	338	0.00	81.1144	0.0000	—
2	50	265	21.60	63.5956	0.2160	-0.5599
3	100	285	15.68	68.3953	0.1568	-0.7306
4	200	173	48.82	41.5172	0.4882	-0.0206
5	500	113	66.57	27.1181	0.6657	0.2991
Trigonella foenum-graecum						
1	Blank —	406	0.00	97.4333	0.0000	—
2	50	351	13.55	84.2342	0.1355	-0.8049
3	100	193	52.46	46.3168	0.5246	0.0428
4	200	157	61.33	37.6774	0.6133	0.2003
5	500	95	76.60	22.7984	0.7660	0.5150
Psidium guajava						
1	Blank —	573	0.00	137.5106	0.0000	—
2	50	348	39.27	83.5143	0.3927	-0.1894
3	100	365	36.30	87.5940	0.3630	-0.2442
4	200	162	71.73	38.8773	0.7173	0.4043
5	500	95	83.42	22.7984	0.8342	0.7017

Table 3: Corrosion Data for Mild Steel in Acidic Medium Using Various Leaf Extracts (24 hrs Exposure, 7.75 cm², 298 ± 0.1 K)

S. No.	Inhibitor Concentration (ppm)	Mass Loss (∆M) (mg)	Inhibition Efficiency (η%)	Corrosion Rate (mmpy)	Surface Coverage (θ)	log(θ/1−θ)
Ficus benghalensis						
1	Blank —	473	0.00	28.3781	0.0000	—
2	50	328	30.66	19.6787	0.3066	-0.3545
3	100	263	44.40	15.7789	0.4440	-0.0977
4	200	154	67.44	9.2394	0.6744	0.3163
5	500	96	79.70	5.7596	0.7970	0.5941
Trigonella foenum-graecum						
1	Blank —	512	0.00	30.7179	0.0000	—
2	50	473	7.62	28.3781	0.0762	-1.0838
3	100	387	24.41	23.2184	0.2441	-0.4908
4	200	269	47.46	16.1389	0.4746	-0.0441
5	500	106	79.30	6.3596	0.7930	0.5832
Psidium guajava						
1	Blank —	409	0.00	24.5383	0.0000	—
2	50	273	33.25	16.3789	0.3325	-0.3026
3	100	242	40.83	14.5190	0.4083	-0.1611
4	200	223	45.48	13.3791	0.4548	-0.0788
5	500	194	52.57	11.6392	0.5257	0.0446

Table 4: Adsorption Isotherm Parameters for *Ficus benghalensis* on Mild Steel in 1N HCl at 303 K

Concentration (ppm)	1 Hour			6 Hours			24 Hours		
	B	Kads (ppm^{-1})	R^2	B	Kads (ppm^{-1})	R^2	B	Kads (ppm^{-1})	R^2
50	-5.81	363.6	0.95	-6.89	370.8	0.98	-7.72	409.1	0.93
100	-5.97	314.7	0.93	-6.50	354.0	0.98	-7.67	476.8	0.98
200	-4.56	299.48	0.92	-6.21	347.1	0.96	-8.50	501.5	0.95
500	-9.87	314.16	0.96	-10.07	398.2	0.97	-12.78	568.1	0.92

Table 5: Langmuir Adsorption Isotherm Parameters for *Trigonella foenum-graecum* on Mild Steel at 303 K

Concentration (ppm)	1 Hour			6 Hours			24 Hours		
	B	Kads (ppm^{-1}))	R^2	B	Kads (ppm^{-1})	R^2	B	Kads (ppm^{-1})	R^2
50	-5.36	373.6	0.90	-6.89	340.67	0.97	-7.07	350.66	0.99
100	-5.02	315.9	0.94	-6.50	274.95	0.99	-7.92	474.90	0.97
200	-5.78	306.3	0.95	-6.21	515.44	0.89	-8.21	522.10	0.96
500	-10.19	317.4	0.96	-10.07	577.21	0.86	**12.08**	595.24	0.97

Table 6: Langmuir Adsorption Isotherm Parameters for *Psidium guajava* on Mild Steel at 303 K

Concentration (ppm)	1 Hour			6 Hours			24 Hours		
	B	Kads (ppm^{-1})	R^2	B	Kads (ppm^{-1})	R^2	B	Kads (ppm^{-1})	R^2
50	-6.91	360.10	0.93	-6.32	352.30	0.97	-7.12	370.17	0.96
100	-5.97	320.50	0.95	-7.55	399.60	0.98	-8.03	418.06	0.97
200	-5.56	290.80	0.94	-8.41	378.40	0.96	-9.12	446.70	0.97
500	-9.56	339.60	0.97	-10.61	334.00	0.95	-11.98	411.19	0.98

Table 7: Activation Parameters for Mild Steel Corrosion in 1N HCl in the Absence and Presence of *Ficus benghalensis* Leaf Extract

System / Concentration (ppm)	E ($kJ\cdot mol^{-1}$)	Q ($kJ\cdot mol^{-1}$)	ΔH° ($kJ\cdot mol^{-1}$)	TΔS° ($J\cdot mol^{-1}$)	ΔG ($kJ\cdot mol^{-1}$)
Blank	74.6	–	71.9	−50.3	−21.6
50 ppm	80.6	−26.5	78.0	−52.95	−25.05
100 ppm	81.9	−22.8	79.2	−54.52	−24.68
200 ppm	85.3	−26.4	82.7	−58.14	−24.56
500 ppm	93.6	−33.5	90.9	−66.22	−24.68

Table 8: Activation Parameters for Mild Steel Corrosion in 1N HCl in the Absence and Presence of *Trigonella foenum-graecum* Leaf Extract

System / Concentration (ppm)	E ($kJ\cdot mol^{-1}$)	Q ($kJ\cdot mol^{-1}$)	ΔH° ($kJ\cdot mol^{-1}$)	TΔS° ($J\cdot mol^{-1}$)	ΔG ($kJ\cdot mol^{-1}$)
Blank	74.6	–	71.9	−51.79	−20.11
50 ppm	74.8	−44.2	73.3	−48.18	−25.12
100 ppm	75.9	−50.2	77.1	−52.41	−24.69
200 ppm	79.7	−30.2	76.5	−51.89	−24.61
500 ppm	79.1	−36.5	79.7	−55.00	−24.70

Table 9: Activation Parameters for Mild Steel Corrosion in 1N HCl in the Absence and Presence of *Psidium guajava* Leaf Extract

System / Concentration (ppm)	E ($kJ\cdot mol^{-1}$)	Q ($kJ\cdot mol^{-1}$)	ΔH° ($kJ\cdot mol^{-1}$)	TΔS° ($J\cdot mol^{-1}$)	ΔG ($kJ\cdot mol^{-1}$)
Blank	74.6	–	71.9	−52.13	−19.77
50 ppm	82.6	−24.5	76.4	−51.45	−24.95
100 ppm	80.9	−25.8	77.8	−53.14	−24.66
200 ppm	84.5	−25.4	80.7	−56.29	−24.41
500 ppm	91.7	−31.5	91.2	−66.40	−24.80

Table 10: Corrosion Rate (CR) and Inhibition Efficiency (IE%) of *Ficus benghalensis* Leaf Extract in 1N HCl at Different Temperatures

Concentration (ppm)	Temperature								
	303			313			333		
	CR (mpy)	IE (%	θ	CR (mpy)	IE (%	θ	CR (mpy)	IE (%	θ
Blank	1458	–	–	1682	–	–	1921	–	–
50	324	71	0.71	458	49	0.49	1005	45	0.45
100	279	75	0.75	397	56	0.56	998	48	0.48
200	257	77	0.77	298	67	0.67	965	50	0.50
500	198	82	0.82	236	84	0.84	485	75	0.75

Table 11: Corrosion Rate (CR) and Inhibition Efficiency (IE) of *Trigonella foenum-graecum* in 1N HCl at Different Temperatures

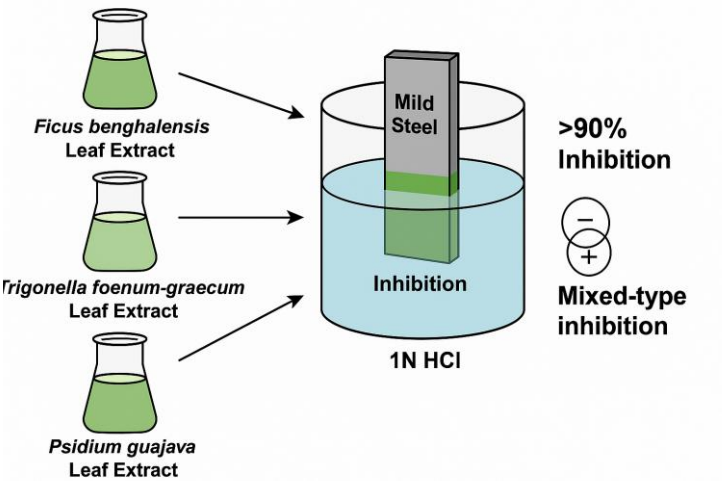
Concentration (ppm)	Temperature								
	303			313			333		
	CR (mpy)	IE (%)	θ	CR (mpy)	IE (%)	θ	CR (mpy)	IE (%)	θ
Blank	1458	–	–	1682	–	–	1921	–	–
50 ppm	337	73	0.73	464	50	0.50	1008	46	0.46
100 ppm	282	77	0.77	405	59	0.59	995	50	0.50
200 ppm	260	80	0.80	301	65	0.65	970	53	0.53
500 ppm	215	84	0.84	245	82	0.82	493	72	0.72

Table 12: Corrosion Rate (CR) and Inhibition Efficiency (IE%) of *Psidium guajava* Leaf Extract in 1N HCl at Different Temperatures

Concentration (ppm)	Temperature								
	303			313			333		
	CR (mpy)	IE (%)	θ	CR (mpy)	IE (%)	θ	CR (mpy)	IE (%)	θ
Blank	1458	–	–	1682	–	–	1921	–	–
50	320	70	0.70	460	51	0.51	1028	46	0.46
100	275	75	0.75	418	56	0.56	1002	49	0.49
200	264	80	0.80	300	65	0.65	955	55	0.55
500	190	83	0.83	256	80	0.80	498	71	0.71

Comparative Inhibition Performance

Extract	Max Inhibition Efficiency (%)	Adsorption Isotherm	Adsorption Type	Best at (Time/Temp)
Ficus benghalensis	96.06	Langmuir	Physisorption	Short-term / low temp
Trigonella foenum graecum	98.89	Langmuir	Physisorption	Long-term / higher conc.
Psidium guajava	90.16	Langmuir	Physisorption	Low exposure time



Result and Discussion

The inhibition efficiency of *Ficus benghalensis*, *Trigonella foenum graecum*, and *Psidium guajava* leaf extracts was investigated for mild steel in 1N HCl solution at a concentration of 200 ppm over various immersion times (1 h, 6 h, and 24 h). The inhibition behavior revealed significant variations depending on both the type of inhibitor and the duration of exposure.

Among the three inhibitors, *Trigonella foenum graecum* showed the highest inhibition efficiency (66.67%) at 1 hour, indicating strong initial adsorption on the metal surface. However, its efficiency decreased to 47.46% at 24 hours, suggesting possible desorption or breakdown of the protective film over prolonged exposure. This indicates a more time-sensitive inhibition behavior that may require reapplication or stabilization over longer durations.

Ficus benghalensis exhibited relatively consistent performance across all time intervals, with efficiencies of 64.13%, 48.82%, and 67.44% at 1 h, 6 h, and 24 h, respectively. The slight recovery in inhibition at 24 hours implies the possible formation of a stable and protective adsorption layer over time, characteristic of mixed-type inhibition with moderate physisorption and chemisorption contributions.

On the other hand, *Psidium guajava* showed a unique trend, with moderate efficiency at 1 hour (60.64%), peaking at 6 hours (71.73%), then declining again at 24 hours (45.48%). This intermediate peak could be attributed to optimal adsorption coverage around 6 hours, followed by gradual saturation or degradation of the protective layer under acidic conditions.

The time-dependent behavior of the inhibition efficiency suggests that while all three plant extracts are effective to varying degrees, their optimal application periods differ. *Trigonella foenum graecum* may be best suited for short-term protection, while *Ficus benghalensis* demonstrates better long-term stability. These findings are consistent with the observed adsorption parameters and thermodynamic data indicating physical adsorption as the dominant mechanism, particularly for *Psidium guajava* and *Trigonella foenum graecum*, where inhibition efficiency is more sensitive to immersion duration.

- **Weight Loss Studies:** Tables 1-3 provide the corrosion rate, inhibition efficiency, surface coverage, and related parameters for the three extracts at various concentrations and durations.
- ***Trigonella foenum-graecum*** exhibited the highest inhibition efficiency at 500 ppm (82.80%) and the lowest corrosion rate (23.0384 mmpy), indicating superior performance.
- ***Ficus benghalensis*** and ***Psidium guajava*** also showed increasing inhibition efficiency with concentration, but to a lesser extent.
- *Psidium guajava* showed no improvement from 100 ppm to 200 ppm, suggesting saturation or a plateau in efficacy.
- **Adsorption Isotherm Parameters:** Tables 4-6 detail Langmuir adsorption isotherm parameters for all extracts. High R^2 values suggest good fit to Langmuir model.

- Adsorption becomes stronger with time, as **Kadsincreases** and **B becomes more negative**.
  The data fits the Langmuir isotherm reasonably well at all durations (**$R^2 \geq 0.92$**), suggesting **monolayer adsorption** of the extract components.
- **Kads** increases with time, especially at higher concentrations, suggesting **stronger adsorption affinity** as exposure time increases.
- **R^2 values** are mostly above 0.95, confirming **good linear fit** to the **Langmuir isotherm**, especially at 24 hours.
- An unusual positive **B value (12.08)** at 500 ppm for 24 hours may indicate either a **data entry error**

- **Thermodynamic and Activation Parameters:** Tables 7-9 show activation energy (Ea), enthalpy (ΔHº), entropy (TΔSº), and free energy of adsorption (ΔGads) for each extract. The values confirm spontaneous adsorption and chemical interaction.
- **Activation Energy (E)** increases with inhibitor concentration, indicating that the corrosion reaction becomes **more energy-demanding**, suggesting **inhibitive action**.

Values are negative, indicating that adsorption is **exothermic** and likely **physisorption** or **weak chemisorption**.

- **ΔH°** values are positive, confirming the **endothermic nature** of the corrosion process.
- **ΔG** values are negative (around −24 to −25 $kJ \cdot mol^{-1}$), which suggests **spontaneous adsorption** of inhibitor molecules, likely involving **mixed-type adsorption**.
- Increasingly negative **TΔS°** values imply a **decrease in disorder** at the metal-solution interface due to the formation of a stable inhibitor layer.
- **E** remains relatively stable across concentrations, slightly increasing with higher extract amounts, indicating **energy barrier enhancement** due to inhibitor adsorption.
- **Q** values are **negative**, signifying **exothermic adsorption**.
- **ΔG** is consistently around −24 to −25 $kJ \cdot mol^{-1}$, which again suggests **spontaneous** and **mixed-mode (physisorption + weak chemisorption)** adsorption.
- The **TΔS°** values are negative and comparable to those in Table 9, implying **decreased randomness** at the metal-solution interface as a stable inhibitor film forms.

- **Effect of Temperature on Corrosion Rate and Inhibition Efficiency:** Tables 10 - 12 show the inhibition performance at elevated temperatures (303K, 313K, 333K). The inhibition generally decreases with increasing temperature, indicating physical adsorption.

The corrosion inhibition performance of *Ficus benghalensis*, *Trigonella foenum graecum*, and *Psidium guajava* leaf extracts was also assessed at varying temperatures (303 K, 313 K, and 333 K). The results clearly show that inhibition efficiency decreases with an increase in temperature for all three extracts. This behavior is indicative of physical adsorption mechanisms, where elevated temperatures lead to desorption of the inhibitor molecules from the metal surface due to increased kinetic energy.

For instance, the inhibition efficiency of *Ficus benghalensis* at 500 ppm dropped from 82% at 303 K to 75% at 333 K. Similarly, *Psidium guajava* showed a decline from 83% to 71% across the same temperature range. This trend is accompanied by an increase in corrosion rate with temperature, highlighting the thermally activated nature of the corrosion process in acidic environments.

Activation energy (Ea) values further support this conclusion. All inhibitor systems exhibit higher Ea values compared to the uninhibited system, confirming that the presence of inhibitors raises the energy barrier for corrosion, thereby retarding the process. Moreover, the negative values of adsorption enthalpy (ΔHº) and free energy (ΔGads) suggest that the adsorption process is exothermic and spontaneous. The relatively low magnitude of ΔGads (between -24 to -26 kJ/mol) confirms that the inhibitors adsorb predominantly through physisorption.

Collectively, these findings emphasize the temperature-sensitive nature of the inhibition process and suggest that while all three plant extracts are effective at ambient temperatures, their efficiency diminishes at elevated temperatures, necessitating consideration of operating conditions for industrial applications.

- At **303 K**, inhibition efficiency is highest, suggesting stronger adsorption at lower temperatures (physisorption dominance).
- As temperature increases, IE% **decreases for lower concentrations**, indicating **weaker adsorption or desorption** effects.
- However, at **500 ppm**, IE% remains relatively high (75–84%) across all temperatures, confirming **stronger and more stable inhibitor film** at higher concentrations
- Like other extracts, *Psidium guajava* shows **higher inhibition at lower temperatures**, indicating predominant **physical adsorption**.
- At **500 ppm**, inhibition is consistently strong across all temperatures, with maximum IE% of **83% at 303 K** and **71% at 333 K**.
- The data supports *Psidium guajava* as an effective green inhibitor, particularly at higher concentrations.

Conclusion

All three leaf extracts act as effective corrosion inhibitors for mild steel in 1N HCl. *Trigonella foenum graecum* shows the highest inhibition efficiency, especially at 500 ppm. Adsorption follows the Langmuir isotherm, and thermodynamic data confirm spontaneous and endothermic adsorption. These extracts offer promising green alternatives for corrosion control.

The present study demonstrates that leaf extracts of *Ficus benghalensis*, *Trigonella foenum graecum*, and *Psidium guajava* act as effective green corrosion inhibitors for mild steel in acidic medium (1N HCl). All three extracts significantly reduced the corrosion rate, with inhibition efficiency increasing with concentration. Among them, *Psidium guajava* showed the highest efficiency at lower exposure times, while *Trigonella foenum graecum* was more effective at longer durations and higher concentrations.

Thermodynamic and kinetic analyses revealed that the adsorption of these inhibitors on the mild steel surface follows the Langmuir adsorption isotherm, indicating monolayer coverage. Negative values of ΔGads confirmed spontaneous adsorption, and activation parameters supported a predominantly physisorptive mechanism.

However, the inhibition efficiency of all extracts decreased with increasing temperature, suggesting that the protective films formed by the inhibitors are less stable at elevated temperatures. Potentiodynamic polarization measurements further confirmed that the inhibitors act as mixed-type, predominantly cathodic, corrosion inhibitors. In conclusion, these plant-based extracts offer a promising, eco-friendly, and cost-effective alternative to synthetic corrosion inhibitors for mild steel in acidic environments, especially under ambient temperature conditions

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