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Inhibitive Potential of *Ficus exasperata* (Sandpaper Leaf) Extract as a Green Corrosion Inhibitor for Mild Steel in 1M HCl-Induced Environment

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Abstract: This study evaluates the corrosion inhibition performance of *Ficus exasperata* (Sandpaper Leaf) leaf extract on mild steel in 1.0 M hydrochloric acid using the weight loss (gravimetric) method. Compared with previous studies that investigated *Ficus exasperata* in different acidic media or experimental conditions, this work evaluates its performance in 1.0 M HCl at low concentrations (100–400 ppm) over 24, 48, and 72 hours. The extract achieved a maximum inhibition efficiency of 93.00% at 400 ppm after 48 hours,with Langmuir adsorption isotherm showing strong correlation (R^2 = 0.994). The calculated standard free energy of adsorption (ΔG^o_{ads} = –0.98 kJ/mol) suggested a spontaneous and predominantly physical adsorption mechanism. The corrosion inhibition performance is attributed to the presence of bioactive phytochemicals previously reported in *Ficus exasperata* leaves, which are known to contain functional groups capable of adsorption on metal surfaces. Although no phytochemical or surface characterization was performed in this study, the observed inhibition behavior is consistent with adsorption of organic constituents forming a protective barrier on the steel surface.These findings highlight the feasibility of using low-cost, green, and industry-compatible aqueous extracts of *F. exasperata* for sustainable corrosion mitigation in acidic systems.

Introduction

Corrosion of metals, especially mild steel, in acidic environments remains a persistent challenge in various industrial sectors, including petrochemical processing, acid pickling, and cleaning operations. Hydrochloric acid (HCl), commonly used in these industries, aggressively attacks mild steel, leading to material degradation, reduced equipment lifespan, and substantial economic losses (Umoren & Solomon, 2015). Conventional corrosion-control methods typically involve synthetic inhibitors, many of which are effective but pose serious environmental and health hazards due to their toxicity, high cost, and non-biodegradable nature (Zarrok et al., 2013; Verma et al., 2018).

In recent years, there has been a growing interest in developing environmentally friendly, cost-effective, and sustainable alternatives, a movement that has given rise to the exploration of green corrosion inhibitors (Aouniti et al., 2013; Merimi et al., 2023; Tidke et al., 2025). These are typically derived from natural products, especially plant extracts, which contain phytochemicals such as flavonoids, tannins, alkaloids, and saponins. These compounds have been shown to adsorb onto metal surfaces, forming protective films that mitigate corrosion (Raja & Sethuraman, 2008; Aourabi *et al.*, 2021; Okonji & Lawal, 2025). Despite the increasing volume of research in this area, the pool of plant species investigated for corrosion inhibition is still relatively small compared to the biodiversity available, particularly in tropical regions like Nigeria. Therefore, there remains a significant opportunity to identify and evaluate novel plant-based corrosion inhibitors that are both effective and readily accessible.

Figure 1 shows *Ficus exasperata*, commonly known as Sandpaper Leaf, due to its rough texture, is a medicinal plant native to West Africa. Traditionally, it has been used to treat ailments such as fever, inflammation, and hypertension (Ayinde et al., 2007). Phytochemical analyses of *Ficus exasperata* have revealed the presence of biologically active compounds including tannins, flavonoids, and phenolic acids (Yakubu et al., 2020), compounds that are known to play crucial role in corrosion inhibition through adsorption and complex formation on metal surfaces (Anees & Quraishi, 2010). Although previous studies have investigated the corrosion inhibition potential of Ficus exasperata in various systems and media (Patel et al., 2009; Popoola, 2021; Oyewole et al., 2021), differences in extraction methods, concentration ranges, and experimental conditions warrant further evaluation, particularly using low-concentration aqueous extracts in standardized 1.0 M HCl environments.

Figure 1. Fresh leaves and fruit of *Ficus exasperata*

Several studies have explored the corrosion inhibition potential of *Ficus exasperata* extracts or related plant-based inhibitors. For example, Patel et al. (2009) reported the inhibitive effect of *F. exasperata* extract on the acid corrosion of mild steel, while Popoola (2021) evaluated its eco-friendly corrosion inhibition performance in seawater environments. Oyewole et al. (2021) assessed *F. exasperata* leaf extract as a corrosion inhibitor for mild steel in acidic medium. Other plant extracts such as Sapium ellipticum (Onukwuli et al., 2020), Gossypium hirsutum (Abiola et al., 2011), and Origanum vulgare (Dhaundiyal et al., 2019) have demonstrated green inhibition behavior, often interpreted through adsorption models like Langmuir. However, there remains a need for systematic assessment of *F. exasperata* using simple aqueous extraction at low concentrations and standardized 1.0 M HCl across multiple immersion times, which is essential for comparing inhibition performance under well-controlled corrosive conditions.

2. Materials and Methods

2.1 Preparation of Mild Steel Coupons

Mild steel coupons measuring 4 cm × 2 cm × 0.1 cm were cut and polished using emery papers (400–1200 grit) to achieve a smooth finish. The coupons were washed, degreased with ethanol, dried, and stored in a desiccator:

Total Surface area = 2(lw+lh+wh) =2(8+0.4+0.2) =17.2cm^2

2.2 Collection and Extraction of Ficus exasperata Leaves

Fresh leaves of *Ficus exasperata* (Sandpaper Leaf) were harvested from wild-grown trees in Ado-Ekiti, Ekiti State, Nigeria. Leaves were washed thoroughly, shade-dried at room temperature for 10 – 14 days, then ground into fine powder. Aqueous extraction was performed by soaking 100 g of powdered leaves in 1000 mL distilled water for 48 hours with occasional stirring. The mixture was filtered using Whatman No. 1 filter paper, and the filtrate concentrated at 50 °C in a water bath. The resulting crude extract was stored at 4°C until use.The calculated masses of crude extract (10 mg, 20 mg, 30 mg, and 40 mg) were weighed and dissolved in 100 mL portions of 1.0 M HCl to obtain final concentrations of 100, 200, 300, and 400 ppm, respectively.

2.3 Preparation of Acidic Test Solution

A 1.0 M HCl solution was prepared by diluting 83.3 mL of concentrated HCl (≈12 M, 37%) with distilled water and making up the volume to 1 L in a volumetric flask. *Ficus exasperata* extract was added to portions of the acid to reach concentrations of 100 ppm, 200 ppm, 300 ppm and 400 ppm

2.4 Weight Loss Method

Pre-weighed coupons were immersed in 100 mL of either blank 1.0 M HCl or HCl containing the extract. Each coupon was suspended using nylon thread in a 250 mL beaker at room temperature. Immersion times were 24, 48, and 72 hours. After each period, coupons were removed, rinsed, brushed gently, dried, and reweighed. The **corrosion rate (CR)** was calculated using:

$$CR = \frac{W_1 - W_2}{A \times t}$$

Where:
W_1 = Initial Weight (g)
W_2 = Final Weight (g)
A = Surface Area of Coupon (cm^2)
t = immersion time (days)

2.5 Inhibition Efficiency (IE%)

The inhibition efficiency of the extract was calculated using the following equation:

$$IE = \frac{CR_{blank} - CR_{inh}}{CR_{blank}} \times 100$$

Where CR_{blank} = Corrosion Rate without Inhibitor and CR_{inh} = Corrosion Rate with Inhibitor

2.6 Adsorption Isotherm Analysis

To understand the nature of interaction between the *Ficus exasperata* extract and the mild steel surface, adsorption behavior was evaluated using the Langmuir adsorption isotherm model. This model assumes monolayer adsorption of inhibitor molecules on a homogeneous metal surface without interaction between adsorbed species.
The Langmuir isotherm is expressed as:

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C$$

Where:
C = Inhibitor concentration (ppm)
θ = surface coverage, calculated as $\theta = \frac{IE\%}{100}$
K_{ads} = equilibrium constant of adsorption (L/mg)

The adsorption data were fitted to the Langmuir isotherm model by plotting C/θ against C to evaluate linearity. The **s**lope and intercept of the linear plot are used to calculate the adsorption parameters:

The slope indicates the extent of surface coverage consistency

The intercept is equal to: $1/K_{ads}$ From which K_{ads} is determined
The strength of adsorption was further evaluated using the calculated standard free energy of adsorption ($\Delta G°_{ads}$). In corrosion studies, values of $\Delta G°_{ads}$ around −20 kJ/mol or less negative are generally associated with physical adsorption, whereas values more negative than −40 kJ/mol indicate chemisorption. Intermediate values suggest mixed adsorption behavior. Therefore, adsorption type was interpreted based on these established thermodynamic thresholds rather than solely on the magnitude of K_{ads}. The feasibility and spontaneity of the adsorption process can be evaluated by calculating the standard free energy of adsorption (ΔG^o_{ads}) using the relation:

$$\Delta G^{\circ}_{ads} = -RT \ln(K_{ads} \times 55.5)$$

Where: universal gas constant (8.314 J/mol-K) and T= temperature in Kelvin

The value 55.5 mol·L^{-1} corresponds to the molar concentration of water under standard aqueous conditions and is introduced to render the adsorption equilibrium constant dimensionless.

A negative value of $\Delta G°_{ads}$ indicates spontaneous adsorption. In corrosion inhibition studies, $\Delta G°_{ads}$ values around −20 kJ/mol or less negative are generally associated with physical adsorption, whereas values more negative than −40 kJ/mol indicate chemisorption. Values between −20 and −40 kJ/mol suggest mixed adsorption behavior.

3. Results and Discussion

3.1 Weight Loss Data

The corrosion behavior of mild steel in 1.0 M hydrochloric acid, in the absence and presence of *Ficus exasperata* extract, was assessed by measuring the weight loss of steel coupons over immersion times of 24, 48, and 72 hours. Table 1 shows that the blank solution exhibited the highest weight loss, indicating aggressive corrosion. In contrast, the presence of the plant extract significantly reduced the extent of weight loss, with improved performance observed at higher concentrations and longer immersion periods.

Table 1: Initial and Final Weights of Mild Steel Coupons in 1.0 M HCl with Varying Concentrations of *Ficus exasperata* Extract

Concentration (ppm)	Time (hrs)	Metal Coupon	Initial Weight (g)	Final Weight (g)
0	24	A	4.800	4.774
0	48	A	4.800	4.600
0	72	A	4.800	4.581
100	24	B	4.800	4.779
100	48	B	4.800	4.752
100	72	B	4.800	4.710
200	24	C	4.800	4.780
200	48	C	4.800	4.768
200	72	C	4.800	4.734
300	24	D	4.800	4.787
300	48	D	4.800	4.775
300	72	D	4.800	4.763
400	24	E	4.800	4.793
400	48	E	4.800	4.786
400	72	E	4.800	4.771

3.2 Weight Loss, Corrosion Rate, and Inhibition Efficiency

The corrosion rate (CR) and inhibition efficiency (IE%) were computed using the weight loss data. Figure 2 presents the variation of corrosion rate with inhibitor concentration at different immersion times. A progressive decrease in corrosion rate was observed as the concentration of Ficus exasperata extract increased from 100 to 400 ppm, confirming concentration-dependent inhibition behavior. As shown in Table 2, the corrosion rate of mild steel decreased consistently with increasing concentration of *Ficus exasperata* extract. Inhibition efficiency improved accordingly, with the highest value of **93.00%** recorded at 400 ppm after 48 hours. Figure 3, illustrates the variation of corrosion rate with immersion time for different extract concentrations. While the blank solution exhibited pronounced fluctuations in corrosion rate, inhibited systems showed relatively stable and lower corrosion rates over time, indicating sustained surface protection.

All values represent the average of three independent measurements. Standard deviation values were within ±X%, indicating good repeatability. **Figure. 4** illustrates the Inhibition Efficiency (%) of *Ficus exasperata* Extract at Different Concentrations and Time Intervals.

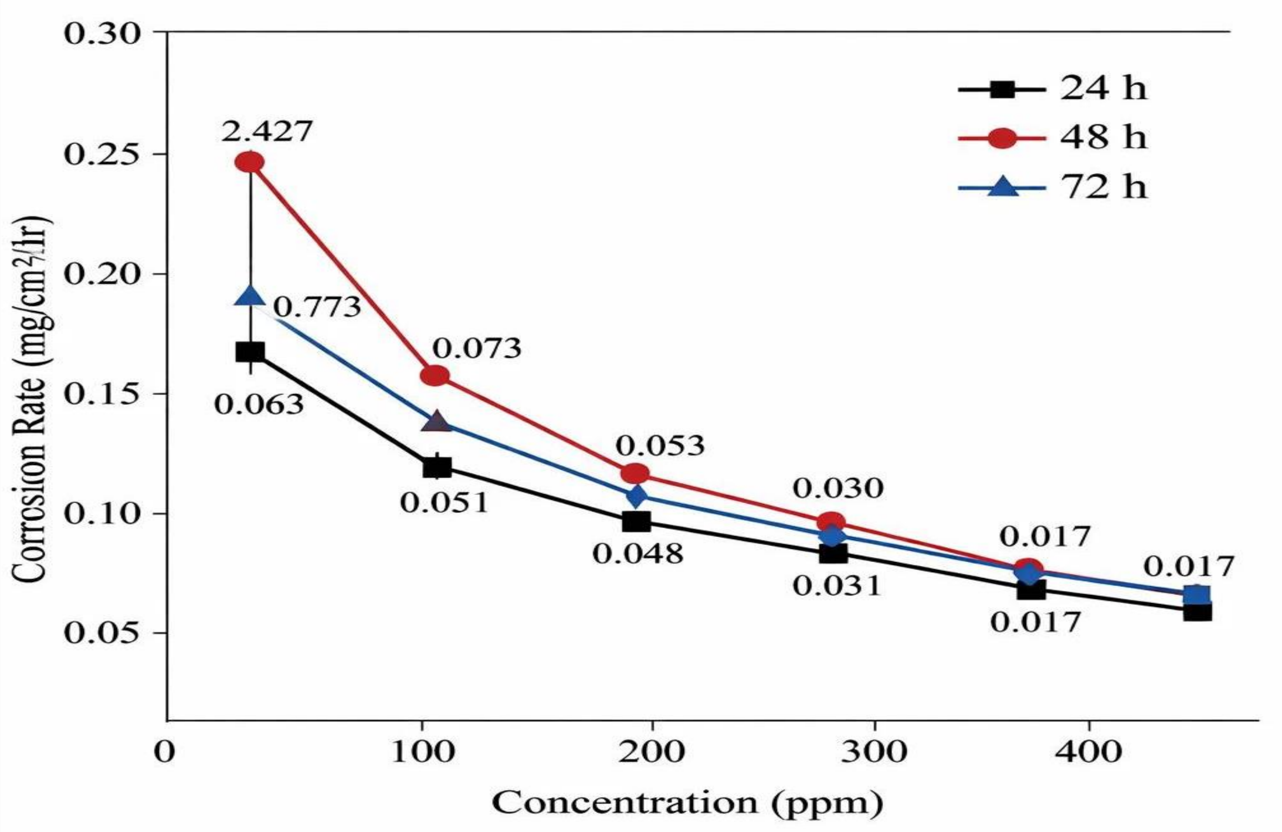

Figure 2. Corrosion Rate vs Concentration

Table 2: Weight Loss, Corrosion Rate, and Inhibition Efficiency of Mild Steel in 1.0 M HCl with Varying Concentrations of Ficus exasperata Extract

Concentration (ppm)	Time (hrs)	Metal Coupon	Weight (mg)	Loss CR ($mg/cm^2/hr$)	IE (%)
0	24	A	26.0	0.063	–
0	48	A	200.0	0.242	–
0	72	A	219.0	0.177	–
100	24	B	21.0	0.051	19.23
100	48	B	48.0	0.058	76.00
100	72	B	90.0	0.073	58.90
200	24	C	20.0	0.048	23.08
200	48	C	32.0	0.039	84.00
200	72	C	66.0	0.053	69.86
300	24	D	13.0	0.031	50.00
300	48	D	25.0	0.030	87.50
300	72	D	37.0	0.030	83.11
400	24	E	7.0	0.017	73.08
400	48	E	14.0	0.017	93.00
400	72	E	29.0	0.023	86.76

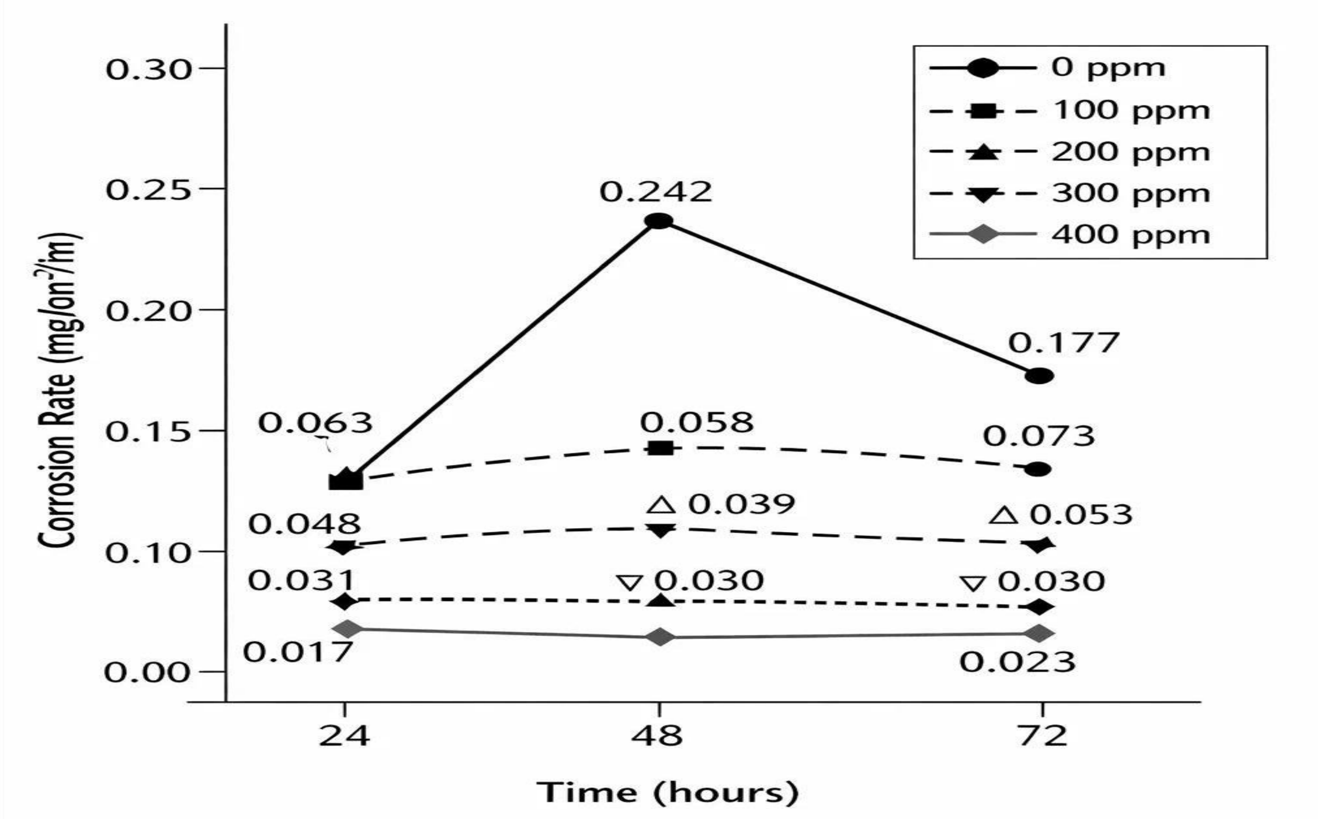

Figure 3. Corrosion Rate vs Time

This graph illustrates the trend of inhibition efficiency as a function of extract concentration (100–400 ppm) over 24, 48, and 72 hours. The efficiency increases with concentration at all time points, peaking at 93.00% after 48 hours at 400 ppm, indicating a strong time- and concentration-dependent inhibition behavior of *F. exasperata* on mild steel in 1.0 M HCl.

3.3 Adsorption Isotherm Studies

The Langmuir adsorption isotherm model was applied to the 72-hour data to evaluate the adsorption behavior of *Ficus exasperata* on mild steel. The surface coverage (θ) and C/θ values were calculated and are shown in **Table 3.**

Table 3: Langmuir Adsorption Isotherm Parameters (72 hrs)

Concentration (ppm)	IE (%)	θ	C/θ
100	58.90	0.589	169.77
200	69.86	0.699	286.28
300	83.11	0.831	360.99
400	86.76	0.868	461.05

The plot of C/θ against C gave a straight-line equation:

$C/\theta = 0.949C + 82.38$ ($R^2 = 0.994$)

From the intercept, the adsorption equilibrium constant (K_{ads}) was calculated as:

$K_{ads} = 1 / 82.38 = 0.0121$ L/mg

The standard free energy of adsorption (ΔG°_{ads}) was calculated using the equation:

$\Delta G^\circ_{ads} = -RT \ln(K_{ads} \times 55.5)$

Substituting the values gives:

$\Delta G^\circ_{ads} \approx -0.98$ kJ/mol

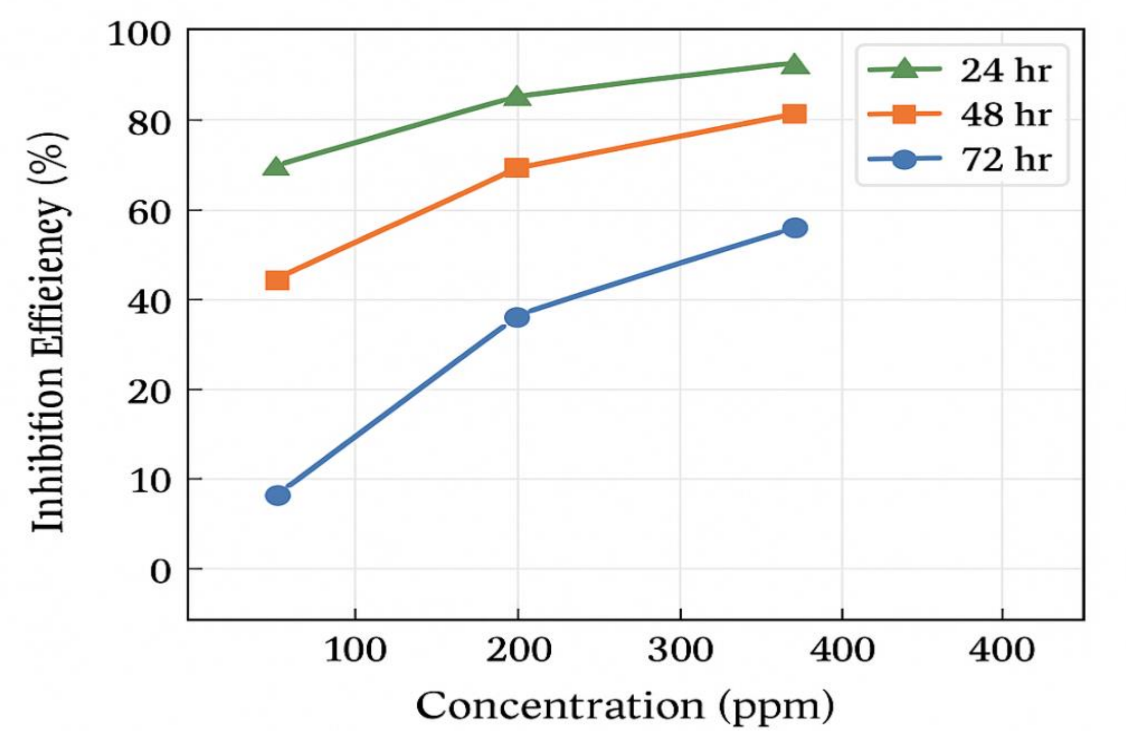

Figure 4. Inhibition Efficiency of *Ficus exasperata* Extract at Different Times

The negative value of ΔG°_{ads} (–0.98 kJ/mol) indicates that the adsorption process is spontaneous. However, this value is significantly lower than the typical range for physical adsorption (–20 to –40 kJ/mol), and far below that for chemisorption (–80 kJ/mol or more negative). Such a small magnitude suggests either very weak adsorption interactions or potential experimental or computational limitations, particularly the low value of the adsorption equilibrium constant (K_{ads}= 0.0121 L/mg). Despite this, the extract demonstrated a high inhibition efficiency of up to 93%, indicating that additional mechanisms, such as multilayer adsorption, surface complexation by multiple phytochemicals, or rapid surface saturation, may be contributing to the observed protection. This apparent discrepancy between thermodynamic magnitude and performance warrants further investigation through electrochemical and surface characterization techniques. The linear relationship observed in Figure 5 confirms that the adsorption of phytochemicals from the *Ficus exasperata* extract onto the mild steel surface conforms to the Langmuir isotherm model. The high correlation coefficient ($R^2 = 0.994$) suggests monolayer adsorption on a homogeneous surface with no significant interaction between adsorbed species. This validates the assumption of uniform surface coverage by the inhibitor molecules and supports a predominantly physical adsorption mechanism, as further evidenced by the low value of the standard free energy of adsorption (ΔG^0_{ads} = –0.98 kJ/mol).

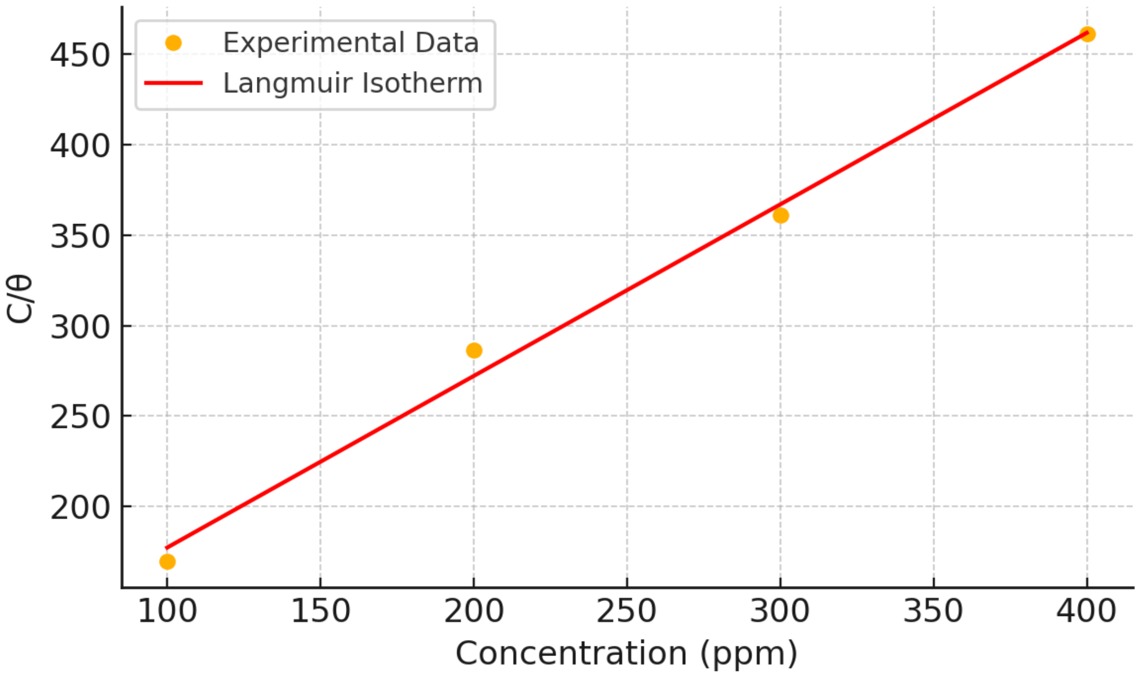

Figure 5. Langmuir Adsorption Isotherm

3.4 Discussion

Although several studies have investigated the corrosion inhibition potential of *Ficus exasperata*, they often utilized ethanolic or mixed extracts, tested at higher concentrations (up to 1 g/L), or focused on alternative media such as seawater or sulfuric acid (Patel et al., 2009; Popoola, 2021; Oyewole et al., 2021). In contrast, this study employs a simple aqueous extraction method and explores its effect in 1.0 M HCl at low concentrations (100–400 ppm) using only the weight loss technique, a practical, cost-effective approach for field conditions.

The results of this study demonstrate that the aqueous extract of *Ficus exasperata* acts as an effective green corrosion inhibitor, achieving a peak efficiency of 93.00% at 400 ppm. This high efficiency at relatively low concentrations (0.4 g/L) distinguishes this work from earlier studies that often-required concentrations exceeding 1.0 g/L to achieve similar protection (Okonji et al., 2026). The observed increase in inhibition efficiency with concentration suggests that more inhibitor molecules are available to cover the active sites on the mild steel surface, thereby reducing the corrosion rate. Comparing these results with other indigenous Nigerian flora, the performance of *F. exasperata* is superior to several recently reported inhibitors. For instance, the inhibition efficiency recorded here exceeds that reported for *Jatropha gossypiifolia* (82%) under similar acidic conditions (Okonji & Lawal, 2025). Furthermore, the performance is comparable to *Massularia acuminata*, which showed high efficiency but required higher dosages to maintain stability over 72 hours (Okonji 2025). The ability of *F. exasperata* to maintain 86.76% efficiency even after 72 hours suggests a robust and persistent protective film, a characteristic often sought in industrial pickling inhibitors (Sheikhshoaie & Nezamabadipour, 2009; Adindu et al., 2016).

The fitting of experimental data to the Langmuir isotherm (R^2 = 0.994) confirms that the inhibition occurs via monolayer adsorption on a homogeneous metal surface. This suggests that each adsorption site accommodates only one molecule of the phytochemical constituent, and there are no lateral interactions between the adsorbed molecules. Similar Langmuirian behavior has been reported for *Sapium ellipticum* extract, where it was noted that high correlation coefficients validate the formation of a stable molecular layer (Onukwuli et al., 2020). The calculated $\Delta G°_{ads}$ value of -0.98kJ/mol indicates a spontaneous process. While the magnitude is lower than the typical -20 kJ/mol threshold for strong physisorption, it's not uncommon in complex plant extracts where multiple components compete for surface sites. Previous findings observed that the presence of diverse phytochemicals in *Gossypium hirsutum* can lead to lower apparent thermodynamic values due to the synergistic or competitive adsorption of different functional groups (Abiola et al., 2011). This small negative value suggests that the adsorption is predominantly physical, involving weak electrostatic interactions between the charged metal surface and the polar functional groups (Okafor et al., 2008; Okafor et al., 2004). It's also important to note that the determination of ΔG°_{ads} for the extract using concentration in ppm, (mg/L) is lower to emet conclusion of the adsorption nature (Khadom et al., 2022; Lrhoul et al., 2023), hence the inhibition process is interpreted by the action of various components on the metal surface; generally called intermolecular synergistic effect.

The inhibitory action of *F. exasperata* is further attributed to its rich phytochemical profile, including tannins, flavonoids, and saponins (Asue et al., 2025). These molecules contain heteroatoms (Oxygen) and aromatic π-electrons which serve as centers of adsorption. As illustrated in Figure 6, the presence of hydroxyl (-OH) and carbonyl (C=O) groups allows for the formation of a protective barrier. This mechanism aligns with data from previous literature, demonstrating that oxygen-rich moieties in plant extracts facilitate the displacement of water molecules from the steel surface, thereby hindering the anodic and cathodic reactions (Dhaundiyal et al., 2019). Furthermore, it has been highlighted that the molecular size and structure of tannins play a critical role in blocking the pores of the metal surface, a factor likely contributing to the 93% efficiency observed in the current study (Eddy & Ebenso, 2010; Sheikhshoaie & Nezamabadipour, 2009; Adindu et al., 2016; Okafor et al., 2008; Okafor et al., 2004). The aqueous extraction method used here likely optimized the recovery of these water-soluble polyphenols, ensuring a high density of anchoring groups for surface attachment (Umoren et al., 2013; Al-Snafi, 2020).

The industrial relevance of these findings is significant, as 1.0 M HCl provides a standardized benchmark for acid cleaning and descaling processes. The effectiveness of *F. exasperata* at concentrations as low as 100ppm makes it an economically viable alternative to synthetic inhibitors like thiourea or benzimidazole derivatives, which are associated with high toxicity (Hussin et al., 2016; Al-Otaibi et al., 2014). Similar studies on *Hibiscus* and *Henna* extracts have shown that plant-based inhibitors provide a sustainable "green" shield without the environmental footprint of heavy-metal based inhibitors (Ebenso et al., 2021; Ostovari et al., 2009). This study's reliance on weight loss measurements provides a direct and reliable assessment of material degradation that is easily translatable to field applications in Nigerian industries (Buchweishaija, 2009; Koushik et al., 2026; Okonji, 2026). The novelty of this study lies in the application of a simple aqueous extraction method combined with low-concentration inhibitor evaluation (100–400ppm) in a standardized 1.0 M HCl environment over multiple immersion times using a simple gravimetric (weight loss) technique. Unlike many previous reports that employed higher concentrations, organic solvent extraction, or complex electrochemical techniques, this work emphasizes an economically viable and reproducible approach integrated with thermodynamic adsorption analysis to evaluate the inhibition mechanism. This supports the successful use of a low-concentration aqueous extract, which minimizes chemical waste while maintaining high protection levels, reinforcing the potential of *F. exasperata* as a high-performance, eco-friendly additive for acid-induced environments (Ahamad et al., 2010).

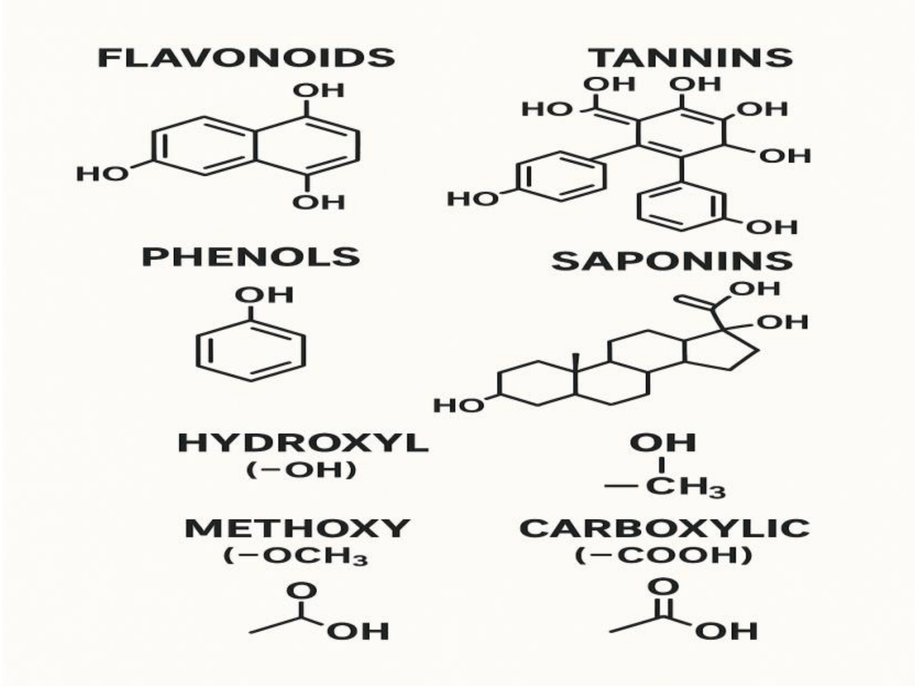

Figure 6. Schematic representation of major phytochemicals identified in *Ficus exasperata* leaves (Asue *et al.*, 2025).

Conclusion

This study demonstrates that an aqueous extract of *Ficus exasperata*, applied at low concentrations (100–400 ppm), can serve as an effective and sustainable corrosion inhibitor for mild steel in 1.0 M HCl**.** Using the weight loss method over 72 hours, a maximum inhibition efficiency of 93.00% was recorded at 400 ppm after 48 hours. The adsorption process followed the Langmuir isotherm model ($R^2 = 0.994$), and the calculated standard free energy ($\Delta G^o_{ads} \approx -0.98$ kJ/mol) confirmed that spontaneous physisorption governed the interaction between inhibitor molecules and the steel surface. Compared to prior studies involving higher inhibitor concentrations or ethanol-based extractions, this work presents a greener, safer, and more cost-effective approach. Its relevance is especially strong for industries in developing economies, where local sourcing and biodegradability are critical. Future investigations using electrochemical methods (EIS, PDP) and surface analysis tools (SEM, FTIR) are encouraged to further elucidate the inhibition mechanism and validate its industrial scalability.

Author Contribution

Kanayo Samuel Okonji: Conceptualization, Methodology, Investigation, Formal analysis, Writing – Original Draft, Supervision, Data curation, Writing – Review & Editing.

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