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Mechanistic Investigation of the Corrosion Inhibition Performance of *Ficus sur* Leaf Extract on Mild Steel in 1 M HCl: Insights from Electrochemical and Thermodynamic Analyses

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Abstract: This study used gravimetric and electrochemical methods to assess how well *Ficus sur* leaf extract inhibited corrosion on mild steel in a 1 M HCl solution. Potentiodynamic polarization (PDP), electrochemical impedance spectroscopy (EIS), and open circuit potential (OCP) investigations were used to examine the inhibition mechanism while weight loss measurements were carried out at various inhibitor doses and temperatures. The findings demonstrated that while inhibition efficiency rose to a maximum of 80% using the gravimetric approach, corrosion rate reduced with increasing inhibitor concentration.The formation of a highly protective surface film was confirmed by electrochemical studies, which showed significantly higher efficiencies of 98.7% (PDP) and 98.6% (EIS) at 0.60 g/L. PDP results showed that *Ficus sur* functions as a mixed-type inhibitor by suppressing both anodic and cathodic reactions; adsorption of the inhibitor followed the Langmuir adsorption isotherm, with negative Gibbs free energy values indicating spontaneous physisorption. Overall, *Ficus sur* showed great potential as an environmentally friendly corrosion in chloride media.

Keywords: *Physiorption, Electrochemical, Corrosion, Adsorption, Inhibition*

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1.0 Introduction

Corrosion is a persistent materials degradation problem that affects metallic structures and equipment exposed to aggressive chemical and environmental conditions (Ajike *et al*., 2024;Ejike, 2023; Issa, 2019). It is an undergoes oxidation as it interacts electrochemical process in which a metal with its surrounding environment, resulting in progressive deterioration of its physical, mechanical, and functional properties (Assad *et* al., 2025; Antony Jose *et al*., 2025). The consequences of corrosion include material loss, reduction in structural integrity, increased maintenance and replacement costs, production downtime, and potential environmental contamination (Harsimran *et* al., 2021; Bender *et al*., 2022; Eddy *et al*., 2008; Lgas *et al*., 2020). Mild steel is particularly susceptible to corrosion because of its relatively low alloying content and high reactivity in aggressive media. Its extensive application in

construction, transportation, petroleum refining, chemical processing, storage tanks, pipelines, and other engineering systems therefore makes effective corrosion control particularly important.

Acidic environments are among the most aggressive conditions for mild steel corrosion. Hydrochloric acid (HCl), in particular, is widely encountered in industrial operations such as acid pickling, cleaning, descaling, oil-well acidizing, and chemical processing. In such environments, corrosion proceeds predominantly through anodic dissolution of iron accompanied by cathodic hydrogen evolution. The severity of the process makes corrosion inhibitors an important means of protecting metallic surfaces. Numerous organic compounds containing heteroatoms and electron-rich functional groups have been investigated as corrosion inhibitors because they can interact with the metal surface and reduce the rates of anodic and/or cathodic electrochemical reactions (Nnanna *et* al., 2010; Quraishi *et al.*, 2020; Verma *et al*., 2021; Zhang *et al*., 2022). For example, derivatives of cyclopenta-1,3-diene have demonstrated inhibition potentials for mild steel corrosion in HCl through experimental and theoretical investigations (Eddy & Ita, 2011), while pyridoxal hydrochloride-2,4-dinitrophenyl hydrazone has also been reported to inhibit mild steel corrosion in hydrochloric acid medium (Odoemelam & Eddy, 2008). Similarly, Eddy *et al*. (2011) demonstrated the corrosion-inhibition potential of ethanol extract of *Andrographis paniculata* on mild steel in HCl, highlighting the potential of naturally occurring organic compounds as alternatives to conventional synthetic inhibitors. Other organic inhibitors have likewise been investigated for the protection of metallic materials in acidic environments (Eddy *et al*., 2008; Eddy *et al*., 2011).

Despite their effectiveness, many conventional corrosion inhibitors may present limitations associated with toxicity, environmental persistence, cost, and difficulties in safe disposal. These concerns have stimulated increasing interest in green corrosion inhibitors derived from renewable biological resources, particularly plant extracts. Plant extracts contain diverse phytochemicals, including alkaloids, flavonoids, tannins, phenolic compounds, terpenoids, saponins, glycosides, and other oxygen-, nitrogen-, and sulfur-containing compounds. These constituents possess functional groups and π-electron systems capable of interacting with metallic surfaces through electrostatic attraction, donor–acceptor interactions, and, depending on the chemical composition and environmental conditions, physical and/or chemical adsorption. The resulting adsorbed layer can reduce the active surface area available for metal dissolution and interfere with the anodic and cathodic reactions responsible for corrosion. Consequently, plant extracts are increasingly regarded as promising environmentally benign alternatives to some conventional corrosion inhibitors. Recent developments in surface-protection technologies further demonstrate the continuing interest in environmentally compatible approaches to corrosion control, including nanocomposite protective coatings for mild steel (Akpanudo, 2026).

The effectiveness of plant-derived inhibitors is strongly dependent on their chemical composition, concentration, temperature, exposure time, and the nature of the metal and corrosive medium. Electrochemical and gravimetric investigations are therefore important for establishing both inhibition efficiency and inhibition mechanism. In particular, potentiodynamic polarization (PDP) provides information on the influence of an inhibitor on anodic and cathodic reactions and can indicate whether an inhibitor behaves predominantly as an anodic, cathodic, or mixed-type inhibitor. Electrochemical impedance spectroscopy (EIS) provides complementary information about charge-

transfer processes and the formation of protective interfacial films, while open-circuit potential (OCP) measurements provide information about changes in the electrochemical state of the metal surface. Gravimetric measurements, particularly weight-loss experiments, provide a direct assessment of corrosion rate and inhibition efficiency under different concentrations and temperatures. Combining these techniques can therefore provide a more comprehensive understanding of inhibitor performance than reliance on a single analytical method.

The growing interest in *Ficus* species as corrosion inhibitors provides a useful basis for investigating *Ficus sur*. Several studies have demonstrated the corrosion-protection potential of extracts obtained from related *Ficus* species. Anh *et al*. (2020), for example, reported that *Ficus racemosa* leaf extract significantly inhibited carbon-steel corrosion in 0.1 M HCl, with an optimum inhibition efficiency of 93.11 ± 1.99% at 1500 ppm. The authors attributed the protection to the formation of a compact protective layer resulting from adsorption of extract constituents on the steel surface. Interestingly, increasing the extract concentration to 2000 ppm reduced the inhibition efficiency to 88.86 ± 2.15%, demonstrating that excessively high concentrations do not necessarily produce improved corrosion protection and that optimum inhibitor concentration is an important consideration (Anh *et al*., 2020). Quantum-chemical calculations in that study further indicated favourable interactions between extract constituents and the carbon-steel surface, supporting the role of adsorption in corrosion inhibition.

Similarly, Ogwo *et al*. (2017) investigated *Ficus sycomorus* leaf extract for the protection of mild steel and aluminium in 1 M HCl. For mild steel, inhibition efficiency increased with extract concentration and reached 87.84% at 5 g/L. The adsorption behaviour was better described by the Langmuir isotherm than the Temkin isotherm, while the negative values of the standard Gibbs free energy of adsorption indicated that adsorption occurred spontaneously. These findings demonstrate that extracts from *Ficus* species can provide appreciable protection of mild steel in hydrochloric acid and that adsorption behaviour can be effectively evaluated using thermodynamic and adsorption-isotherm analyses (Ogwo *et al*., 2017).

Further evidence for the suitability of fig-derived plant materials as green corrosion inhibitors was provided by Rahmouni *et al*. (2024), who investigated fig leaf extract for steel protection in 1 M HCl using gravimetric measurements, potentiodynamic polarization, electrochemical impedance spectroscopy, spectroscopic analysis, and surface characterization. The extract exhibited a maximum inhibition efficiency of approximately 94% and behaved as a mixed-type inhibitor. Its adsorption was described by the Langmuir isotherm, while thermodynamic and activation-parameter analyses provided evidence concerning the nature of the interaction between inhibitor constituents and the steel surface. FTIR and surface-characterization results further supported the formation of an inhibitor-derived protective layer (Rahmouni *et al*., 2024). Collectively, these findings demonstrate the value of integrating gravimetric, electrochemical, spectroscopic, and thermodynamic approaches when elucidating the corrosion-inhibition mechanism of plant extracts.

Although the available evidence demonstrates the promising corrosion-inhibition properties of several plant extracts and related *Ficus* species, important questions remain concerning the specific behaviour of *Ficus sur* leaf extract toward mild steel in strongly acidic hydrochloric acid medium. In particular, there is limited information on the combined concentration- and temperature-dependent inhibition behaviour of *Ficus sur*, the extent to which its constituents influence both anodic

and cathodic reactions, the characteristics of the protective interfacial film, and the thermodynamic nature of its adsorption on mild steel. Furthermore, a comprehensive assessment integrating gravimetric measurements with OCP, PDP, and EIS can provide complementary evidence that is useful for distinguishing inhibition efficiency from the underlying interfacial mechanism. Establishing the adsorption isotherm and evaluating thermodynamic parameters are also essential for determining whether the interaction between *Ficus sur* constituents and the mild-steel surface is spontaneous and for gaining insight into the dominant adsorption process.

Therefore, this study aims to investigate the corrosion-inhibition performance and mechanism of *Ficus sur* leaf extract on mild steel in 1 M HCl using complementary gravimetric and electrochemical techniques. The effects of inhibitor concentration and temperature are evaluated through weight-loss measurements, while OCP, PDP, and EIS are employed to elucidate the electrochemical behaviour and inhibition mechanism. Adsorption-isotherm and thermodynamic analyses are further used to characterize the interaction between the extract constituents and the mild-steel surface. The study is significant because it provides mechanistic evidence for the possible application of *Ficus sur* leaf extract as a renewable and environmentally compatible corrosion inhibitor and contributes to the broader development of plant-based alternatives for corrosion control in acidic industrial environments.

2.0. Materials and Method

2.1. Metal preparation

Corrosion studies were performed using mild-steel sheets as the test specimens. Prior to the corrosion experiments, the mild-steel sheets were mechanically cut into coupons of specified dimensions. A hole was drilled at one end of each coupon to facilitate suspension during immersion, and the coupons were individually identified.. The dimensions, exposed surface area, and chemical composition of the mild steel should be reported to ensure reproducibility of the experiments. he surface of each coupon was sequentially polished with 220-, 800-, and 1200-grit emery papers to obtain a uniform and smooth surface.. The coupons were further degreased with The polished coupons were degreased with acetone, thoroughly rinsed with distilled water to remove residual debris, and dried in warm air prior to use, following the procedure reported by Khadom *et al.* (2015).

2.2. Preparation of Ficus sur Leaf Extract

Fresh *Ficus sur* leaves were collected from the botanical garden of the Michael Okpara University, , authenticated by Michael Okpara university research institute, and thoroughly washed with distilled water to remove adhering dirt and foreign materials. The leaves were dried for three days under [under the sun to reduce their moisture content.. After drying, the leaves were pulverized to increase their surface area and stored in a clean, airtight container until extraction. Twenty grams of the pulverized *Ficus sur* leaves were weighed and transferred into a reflux flask containing 200 mL of [insert actual extraction solvent]. The mixture was refluxed for 3 h at [insert actual temperature].. After extraction, the mixture was allowed to cool to room temperature and filtered to separate the extract from the residual plant material. The filtrate was collected for preparation of the inhibitor solutions.The residues were oven dried and reweighed. Stock solutions were prepared from the resulting extract, from which inhibitor solutions with concentrations of 0.2, 0.4, 0.6, 0.8, and 1.0 g L^{-1} were prepared following the procedure reported by Emea *et al*. (2023).(Emea *et al.,* 2023).

2.3. Gravimetric Method

For the gravimetric measurements, pre-weighed mild-steel coupons were completely immersed in 100 mL of 1 M HCl in the absence and presence of *Ficus sur* leaf extract at the

specified inhibitor concentrations. The initial experiments were conducted at 303 K.. The coupons were removed from the test solutions at 2 h intervals over a total exposure period of 10 h (2, 4, 6, 8, and 10 h).. Separate coupons were used for each exposure period to minimize disturbance of the corrosion system. After each exposure period, the coupons were removed and subjected to the specified post-immersion cleaning procedure to remove corrosion products. The cleaned coupons were thoroughly rinsed with distilled water, followed by ethanol and acetone, and then dried before weighing.. After each exposure period, the coupons were removed and subjected to the specified post-immersion cleaning procedure to remove corrosion products. The cleaned coupons were thoroughly rinsed with distilled water, followed by ethanol and acetone, and then dried before weighing. All measurements were performed in 2 replicates, and the results are reported as mean ± standard deviation The corrosion rate was calculated from the mass-loss data and expressed in the appropriate corrosion-rate units. The inhibition efficiency (η%) was calculated from mass loss using the following equations: (Okafor *et al.,* 2021)

$$\Delta w = (w_1 - w_2)X\,1000 \ (mg) \qquad (1)$$

$$A = 2\left[(LXB - \frac{\pi d^2}{4}) + 2(LXH) + 2(BXH) + \pi dH\right] \qquad (2)$$

$$p = \frac{w_o}{v} \qquad (3)$$

$$v = (LXBXH) - \frac{\pi d^2}{4}H$$

$$(4)C.R. = \frac{K\Delta w}{APT} \qquad (5)$$

where C.R.= corrosion rate, $\Delta w =$ change in weight (mg), A= cross sectional area of (cm^2) P = density of , (g/cm^3), K= 87.6 (corrosion constant), t = time of study (hrs), w_1 and w_2 are the initial and final weights of coupon. L, B, H, and d represent length, breadth, height and the diameter of the coupon. . Concentrations that showed better curves were selected for thermodynamic examinations.

$$\text{Inhibition efficiency \%} = \frac{W_B - W_A}{W_B}X\frac{100}{1} \qquad (6)$$

Where w_B and $w_{A\ are}$ weight loss in the absence and presence of the inhibitor. The degree of surface coverage (θ) was calculated from the weight loss measurements using Equation (7):

Surface coverage

$$\theta = \frac{W_B - W_A}{W_B} \qquad (7)$$

where w_B and w_A are the weight loss in the absence and presence of the inhibitor.

The effect of temperature on the inhibition efficiency of the inhibitor was carried out at the temperature of 303K and 318Kusing weight loss measurements.

2.4. Thermodynamic Adsorption Isotherm

2.4.1. Langmuir Isotherm

Basic information on the interaction between the inhibitor and the metal can be provided by the adsorption isotherm. The manner of adsorption (physisorption or chemisorption) is determined by the electronic structure of the metal, the nature of the corrodent and the chemical nature of the inhibitor. The Langmuir adsorption isotherm equation is given by the equation 8 (Nnanna & Iroha, 2020)

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \qquad (8)$$

W

where C is the concentration of *Ficus sur* and θ is the surface coverage and $K_{ads}$is the adsorptive equilibrium constant.(Iroha and Hamilton, 2018).

The adsorption free energy (ΔG^0ads) is related to K_{ads} by the (9)

$$\Delta G^O_{ads} = -RT\ln(K_{ads}X\,55.5) \qquad (9)$$

where R is the gas constant (8.314 kJ/mol) and T is the absolute temperature. The value 55.5 is the concentration of water in solution in mol/L. The adsorption parameters from Langmuir adsorption isotherms are estimated for 303K, 318K and 333K at different concentrations of the respective inhibitors (*Ficus sur*).

2.4.2 Temkin isotherm

Equation 12 relates the degree of surface coverage (θ) and the inhibition concentration (c). After linearization using logarithmic transformation, the constant K and the parameter "a" were obtained for isotherm at various temperatures and time. From equation 12, this was achieved by making a plot of θ against logc.

$$\theta = -\frac{-2.303\ln k}{2a} - \frac{2.303\ln c}{2a} \quad (12)$$

2.5 Thermodynamic Studies

The mode of adsorption of inhibitors which can either be physio or chemisorption may be predicted from the knowledge of thermodynamic parameters that govern the adsorption process. The activation energies Ea for corrosion process in the absence and presence of leaf extract of *Ficus sur*were calculated using Arrehnius equation (10)

$$\ln W = \ln A + \frac{-E_a}{2.303RT} \quad (10)$$

Where w is the corrosion rate, A is the frequency factor R is the gas constant and Ea is the activation energy which can be obtained when lnW is plotted against the inverse of absolute temperature 1/T. The activation energy becomes

$$E_{a} = -\text{slope} \times 2.303 \times R \quad (11)$$

where R = 8.314 J/K/mole, the real gas constant

2.6 Electrochemical Study

Electrochemical analyses were conducted in 0.5 M HCl, and 3.5% HCl, corrosive electrolytes. To prevent charging current and confirm system stability open circuit potential (OCP) was recorded for a duration of 1800 s (30 mins). This is required for the metal to dissolves at its equilibrium or free potential (E_{corr}) which is achieved at stable OCP. Thereafter, all the electrochemical experiments were carried out at OCP condition (Singh *et al.,* 2022). The electrochemical tests were run using a cell assembly consisting of three electrodes which includes; 1 cm^2 exposed metal surface mild steel which served as the working electrodes (WE), silver/silver chloride (Ag/AgCl) was used as a reference electrode (RE); all the reported potentials in this work are vs. Ag/AgCl, while platinum wire was utilized as a counter electrode (CE). The electrochemical impedance spectroscopy (EIS) was measured with a signal amplitude perturbation of 10 mV throughout a frequency range of 100 kHz–10 mHz. The data were later analyzed using appropriate electrochemical analytical software such as Zsimpwin 3.2 model for EIS with the fitted equivalent circuit simulated for the specific metal/ electrolyte environment and EC-lab was utilized for the potentiodynamic polarization, analyses and all data were plotted using origin pro 2016 model software.

3.0 Results and Discussion

3.1 Mass Loss of Mild Steel in 1 M HCl in the Presence of Ficus sur Leaf Extract

The variation in mass loss of mild steel immersed in 1 M HCl containing different concentrations of *Ficus sur* leaf extract at different temperatures is presented in **Fig. 1**. The mass loss increased progressively with exposure time in all the test solutions, confirming continuous dissolution of the mild-steel substrate in the acidic medium. However, the extent of mass loss was substantially lower in the presence of *Ficus sur* extract than in the uninhibited solution. This behaviour indicates that constituents of the leaf extract adsorbed onto the mild-steel surface and reduced the extent of metal dissolution.

At a given temperature and exposure period, increasing the inhibitor concentration generally resulted in a reduction in mass loss. This concentration-dependent behaviour suggests progressive occupation of active corrosion sites by the phytochemical constituents of *Ficus sur*. The adsorbed molecules can form a protective interfacial layer that limits the access of aggressive species, particularly hydrogen ions and chloride-containing species, to the metallic surface. Similar concentration-dependent reductions in corrosion of steel have been reported for plant-derived inhibitors and *Ficus*-

based extracts (Anh *et al*., 2020; Ogwo *et al*., 2017; Rahmouni *et al*., 2024).

Temperature also exerted an appreciable influence on mass loss. The higher mass loss observed at elevated temperature indicates acceleration of the electrochemical reactions responsible for mild-steel dissolution. Nevertheless, the presence of *Ficus sur* continued to suppress mass loss, demonstrating that the extract retained appreciable inhibitory activity over the investigated temperature range. The reduction in mass loss in the inhibited systems provides the first experimental evidence that *Ficus sur* leaf constituents interact with the mild-steel surface and retard the corrosion process.

The inhibitory effect of *Ficus sur* is chemically plausible because plant extracts contain oxygen-, nitrogen-, and other heteroatom-containing compounds as well as π-electron systems capable of interacting with metallic surfaces. Such compounds may compete with water and aggressive ions for adsorption sites and consequently reduce the active surface area available for corrosion. Previous studies have similarly demonstrated the ability of organic compounds and plant extracts to inhibit mild-steel corrosion in acidic media (Eddy & Ita, 2011; Eddy *et al*., 2011a; Odoemelam & Eddy, 2008).

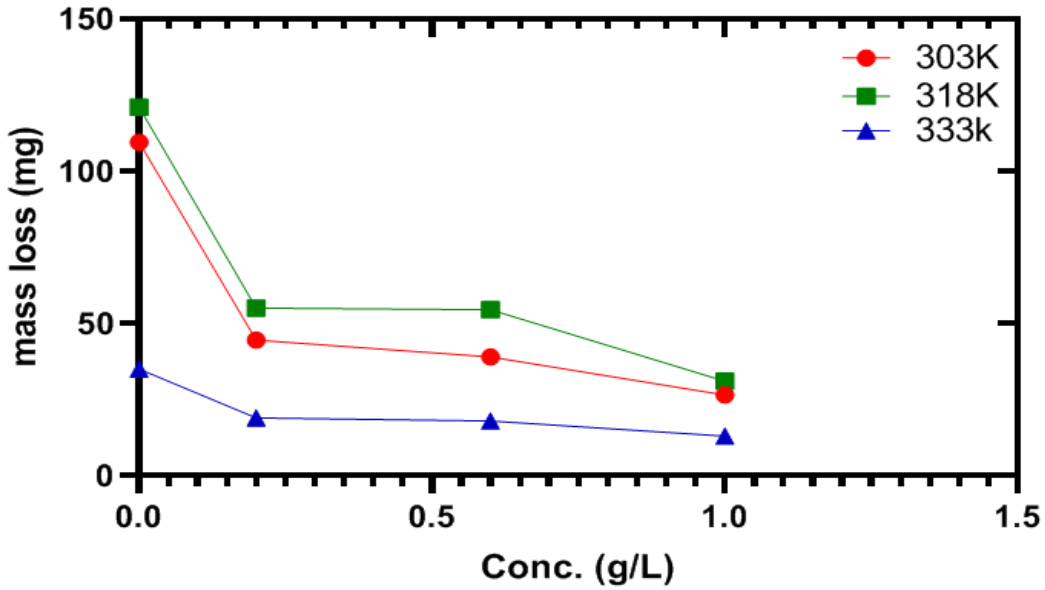

Fig. 1: Mass loss of Mild steel in different concentrations of *Ficus sur* in 1M HCl at different temperatures in 2hrs.

3.2. Corrosion Rate of Mild Steel in Ficussur ***(1M HCl)***

3.2 Corrosion Rate of Mild Steel in 1 M HCl Containing Ficus sur Extract

The corrosion-rate behaviour of mild steel in 1 M HCl containing different concentrations of *Ficus sur* extract is presented in Fig. 2. The results show that corrosion rate decreased with increasing inhibitor concentration. This trend is consistent with the mass-loss results and confirms that the reduction in mass loss was associated with an actual decrease in the rate of electrochemical metal dissolution rather than merely a transient surface effect. The uninhibited mild steel exhibited the highest corrosion rate, reflecting the aggressive nature of 1 M HCl toward the steel surface. In acidic solution, anodic dissolution of iron is accompanied by cathodic hydrogen-evolution reactions, producing relatively rapid degradation of the metal. Addition of *Ficus sur* extract progressively suppressed these

processes, presumably through adsorption of phytochemical constituents onto electrochemically active sites.

The temperature-dependent results further indicate that the corrosion process became more pronounced as temperature increased. The highest corrosion rates were observed at 333 K, whereas lower rates were obtained at 303 K. The increased corrosion rate at elevated temperature can be attributed to enhanced molecular mobility, faster interfacial reaction kinetics, and increased transport of corrosive species toward the steel surface. Importantly, the inhibitor-containing systems still exhibited lower corrosion rates than the blank, demonstrating that *Ficus sur* provides measurable protection even under thermally accelerated corrosion conditions.

The observed behaviour agrees with the findings of Ogwo *et al*. (2017), who reported that *Ficus sycomorus* leaf extract decreased the corrosion rate of mild steel and aluminium in 1 M HCl. Similarly, Anh *et al*. (2020) observed substantial corrosion protection of carbon steel by *Ficus racemosa* leaf extract in hydrochloric acid. Rahmouni *et al*. (2024) also demonstrated effective inhibition of steel corrosion by fig leaf extract using complementary gravimetric and electrochemical techniques. Thus, the present results extend the evidence for the corrosion-inhibiting capability of *Ficus* species to *Ficussur*.

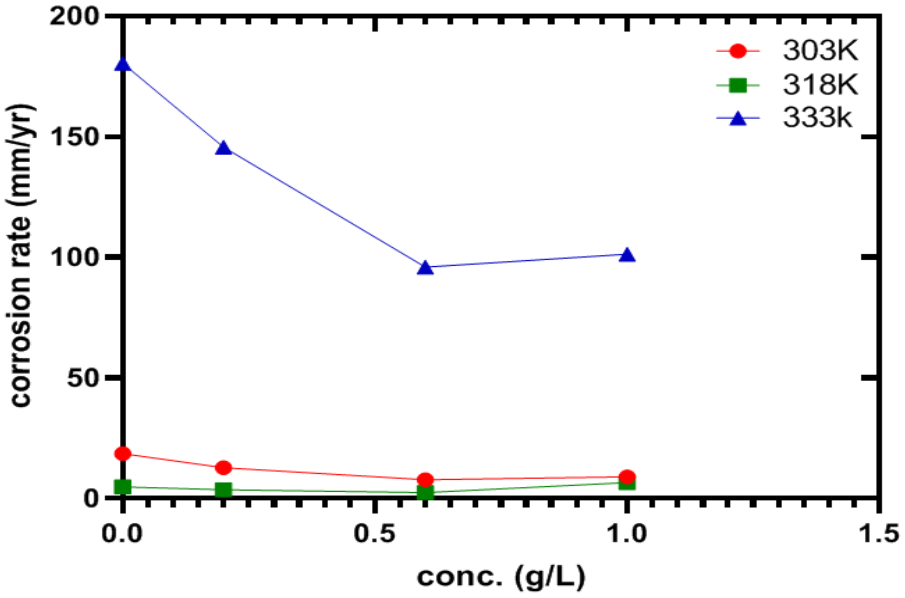

Fig. 2: Corrosion rate of alloy in different concentrations of *Ficus sur* in 1M HClat different temperature in 2 hours

3.3. Inhibition Efficiency of Ficus sur *on Mild Steel in 1 M HCl*

The inhibition efficiency obtained from the gravimetric measurements is presented in **Fig. 3**. In general, inhibition efficiency increased with increasing concentration of *Ficus sur* extract, demonstrating that a greater amount of inhibitor promoted more extensive surface coverage. The maximum gravimetric inhibition efficiency was approximately **80%**, indicating substantial protection of mild steel against corrosion in 1 M HCl. The increase in inhibition efficiency with concentration can be explained by progressive adsorption of inhibitor molecules onto the metal surface. At low concentrations, only a fraction of the available active sites is occupied, leaving portions of the steel surface exposed to the acidic electrolyte. Increasing the inhibitor concentration increases the number of inhibitor

molecules available for adsorption and therefore promotes greater surface coverage. Once a substantial proportion of the active sites has been occupied, further increases in concentration may produce comparatively smaller improvements in inhibition efficiency because the surface approaches saturation.

Temperature also influenced the inhibition efficiency. The gravimetric results indicate that the protective effect was generally more pronounced at the lower temperature, while increasing temperature tended to reduce the inhibition efficiency. Such behaviour may indicate partial desorption of physically adsorbed inhibitor species as thermal agitation increases. However, the persistence of significant inhibition at elevated temperature indicates that the adsorbed layer was not completely disrupted.

The maximum gravimetric inhibition efficiency obtained in the present study is lower than some values reported for related *Ficus* extracts. For example, Ogwo *et al*. (2017) reported inhibition efficiencies of 87.84% for mild steel and 98.92% for aluminium using *Ficus sycomorus* extract in 1 M HCl, while Anh *et al*. (2020) reported an inhibition efficiency of approximately 93.11% for *Ficus racemosa* extract at an optimum concentration in 0.1 M HCl. Rahmouni *et al*. (2024) reported a maximum efficiency of approximately 94% for fig leaf extract in 1 M HCl. Differences among these studies may arise from differences in plant species, phytochemical composition, extraction solvent, extraction temperature, inhibitor concentration, metal composition, acidic-medium concentration, and experimental conditions.

The present result nevertheless demonstrates that *Ficus sur* possesses considerable potential as a green corrosion inhibitor. The effectiveness of the extract is particularly relevant because plant-derived inhibitors provide a potentially less hazardous alternative to some conventional synthetic corrosion inhibitors.

The concentration-dependent inhibition observed here is also consistent with earlier investigations of organic corrosion inhibitors. Eddy and Ita (2011) demonstrated that organic compounds containing electron-rich functional groups can interact strongly with mild-steel surfaces, while Eddy *et al*. (2011a) reported significant corrosion-inhibition activity for constituents identified from *Andrographis paniculata* extract. These studies support the interpretation that adsorption of electron-rich organic constituents is an important component of the inhibition mechanism.

3.4 Adsorption Behaviour and Surface Coverage

The degree of surface coverage (θ) obtained from the gravimetric data increased with inhibitor concentration at all investigated temperatures. The plot supplied for the adsorption analysis shows that θ increased from approximately 0.54 to 0.75 at 303 K, from approximately 0.49 to 0.72 at 318 K, and from approximately 0.41 to 0.62 at 333 K as inhibitor concentration increased.

This concentration-dependent increase in surface coverage provides direct evidence that *Ficus sur* constituents progressively occupy active sites on the mild-steel surface. The lower surface coverage observed at 333 K compared with 303 K at corresponding concentrations is consistent with the temperature-dependent reduction in gravimetric inhibition efficiency and suggests weakening or partial desorption of adsorbed inhibitor molecules at higher temperature.

The surface-coverage behaviour is important because it provides a link between the gravimetric and adsorption results. As more inhibitor molecules become adsorbed, fewer electrochemically active sites remain available for iron dissolution and hydrogen evolution. Consequently, corrosion rate decreases while inhibition efficiency increases.

The adsorption behaviour is consistent with previous studies of plant-based inhibitors. Ogwo *et al*. (2017) found that *Ficus sycomorus* adsorption on mild steel in 1 M HCl was better described by the Langmuir model than by the Temkin model. Rahmouni *et al*. (2024) similarly reported Langmuir adsorption behaviour for fig leaf extract on steel in 1 M HCl.

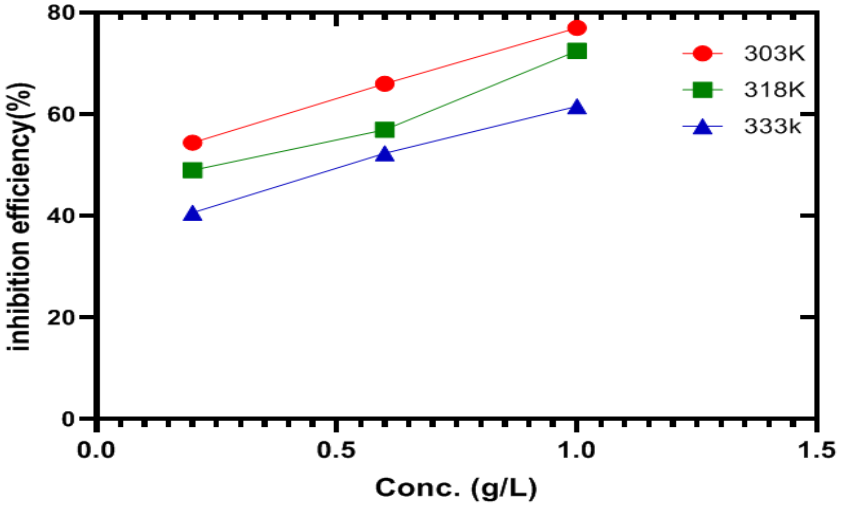

Fig. 3: Inhibition efficiency of Mild steel in different concentrations of *Ficus sur* in 1M HCl at different temperatures in 2hrs.

3.5 Adsorption Isotherm and Thermodynamic Analysis

3.5.1 Langmuir Adsorption Isotherm

The adsorption behaviour of *Ficus sur* extract was investigated using adsorption isotherm models. The calculated Langmuir parameters are presented in Table 1, while the corresponding adsorption plot is presented in Fig. 5. The regression coefficients and adsorption parameters indicate a strong relationship between inhibitor concentration and surface coverage.

The good agreement with the Langmuir model suggests that adsorption of the active constituents of *Ficus sur* occurs preferentially at available sites on the mild-steel surface. In the classical Langmuir model, adsorption is assumed to involve a finite number of energetically equivalent sites and formation of an approximately monolayer protective film without significant lateral interaction among adsorbed species. The high inhibition efficiencies obtained from the electrochemical measurements further support substantial occupation of the steel surface by inhibitor molecules.

The negative values of ΔGads∘ reported in Table 1 indicate that adsorption is thermodynamically spontaneous. The magnitude of ΔGads∘ should, however, be interpreted cautiously when assigning the adsorption mechanism. Values around or less negative than approximately −20 kJ mol^{-1} are commonly associated with predominantly physical adsorption, whereas substantially more negative values may indicate increasing contribution from chemical interactions. These ranges are empirical guidelines rather than absolute criteria.

The adsorption behaviour observed in the present study can therefore be attributed to interactions between phytochemical constituents of *Ficus sur* and the mild-steel surface. Such interactions may involve electrostatic attraction, donor–acceptor interactions involving heteroatoms, and interactions between π-electron systems and

the metal surface. The precise contribution of each mechanism would require complementary surface or spectroscopic characterization.

The present observation is consistent with Ogwo *et al*. (2017), who reported Langmuir adsorption of *Ficus sycomorus* extract on mild steel in 1 M HCl with negative Gibbs free-energy values. Rahmouni *et al*. (2024) also reported Langmuir adsorption and spontaneous adsorption for fig leaf extract in acidic medium. The agreement among these studies strengthens the possibility that adsorption is a fundamental mechanism underlying the corrosion protection provided by *Ficus* leaf extracts.

Table 1. Calculated Langmuir adsorption parameters for mild steel in 1 M HCl containing *Ficus sur* leaf extract. Fig. 5. Adsorption isotherm for *Ficus sur* on mild steel in 1 M HCl after 2 h exposure.

Table 1: Langmuir isotherm parameters for the for the adsorption of *Ficus sur on mild steel in* 1 M HCl

Temperature (K)	Time (hr)	R^2	Slope	Kads	ΔGads (kJ/mol)
303	2	0.8059	3.000	-8.333	-5.552
318	2	0.9296	2.150	1.072	-3.696
333	2	0.9907	1.413	4.181	-4.928

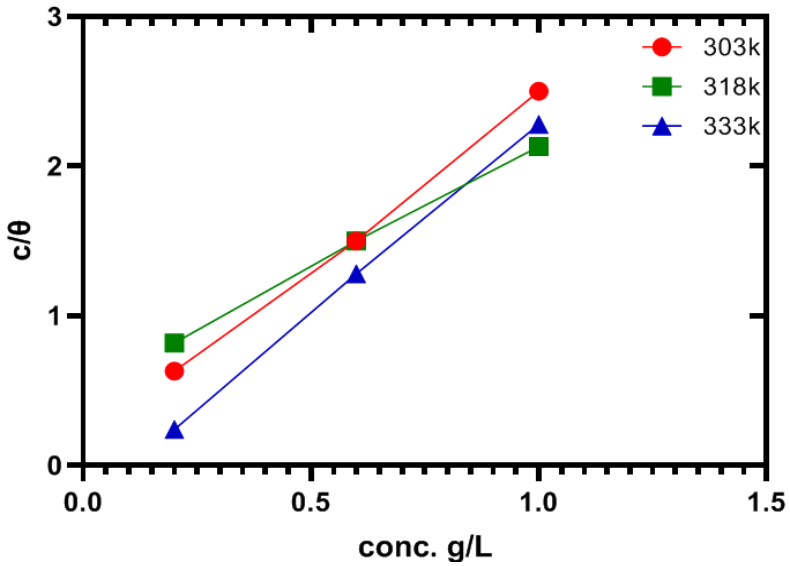

Fig. 5: Langmuir isotherm of in different concentrations of *Ficussur* in 1 M HCl in 2hrs

3.5.2 Activation Energy

The temperature dependence of the corrosion rate was evaluated using the Arrhenius relationship, and the corresponding plots are presented in Fig. 6. The calculated activation parameters are presented in Table 3. The slopes reported for the blank and inhibited systems decrease progressively from 3611 for the blank to 2757, 2511, and 1916 at 0.2, 0.6, and 1.0 g L^{-1} *Ficus sur*, respectively.

The decrease in slope with increasing inhibitor concentration indicates a substantial alteration of the apparent temperature dependence of the corrosion process in the presence of the extract. This behaviour is consistent with the formation of an adsorbed inhibitor layer that modifies the interfacial corrosion reactions.

However, the activation-energy values presented in Table 3 require mathematical

verification before publication. Using the Arrhenius relationship

$$\ln(CR) = lnA + \frac{-E_{aRT}}{2.303RT} \quad (12)$$

Thus, a positive slope of 3611 K would yield an Ea of approximately −30.0 kJ mol⁻¹, not −691.30 kJ mol⁻¹. Similar discrepancies occur for the other entries. Therefore, the activation-energy values currently reported in Table 3 should not be interpreted until the calculation, ogarithmic transformation, slope, and units have been checked.

More importantly, activation energy should not be interpreted as being negative simply because the corrosion process is exothermic. A negative activation energy and a negative enthalpy of activation are different quantities and have different physical meanings. If the intention is to demonstrate that adsorption is exothermic, the appropriate parameter is the enthalpy of adsorption or the temperature dependence of the adsorption equilibrium constant. Once the activation-energy calculations are corrected, comparison of the blank and inhibited systems can provide useful evidence regarding the effect of *Ficus sur* adsorption on the corrosion-energy barrier. This analysis should be presented together with the adsorption free energy and temperature-dependent inhibition efficiency rather than being used independently to assign physisorption or chemisorption.

3.5.2. Temkin Adsorption Isotherm

The Temkin adsorption parameters are presented in Table 4, and the corresponding plots are shown in Fig. 7. The Temkin model provides additional information about possible interactions among adsorbed inhibitor molecules and the energetic heterogeneity of the metal surface.

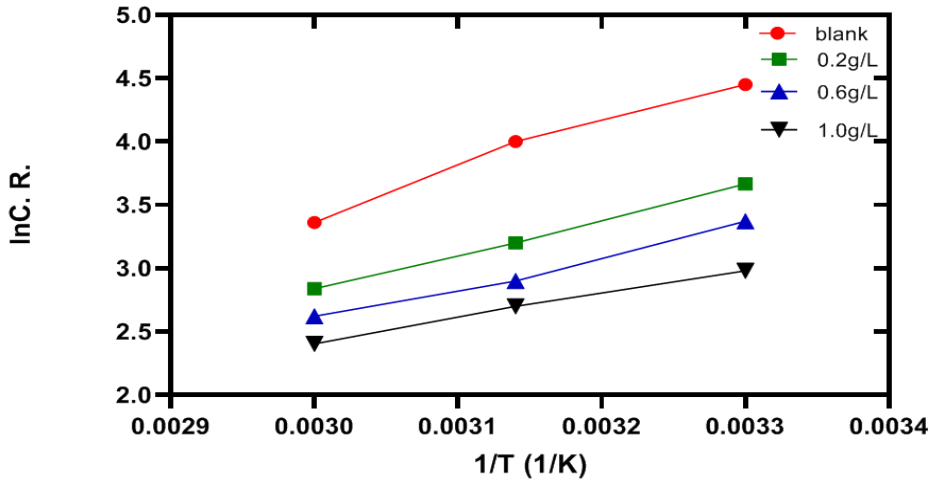

Fig. 6: Plot of lnC.R. versus 1/T for Mild steel corrosion in 1.0M HCl (Blank) and inhibited solutions at various concentrations of *Ficus sur* for 2hrs.

Table 3: Activation energy value of *Ficus sur* in 1M HCl for mild steel in 2 hours

Conc. (g/L)	Slope	Activation Energy KJ/mol
Blank	3611	-691.30
0.2	2757	-527.89
0.6	2511	-480.78
1.0	1916	-366.86

The Temkin analysis indicates that the adsorption process is associated with

interactions among adsorbed species. The reported positive interaction parameter suggests appreciable interaction between inhibitor molecules at the steel/electrolyte interface. Such interactions may influence the organization and stability of the protective adsorbed layer.

The Temkin results should be considered complementary to the Langmuir analysis rather than as evidence, by themselves, of chemisorption. The adsorption mechanism should instead be inferred from the combined behaviour of the adsorption equilibrium constants, ΔGads∘, temperature dependence, and electrochemical measurements.

The overall adsorption results suggest that *Ficus sur* forms a surface film whose protective properties increase with inhibitor concentration. This provides a mechanistic explanation for the decrease in corrosion rate and increase in inhibition efficiency observed in the gravimetric experiments.

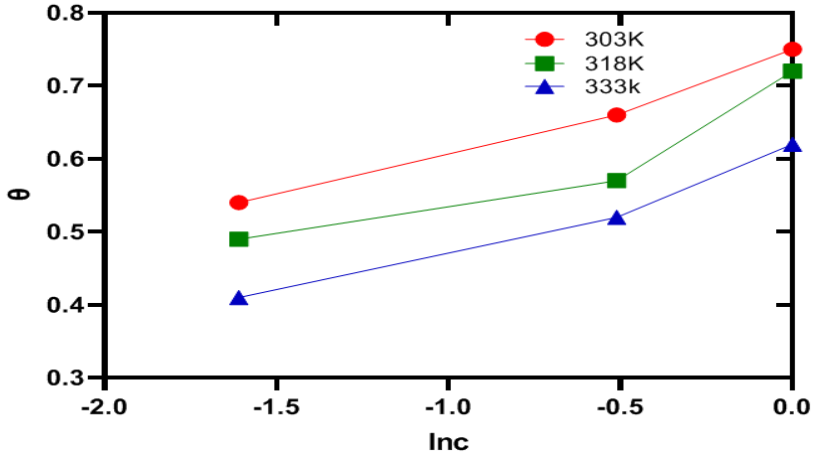

Fig. 7:Temkin isotherm for adsorption of *Ficus sur* on the surface of mild steel in 1M HCl at 2hrs.

Table 4: The Temkin parameters for *Ficus sur* on the surface of mild in 1M NaCl

T (K)	R^2	Slope	K_{ads}	ΔG_{ads} $(KJ/mol$
303	0.9843	0.1271	2.3×10^3	29.621
318	0.8612	0.1318	688.243	27.894
333	0.9678	0.1257	1.7×10^3	31.713

3.6. Open Circuit Potential (OCP) Analysis of Mild Steel in 1 M HCl Medium at different concentrations of Ficus sur

The variation of open-circuit potential with immersion time for mild steel in 1 M HCl in the absence and presence of *Ficus sur* extract is shown in Fig. 8. The blank electrode maintained a relatively negative potential throughout the measurement, indicating an active electrochemical state in the acidic medium. The addition of *Ficus sur* substantially altered the OCP response. At 0.60 g L^{-1}, the potential shifted to considerably more positive values during the initial period and gradually stabilized at a value substantially nobler than that of the blank. The 1.00 g L^{-1} system exhibited a smaller positive shift and eventually stabilized close to the blank potential. These differences demonstrate that the extract modifies the interfacial electrochemical condition of the mild-steel surface.

The positive shift in OCP in the 0.60 g L^{-1} system is consistent with the formation of an adsorbed protective layer that changes the relative kinetics of the anodic and cathodic processes. However, OCP displacement alone should not be used to classify the inhibitor as anodic, cathodic, or mixed type. Such classification is better established from potentiodynamic polarization data, particularly the changes in icorr, βa, and βc.

The relatively stable potentials observed toward the end of the 1800-s monitoring period indicate that the electrode/electrolyte systems approached quasi-steady interfacial conditions before subsequent electrochemical measurements. This supports the use of the stabilized OCP as the reference condition for EIS and polarization measurements.

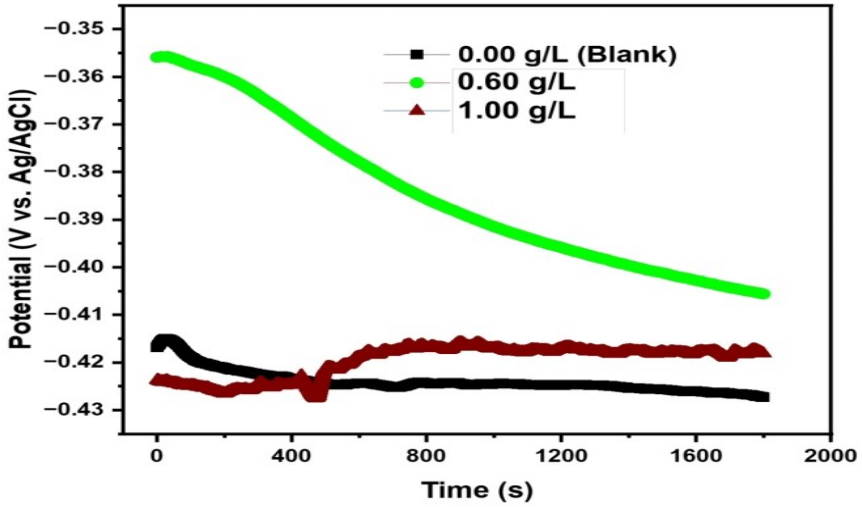

Fig. 8: Open circuit potential (OCP) analysis of mild steel for blank uninhibited system in comparison with the inhibited (*Fiscus sur* extract), tested in 1 M HCl corrosive environment at room temperature

3.7. Potentiodynamic Polarization (PDP) Analysis of Mild Steel in 1 M HCl Medium at different concentrations of Ficus sur

The potentiodynamic polarization curves for mild steel in 1 M HCl in the absence and presence of *Ficus sur* extract are presented in Fig. 9, while the corresponding electrochemical parameters are summarized in Table 5. The polarization curves show a pronounced decrease in both anodic and cathodic current densities following addition of the inhibitor.

The uninhibited mild steel exhibited a corrosion current density (icorr) of 1819 µA cm^{-2}, demonstrating the highly corrosive nature of 1 M HCl. Addition of *Ficus sur* dramatically reduced the corrosion current density to 23 µA cm^{-2} at 0.60 g L^{-1} and 25 µA cm^{-2} at 1.00 gL^{-1}. These reductions correspond to inhibition efficiencies of 98.7% and 98.6%, respectively.

The approximately 98.7% reduction in corrosion current density at 0.60 g L^{-1} is particularly significant because corrosion current density is directly related to the rate of electrochemical corrosion. Thus, the PDP results demonstrate that the extract does not merely alter the surface appearance but strongly suppresses the electrochemical reactions responsible for steel dissolution.

The corrosion potential also shifted from −410 mV for the blank to −399 and −398 mV at 0.60 and 1.00 gL^{-1}, respectively. These relatively small shifts of approximately 11–12 mV are insufficient to classify the extract as either predominantly anodic or cathodic based on Ecorr alone. Instead, the substantial suppression of both branches of the

polarization curve indicates that *Ficus sur* behaves as a mixed-type corrosion inhibitor.

The changes in the anodic and cathodic Tafel slopes provide further evidence of modification of both partial corrosion reactions. The anodic Tafel slope decreased from 89 mV dec^{-1} in the blank to 64 and 71 mV dec^{-1} at 0.60 and 1.00 g L^{-1}, respectively, while the cathodic slope changed from 120 mV dec^{-1} to 72 and 94 mVdec^{-1}. These changes demonstrate that adsorption of the extract modifies the kinetics of both metal dissolution and the cathodic reaction.

The optimum electrochemical performance was observed at 0.60 g L^{-1}, rather than at 1.00 gL^{-1}. This is an important observation because it indicates that increasing inhibitor concentration beyond the optimum does not necessarily produce greater protection. At 1.00 g L^{-1}, the inhibition efficiency remained very high at 98.6%, but was marginally lower than the 98.7% obtained at 0.60 gL^{-1}. This may reflect near-saturation of the surface, differences in the organization of the adsorbed film, or the presence of excess extract constituents in solution that do not contribute proportionally to surface protection.

The electrochemical results are consistent with the gravimetric observations but show substantially higher inhibition efficiencies. The maximum gravimetric efficiency was approximately 80%, whereas PDP gave 98.7%. Such differences can arise because gravimetric measurements integrate cumulative metal loss over a relatively long exposure period, whereas electrochemical measurements assess the instantaneous interfacial corrosion kinetics under controlled conditions.

The present PDP results compare favourably with previous studies. Anh *et al*. (2020) reported strong protection of carbon steel by *Ficus racemosa* extract, while Rahmouni *et al*. (2024) reported approximately 94% inhibition efficiency for fig leaf extract using electrochemical and gravimetric approaches. The higher electrochemical efficiency obtained here suggests that *Ficus sur* contains constituents capable of producing a particularly effective interfacial barrier under the present experimental

3.8 Electrochemical Impedance Spectroscopy Analysis

The Nyquist plots obtained from EIS measurements are presented in Fig. 10, while the corresponding impedance parameters are summarized in Table 6. A clear difference is observed between the uninhibited and inhibited systems. The blank solution produced a relatively small impedance response, whereas addition of *Ficus sur* resulted in a dramatic enlargement of the impedance response.

The charge-transfer resistance (Rct) provides an important measure of resistance to the electrochemical corrosion reaction. As shown in Table 6, Rct increased from only 450 Ω cm^2 for the blank to 35,000 Ω cm^2 at 0.60 gL^{-1} and 31,000 Ωcm^2 at 1.00 gL^{-1}. The approximately 78-fold increase in Rct at 0.60 gL^{-1} demonstrates a very substantial reduction in the rate of charge transfer across the steel/electrolyte interface.

The particularly high Rct value at 0.60 g L^{-1} corresponds closely with the maximum PDP inhibition efficiency. The slight decrease in Rct at 1.00 g L^{-1} is also consistent with the small reduction in PDP inhibition efficiency from 98.7% to 98.6%. Thus, the independent EIS and PDP techniques identify 0.60 g L^{-1} as the optimum electrochemical inhibitor concentration.

The polarization resistance (Rpo) also increased markedly, from 50 Ω cm^2 in the blank to 1500 Ω cm^2 at 0.60 g L^{-1} and 1000 Ω cm^2 at 1.00 g L^{-1}. The increase in both Rct and Rpo indicates that the inhibitor substantially increases the resistance of the metal/electrolyte interface to electrochemical reactions. The corresponding inhibition efficiencies obtained from EIS were 98.6% at 0.60 g L^{-1} and 98.4% at 1.00 g L^{-1}. These values are remarkably close to the PDP efficiencies of 98.7% and 98.6%, respectively.

The agreement between the two independent electrochemical techniques strongly supports the reliability of the observed inhibition effect. The Nyquist response therefore provides strong evidence for the formation of a protective adsorbed film. The inhibitor molecules appear to increase the difficulty with which charged species cross the interfacial region, thereby suppressing the charge-transfer processes responsible for corrosion.

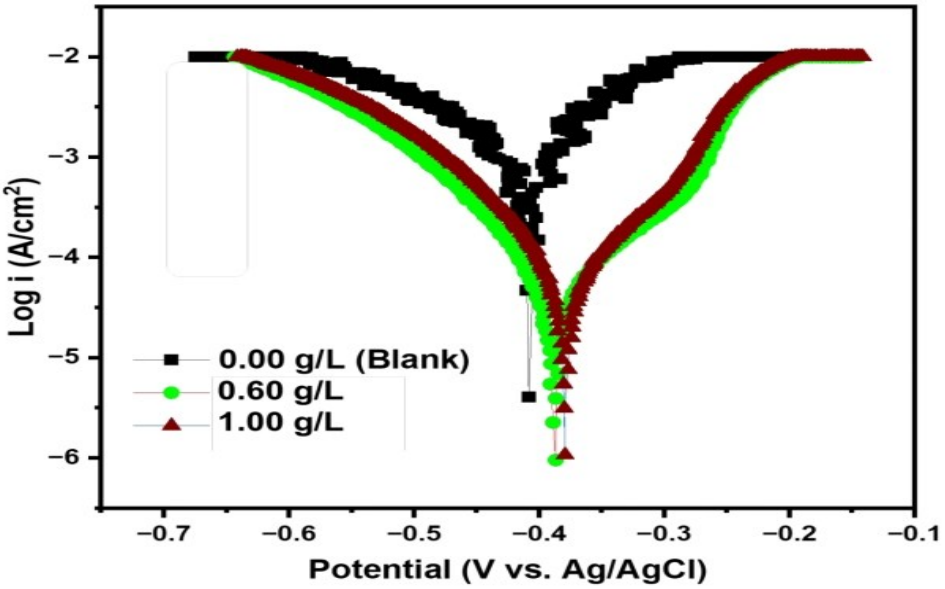

Fig. 9. Potentiodynamic polarization (PDP) analysis of mild steel for blank uninhibited system in comparison with the inhibited (fiscussur extract), tested in 1 M HCl corrosive environment at room temperature.

Table 5. Potentiodynamic polarization (PDP) parameters relating to mild steel for blank uninhibited system in comparison with the inhibited (*ficus sur* extract), tested in 1 M HCl corrosive environment at room temperature

System	Ecorr (mV/Ag/AgCl)	Icorr (μAcm⁻²)	βa (mVdec⁻¹)	βc (mVdec⁻¹)	θ	IE (%)
0.00 g/L (Blank)	-410	1819	89	120	-	-
0.60 g/L	-399	23	64	72	0.987	98.7
1.00 g/L	-398	25	71			

3.8.1 Bode Impedance and Phase-Angle Response

The Bode impedance-modulus and phase-angle plots are presented in Fig. 11(a–b). The impedance modulus increases substantially following addition of *Ficus sur* extract. The inhibited systems exhibit considerably higher impedance values over a broad frequency range compared with the blank, indicating increased resistance to interfacial charge transfer.

The phase-angle response also changes markedly in the presence of the inhibitor. The inhibited systems exhibit considerably higher phase angles than the blank over a wide intermediate-frequency range, with the maximum phase angle approaching approximately 80°. The increase in phase angle

indicates that the inhibited interface exhibits a stronger capacitive response and behaves more like a relatively compact and protective interfacial layer.

The blank system exhibits a considerably lower phase-angle response, consistent with a more active and less protected metal/electrolyte interface. The development of the higher phase-angle response after addition of *Ficus sur* suggests that the extract changes the electrical characteristics of the interface through adsorption and film formation.

The Bode plots therefore complement the Nyquist results. Whereas the Nyquist plot demonstrates a large increase in resistance, the Bode plots show that the inhibitor also changes the frequency-dependent interfacial response. Together, these results provide strong evidence that *Ficus sur* produces a protective surface film..

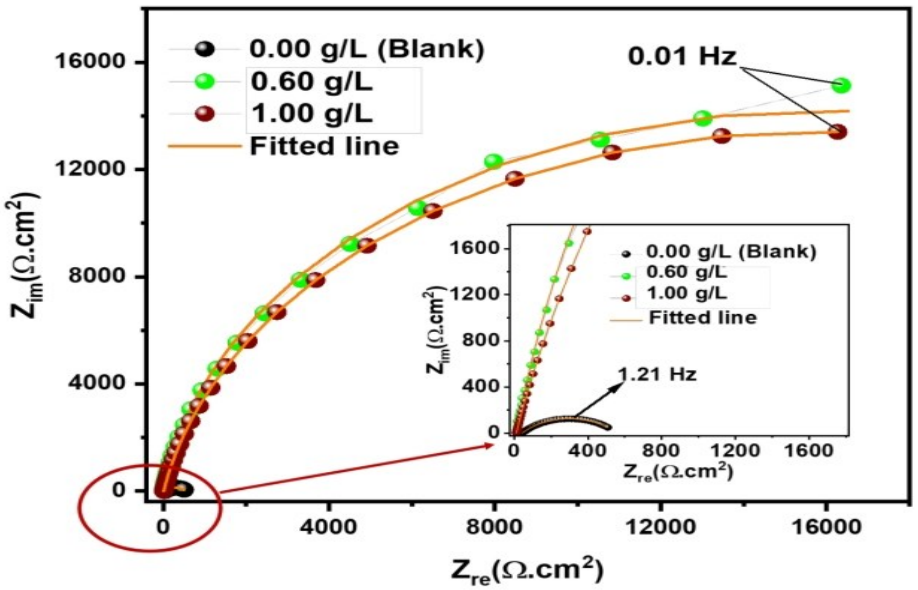

Fig. 10. Nyquist plots of mild steel in 1 M HCl in the absence and presence of *Ficus sur* leaf extract at room temperature.

Table 6. Electrochemical impedance parameters of mild steel in 1 M HCl in the absence and presence of *Ficus sur* extract

Parameter	0.00 g/L (Blank)	0.60 g/L	1.00 g/L
Rs ($\Omega \cdot cm^2$)	17.91	19.07	18.17
Rpo ($\Omega \cdot cm^2$)	50	1500	1000
$Q_1 \times 10^{-5}$ ($\mu\Omega^{-1} s^n cm^{-2}$)	87.9	52.2	68.7
n_1	0.89	0.99	0.98
R_{ct} ($\Omega \cdot cm^2$)	450	35000	31000
$Q_2 \times 10^{-5}$ ($\mu\Omega^{-1} s^n cm^{-2}$)	86.77	55.04	66.29
n_2	0.89	0.99	0.98
θ	-	0.986	0.984
IE (%)	-	98.6	98.4

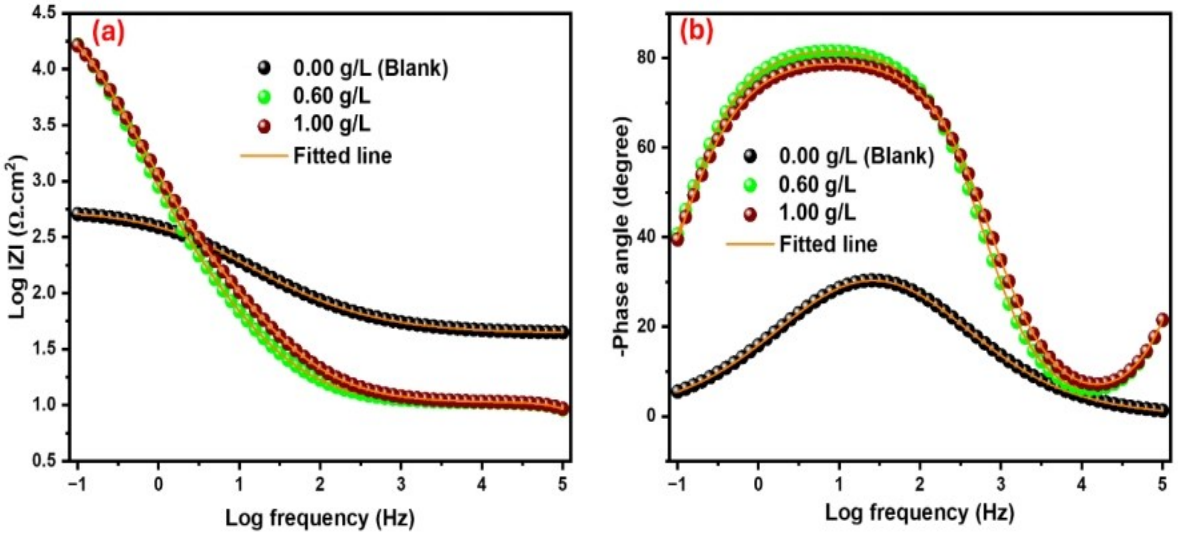

Fig. 11. Bode plots (a) modulus and (b) phase angle for electrochemical impedance spectroscopy (EIS) analysis of mild steel for blank uninhibited system in comparison with the inhibited (*Ficus sur* extract), tested in 1 M HCl corrosive environment at room

3.8.2 Constant Phase Element and Interfacial Heterogeneity

The constant phase element (CPE) parameters presented in Table 6 provide additional information about the condition of the steel/electrolyte interface. The n values increase from approximately 0.89 for the blank to 0.99 at 0.60 g L^{-1} and 0.98 at 1.00 g L^{-1}. Because an ideal capacitor has n=1, the movement of the n values toward unity indicates that the inhibited surface exhibits a more nearly ideal capacitive response than the uninhibited surface.

The increase in n suggests a reduction in interfacial heterogeneity and may be associated with the formation of a more uniform adsorbed layer. The inhibitor therefore appears to transform the initially heterogeneous and highly active steel surface into an interface with more uniform electrochemical characteristics.

The CPE parameters should nevertheless be interpreted together with the equivalent-circuit model rather than independently. The observed increase in Rct, Rpo, and n, together with the increased phase angle, provides mutually consistent evidence of improved surface protection.

3.8.3 Equivalent-Circuit Analysis

The equivalent circuit used to fit the experimental EIS data is presented in Fig. 12. The circuit incorporates solution resistance (Rs), polarization resistance (Rpo), charge-transfer resistance (Rct), and constant phase elements representing non-ideal capacitive behaviour of the electrochemical interface.

The close agreement between the experimental and fitted impedance responses demonstrates that the proposed circuit adequately describes the electrochemical behaviour of the systems. The presence of more than one interfacial time constant suggests that the electrochemical response is not controlled solely by the metal/electrolyte double layer. Instead, the response can reasonably be associated with both the charge-transfer/double-layer processes and the protective inhibitor film.

The appearance of the additional interfacial contribution in the inhibited systems is particularly important because it supports the proposed adsorption mechanism. Following addition of *Ficus sur*, the adsorbed phytochemical layer introduces an additional barrier through which electrochemical species must pass. Consequently, charge transfer

becomes more difficult, R_{ct} increases substantially, and the corrosion rate decreases. The EIS findings therefore provide strong mechanistic support for the gravimetric and PDP results. The gravimetric measurements demonstrate reduced metal loss, PDP demonstrates suppression of both anodic and cathodic reactions, while EIS demonstrates a large increase in interfacial resistance and development of a more capacitive surface. The convergence of these three independent approaches strongly indicates that adsorption and protective-film formation are central to the corrosion-inhibition mechanism of *Ficus sur*.

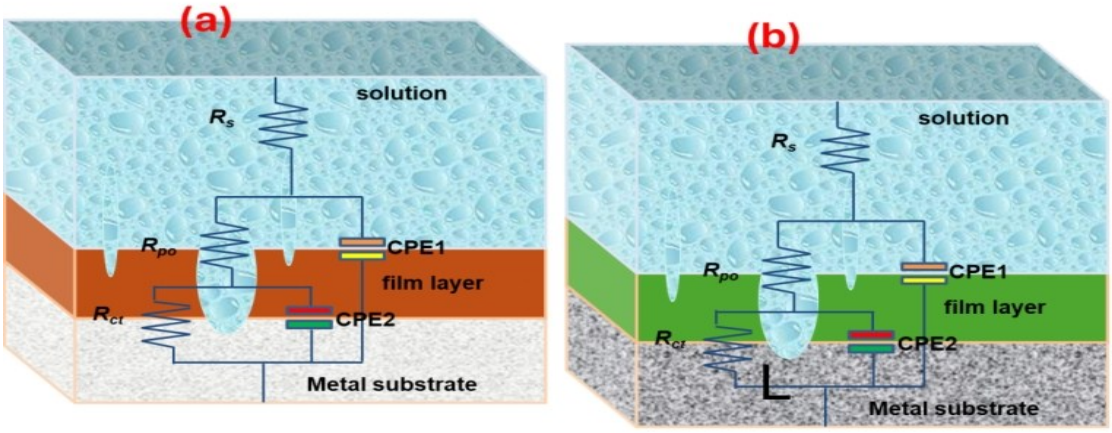

Fig. 12: Electrochemical equivalenet circuit fit for blank uninhibited in comparison with the different concentrations of the inhibited tested at room temperature

3.9 Integrated Mechanism of Corrosion Inhibition

The results obtained from the gravimetric, adsorption, OCP, PDP, and EIS investigations collectively indicate that *Ficus sur* leaf extract protects mild steel in 1 M HCl primarily through adsorption of its phytochemical constituents onto the metal surface.

The proposed mechanism can be summarized as follows. In the uninhibited solution, mild steel undergoes anodic dissolution accompanied by cathodic reactions in the acidic electrolyte. Addition of *Ficus sur* introduces organic molecules containing functional groups and electron-rich centres capable of interacting with the metal surface. These molecules compete with corrosive species for active surface sites and progressively cover the steel surface.

The increasing surface coverage with inhibitor concentration, shown by the adsorption analysis, is consistent with this interpretation. The consequent reduction in corrosion rate and mass loss demonstrates that the adsorbed molecules reduce the number of electrochemically active sites. The strongly increased Rct and Rpo values obtained from EIS indicate that the adsorbed layer also increases resistance to interfacial charge transfer.

The PDP results further demonstrate that both anodic and cathodic reactions are suppressed. The relatively small displacement of Ecorr, together with significant changes in both Tafel branches, supports classification of *Ficus sur* as a mixed-type inhibitor under the investigated conditions. The close agreement between PDP and EIS efficiencies—98.7% and 98.6% from PDP and 98.6% and 98.4% from EIS at 0.60 and 1.00 gL^{-1}, respectively—provides particularly strong evidence for the effectiveness of the extract.

The optimum electrochemical performance at 0.60 gL^{-1} is also noteworthy. Increasing the concentration to 1.00 g L^{-1} did not improve the inhibition efficiency and, in fact, resulted in a

slight decrease in both Rct and inhibition efficiency. This indicates that the surface had probably approached an optimum coverage at 0.60 g L^{-1} and that additional extract did not provide proportional improvement.

Overall, the findings are consistent with previous reports on plant-derived corrosion inhibitors and particularly with studies of *Ficus* species. Ogwo *et al*. (2017) reported strong inhibition of mild steel by *Ficus sycomorus* in 1 M HCl, while Anh *et al*. (2020) demonstrated significant protection of steel by *Ficus racemosa* extract. Rahmouni *et al*. (2024) similarly showed that fig leaf extract could provide high inhibition efficiency through adsorption and formation of a protective surface layer. The present study therefore provides further evidence that *Ficus* leaf extracts represent promising environmentally compatible corrosion inhibitors for acidic environments.

4.0 Conclusion

This study demonstrates that *Ficus sur* leaf extract serves as a highly effective, eco-friendly green corrosion inhibitor for mild steel in 1 M HCl environments. Gravimetric experiments confirm that the extract significantly reduces mild steel mass loss and corrosion rates, achieving a maximum gravimetric inhibition efficiency of approximately 80% at 303 K as concentration increases. Electrochemical measurements reveal exceptional protection at room temperature, where an optimum extract concentration of 0.60 g/L yields maximum inhibition efficiencies of 98.7% via potentiodynamic polarization and 98.6% via electrochemical impedance spectroscopy. This performance is marked by a dramatic drop in corrosion current density from 1819 μA cm^{-2} to 23 μA cm^{-2} and a corresponding 78-fold increase in charge-transfer resistance from 450 Ω·cm^2 to 35,000 Ω·cm^2.

Mechanistically, the minimal shifts in corrosion potential alongside the simultaneous suppression of both anodic metal dissolution and cathodic hydrogen evolution classify *Ficus sur* as a mixed-type inhibitor. Impedance, phase angle, and constant phase element analyses further confirm that the adsorbed phytochemical constituents form a compact, uniform protective interfacial film that significantly reduces surface heterogeneity. Furthermore, the degree of surface coverage fits the Langmuir adsorption isotherm model, indicating monolayer adsorption onto active metal sites, while the negative Gibbs free energy of adsorption values establish that this protective process is thermodynamically spontaneous. Ultimately, *Ficus sur* leaf extract presents a viable, highly efficient, and sustainable alternative to hazardous synthetic inhibitors for acid-corrosion mitigation.

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Declarations

Consent for Publication

Not applicable.

Availability of Data

The data used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests and no conflict of interest regarding the publication of this manuscript.

Ethical Consideration

Not applicable.

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Authors' Contributions

AEE: conceptualization, methodology, investigation, data analysis, and manuscript preparation. LAN: supervision, methodology, electrochemical analysis, and critical review. CIO: experimental investigation, data interpretation, and manuscript review. IEK validation, and critical revision. All authors reviewed and approved the final manuscript and accepted responsibility for the integrity of the work.