



ORIGINAL RESEARCH ARTICLE

INVESTIGATION OF PLANTAIN EXTRACT FOR ENHANCING COPPER DURABILITY IN ACID-BASED CORROSIVE ENVIRONMENTS

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ARTICLE INFORMATION

Received: 29th April 2025

Revised: 4th May 2025

Accepted: 4th May 2025

Keywords:

Copper

Corrosion

Inhibition

Optimization

Plantain peduncle extract

ABSTRACT

This study investigates the application of plantain peduncle extract (PPE) as a green corrosion inhibitor of copper in 1 M hydrochloric acid (HCl) using electrochemical, adsorption, and surface analysis techniques. Ethanol-extracted PPE was tested at concentrations of 0.1–0.3 mL and temperatures of 30–50°C. Electrochemical tests, such as potentiodynamic polarization and open circuit potential (OCP) measurement, proved PPE to inhibit corrosion current density (j_{corr}) by a maximum of 88% and anodically shift corrosion potential (E_{corr}), with the maximum inhibition efficiency of 89.5% occurring at 0.3 mL PPE and 40°C. Similarly, adsorption experiments confirmed that Freundlich isotherm ($R^2 = 0.906$ at 40°C) best described the process, indicating heterogeneous multilayer physisorption, also confirmed by Gibbs free energy values ($\Delta G_{ads} = -16.58$ to -19.78 kJ/mol). In addition, optical micrographs confirmed these findings, with minimal pitting and smooth surfaces in ideal conditions (0.3 mL PPE, 40°C), compared to extensive corrosion in uninhibited samples. Statistical comparison using Analysis of Variance, (ANOVA) revealed the significant influence of concentration ($p < 0.0001$) and temperature ($p = 0.0048$), with their interaction ($p = 0.0213$) showing the necessity of balanced operating parameters. While PPE functioned well under middle temperatures, efficiency reduced at 50°C (IE% = 80.2%), reflecting thermal limitations.

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1.0 Introduction

Corrosion is the natural degradation of materials in various situations, which is undesirable. Scientifically, it is described as the simultaneous exchange of mass and charge at the material-solution interface (Frankel, 2014). In other words, it is the attack on metal through biological or electrochemical interactions with its surrounding environment. Corrosion is among the processes with which man has had to cope ever since engineering materials have been extensively utilised (Bilgiç, 2023; Farag et al., 2022; McCafferty, 2010). Preventing engineering materials from corroding is a significant challenge in the industrial sector (Savita et al., 2016). The effects of corrosion have evolved into a persistent and major issue on a global scale (Roberge & Eng, 2005).

Copper and its alloys are widely utilized in industrial applications owing to their superior mechanical properties, necessitating a focus on their corrosion behaviour (Tan et al., 2023). While copper resists atmospheric and chemical degradation through a naturally forming protective oxide layer, it becomes highly prone to corrosion in acidic, chloride-rich environments, such as during acid cleaning treatments (Zhang et al., 2018). To address this vulnerability, corrosion inhibitors—chemical additives that minimize metal degradation—are critical (Tamalmani & Husin, 2020; Olajire, 2017). These inhibitors fall into two categories: inorganic (e.g., chromates) and organic (e.g., plant extracts), each tailored to specific corrosive conditions (Wu et al., 2024).

However, the traditional corrosion inhibitors currently employed are susceptible to environmental pollution as a result of high toxicity (Qiang *et al.*, 2018). With the evolution of green chemistry and growing concern for environmental health, the development and investigation of eco-friendly and efficient corrosion inhibitors have become a crucial focus in recent times (Asadi *et al.*, 2019). Corrosion inhibitors need to be cost-effective and safe, making plant extracts an environmentally friendly, readily available, and renewable option. These represent a rich source of ingredients, having a high inhibition efficiency (Raja *et al.*, 2008). Extensive research has been conducted to identify green corrosion inhibitors that are more cost-effective than the toxic inhibitors traditionally used (Zdravković *et al.*, 2023; Kehinde *et al.*, 2025). A study by Wu *et al.*, (2024) investigating *Ipomoea Batatas* Leaf Extract as a biodegradable corrosion inhibitor for copper in 0.5M H₂SO₄ solution concluded that the electrochemical tests revealed a remarkable inhibition efficiency of 96.7% with an 800 mg/L concentration of IBLE. Despite an increase in temperature, IBLE continued to exhibit high anti-corrosion performance with an efficiency of over 95% at a temperature of 315 K (Wu *et al.*, 2024). Another study by Dahmani *et al.*, (2023) reveals that an electrochemical impedance spectroscopy evaluation shows that the inhibitor efficiency increases with increased inhibitor concentrations and reaches 94% efficiency with the use of 2 g/L of *Cupressus sempervirens* (EO), supported by potentiodynamic polarization studies.

Plantain extract has been studied by Es'hagi *et al.*, (2018) as an eco-friendly corrosion inhibitor on mild steel in 1M HCl solution, confirming its potential as an eco-friendly corrosion inhibitor. Similarly, Essang (2022) investigated plantain peduncle extract as a corrosion inhibitor for mild carbon steel and reported reduced weight loss and corrosion rates across inhibited samples. The highest inhibition efficiency was observed at a 3.0% v/v concentration, followed by 2.0% v/v. However, no prior studies have specifically examined plantain extract as a corrosion inhibitor for copper. To address this gap, the objective of this research is to evaluate the inhibitory properties of plantain extract on copper in a 1 M HCl medium

2. Materials and Method

2.1 Preparation of Materials

The test copper samples were machined using a manual lathe machine (Jet GHB-1340A) to achieve the desired (4×2×0.3) cm dimension. The dimensioned samples were mechanically polished using emery paper, washed with ethanol before being dried. A 1 M hydrochloric acid (HCl) solution was prepared in the laboratory by diluting concentrated HCl (37% w/w, analytical grade) with deionized water, using a calibrated volumetric flask to ensure precise molarity. Fresh plantain peduncles were obtained from local markets in Ogun State, Nigeria, as agricultural waste in order to make the inhibitor. To guarantee uniform drying and effective extraction of bioactive components, the peduncles were manually cut into 1-2 cm segments using a sterile stainless-steel blade after being properly cleaned with distilled water to eliminate surface contaminants. They were then further sliced into 0.3-0.5 cm thick cross-sections.

To prepare the inhibitor, the plantain peduncle was obtained from the waste, washed thoroughly with distilled water and then cut reduced to. They were then placed in an oven at 60°C to dry for 10 hours and ground into fine powder using a blender. A mixture of a 70% ethanol-water solution and the dried plantain powder is combined in a ratio of 1:10 (w/v). To ensure homogeneity, the mixture was mechanically stirred for 30 minutes at 300 rpm using a magnetic stirrer. This was followed by a 24-hour equilibration phase at room temperature to promote the diffusion of phytochemicals. It was then filtered with a filter paper. The resulting extract of plantain peduncle was placed in an evaporator to concentrate the extract. Table 1a shows the compositional properties of the copper coupons, which were dimensioned to (4×2×0.3cm). Table 1b show the present phytochemicals in the plantain extract. Similar methodology was carried out by Oyewole *et al.*, (2025).

Table 1a: Chemical Composition of Copper Sample

Element	M (mass%) × 10 ⁻³
Si	7
P	16.5
Ti	0.4
V	0.3
Mn	2.65
Sb	0.6
Co	0.15
Ni	2.8
Nb	1.6
Mo	1.1
Sn	2.7
Cu	Bal.

Table 1b: Phytochemicals present in the plantain extract

Phytochemical	Plantain Extract
Alkaloid	+
Flavonoid	-
Saponin	-
Phenol	-
Terpenoid	+
Phlobatannin	-
Steroid	+

+ rep. present – rep. absent

2.2 Experimental Procedures

The electrode employed as the working electrode for the electrochemical experiments is the already polished and dimensioned copper samples. The tests were carried out in batches of 50ml 1M HCl solutions at a temperature of 30°C (303K). The plantain peduncle extract (PPE) was added to the acidic corrosion medium in different volumes of 0.1ml, 0.2ml, 0.3ml, and the control solution with 0ml. Table 2 shows the experimental setup of the samples

Table 2: Experimental Arrangement

Experimental Arrangement	Test environment
Control (0.0 ml PPE)	50ml HCl
0.1ml PPE	0.1ml PPE + 50ml HCl
0.2ml PPE	0.2ml PPE + 50ml HCl
0.3ml PPE	0.3ml PPE + 50ml HCl

2.3 Electrochemical Test Set-Up

The tests were carried out in line with ASTM G5-14 and ASTM G59-97 standards using a three-electrode setup within a study cell, comprising a copper working electrode, a graphite counter electrode, and a reference electrode filled with KCl. The Autolab PGSTAT 101 Metrohm potentiostat (plate 1) was used for potentiodynamic linear polarization tests on the copper samples. The scanning speed used in this study was 0.01 mV/s in the sinusoidal voltage range of 1.5 V to +1.5 V. In all the experimental conditions, the stability of the free potential was ensured. Corrosion parameters such as corrosion potential (E_{corr}), the corrosion current density (j_{corr}), inhibition efficiency (IE%), and the surface coverage were determined from Tafel plots in addition to the use of Equations 1 and 2. Further, adsorption behavior of the inhibitor was studied based on some models that included Langmuir, Freundlich, and Temkin isotherms.

$$\text{Surface Coverage } (\theta) = \frac{j_{corr}^0 - j_{corr}}{j_{corr}^0} \quad 1$$

$$\% \text{ IE} = \frac{j_{corr}^0 - j_{corr}}{j_{corr}^0} \times 100 \quad 2$$

Where j_{corr}^0 and j_{corr} are the corrosion current densities with and without the inhibitor, respectively.

2.4 Surface Characterisation

The copper (4×2×0.3cm) was dipped in 50ml HCl acid solution at varying temperatures of 30°C, 40°C, and 50°C, both without the PPE (control) and at the different volumes of 0.1ml, 0.2ml, and 0.3ml, and polarisation was applied. Metallurgical microscopy (Olympus BX53M) was deployed to study the surface morphology of the inhibited copper samples.

2.5 Statistical Analysis

Statistical analysis was conducted using Design Expert Software 13. Mathematical regression models and Response Surface Methodology (RSM) were used to evaluate and predict the performance of the inhibitor. Analysis of variance (ANOVA) also assessed the significance of the input experimental variables on the response properties, providing critical insights for optimizing the process.



Plate 1: Electrochemical setup

3. Results and Discussion

3.1 Response of Uninhibited and Inhibited Test Samples to Corrosion

The Tafel polarisation and open circuit potential (OCP) measurements were used to assess the electrochemical behaviour of copper in 1 M HCl, both uninhibited and inhibited with plantain peduncle extract (PPE). Table 3 shows some important patterns in corrosion metrics at different inhibitor concentrations (0–0.3 mL) and temperatures (30–50°C). With a corrosion potential (E_{corr}) of -0.625 V, a corrosion current density (J_{corr}) of 1.94×10^{-4} A/cm², and a corrosion rate (CR) of 2.27 mm/year, the control sample showed aggressive corrosion at 30°C. Significant anodic inhibition was indicated by E_{corr} shifting favourably to -0.091 V (0.3 mL), J_{corr} decreasing to 1.06×10^{-4} A/cm², and CR decreasing by about 45% as the PPE concentration increased (Aslam et al., 2022). As a result of impeded charge transfer reactions, polarisation resistance (PR) also increased from 134 Ω (control) to 246 Ω (0.3 mL).

Table 3: Inhibited samples Tafel data

30°C				
Samples	E_{corr} (V)	J_{corr} (A/Cm ²)	CR (mm/yr)	PR (Ω)
Control	-0.625	1.94E-04	2.27	1.34E+02
0.1ml	-0.318	1.81E-04	2.12	1.44E+02
0.2ml	-0.175	1.08E-04	1.26	2.41E+02
0.3ml	-0.091	1.06E-04	1.24	2.46E+02
40°C				
Control	-0.364	4.55E-04	5.34	5.71E+01
0.1ml	-0.292	3.02E-04	3.08	9.91E+01
0.2ml	-0.152	8.26E-05	0.97	3.15E+02
0.3ml	-0.135	5.60E-05	0.75	4.64E+02
50°C				
Control	-0.341	5.13E-04	6.02	5.07E+01
0.1ml	-0.247	3.598E-04	3.61	8.45E+01
0.2ml	-0.127	2.62E-04	2.95	1.03E+02
0.3ml	-0.083	9.76E-05	1.15	2.66E+02

Figure 1 illustrates the open circuit potential (OCP) of copper in 1 M HCl at 30°C for various concentrations of PPE (0–0.3 mL). The control sample (0 mL PPE) records a highly negative potential (-0.625 V), an indicator of active corrosion. With rising inhibitor concentration, the OCP shifts more and more towards positive directions (e.g., -0.091 V at 0.3 mL), an indicator of surface stabilization by adsorption of the inhibitor. Stabilization is quicker at high concentration, suggesting rapid development of a protective film. For 40°C, the OCP plot (Figure 2) shows maximum value of positive shift potential (-0.364 V for control to -0.135 V for 0.3 mL PPE), demonstrating maximum inhibition efficiency (89.5%). The plateau potentials at the higher concentrations indicate good adsorption, likely due to greater molecular interaction between the copper

surface and PPE at this intermediate temperature. The OCP curve at 50°C (Figure 3) indicates less positive shift (-0.341 V for control to -0.083 V at 0.3 mL PPE), suggesting decreased inhibitor efficiency. Thermal agitation likely ruins the adsorbed film of the inhibitor and leads to partial desorption and weaker surface protection (Shwetha et al., 2024).

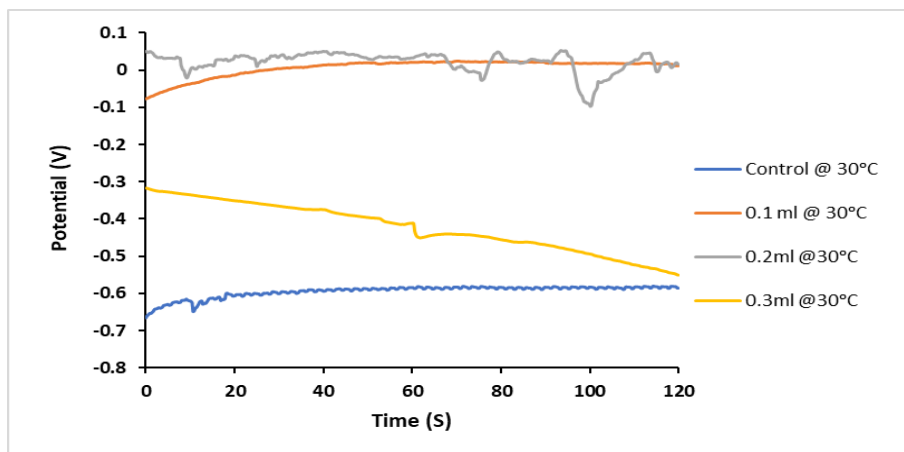


Figure 1: OCP Plot at 30°C

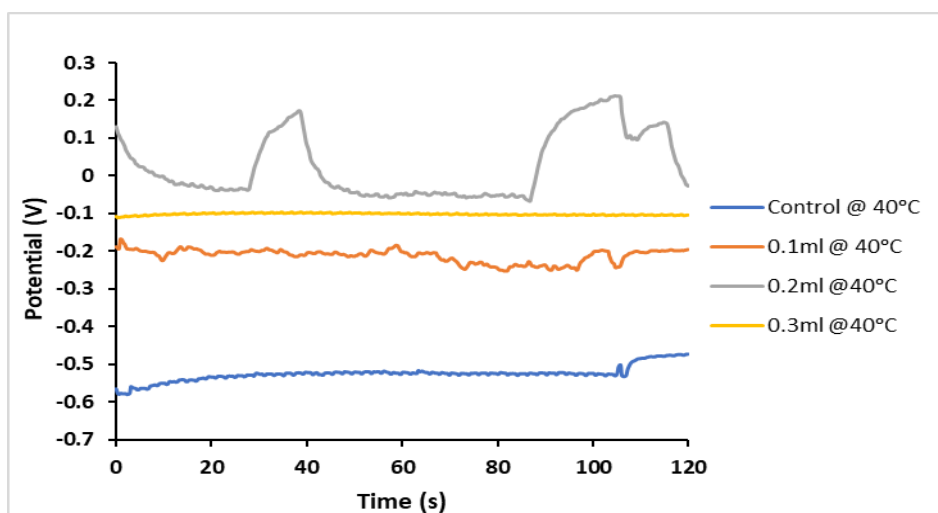


Figure 2: OCP Plot at 40°C

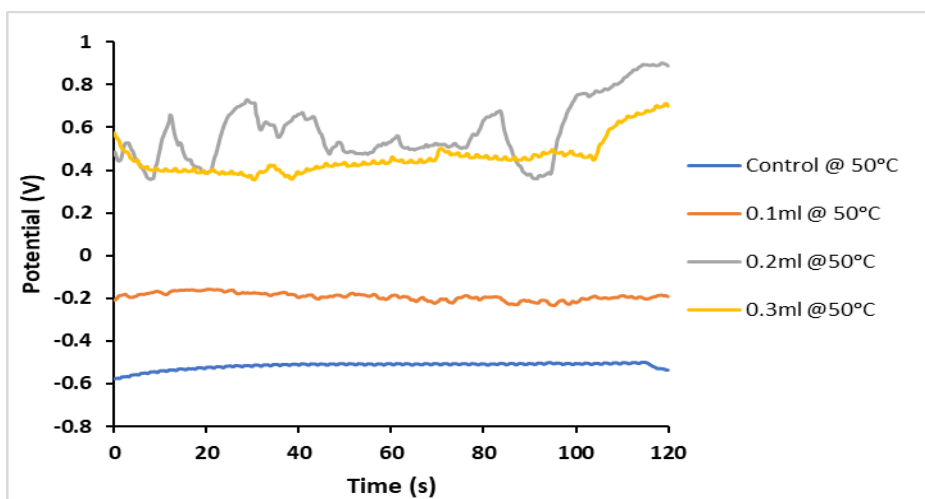


Figure 3: OCP Plot at 50°C

The linear sweep voltammetry (LSV) scans at 30°C yield suppressed anodic currents with improved PPE concentrations, Figure 4. The control sample yields a steep anodic slope, indicating quick metal dissolution. With 0.3 mL PPE, the anodic current density falls quickly, displaying considerable suppression of copper oxidation. At 40°C (Figure 5), the LSV plot yields the greatest suppression of anodic and cathodic currents.

The curves become flatter at 0.3 mL PPE, which indicates mixed-type inhibition. Decrease in cathodic current shows that hydrogen evolution is also inhibited by PPE, and the nearly horizontal anodic segment shows good blocking of metal dissolution. LSV plot at 50°C (Figure 6) shows partial recovery of anodic and cathodic currents even at 0.3 mL PPE, indicating thermal degradation of the inhibitor film. The anodic slope remains more sloping than at 40°C, and the cathodic currents are less repressed, showing disordered adsorption.

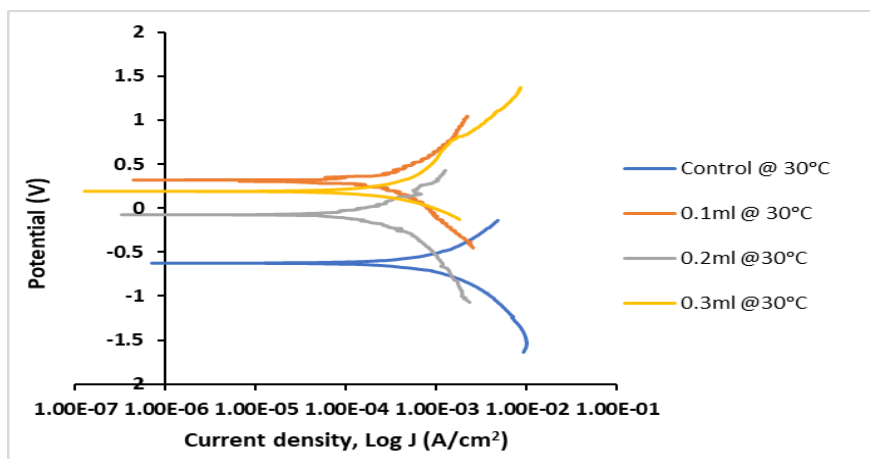


Figure 4: LSV plot at 30°C

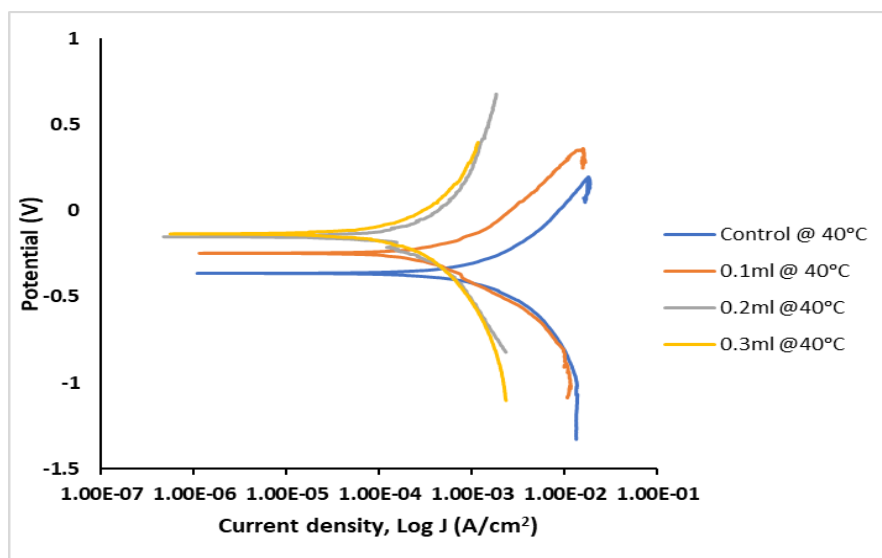


Figure 5: LSV plot at 40°C

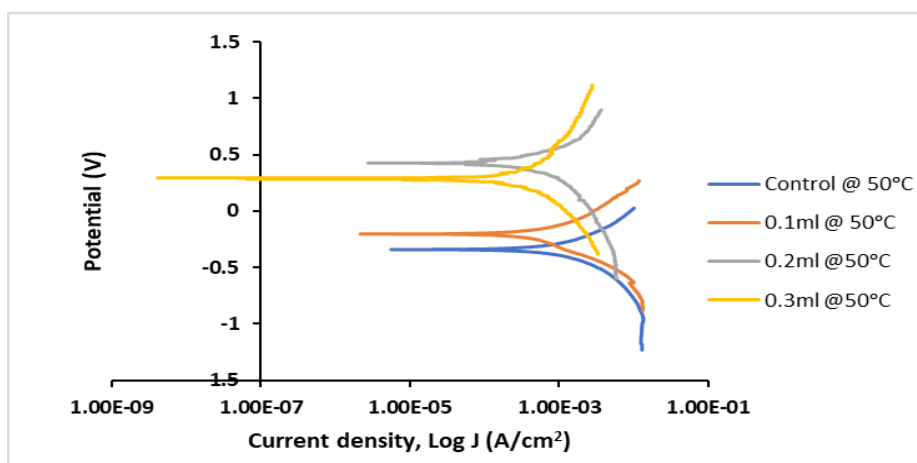


Figure 6: LSV plot at 50°C

3.2 Plantain Peduncle Extract Inhibitory Efficiency

The efficacy of the plantain peduncle extract on copper in a 1M HCl acidic solution can be further examined from the plot of Inhibitory Efficiency (IE) % against inhibitor concentration (ml) in figure 7. It can be observed that an increase in the concentration of the inhibitor generally increases inhibitor efficiency, with the trend strongest at 50°C. At 40°C and 50°C, the increase in inhibitor concentration from 0.2ml to 0.3ml shows only slight increase in inhibitor efficiency, suggesting that after corrosion inhibition with 0.2ml at 40°C, plantain peduncle inhibition becomes negligible. However, corrosion inhibition was most effective across 40°C, suggesting it to be the optimal temperature for the inhibition process. Rahal *et al.* (2016) examined olive leaf extract (OLE) as a corrosion inhibitor for copper in 0.5 M NaCl, and their results are consistent with the inhibitory efficiency trend seen in this work. Both investigations show concentration-dependent IE%; Rahal *et al.* used 2.42 mM OLE to achieve ~90% efficiency at 24 hours. Similarly, at 40°C and 0.3 mL, plantain peduncle extract (PPE) in this study achieved 89.5% IE. However, PPE showed decreased efficacy at 50°C (IE% = 80.2%), most likely as a result of thermal desorption of physisorbed chemicals, whereas Rahal *et al.* found sustained IE% at greater temperatures (up to 328 K). In contrast, OLE's cathodic inhibitory mechanism preserved a high IE% because of oleuropein's strong adsorption.

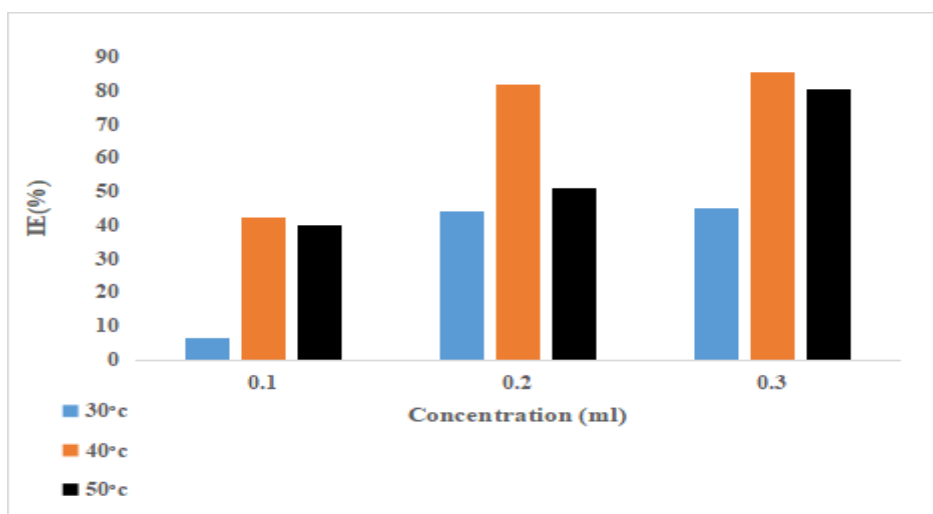


Figure 7: Inhibitor efficiency of Plantain peduncle.

3.3 Adsorption Response of Copper Samples

The adsorption behaviour of plantain peduncle extract (PPE) on copper surfaces in 1 M HCl was studied using Langmuir, Freundlich, and Temkin isotherm models to describe the inhibition process. Freundlich isotherm (Table 4) had the best correlation at 40°C ($R^2 = 0.906$), indicating heterogeneous adsorption with multilayer formation (Al-Ghouthi & Da'ana, 2020). This shows that PPE molecules adsorb on copper through multiple surface sites of varying affinities due to the complex phytochemical nature of the extract (Foo & Hameed, 2010). In contrast, the Langmuir model ($R^2 = 0.572$ – 0.804) poorly described the data, dismissing the hypothesis of monolayer adsorption over homogeneous surfaces (Stefaniu *et al.*, 2014).

Table 4: Adsorption Parameters from the Langmuir and Freundlich Isotherm.

Temperature (°C)	$K_{ads} (mol^{-1})$	R^2
Langmuir Adsorption Isotherm		
30	0.579093767	0.572488467
40	6.10392394	0.803656758
50	4.617737838	0.621181637
Freundlich Adsorption Isotherm		
30	5.668432644	0.87279269
40	2.121607455	0.906101717
50	1.549941388	0.896110591

Temkin isotherm ($R^2 = 0.840$ – 0.919 for 40–50°C) also highlighted adsorbate-adsorbate interaction role as its linearity implied reducing adsorption energy with coverage due to repulsive forces (Table 5) (Johnson & Arnold, 1995; Ayawei *et al.*, 2017). Thermodynamic study revealed Gibbs free energy (ΔG_{ads}) ranges of -16.58 to -19.78 kJ/mol, which is characteristic of spontaneous physisorption driven by weak van der Waals forces rather than chemisorption (Rouquerol *et al.*, 2013). Temperature dependence of the rise in adsorption equilibrium constants (K_{ads}) at 40°C (29.66 mol⁻¹) and 50°C (28.44 mol⁻¹) also revealed stronger inhibitor-
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surface interaction with rising temperature, though thermal agitation at 50°C might have reduced adsorption stability (Ituen *et al.*, 2017).

Table 5: Adsorption Parameters from the Temkin isotherm.

Temp. (°C)	$K_{ads}(\text{mol}^{-1})$	$\Delta G_{ads} \text{ (KJmol}^{-1}\text{)}$	R^2	$\ln(K_{ads})$	$1/T$	$\Delta G_{ads}/T$	B= Slope
30	13.0113	-16.5845	0.8801	2.5658	0.0033	-0.0547	0.3737
40	29.6603	-19.2765	0.9194	3.3898	0.0032	-0.0616	0.4158
50	28.4378	-19.7793	0.8400	3.3477	0.0031	-0.0612	0.3489

The transition from Temkin-controlled adsorption at 30°C to Freundlich-controlled behavior at higher temperatures is in line with enhanced molecular mobility and multilayer development at intermediate temperatures (40°C), at which PPE exhibited highest inhibition efficiency (89.5%). This temperature sensitivity indicates the balance between adsorption intensity and thermal degradation of the protective film similar to the study by Atiba & Fayomi, (2024). Figure 8 plots surface coverage (θ) against the natural logarithm of inhibitor concentration ($\ln C$) to analyze adsorption behavior. At 30°C, the lower slope suggests weaker adsorption, aligning with Temkin's model (Ayawei *et al.*, 2017; Kehinde *et al.*, 2025), which accounts for repulsive interactions at low coverage.

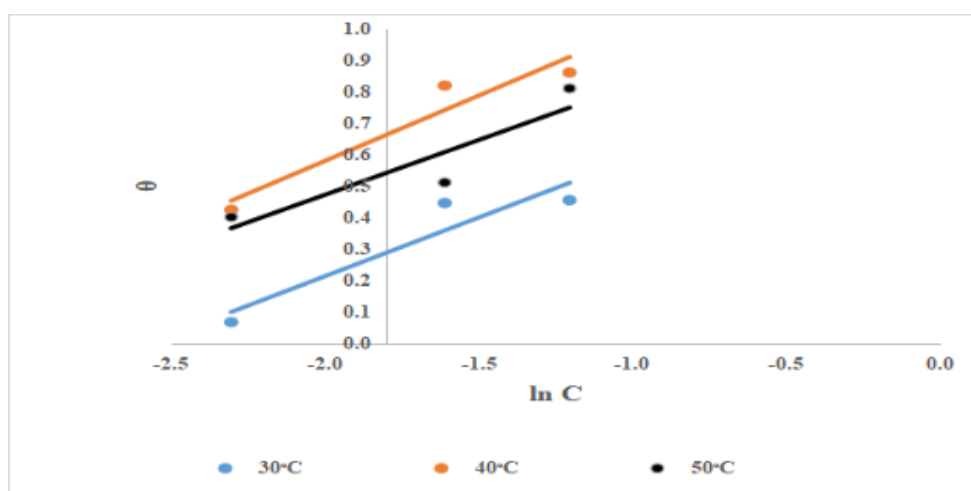


Figure 8: A graph of θ against $\ln C$.

3.4 Optical Micrographs

The optical micrographs of the copper samples exposed to a corrosive environment are displayed in Plate 2(a-d). The surface showed clear evidence of corrosion in the absence of the inhibitor (Plate 2(a)). The addition of different amounts of the PPE (Plate 2(b-c)) showed surface features with minimal corrosive behaviour and therefore indicated a good inhibition effect. Plate 2(d) displays similar surface features; however, slight pitting was observed at the highest inhibitor concentration.

3.5 Empirical Optimization

To systematically evaluate the inhibitory performance of plantain peduncle extract (PPE) on copper in 1 M HCl, the study employed two critical operating parameters: inhibitor concentration (0.0–0.3 mL in 50 mL HCl) and temperature (30–50°C). These parameters were selected to reflect realistic industrial conditions while probing the thermal stability and dose-dependent efficacy of PPE. Lower concentrations (0.1–0.3 mL) tested the extract's ability to mitigate corrosion at minimal doses. Table 6 lists the experimental data from the iterations of the operational parameters. It shows that the highest Corrosion rate (CR) occurs at 60°C without any inhibitor, which aligns with increase in corrosion with temperature. Also, the lowest corrosion rate is recorded at 40°C with 0.3ml of the plantain peduncle inhibitor, with a value of 0.75 mm/yr. Table 7 displays the data of the Analysis of Variance (ANOVA) for the designed experiment, investigating the effects of concentration and temperature and their interaction on the rate of corrosion as the response variable.



(a)



(b)



(c)



(d)

Plate 2 (a-d): Optical Micrographs of Copper Samples (Control, 0.1ml, 0.2ml, 0.3ml).

Table 6: Design of Experiment (DOF) Data

Factor A: Concentration (g)	Factor B: Temperature (°C)	Response I: CR (mm/yr)
0	30	2.27
0.1	30	2.12
0.2	30	1.26
0.3	30	1.24
0	40	5.34
0.1	40	3.08
0.2	40	0.97
0.3	40	0.75
0	50	6.02
0.1	50	3.61
0.2	50	2.95
0.3	50	1.15

The p-value for the model is 0.0002, which is much less than 0.05, indicating that the model is statistically significant. Also, the F-value for the model is 25.11, which further supports the significance of the model. The concentration parameter gave an SS value of 20.53, an F-value of 52.28, and a p-value < 0.0001. This indicates that factor A (Concentration) has a highly significant effect on the response variable. Similarly, the temperature parameter gave an SS value of 5.85, an F-value of 14.89, and a p-value = 0.0048. This indicates that factor B (Temperature) also has a significant effect on the response variable. The p-value of 0.0213 for AB interaction indicates that the interaction between A and B is statistically significant, meaning the effect of one factor depends on the level of the other factor.

The Fisher test was utilized in the evaluation of the statistical measurements by way of comparison of the model's mean square values with its residue and validate the sensitivity and repeatability of the model in Figure 9. To optimize efficiency of the PPE inhibitor, a central composite design (CCD) was used to generate a first-order polynomial regression model that explains the combined effect of concentration and temperature on the corrosion rate in Equation 3. The high R^2 (90.40%) and adjusted R^2 (86.80%) values suggest that the model fits the data well. The predicted R^2 likewise (79.73%) indicates that the model has good predictive capability. Furthermore, the relatively low CV% (24.45%) suggests that the experimental data is precise and reliable

Table 7: ANOVA Data for the Optimized Copper Response to PPE Inhibition

Source	SS	DF	MS	F-value	p-value	Remark
Model	29.59	3	9.86	25.11	0.0002	Sig.
A-Conc.	20.53	1	20.53	52.28	< 0.0001	
B-Temp.	5.85	1	5.85	14.89	0.0048	
AB	3.2	1	3.2	8.16	0.0213	
Residual	3.14	8	0.3928			
Cor Total	32.73	11				

$R^2 = 90.40\%$; Adjusted $R^2 = 86.80\%$; predicted $R^2 = 79.73\%$; CV% = 24.45

** SS- Sum of square; DF- Degree of Freedom; MS- Mean square; Sig.- Significant**

$$CR = 2.563 - 1.755A + 0.855B - 0.849AB \quad (3)$$

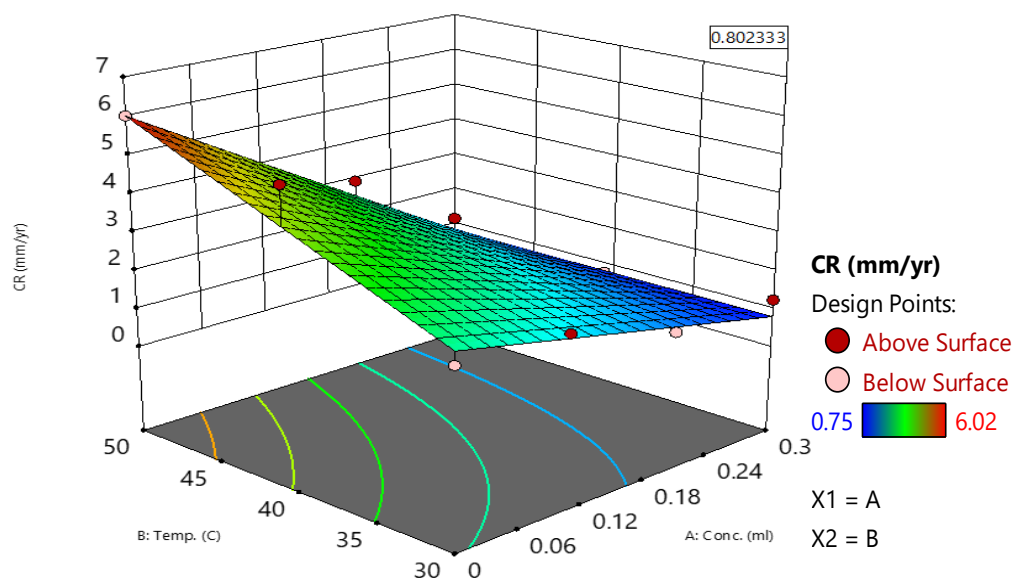


Figure 9: Effect of Plantain Peduncle Extract Concentration and Temperature on the Rate of Corrosion on Sample Copper

4. Conclusion

The results of this study unequivocally show that plantain peduncle extract (PPE) is an effective green corrosion inhibitor for copper in 1 M HCl. According to electrochemical measurements, the corrosion rate (CR) decreased from 5.34 mm/yr (control) to 0.75 mm/yr, with 0.3 mL PPE at 40°C achieving the best inhibition efficiency (IE% = 89.5%). This performance is in line with environmentally friendly goals and outperforms many synthetic inhibitors. The adsorption process, which is primarily driven by physisorption ($\Delta G_{ads} = -19.28$ kJ/mol), was corroborated by the Freundlich isotherm ($R^2 = 0.906$ at 40°C). The efficiency of PPE decreased at 50°C (IE% = 80.2%, CR = 1.15 mm/yr), despite its strong inhibition at intermediate temperatures. This highlights thermal constraints brought on by possible desorption or molecular breakdown. The importance of temperature ($p = 0.0048$) and concentration ($p < 0.0001$) was validated statistically using ANOVA. Their interaction ($p = 0.0213$) underscored the necessity of balanced operating parameters. These findings support the industrial use of PPE in mild-to-moderately acidic conditions, but temperature control is still essential. To improve thermal stability and expand their application to harsher environments, future research should optimise extraction processes. This study provides a workable substitute for harmful synthetic inhibitors by bridging sustainable innovation with real-world corrosion prevention.

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