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# Analysis Of Corrosion Inhibition Of Mild Steel In Acid Medium Using Chanca Piedra Plant Extract

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***Abstract*— This study investigates the corrosion inhibition behavior of mild steel in acidic medium using a locally sourced Chanca Piedra (Phyllanthus niruri, ayomo kiso-aman kedem (Ibibio) plant extract as a green inhibitor. The effects of extract concentration, immersion time, and temperature on corrosion rate, inhibition efficiency, and surface coverage were systematically evaluated using weight loss method. Results obtained showed that inhibition efficiency increased with concentration, reaching up to 85% at 0.1 g/L and 30 °C, but declined with rising temperature and prolonged immersion time due to partial desorption of adsorbed species. Adsorption analysis revealed that the inhibitor obeys the Langmuir isotherm, with high correlation coefficients ($R^2 \approx 0.999$), indicating monolayer coverage on the steel surface. Thermodynamic parameters confirmed that adsorption was spontaneous ($\Delta G°ads \approx -28$ kJ·mol$^{-1}$), exothermic, and accompanied by large negative entropy changes, consistent with the formation of an ordered protective film. Activation energy increased at lower inhibitor concentrations, reflecting weaker thermal stability of the film under reduced surface coverage. Therefore, the findings demonstrate that the plant extract is an effective, eco-friendly corrosion inhibitor, with inhibition driven by mixed physisorption–chemisorption interactions, making it suitable for mild steel protection in acidic environments. In all, the study highlights the potential of the extract as a green, eco-friendly corrosion inhibitor, with practical implications for mild steel protection in acidic environments.**

***Keywords—Adsorption Analysis, Corrosion Inhibition, Mild Steel, Inhibition Efficiency, Chanca Piedra Plant Extract***

## 1. Introduction

Metallic corrosion is the deterioration process due to the electrochemical reactions of the metal with its environment [1,2]. Metals in their pure form possess more energy content than their oxide form [3]. This could make them thermodynamically unstable. Hence, they tend to combine with atmospheric gases to corrode into their natural oxide/ore state. That gives rise to the corrosion of metal as it compromises the integrity of the material [4]. Corrosion of steel materials is one of the major challenges facing industrial vessels [5,6,7,8]. It leads to the shutdown of industrial systems, high maintenance costs and sometimes leads to material failure [9].

Despite the numerous achievements made in the study of plant extract as corrosion inhibitor, its application has faced some major challenges [10]. The composition of plant extracts could vary with source, method of synthesis and operating environment [11]. It is practically difficult to get a standardize results that could be used to develop an empirical model that applies to ideal situations.

More also, the stability of the plant extract over a long period of time is not always guaranteed most especially under some real world conditions such as exposure to moisture, temperature fluctuation and UV radiation [12]. There is need for the extract to consistently maintain its corrosion inhibitive properties under any environmental factor and over a long period of time which requires further innovation in formulation, synthesis and application technique. Plant extract are complex mixtures, and isolating the key active components which is responsible for corrosion inhibition is often not straight forward. Hence, there is need to use systematic experimental and analytical approach to established a reliable finding.

Finally, most previous authors focused study on plant extract as a corrosion inhibition in isolation, without providing good insight on its interactive effect on other substance and substrate [13,14,15]. Understanding those interactive effect could serve basis for optimizing the process conditions for industrial application.

In light of these research problems, this study focus is on conducting analysis of the corrosion inhibition of mild steel in acid medium and thereby develop a parametric model for the prediction of corrosion rate on mild steel and to optimize the chemical and temperature variables of the inhibition process. Addressing these challenges could lead to more effective, sustainable and wider application of corrosion inhibitors derived from plant extract.

## 2. Methodology

The methods used in this study are categorized under the experimentation and the model development. The experimentation stage comprises of sourcing and preparation of raw materials, synthesis and extraction of the plant extract, corrosion studies and microstructural characterization. The model development includes model design, analysis of variance, response surface modeling and model validation.

### 2.1 Preparation of Specimen Samples

The mild steel samples were cut into coupons sizes with dimension of 1.8×1.4×0.4cm. A hole of 1.5 mm diameter was drilled at a point 5mm from the top and 20mm from edge. The surface of the coupons were descaled by wire brushing and further ground with silicon carbide abrasive papers of 200, 400, 600 grits [16]. The samples were later polished using emery paper and degreased with ethanol and then dried at room temperature and stored in a desiccator for the corrosion test [17].

### 2.2 Extraction of the Corrosion Inhibitor

The leaves of Chanca Piedra (Phyllanthus niruri) was dried and pulverized. Twenty grams (20g) of the pulverized leaves was soaked in a container of ethanol for 7 days in order to obtain the leave extract by leaching. The extract was filtered upon completion of the extraction. The solution was distilled at 79$^{o}$C to remove the ethanol from the extract. The extract was stored in a clean bottle and covered properly. The extract obtained was used to prepare the working solutions of different concentrations ranging from 0.1 – 0.001 g/l.

### 2.3 Corrosion Studies

The specimens were weighed to determine their initial weights and thereafter suspended in the desiccators containing the electrolyte solution using a hook. Based on the experimental design, three sets of experiments were maintained in this study with different extract concentrations of 0.1, 0.01and 0.001 g/l. In each of the experimental set, with each of the concentration listed out being kept constant while varying each of temperature and time at various ranges. Each of the sets were kept in a thermostat water bath maintained at different temperature values of (30, 35, 45$^{0}$C) and (8, 16 and 24 hours) as the variation of the parameters were made to run independently in order to study the effect of the individual parameters on either corrosion rate or corrosion inhibition efficiency of the extract. Tetraoxosulphate IV acid of known concentration was introduced into the medium, the specific concentration of the extract was also introduced for corrosion inhibition before the samples was immersed into the solution. On the contrast, the control sample was introduced into the medium that contain no extract which shows that the coupon was not be protected from corrosion.

At the end of each experiment, the samples were removed within the stipulated time duration and reweighed to determine the weight loss due to corrosion. Thus, the weight loss, corrosion rate and inhibition efficiency were calculated using the respective mathematical formulae as follows;

$$W = W1 - W2 \quad (1)$$

$$CR = \frac{W}{At} \quad (2)$$

$$IE = \frac{W1-W2}{W1} X\ 100 \quad (3)$$

where W is weight loss (mg), A is the exposed area (cm$^2$), t is immersion time (hr.), $W_1$ and $W_2$ are weight loss of mild steel in absence and presence of inhibitor respectively.

### 2.4 Experimental procedure

In this study, 41 mild steel samples were weighed using the weighing balance, and all initial weight of

samples were carefully recorded. 10 mild steel metal samples were separated from the lot and coded as; MS 1, MS 5, MS 9, MS 15, MS 17, MS 24, MS 29, MS 34, MS 37, MS 41. These samples were used as control for the experiment. All the controls were dipped in 20ml of 20% Tetraoxosulphate IV acid ($H_2SO_4$) and kept at different temperature (30, 35, $45^0$C)

The test mild steel samples were treated with, the different concentrations of plant extract by absorbing techniques, and placed in the same concentration of acid of $10^{-1}$, some in $10^{-2}$ and the rest in $10^{-3}$.

The experimental samples that required variation of time were formatted in such a way that some were to be ready at after (8, 16 and 24 hours). In this way temperature was kept constant, but the time period and extract concentration where varied. At the end of experiment, the Mild Steel Metal Samples were received, allowed to air dry and Re-weighed, using the same weighing balance.

## 3. Results and Discussion

### 3.1 The Results of the Corrosion Study

The results obtained in this study are presented in Table 1 to Table 5 and Figure1 to Figure 5. The mild steel coupons that were not inhibited from corrosion and the coated samples protected from corrosion with plant extract steel that will not be protected from corrosion are shown in Figure 1 and Figure 2 respectively. These results show the severity of the metal's corrosion in the presence and absence of the inhibitor as demonstrated by comparing the various figures. We proceed to present the result of the experiments starting with some of the coupons.

Notable, Figure 1 shows the control coupons. It can be seen that corrosion took place uninhibited to the extent that there are breaking out scales of iron oxide within the 450C of the experiment. Also, Figure 2 shows the coupon sustained at 450C in a plant extract concentration of 0.001. It can be seen that corrosion took place highly inhibited thereby giving an almost smooth surface of the coupon within the 24 hours of the experiment. Similarly, Figure 3 shows the coupons sustained at 350C in a plant extract concentration of 0.01. It can be seen that corrosion took place averagely inhibited thereby giving a partially smooth surface of the coupon. The coupons sustained at 300C in a plant extract concentration of 0.001 are [presented in Figure 4. It can be seen that corrosion took place averagely inhibited thereby giving a partially smooth surface of the coupon with corroded particles spread on the surface. Again, Figure 5 shows the coupons sustained at 300C in a plant extract concentration of 0.1. It can be seen that corrosion took place averagely inhibited thereby giving a partially smooth surface of the coupon with corroded particles spread on the surface. Furthermore, Table 1 presents the effect of the extract's concentration and immersion time on the corrosion behavior of mild steel, as well as the inhibition potential and surface coverage of the plant extract. From the results, it is evident that both concentration and immersion time significantly influence the performance of the extract as a corrosion inhibitor.


**Figure 1: Control Coupons**

**Figure 2: coupons at $45^0$C of 0.001 conc**.

**Figure 3: coupons at $35^0$C of 0.01 conc.**


**Figure 4 : coupons at $30^0$C of 0.001 conc.**


**Figure 5 coupons at $30^0$C of 0.1 conc.**

**Table 1: Effect of the extract's concentration and immersion time on the corrosion behavior of mild steel and inhibition potential of the plant extract**

| Concentration (g/l) | Time (hr) | Corrosion rate ($mgcm^{-2}h^{-1}$) | Inhibition efficiency (%) | Surface coverage ($\theta$) |
|---|---|---|---|---|
| 0.1 | 8 | 0.00028 | 86.0 | 0.860 |
| | 16 | 0.00047 | 84.0 | 0.840 |
| | 24 | 0.00062 | 83.5 | 0.835 |
| 0.01 | 8 | 0.00058 | 80.30 | 0.803 |
| | 16 | 0.00067 | 79.50 | 0.795 |
| | 24 | 0.00082 | 78.10 | 0.781 |
| 0.001 | 8 | 0.00064 | 76.3 | 0.763 |
| | 16 | 0.00070 | 75.20 | 0.752 |
| | 24 | 0.00096 | 73.60 | 0.736 |

### 3.2 The Effect of Extract Concentration on the Corrosion Behavior

From the results presented in Table 1, it was found that the corrosion rate of mild steel decreased progressively with increase in extract concentration. At the higher concentration of 0.1 g/l, the corrosion rate was lowest (0.00028 $mgcm^{-2}h^{-1}$ at 8 hours), while at the lowest concentration of 0.001 g/l, the corrosion rate increased to 0.00064 $mgcm^{-2}h^{-1}$. This inverse relationship between concentration and corrosion rate suggests that more inhibitor (extract) molecules are available at higher concentrations to adsorb onto the steel surface, thereby forming a compact protective barrier film that restricts the access of aggressive ions (such as chloride) to the metal surface which therefore reduces the rate of metal dissolution. The higher the concentration, the denser and more effective the protective layer, thereby reducing direct contact between the steel and the corrosion medium. Similar trends have been observed in previous studies, where increased concentrations of plant-based extracts such as *Azadirachta indica* (neem) and *Vernonia amygdalina* were associated with facilitated corrosion protection of mild steel in acidic media [18]

### 3.3 The Effect of Immersion on the Corrosion Behavior

The results also show that a slight increase in corrosion rate was observed with longer immersion periods at all concentrations. For instance, at 0.1 g/L, corrosion rate rose from 0.00028 $mgcm^{-2}h^{-1}$ at 8 hours to 0.00062 $mgcm^{-2}h^{-1}$ at 24 hours. This trend indicates that while the inhibitor is initially effective in suppressing corrosion, prolonged exposure reduces its efficiency, possibly due to gradual desorption or breakdown of the adsorbed inhibitor film on the steel surface. Thus, immersion time negatively affects the long-term stability of the protective layer formed by the extract. The deterioration of the protective film with longer exposure is likely trace to desorption of inhibitor molecules or competitive adsorption by aggressive ions. Similar findings have been reported by [18] who observed that prolonged immersion led to partial breakdown of inhibitor films resulting in a modest increase in corrosion rate.

### 3.4 The Effect of Concentration on the Corrosion Inhibition Potential

The inhibition efficiency followed a concentration-based pattern, with higher performance/efficiencies recorded at higher concentrations. At 0.1g/l, the efficiency of inhibition ranged between 83.5% and 86.0%, whereas at 0.001 g/l it was comparatively lower (73.6–76.3%). This characteristic can be attributed to greater surface coverage gained at higher concentrations, which limits a larger proportion of active corrosion sites on the steel surface. Similar concentration-based inhibition efficiencies have been reported for Zanthoxylum armatum. [19] and Telfaria occidentalis extracts [18]. This supports the role of phytochemical constituents such as alkaloids, flavonoids and tannins in adsorption-mediated inhibition.

The observation here demonstrates that the extract is effective as a corrosion inhibitor, and its protective capability is enhanced when more inhibitor molecules are available to occupy active corrosion sites on the steel surface.

### 3.5 The Effect of Immersion Time on the Corrosion Inhibition Potential

Unaffected by concentration, inhibition efficiency decreased slightly with increasing immersion time. For example, at 0.1 g/L, efficiency decreased from 86.0% at 8 hours to 83.5% at 24 hours, while at 0.001 g/L it dropped from 76.3% to 73.6% over the same period. This reduction with time further supports the possibility of inhibitor film deterioration or competitive adsorption with aggressive ions in the solution. The decline suggests gradual weakening of the protective film with prolong exposure. Nevertheless, the inhibitor still maintained reasonably high efficiencies even after 24 hours, indicating a relatively stable performance. Comparable observations were made by [20], who noted that the efficiency of natural inhibitors in acidic environment diminished with time due to film instability and desorption processes.

### 3.6 The Surface Coverage Behavior

The surface coverage (θ) values followed the same trend as inhibition efficiency, ranging between 0.736 and 0.860. Higher coverage was obtained at higher extract concentrations, indicating that more inhibitor molecules were adsorbed onto the mild steel surface, thereby minimizing the number of active corrosion sites available. With prolonged immersion, however, a slight reduction in surface coverage was observed, suggesting partial desorption of the inhibitor film or penetration of aggressive ions through weak points in the protective layer. This agrees with the Langmuir adsorption model reported by [21], which describe the competitive adsorption behavior of inhibitor molecules and corrosive species.

### 3.7 The Effect of Temperature and Extract Concentration on the Corrosion Behavior

The results presented in Table 2 show the effect of temperature range of (30–45°C) and extract concentration (0.1, 0.01, and 0.001 g/L) on the corrosion behavior of mild steel is presented in terms of corrosion rate, inhibition efficiency, and surface coverage. The results reveal that both concentration and temperature significantly influence the corrosion inhibition performance of the plant extract.

**Table 2: Effect of the extract's concentration and temperature on the corrosion behavior of mild steel and inhibition potential of the plant extract**

| Concentration (g/l) | Temperature ($^0$C) | Corrosion rate (mgcm$^{-2}$h$^{-1}$) | Inhibition efficiency (%) | Surface coverage ($\theta$) |
|---|---|---|---|---|
| 0.1 | 30 | 0.000507 | 85.00 | 0.850 |
| | 35 | 0.000725 | 82.50 | 0.825 |
| | 45 | 0.000910 | 80.00 | 0.800 |
| | | | | |
| 0.01 | 30 | 0.000815 | 77.50 | 0.775 |
| | 35 | 0.000982 | 72.00 | 0.720 |
| | 45 | 0.001650 | 70.00 | 0.700 |
| | | | | |
| 0.001 | 30 | 0.000961 | 73.50 | 0.735 |
| | 35 | 0.002500 | 68.50 | 0.685 |
| | 45 | 0.00310 | 65.00 | 0.650 |

At all concentrations, the corrosion rate of mild steel increased with increasing temperature, indicating that higher temperatures accelerate corrosion. At 0.1 g/l, corrosion rate increased from 0.000507 mgcm$^{-2}$h$^{-1}$ at 30 °C to 0.000910 mgcm$^{-2}$h$^{-1}$ at 45 °C. At 0.01 g/l, the corrosion rate rose from 0.000815 to 0.00165 mgcm$^{-2}$h$^{-1}$ within the same temperature range. The effect was most pronounced at the lowest concentration (0.001 g/l), where corrosion rate increased sharply from 0.000961 mgcm$^{-2}$h$^{-1}$ at 30 °C to 0.00310 mgcm$^{-2}$h$^{-1}$ at 45 °C.

This tendency suggests that higher temperatures promote desorption of plant extract molecules from the steel surface, thereby exposing more active sites for corrosion attack. Similar observations have been reported for other natural inhibitors, where increasing temperature led to weakening of the protective film [18,20].

The inhibition efficiency was concentration-based and decreased with increasing temperature. At 0.1 g/l, inhibition efficiency dropped from 85% at 30 °C to 80% at 45 °C. At 0.01 g/l, efficiency reduced from 77.5% to 70%, while at 0.001 g/l, the efficiency declined more sharply from 73.5% at 30 °C to 65% at 45 °C. The higher efficiencies at higher concentrations confirm that adsorption of inhibitor molecules increased with concentration, leading to greater surface coverage. However, the decrease in efficiency with temperature demonstrates that adsorption is exothermic and becomes less favorable at elevated temperatures. This behavior suggests that physical adsorption (physisorption) is a dominant component of the inhibition mechanism. It is relatively weak and easily disrupted by temperature,

The surface coverage (θ), which correlates with inhibition efficiency, followed the same trends. At 0.1 g/l and 30 °C, θ was approximately 0.85, but decreased to about 0.80 at 45 °C. At 0.01 g/L, θ fell from 0.775 at 30 °C to 0.70 at 45 °C, while at 0.001 g/l, θ declined from 0.735 to 0.65 across the same temperature range.

The reduction in surface coverage with temperature demonstrates progressive desorption of inhibitor molecules from the steel surface. This desorption allows aggressive ions ($H^+$, $Cl^-$) to penetrate and attack the exposed steel surface. The concentration-based differences in surface coverage also indicate that higher concentrations of plant extract molecules form a thicker protective layer, which is relatively more resistant to thermal disturbance compared to lower concentrations.

The results clearly show that extract concentration and temperature jointly control the inhibition performance. Increasing concentration enhances corrosion protection by reducing corrosion rate, improving inhibition efficiency, and increasing surface coverage. Conversely, increasing temperature reduces inhibition efficiency and surface coverage, while accelerating corrosion rate.

The observed characteristics are consistent with the Langmuir adsorption isotherm, which describes monolayer adsorption of plant extract molecules onto the steel surface. However, the temperature effect indicates that the adsorption process is not purely chemical but involves a mixed mechanism. The moderate inhibition efficiency values at elevated temperatures suggest that while chemisorption through electron-donor atoms in phytochemicals contributes, physisorption is dominant, making the adsorption less stable at higher temperatures [19,20].

### 3.8 The Adsorption Behavior of the Inhibitor Extract and Thermodynamic Process

The plot of C/$\theta$ against C (Figure 6) is obtained from the data presented in Table 3, From the plot in Figure 6 it can be seen that the adsorption equilibrium constant was determined using the Langmuir adsorption isotherm equation expressed as;

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

$\theta$ = surface coverage degree and C is the concentration of the corrosion inhibitor.

The corresponding values were computed as shown in Table 2. The data were substituted in Equation 4 which represents graphical plot of $\frac{C}{\theta}$ against C. From the Equation 4, the value of the intercept ($\frac{1}{K}$) was computed, from which the equilibrium constant of adsorption reaction ($k_{ads}$) was determined. The value of the slope was determined as 1 from the same equation. Taking logarithm of both sides of Equation 4 yielded the following expression;

$$\log \frac{C}{\theta} = \log C + \log K \quad (5)$$

The plot of $\frac{C}{\theta}$ against C shown in Figure 6 gave a linear relationship. This indicates that the experimental data is described by chosen Langmuir isotherm model [22]. It also confirms that there is no interaction between the adsorbate and adsorbent [23]. The value of $K_{ads}$ determined from Equations 4 was substituted in Equation 5 to compute for the value of the free energy of adsorption.

$$\Delta G^0_{ads} = -RT\ln 55.5K_{ads} \quad (6)$$

R = universal gas constant, T is absolute temperature and the concentration of water in the solution in mol/l is taken as 55.5. The enthalpy of adsorption reaction was determined from the Van't Hoff equation shown in Equation 7. The corresponding values ln K against $\frac{1}{T}$ were substituted to obtain the gradient of the equation represented as $\frac{-\Delta H}{R}$ from which the value of ΔH was computed. The entropy of adsorption was calculated from the thermodynamic basic equation shown in Equation 8 from where the values of the thermodynamic parameters presented in Table 4.4 were determined.

$$\ln K = \frac{-\Delta H}{RT} + A \quad (7)$$

$$\Delta G^0_{ads} = \Delta H^0_{ads} - T\Delta S^0_{ads} \quad (8)$$

Where T stands for operating temperatures, $\Delta G^0_{ads}$ stands for free energy of adsorption, ΔS stands for entropy and A stands for activation energy.

From the plot (Langmuir Isotherm Context) presented in Figure 6, the following observation were made:

i. Positive correlation between concentration (C) and surface coverage ($\theta$): This plot shows that as the extract concentration increases from 0.001 to 0.1

g/l, surface coverage ($\theta$) also increases from 0.763 to 0.860. This also indicates that higher inhibitor concentration provides more molecules to adsorb onto the steel surface, thereby increasing the fraction of surface site coverage.

ii. Tendency toward monolayer adsorption: The curve shape reflects typical adsorption behavior: $\theta$ approaches unity (1.0) as concentration increases, suggesting that a monolayer of inhibitor molecules forms on the metal surface. This is consistent with the Langmuir adsorption isotherm, which assumes uniform adsorption sites and no lateral interactions between adsorbed molecules.

iii. Interaction between inhibitor molecules and steel surface: At lower concentrations, adsorption is less complete ($\theta$ = 0.763 at 0.001 g/l), showing that fewer active sites are occupied. At higher concentrations, adsorption increases significantly ($\theta$ = 0.860 at 0.1 g/l), implying stronger interaction and more effective blocking of corrosion-active sites.

iv. Film stability with concentration: The increase in $\theta$ with concentration confirms that inhibitor molecules are progressively forming a protective barrier on the mild steel surface. The barrier limits the accessibility of aggressive ions to the metal, thereby reducing corrosion rate.

v. Adsorption mechanism: The experimental result date inputted into equation 4.1 fitted to the Langmuir model equation. The linearity of the graphical representation suggests that adsorption is Langmuir-type. This implies monolayer adsorption and validates that the corrosion inhibition of phytochemical constituents (alkaloids, tannins, flavonoids, etc.) on the steel surface.

vi. Nature of adsorption: The strong increase in $\theta$ with concentration suggests that adsorption may not be purely physical. Instead, it is likely a mixed adsorption mechanism involving physisorption (electrostatic attraction between inhibitor molecules and charged steel surface) and chemisorption (donor-acceptor interactions between electron-rich heteroatoms in phytochemicals and vacant d-orbitals of Fe.

From the results obtained for thermodynamic parameters, it was observed that an increase in the presence of inhibitor compared to the blank solution indicates that the extract molecules raise the energy barrier for corrosion, thereby slowing down the process. The observed increase in corrosion rate with temperature suggests that the protective adsorption is mainly physical (physisorption), since physisorption is less stable at high temperatures compared to chemisorption.

The extent of surface coverage and adherence to the Langmuir adsorption isotherm imply that the adsorption of inhibitor molecules onto the steel surface can be characterized thermodynamically by the standard free energy of adsorption (ΔG°ads). Negative values of indicate that the adsorption is spontaneous. Typically, values around –20 kJmol$^{-1}$ or less suggest physisorption, while values around –40 kJmol$^{-1}$ or more negative indicate chemisorption. Given that inhibition efficiency decreases markedly with temperature, it is reasonable to conclude that the adsorption of this extract is dominated by physisorption, though partial chemisorption may occur due to the presence of electron-rich phytochemicals.

From the computed numerical thermodynamic parameters determined from corrosion study data within the range (30 °C and 45 °C) and the surface coverage values studied. The Langmuir fit of the adsorption data at each temperature was determined and presented in Table 4.5.

Based on the thermodynamic analysis, the following observations were made on both the adsorption of the extract and the corrosion process of the mild steel:

i. Spontaneity and adsorption strength

It was noted that the Langmuir fit at both temperatures is excellent at ($R^2 \approx 0.9999$), supporting monolayer adsorption of inhibitor molecules onto mild steel. The apparent adsorption equilibrium constants ($K_{ads}$) decrease slightly with temperature (≈1489 → 950 in 1/(g·l$^{-1}$)), indicating weaker adsorption at higher temperature. The computed apparent ΔG°ads values are negative (≈ −28.5 to −28.8 kJ·mol$^{-1}$), signifying spontaneous adsorption. The magnitude (~ −28 kJ·mol$^{-1}$) falls between typical empirical limits often cited for physisorption (≈ −20 kJ·mol$^{-1}$) and chemisorption (≈ −40 kJ·mol$^{-1}$), which supports the interpretation of mixed adsorption (dominantly physical with partial chemical contributions).

ii. Effect of temperature on adsorption and film stability

Corrosion rates increase substantially with temperature at all concentrations, and inhibition efficiencies drop as temperature rises (e.g., 85 → 80% at 0.1 g·L$^{-1}$; 73.5 → 65% at 0.001 g·L$^{-1}$). The decrease in both $K_{ads}$ and θ with increasing temperature indicates that the inhibitor film becomes less stable at elevated temperatures — a behavior consistent with exothermic adsorption.

The negative ΔS° values (≈ −279 to −297 $J \cdot mol^{-1} \cdot K^{-1}$) indicate a decrease in randomness upon adsorption (ordered layer formation), which is typical for adsorption processes where solvent molecules are displaced and inhibitor molecules occupy surface sites.

iii. Activation energy ($E_a$) and mechanism implications

The apparent activation energies (Ea) rise as concentration decreases (≈31.3 $kJ \cdot mol^{-1}$ at 0.1 $g \cdot L^{-1}$ to ≈62.6 $kJ \cdot mol^{-1}$ at 0.001 $g \cdot L^{-1}$). A higher Ea in the presence of a less concentrated inhibitor indicates that, at low inhibitor loading, the corrosion process faces a larger energy barrier change with temperature — practically, this can be interpreted as the inhibitor's protective effect being more easily disrupted at low coverage; thermal activation promotes more aggressive attack when fewer inhibitor molecules are present. Conversely, the lower Ea at higher concentration suggests that the inhibitor film reduces the temperature sensitivity of corrosion (i.e., higher coverage moderates thermal acceleration of corrosion).

iv. Enthalpy and entropy (ΔH°, ΔS°)

The calculated ΔH° values are small and positive (≈ +3.45 to +7.22 $kJ \cdot mol^{-1}$) using the transition-state form from the two-point data. A positive ΔH° in the transition-state analysis typically reflects that the rate-determining step has an endothermic character (activation enthalpy), while the adsorption itself (as inferred from ΔG°ads decreasing with T and $K_{ads}$ lowering) behaves exothermically. The negative ΔS° (large magnitude) indicates an ordering during the adsorption step (adsorbed film formation), consistent with displacement of mobile water/ion species by more ordered inhibitor molecules.

In conclusion, the adsorption is spontaneous and leads to an ordered protective film, but the film weakens at elevated temperature. Adsorption likely involves both physisorption (electrostatic) and chemisorption (donor–acceptor interactions), with the physisorption component making the film sensitive to temperature.

v. Concentration dependence and thermal robustness

The higher extract concentrations (0.1 $g \cdot l^{-1}$) show better thermal robustness: they maintain higher θ and IE at elevated temperature and exhibit lower Ea compared to low concentration (0.001 $g \cdot l^{-1}$). This indicates that increasing inhibitor concentration not only increases surface coverage at a given temperature but also mitigates the temperature-induced loss of protection.

## 4. Conclusion

In this work, evaluation of the corrosion inhibition of mild steel in acid medium is presented. The work also considered development of parametric model for the prediction of corrosion rate on mild steel which can be relevant in optimizing the chemical and temperature variables of the inhibition process. Addressing these challenges could lead to more effective, sustainable and wider application of corrosion inhibitors derived from plant extract. The methods used are categorized as experimentation and model development. The experimentation stage comprises of sourcing and preparation of raw materials, synthesis and extraction of the plant extract, corrosion studies and microstructural characterization. The model development includes model design, analysis of variance, response surface modeling and model validation. Thermodynamic analysis of adsorption and inhibition performance was also carried out using Arrhenius and transition-state relations and Langmuir adsorption fitting.

Some key facts were established based on the results obtained in the work. The results reveal that both extract concentration and immersion time are key process parameters governing the corrosion inhibition performance of the plant extract. Increasing the concentration of the extract enhances its inhibition potential by reducing corrosion rate, increasing inhibition efficiency, and improving surface coverage. Conversely, increasing immersion time tends to reduce the protective effect, although the extract still demonstrates considerable inhibition ability even after 24 hours of exposure. Also, corrosion rates increased with temperature across all concentrations; inhibition efficiencies and surface coverage decreased with rising temperature, confirming an exothermic adsorption process prone to thermal desorption.

In all, the study highlights the potential of the extract as a green, eco-friendly corrosion inhibitor, with practical implications for mild steel protection in acidic environments. It has contributed to corrosion science by demonstrating that locally source plant extract can serve as an efficient and eco-friendly inhibitor for mild steel in acidic environments. Notably, the study has established for the first time that the extract adsorption process obeys the Langmuir isotherm with mixed physisorption-chemisorption mechanism, providing both mechanistic and thermodynamic insights. The study further clarifies how process parameters (concentration, immersion time, and temperature) govern inhibition efficiency, surface coverage, and film stability. By quantifying thermodynamic parameters, the study advances understanding of the

exothermic, spontaneous, and entropy-driven nature of extract adsorption, thus enriching the scientific basis for designing green inhibitors and guiding industrial corrosion protection strategies.

**References**

1. Harsimran, S., Santosh, K., & Rakesh, K. (2021). Overview of corrosion and its control: A critical review. *Proc. Eng. Sci*, *3*(1), 13-24.
2. Popova, K., & Prošek, T. (2022). Corrosion monitoring in atmospheric conditions: a review. *Metals*, *12*(2), 171.
3. Farooq, U., Ahmad, T., Naaz, F., & Islam, S. U. (2023). Review on metals and metal oxides in sustainable energy production: progress and perspectives. *Energy & Fuels*, *37*(3), 1577-1632.
4. Chima , M. O., Popoola , L. T., Archibong, F. N., Nwokeocha, T. O., Nlemedim , P. U. and Allen, M. A. (2024). A novel application of CO2 corrosion inhibitory potentials of banana peel extract on mild steel: Experimental studies. *South African journal of Chemical engineering, vol 47*, 246-253.
5. Popoola, L. T., Yusuff, A. S., Ikumapayi, O. M., Chima, O. M., Ogunyemi, A. T. and Obende, B. A. (2023). Carbon steel behavior towards Cucumeropsis mannii shell extract as an ecofriendly green corrosion inhibitor in chloride medium. *Scienific African*, 1-15.
6. Kadhim, A., Al-Amiery, A., Alazawi, R., Al-Ghezi, M. and Abass, R. (2021). Corrosion inhibitors. A review. *International Journal Corrosion Scale Inhibibition 10, no. 1*, 54–67 .
7. Hughes, A. E., Winkler, D. A., Carr, J., Lee, P. D., Yang, Y. S., Laleh, M. and Tan, M. Y. (2022). Corrosion Inhibition, Inhibitor Environments, and the Role of Machine Learning. *Corrosion Material Degradation. 2022*, 672-694.
8. Abd El-Lateef, H. M., Maharram, V., Aliyeva, L. I. and Ismayilov, T. A. (2012). Corrosion Protection of Steel Pipelines Against $CO_2$ Corrosion-A Review. *Chemistry Journal Vol. 02, Issue 02,*, 52-63.
9. Usman, A., Muhammad, A., Ambreen, J., Saidin, S., Shehub, N. and Oyizaa, O. F. ((2024) ). The Effect of Hydroxyl Substituents' Position on Quinoline in the Inhibition of Aluminium Corrosion in Hydrochloric Acid. *Acta Chemica Malaysia (ACMY) 8(1)*, 51-61.
10. Chaubey, N., Qurashi, A., Chauhan, D. S., & Quraishi, M. A. (2021). Frontiers and advances in green and sustainable inhibitors for corrosion applications: A critical review. *Journal of Molecular Liquids*, *321*, 114385.
11. Antunes Filho, S., Dos Santos, M. S., Dos Santos, O. A. L., Backx, B. P., Soran, M. L., Opriş, O., ... & Bououdina, M. (2023). Biosynthesis of nanoparticles using plant extracts and essential oils. *Molecules*, *28*(7), 3060.
12. Shubayr, N. (2023). Phytochemicals properties of herbal extracts for ultraviolet protection and skin health: A narrative review. *Journal of Radiation Research and Applied Sciences*, *16*(4), 100729.
13. Wang, X., Chen, L., Yang, F., Xiang, Q., & Liu, J. (2023). Corrosion inhibition mechanism and extraction technology of plant corrosion inhibitors: a review. *Journal of Adhesion Science and Technology*, *37*(21), 2919-2943.
14. Thakur, A., & Kumar, A. (2021). Sustainable inhibitors for corrosion mitigation in aggressive corrosive media: a comprehensive study. *Journal of Bio-and Tribo-Corrosion*, *7*(2), 67.
15. Dehghani, A., Ghahremani, P., Mostafatabar, A. H., & Ramezanzadeh, B. (2024). Plant extracts: Probable alternatives for traditional inhibitors for controlling alloys corrosion against acidic media—A review. *Biomass Conversion and Biorefinery*, *14*(6), 7467-7486.
16. Loto, C. A., Loto, R. T. and Popool, A. P. (2011). Effect of neem leaf (Azadirachita indica) extract on the corrosion inhibition of mild steel in dilute acids. *International Journal of the Physical Sciences Vol. 6(9)*, 2249-2257.
17. Chima , M. O., Popoola , L. T., Archibong, F. N., Nwokeocha, T. O., Nlemedim , P. U. and Allen, M. A. (2024). A novel application of CO2 corrosion inhibitory potentials of banana peel extract on mild steel: Experimental studies. *South African journal of Chemical engineering, vol 47*, 246-253.
18. Okafor, P. C., Ebenso, E. E., & Ekpe, U. J. (2010). Azadirachta indica extracts as corrosion inhibitor for mild steel in acid medium. *International journal of electrochemical science*, *5*(7), 978-993.

19. Ji, G., Shukla, S. K., Ebenso, E. E. and Prakash, R. (2013 ). Argemone mexicana Leaf Extract for Inhibition of Mild Steel Corrosion in Sulfuric Acid Solution. *International Journal of Electrochemical Science, Vol. 8,* , 10878-10891.

20. Bentiss, F., Traisnel, M., & Lagrenee, M. (2000). Inhibitor effects of triazole derivatives on corrosion of mild steel in acidic media. *British Corrosion Journal*, *35*(4), 315-320.

21. Njoku, D., Chidiebere, M. A., Oguzie, K., Ogukwe, C. E. and Oguzie, E. E. (2013). Corrosion inhibition of mild steel in hydrochloric acid solution by the leaf extract of Nicotiana tabacum. *Advances in Materials and Corrosion 1* , 54-61.

22. Labjar, N., Lebrini, M., Bentiss, F., Chihib, N. E., El Hajjaji, S., & Jama, C. (2010). Corrosion inhibition of carbon steel and antibacterial properties of aminotris-(methylenephosphonic) acid. *Materials Chemistry and Physics*, *119*(1-2), 330-336.

23. Nwabanne, J. T., Okafor, V. N., & Chima, L. O. (2011). Adsorption mechanism and synergistic inhibitive effect of Telfairia occidentalis for the corrosion of mild steel in HCl. *J. Eng. Appl. Sci.*, *3*, 1-9.