Corrosion Inhibition and Adsorption Properties of *Commelina benghalensis* Leaves Extract on Mild Steel in 1M H$_2$SO$_4$ Solution

Collins Chibuzor Odidika[1, *], Vincent Ishmael Egbulefu Ajiwe[1], Charity Nkiruka Eboagu[1], Chiagozie Michael Ekwunife[1], Chioma Irene Awuzie[2]

[1]Department of Pure and Industrial Chemistry, Nnamdi Azikiwe University, Awka, Nigeria

[2]Department of Science Laboratory Technology, Federal Polytechnic, Oko, Nigeria

Email address:
cc.odidika@unizik.edu.ng (C. C. Odidika), vaj_04@yahoo.com (V. I. E. Ajiwe), nc.eboagu@unizik.edu.ng (C. N. Eboagu),
cm.ekwunife@unizik.edu.ng (C. M. Ekwunife), alwayschioma4sure@yahoo.com (C. I. Awuzie)
[*]Corresponding author

Abstract: The corrosion inhibition of mild steel in 1M sulphuric acid solution by the ethanol extract of *Commelina benghalensis* (C. B) leaves was determined using gravimetric technique. Phytochemical analysis was carried out on the extract and the effect of extract concentration, temperature, immersion time and acid concentration on the corrosion process was determined. The corrosion inhibition efficiency of the extract increased with increase in the concentration of the extract and decreased with increase in temperature. Increase in temperature also increased the corrosion rate of mild steel in 1M sulphuric acid in the absence and presence of different concentrations of the extract. The adsorption of the plant extract obeyed Langmuir and Freundlich adsorption isotherms. The process of physical adsorption was proposed for the extract from the trends of inhibition efficiency with temperature and from calculated values of Gibbs free energy, activation energy and enthalpy of adsorption. Gibbs free energy values for the reactions were less than 20kJ/mol, indicating physical adsorption process and were also found to be negative, indicating that the adsorption process was spontaneous. The corrosion inhibition efficiency (% IE) of the plant extract was attributed to the phytochemical constituents (alkaloids, flavonoids, tannins, saponins, phenolics, steroids and cardiac glycosides) present in them. The results showed that *Commelina benghalensis* can serve as a good corrosion inhibitor of mild steel in acid medium, since it reached a corrosion inhibition efficiency (% IE) of 91.91% at 2.0g/L extract concentration.

Keywords: *Commelina benghalensis*, Mild Steel, Adsorption, Sulphuric Acid, Corrosion Inhibitor, Gravimetric Technique

1. Introduction

Corrosion is commonly defined as the deterioration or wearing off of metals due to chemical reactions, but in more scientific meaning it is a physiochemical interaction between any exposed metal and its surrounding environment (e.g. oxygen) that results in the formation of an oxide called rust. Rust is the combination between iron, water and oxygen and usually forms if humidity is over 30% [1-3].

Corrosion of metals remains a global scientific problem as it affects the metallurgical, chemical, food processing and oil industries. It is invariably present in most industries whose facilities are constituted by metallic structures.

Acidic solutions are commonly used in various industries, and it's applications include: Acid pickling, industrial cleaning, acid rescaling, oil-well acidification, and petrochemical processes [4]. Among the acid solutions, sulphuric acid (H$_2$SO$_4$) and hydrochloric acid (HCl) are the most widely used in the pickling processes of metals. The use of organic and inorganic corrosion inhibitors, is one of the efficient method to prevent the corrosion of metal surfaces in corrosive media especially in acid solutions to avoid metal

dissolution or degradation [5], it have been used extensively in most industries to reduce the corrosion rate of many metals. However, in the application of these inhibitors for corrosion control they were found to be expensive, toxic, carcinogenic, non-biodegradable and environmentally unfriendly. This then made the investigation and ongoing trend of finding safe, cheap, biodegradable, renewable and environmentally friendly corrosion inhibitors like plant extracts of great importance to many industries. Extracts from plant leaves, barks, fruits, seeds, and roots comprise of mixtures of organic compounds containing nitrogen, sulphur, and oxygen atoms, and some have been reported to function as effective inhibitors of metal corrosion in different aggressive environments [6-13], hence the search for organic green corrosion inhibitors. In view of our interest in environmentally friendly corrosion inhibitors, this present study investigates the inhibitive effects of *Commelina benghalensis* leaves extract on the corrosion of mild steel in 1M sulphuric acid (H_2SO_4) solution.

2. Materials and Methods

2.1. Sample Preparation

The mild steel sheet used for this work was obtained from Nkwogbe Market, Ihiala, Anambra State, Nigeria and was 0.15cm (1.5mm) in thickness. It was mechanically cut into coupons of 3cm x 3cm (surface area 19.8 cm^2). A small hole was drilled at one end of the coupons for easy hooking. The surfaces of the mild steel coupons were mechanically polished with emery paper (sand paper) to remove any corroded surface. They were washed with distilled water, degreased with ethanol, dipped into acetone, air dried and weighed using a digital weighing balance. The weights were recorded and the weighed coupons stored in moisture free desiccators before their use in corrosion studies.

2.2. Extraction of Plants Extracts

The leaves of *Commelina benghalensis* were collected from a farmland in Umudimogo village, Ihiala, Anambra State, Nigeria. They were air dried under room temperature away from direct sunlight for 30 days and ground into powder using a mechanical grinder. 100g of the plant powders were extracted with ethanol using a soxhlet extractor for 24 hours. After recovering most of the solvents, the extract was heated on a water bath at 60°C until almost the entire solvent (ethanol) evaporated. Different concentrations of the extract obtained were prepared by dissolving 0.5, 1.0, 1.5 and 2.0 gram of the extract in 1 litre (1000 ml) of 1M H_2SO_4 respectively.

2.3. Phytochemical Analysis

Phytochemical analysis of the ethanol extracts of the leaves of *Commelina benghalensis* were carried out to ascertain the presence of different phytochemicals in the leaves extracts as described in literature [6].

2.4. Gravimetric Analysis (Weight Loss Method)

Gravimetric analysis was carried out using weight loss technique. During this analysis, the effect of immersion time, temperature and acid concentration on the corrosion process was determined.

In determining the effect of immersion time on the corrosion process the weighed mild steel coupons were each suspended and completely immersed in beakers containing 100ml of the test solutions (IM H_2SO_4) in the absence and presence of different concentrations of the plant extract, i.e. 0.5g/L, 1.0g/L, 1.5g/L and 2.0g/L with the help of threads and sticks for 24 hours, 72 hours, 120 hours, and 168 hours at ambient temperature and properly labeled. The coupons were retrieved as each time elapsed and then washed, scrubbed with bristle brush under fast flowing water, rinsed in ethanol to remove the corrosion product, dried using acetone and re-weighed.

In determining the effect of temperature on the corrosion process, this same procedure was repeated using a water bath at temperatures of 30°C (303K), 40°C (313k), 50°C (323K), and 60°C (333K), each maintained for 6 hours and properly labeled. For each temperature that is been determined, the mild steel coupons were retrieved after 6 hours.

In determining the effect of acid concentration on the corrosion process the weighed mild steel coupons were each suspended and completely immersed in beakers containing 100ml of different concentrations of the acid, i.e. IM, 2M, 3M and 4M in the absence and presence of different concentrations of the plant extract, i.e. 0.5g/L, 1.0g/L, 1.5g/L and 2.0g/L at ambient temperature for 24 hours and properly labeled. For each acid concentration that is being determined the coupons were retrieved after 24 hours and then scrubbed with bristle brush under fast flowing water, rinsed in ethanol, dried using acetone and re-weighed.

The weight loss of the mild steel was evaluated in grams as the difference in the initial and final weight of the coupons. These experiments were carried out for the *Commelina benghalensis* leaves extract using concentrations of 0.5g/L, 1.0g/L, 1.5g/L and 2.0g/L. From the weight loss data the corrosion rates (CR) were calculated using equation 1 [6]:

$$CR \ (gcm^{-2}h^{-1}) = \frac{WL}{At} \qquad (1)$$

Where WL is weight loss in gram, A is the metal surface area and t is the time of immersion in hours.

From the corrosion rate values, the degree of surface coverage (θ) was got using equation 2:

$$\theta = \left[\frac{CR_{blank} - CR_{Inh}}{CR_{blank}} \right] \qquad (2)$$

The inhibition efficiencies (% 1E) of the plants extracts were determined using equation 3:

$$\% \ IE = \left[\frac{CR_{blank} - CR_{Inh}}{CR_{blank}} \right] x \ 100 \qquad (3)$$

Where CR_{blank} and CR_{Inh} are the corrosion rates in the absence and presence of the plants extracts respectively.

2.5. Thermodynamic and Adsorption Studies

The effect of temperature on the corrosion process was studied using the Arrhenius equation 4:

$$k = Ae^{-E_a/RT} \qquad (4)$$

Where k is the rate constant, A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant and T is the absolute temperature.

Rate law states that:

$$\text{rate} = \frac{-d(I)}{dt} = k(I)^n \qquad (5)$$

Where I is the inhibitor, (I) is the concentration of the inhibitor in mol per dm^3, t is the reaction time, k is the rate constant and n is the order of the reaction.

However, corrosion inhibition studies are done on the assumption of pseudo zero order condition [14]. Therefore:

$$\text{rate} = \frac{-d(I)}{dt} = k(I)^0 \qquad (6)$$

Equation 6 becomes:

$$\text{rate} = \frac{-d(I)}{dt} = k \qquad (7)$$

Hence in calculating the activation energy (E_a) using the condensed Arrhenius equation 8, k was substituted with the corrosion rate CR.

$$E_a = 2.303R \left[\log\left(\frac{CR_2}{CR_1}\right) \times \left(\frac{T_1 T_2}{T_2 - T_1}\right) \right] \qquad (8)$$

Where CR_1 and CR_2 are the corrosion rates at temperatures T_1 and T_2 respectively, and R is the universal gas constant.

The heat of adsorption (Q_{ads}) of the ethanol extracts of the leaves of the plants was calculated using equation 9:

$$Q_{ads} = 2.303R \left[\log\left(\frac{\theta_2}{1-\theta_2}\right) - \log\left(\frac{\theta_1}{1-\theta_1}\right) \left(\frac{T_1 T_2}{T_2 - T_1}\right) \right] \qquad (9)$$

Where θ_1 and θ_2 are the values of degree of surface coverage at temperatures T_1 and T_2 respectively. These values are approximately equal to change in enthalpy of adsorption (ΔH_{ads}) because the reactions were carried out at constant pressure.

Langmuir and Freundlich adsorption isotherms were tested to see if they fit the experimental data.

Langmuir adsorption isotherm postulates a monolayer adsorption of the adsorbate onto the adsorbent which is expected to have a coefficient of determination (R^2) of unity [10]. The R^2 value is also an indication that the plant extract's components are approximated by Langmuir adsorption isotherm and the monolayer of the extract species must have been attached to the metal surface without lateral interaction between the adsorbed species.

Langmuir adsorption isotherm is given by the expression:

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + c \qquad (10)$$

Where θ is the surface coverage, c is the concentration of the inhibitor, K_{ads} is the equilibrium constant of adsorption.

c/θ was plotted against c with the value of the intercept equal to $1/K_{ads}$, hence K_{ads} was calculated.

Freundlich adsorption isotherm postulate a multilayer adsorption of the adsorbate onto the adsorbent which is expected to have a coefficient of determination (R^2) of unity [15].

Freundlich adsorption isotherm is given by the expression:

$$\log \theta = \log k + 1/n \log c \qquad (11)$$

Where θ is the surface coverage, c is the concentration of the inhibitor, k and n are constants for a given adsorbate and adsorbent at a particular temperature. k is a function of energy of adsorption and temperature, and is a measure of adsorptive capacity while n determines the intensity of adsorption [16, 17].

$\log \theta$ was plotted against $\log c$ with the value of the intercept equal to $\log k$, hence k was calculated.

The standard Gibbs free energy of adsorption (ΔG^{θ}_{ads}) was obtained using equation 12:

$$\Delta G^{\theta}_{ads} = -2.303RT \log (55.5 k_{ads}) \qquad (12)$$

Where the numeral 55.5 is the molar concentration of water in solution, R is the universal gas constant ($8.314 Jmol^{-1}K^{-1}$), T is the absolute temperature and K_{ads} is the equilibrium constant of adsorption [6].

3. Results and Discussion

3.1. Phytochemical Screening of Plants Extracts

Table 1 showed the results of the phytochemical screening of the extract of *Commelina benghalensis* (C. B).

Table 1. Results of phytochemical screening.

Chemical Constituents	C. B
Alkaloids	+
Flavonoids	+
Tannins	+
Saponins	+
Phenols	+
Steroids	+
Cardiac Glycosides	+

Note: + = present
C. B = Commelina benghalensis

Table 1 showed that the plant extract contained considerable quantities of phytochemicals (alkaloids, flavonoids, tannins, saponins, phenols, steroids and cardiac glycosides). Therefore the inhibition efficiencies of the plant extract might be due to the presence of these constituents in the extract.

3.2. Effect of Time on the Corrosion of Mild Steel in 1M H_2SO_4 Solution

Table 2. *Weight loss of mild steel in 1M H_2SO_4 solution for different times at ambient temperature.*

Weight loss (g)					
Plant Sample	Extract Conc. (g/L)	24hr	72hr	120hr	168hr
C. B	Blank	2.267	4.027	5.628	6.108
	0.5	1.192	2.686	4.462	5.288
	1.0	0.822	2.037	3.714	4.959
	1.5	0.742	1.772	2.875	3.335
	2.0	0.681	1.231	1.872	2.510

From Table 2 it was observed that the weight loss of mild steel increased with increase in time, indicating that the rate of corrosion of mild steel in acid medium increased with time. Table 2 also showed that the weight loss of mild steel decreased with increase in the concentration of the ethanol extract of *Commelina benghalensis* leaves, showing that the corrosion of mild steel in the acid medium was retarded as the concentration of the inhibitor (extract) was increased.

3.3. Effect of Temperature on the Corrosion of Mild Steel in 1M H_2SO_4 Solution

Table 3. *Weight loss of mild steel in 1M H_2SO_4 solution at different temperatures for 6 hours.*

Weight loss (g)					
Plant Sample	Extract Conc. (g/L)	30°C	40°C	50°C	60°C
C. B	Blank	1.617	2.034	3.588	5.872
	0.5	0.430	0.758	2.117	4.214
	1.0	0.273	0.666	1.667	3.996
	1.5	0.200	0.551	1.520	2.902
	2.0	0.130	0.461	0.876	2.115

From Table 3 it was seen that the weight loss of mild steel increased with increase in temperature, an indication that the rate of corrosion of mild steel in acid medium increased with increase in temperature. This is because the rate of a chemical reaction increases with increase in temperature, due to increase in the kinetic energy of the reactant particles, leading to an increase in the frequency of collision.

It was also observed from Table 3 that the weight loss of mild steel decreased with increase in the concentration of the inhibitors. This showed that the inhibitors inhibited the corrosion of mild steel in H_2SO_4 medium.

3.4. Effect of Acid Concentration on the Corrosion of Mild Steel at Ambient Temperature

Table 4. *Weight loss of mild steel in different concentrations of H_2SO_4 solution for 24 hours at ambient temperature.*

Weight loss (g)					
Plant Sample	Extract Conc. (g/L)	1M	2M	3M	4M
C. B	Blank	3.348	6.438	9.762	10.046
	0.5	1.526	3.146	6.796	8.230
	1.0	1.232	2.607	5.914	7.024
	1.5	0.922	2.003	4.475	6.039
	2.0	0.422	1.263	3.187	5.786

Table 4 showed that the weight loss of mild steel increased with increase in acid concentration (H_2SO_4). This showed that the rate of corrosion of mild steel in acid medium increased with increase in the acid concentration (H_2SO_4). This could be attributed to the fact that the rate of a chemical reaction increases with increase in the concentration of the active species. Table 4 also indicated that the weight loss of mild steel decreased with increase in the concentration of the ethanol extract of *Commelina benghalensis* leaves for each acid concentration. This showed that the corrosion of mild steel in the acid medium was retarded as the concentration of the inhibitor (extract) was increased.

3.5. Corrosion Rate Data for Mild Steel Corrosion

Table 5. *Corrosion rate of mild steel in 1M H_2SO_4 solution at different temperatures.*

Corrosion rate (gcm^{-2} hr^{-1})					
Plant Sample	Extract Conc. (g/L)	30°C	40°C	50°C	60°C
C. B	Blank	0.0136	0.0171	0.0302	0.0494
	0.5	0.0036	0.0064	0.0178	0.0355
	1.0	0.0023	0.0056	0.0140	0.0336
	1.5	0.0017	0.0046	0.0128	0.0244
	2.0	0.0011	0.0039	0.0074	0.0178

It was seen from Table 5 that the corrosion rate of mild steel increased with increase in temperature. This showed that the rate of a chemical reaction increases with increase in temperature.

It was also observed from Table 5 that the corrosion rate decreased with increase in the extracts concentration. This might have resulted from the fact that adsorption and surface coverage increases with increase in extract concentration, thus, separating the surface of the metal from the acid medium (H_2SO_4), thereby preventing the metal from acid corrosion. This showed that the extract inhibited the corrosion of mild steel in 1M H_2SO_4 solution [10].

3.6. Surface Coverage and Corrosion Inhibition Efficiency Data for the Extract of Commelina Benghalensis

Table 6 indicated that the inhibition efficiency increased with increase in extract concentrations. It reached 91.91% at 2.0g/L C. B. An increase in the concentration of the plant extract meant that the degree of surface coverage (θ) of the mild steel surface by the inhibitor was increased, leading to increase in adsorption of the inhibitor molecules on the mild steel surface thereby protecting the "covered" surface from further corrodent (H_2SO_4) attack. This showed that the extracts inhibited the corrosion of mild steel in H_2SO_4 solution. From Table 6, it was observed that inhibition efficiency decreased with increase in temperature. The drop in inhibition efficiency could be due to solubility of the protective films on the mild steel surface as temperature increased, which increased the susceptibility of the metal to acid corrosion, as noted by [18] or due to desorption of the inhibitor as explained by [19].

Table 6. *Surface coverage and corrosion inhibition efficiency of C. B extract on mild steel in 1M H_2SO_4 solution at different temperatures.*

Inhibition Efficiency (%IE)						Surface Coverage (θ)			
Plant Sample	Extract Conc. (g/L)	30°C	40°C	50°C	60°C	30°C	40°C	50°C	60°C
C. B	0.5	73.53	62.57	41.06	28.14	0.7353	0.6257	0.4106	0.2814
	1.0	83.09	67.25	53.64	31.98	0.8309	0.6725	0.5364	0.3198
	1.5	87.50	73.10	57.62	50.61	0.8750	0.7310	0.5762	0.5061
	2.0	91.91	77.19	75.50	63.97	0.9191	0.7719	0.7550	0.6397

As temperature increased, adsorption and the degree of surface coverage decreased since there was reduced adsorption of the extract on the metal surface, which was physical in nature. Decrease in inhibition efficiency with increase in temperature was suggestive of physical adsorption process (physiosorption) [20].

3.7. Thermodynamic Data for the Corrosion of Mild Steel in 1M H_2SO_4 Solution

Table 7. *Thermodynamic parameters for mild steel coupons in 1M H_2SO_4 solution at 30°C and 40°C.*

	C. B	
Extract Conc. (g/L)	E_a (kJ/mol)	ΔH_{ads} (kJ/mol)
Blank	18.07	-
0.5	45.38	-40.06
1.0	70.18	-68.82
1.5	78.50	-74.62
2.0	99.82	-95.52

Calculated values of activation energy were presented in Table 7. The values were found to increase with increase in the concentration of the extract (inhibitor), meaning that a higher protection efficiency was attained due to increase in the energy barrier for the reaction as the concentration of the extract increased. This showed that the extract (inhibitor) was physically adsorbed on the surface of the mild steel [9].

Calculated values of heat of adsorption (Q_{ads}) were presented in Table 7. These values are approximately equal to change in enthalpy of adsorption (ΔH_{ads}) because the reactions were carried out at constant pressure [6].

It was observed from Table 7 that the values of (ΔH_{ads}) was negative for the plant extract indicating that the adsorption of the extract of the plant was exothermic (exothermic adsorption process). Exothermic adsorption process signifies either physical or chemical adsorption, while endothermic adsorption process is attributed to chemical adsorption (chemisorption). In an exothermic adsorption process, physical adsorption is distinguished from chemical adsorption by considering the absolute value of adsorption enthalpy. Typically, enthalpy of physical adsorption process is lower than 80kJmol[-1] while the enthalpy of chemisorption process approaches 100kJmol[-1] [21].

Except for the ΔH_{ads} value for *Commelina benghalensis* at 2.0g/L (-95.52kJmol[-1]), all other values of the calculated enthalpy of adsorption (ΔH_{ads}) for the extract of the plant suggested physical adsorption of the inhibitors (plants extracts) on the surface of the metal.

3.8. Adsorption Data for the Corrosion of Mild Steel in 1M H_2SO_4 Solution

The experimental data was subjected to Langmuir and Freundlich adsorption isotherm equations.

Table 8. *Data for Langmuir adsorption isotherm plots for the adsorption of C. B extract on the surface of mild steel.*

Surface Coverage (θ)						C/θ			
Plant Sample	Extract Conc. (g/L)	30°C	40°C	50°C	60°C	30°C	40°C	50°C	60°C
C. B	0.5	0.7353	0.6257	0.4106	0.2814	0.6800	0.7991	1.2177	1.7768
	1.0	0.8309	0.6725	0.5364	0.3198	1.2035	1.4870	1.8643	3.1270
	1.5	0.8750	0.7310	0.5762	0.5061	1.7143	2.0520	2.6033	2.9638
	2.0	0.9191	0.7719	0.7550	0.6397	2.1760	2.5910	2.6490	3.1265

Table 9. *Data for Freundlich adsorption isotherm plots for the adsorption of C. B extract on the surface of mild steel.*

			Surface Coverage (θ)				log θ			
Plant Sample	Extract Conc.	log C	30°C	40°C	50°C	60°C	30°C	40°C	50°C	60°C
C. B	0.5	-0.3010	0.7353	0.6257	0.4106	0.2814	-0.1335	-0.2036	-0.3866	-0.5507
	1.0	0.0000	0.8309	0.6725	0.5364	0.3198	0.0805	-0.1723	-0.2705	-0.4951
	1.5	0.1761	0.8750	0.7310	0.5762	0.5061	0.0580	-0.1361	-0.2394	-0.2958
	2.0	0.3010	0.9191	0.7719	0.7550	0.6397	0.0366	-0.1124	-0.1221	-0.1940

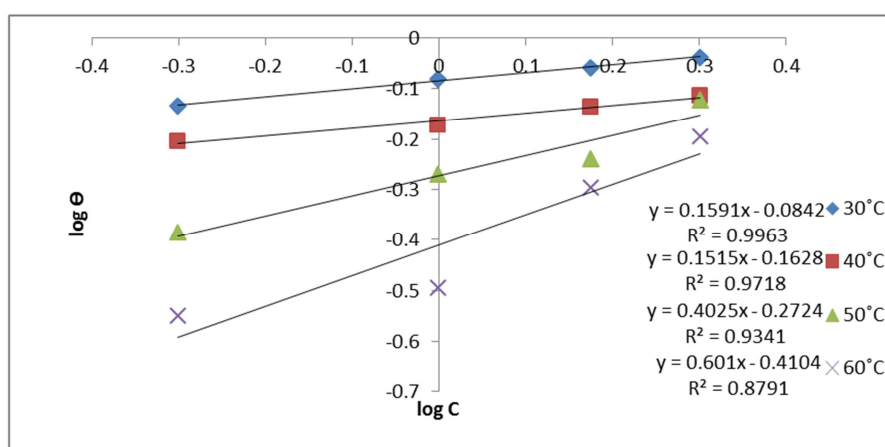*Figure 1.* Langmuir plots for Commelina benghalensis at different temperatures.

Plot legends:
$y = 0.9998x + 0.1937$, $R^2 = 0.9992$, 30°C
$y = 1.1881x + 0.2471$, $R^2 = 0.9966$, 40°C
$y = 1.0066x + 0.8253$, $R^2 = 0.9127$, 50°C
$y = 0.7772x + 1.777$, $R^2 = 0.5914$, 60°C

Figure 2. Freundlich plots for Commelina benghalensis at different temperatures.

Plot legends:
$y = 0.1591x - 0.0842$, $R^2 = 0.9963$, 30°C
$y = 0.1515x - 0.1628$, $R^2 = 0.9718$, 40°C
$y = 0.4025x - 0.2724$, $R^2 = 0.9341$, 50°C
$y = 0.601x - 0.4104$, $R^2 = 0.8791$, 60°C

Table 10. Langmuir and Freundlich adsorption isotherm parameters for the adsorption of C. B extract on the surface of mild steel.

Temperature (°C)	Langmuir			Freundlich	
	K_{ads}	R^2	ΔG^θ_{ads} (kJ/mol)	k	R^2
30	5.181	0.999	-14.26	0.824	0.996
40	4.049	0.996	-14.09	0.689	0.972
50	1.212	0.912	-11.30	0.535	0.934
60	0.563	0.591	-9.53	0.389	0.879

Linear plots were obtained from Figures 1 and 2, with good coefficients of determination (R^2) which were almost equal to unity (1). This showed that the adsorption of the extract (inhibitor) obeyed Langmuir and Freundlich adsorption isotherms. It was observed from Table 10 that the values of K_{ads} obtained from the intercept of the Langmuir isotherm plots decreased with increase in temperature indicating that the extract (inhibitor) was physically adsorbed on the surface of the mild steel [22]. It was also seen from Table 10 that the values of k (adsorptive capacity) calculated from the intercept of the Freundlich isotherm plots, decreased with increase in temperature indicating that the adsorption of the extract on the mild steel surface was reduced at higher temperatures, since adsorptive capacity decreased with

increase in temperature. Values of K_{ads} obtained from the Langmuir adsorption isotherm were used to calculate ΔG^θ_{ads} using equation 12. Generally, value of ΔG^θ_{ads} around -20kJmol^{-1} or lower are consistent with physisorption i.e. the electrostatic interaction between the charged molecules and the charged metal; those around -40kJ/mol or higher are consistent with chemisorption which involve charge sharing or transfer from the inhibitor molecules to the metal surface to form a coordinate type of bond [23, 24]. The ΔG^θ_{ads} values obtained showed that the adsorption mechanism of the plant extract on mild steel was by physical adsorption mechanism (physisorption), since they were less than -20kJ/mol. The negative values of ΔG^θ_{ads} showed that the adsorption process was spontaneous.

4. Conclusion

The corrosion inhibition efficiency of the plant extract could be due to their phytochemical constituents (alkaloids, flavonoids, tannins, saponins, phenols, steroids and cardiac glycosides) which aided their adsorption on the surface of the mild steel. The corrosion inhibition efficiency of the plant extract is temperature and extract concentration dependent, since it increased with increase in the concentration of the extract and decreased with increase in temperature. The adsorption of the plant extract are consistent with the process of physical adsorption and are spontaneous, since their Gibbs free energy values (ΔG^θ_{ads}) were less than 20kJ/mol and found to be negative. The adsorption of the ethanol extract of the leaves of *Commelina benghalensis* obeyed Langmuir and Freundlich adsorption isotherms, since linear plots were obtained from both isotherms with good coefficients of determination (R^2), which were almost equal to unity (1). The ethanol extract of the leaves of *Commelina benghalensis* is a good corrosion inhibitor of mild steel in acidic solutions (1M H$_2$SO$_4$), since it reached a corrosion inhibition efficiency of 91.91% at 2.0g/L extract concentration.

References

[1]   Akhmetov, B., Novichenko, Y. V. and Chapurin, V., (1989). Physical and Colloid Chemistry, 1st edition, Mir Publishers, Moscow, pp. 345-432.

[2]   Fontana, M. G. and Greene, N. D., (1967), Corrosion Engineering, McGraw-Hill Book Company., New York, p. 1679.

[3]   Uhlig, H. H., (1971). Corrosion and Corrosion Control, 2nd edition., John Wiley and Sons, New York, pp. 257-346.

[4]   Fontana, M. G., (1987). Corrosion Engineering, 3rd Edition, McGraw-Hill Book Company, Boston, p. 143-160.

[5]   Sorkhabi, H. A., Seifzadeh, D., Hosseini, M. G., (2008). EIS and polarization studies to evaluate the inhibition effect of 3H-phenothiazin-3-one, 7-dimethylamine on mild steel corrosion in 1M HCl solution, *Corrosion Science*, 50: 3363.

[6]   Odidika, C. C., Ajiwe, V. I. E., Eboagu, N. C., and Awuzie, C. I., (2020). Corrosion inhibitive action of *Euphorbia heterophylla* leaves extract on mild steel in 1 M H$_2$SO$_4$ solution. *Open Science Journal of Analytical Chemistry*. 5 (1): 1-8.

[7]   Udensi, S. C., Ekpe, O. E., and Nnanna, L. A., (2020). *Newbouldia laevis* leaves extract as tenable eco-friendly corrosion inhibitor for aluminium alloy AA7075-T7351 in 1 M HCL corrosive environment: Gravimetric, electrochemical and thermodynamic studies. *Chemistry Africa*. 3: 303-316.

[8]   Zheng, X., Gong, M., Li, Q., and Guo, L., (2018). Corrosion inhibition of mild steel in sulfuric acid solution by loquat (Eriobotrya japonica Lindl.) leaves extract. *Sci Rep* 8: 9140.

[9]   Ishak, A., Adams, F. V., Madu, J. O., Joseph, I. V., and Olubambi, P. A., (2019). Corrosion inhibition of mild steel in 1 M hydrochloric acid using *Haematostaphis barteri* leaves extract. *Procedia Manufacturing*. 35: 1279-1285.

[10]   Singh, M. R., Gupta, P., and Gupta, K., (2019). The Litchi (*Litchi Chinensis*) peels extract as a potential green inhibitor in prevention of corrosion of mild steel in 0.5 M H$_2$SO$_4$ solution. *Arabian Journal of Chemistry* 12 (7): 1035-1041.

[11]   Ajiwe, V. I. E., and Ejike, C. M., (2019). Corrosion inhibition of mild steel in sulphuric acid by methanol leaf extracts of Milicia excels. *Open Science Journal of Analytical Chemistry.* 4 (2): 13-19.

[12]   Okafor, P. C. and Apebende, E. A., (2014). Corrosion Inhibition Characteristics of *Thymus vulgaris*, *Xylopia aethiopica* and *Zingiber officinale* Extracts on Mild Steel in H$_2$SO$_4$ Solution. *Pigment and Resin Technology*, 43 (6): 357-364.

[13]   Al-Mhyawi, S. R., (2014). Inhibition of mild steel corrosion using Juniperus plants as green inhibitors. *African Journal of Pure and Applied Chemistry*, 8 (1): 9-22.

[14]   El-Awady, A. A., Abd-El-Nabey, B. A. and Aziz, S. G., (1992). Kinetic-Thermodynamic and Adsorption Isotherms Analyses for the Inhibition of the Acid Corrosion of Steel by Cyclic and Open Chain Amines, *Journal of Electrochemical Society*, 139 (8): 2149-2154.

[15]   Vasudha V. G. and Shanmuga P. K. (2014) "Corrosion inhib ition of mild steel in H$_2$SO$_4$ media using *Polyalthialongifolia leaves*, Chemical Science Revision Letters, 2 (6): 435-443.

[16]   Uddin, M. T., Islam, M. S. and Abedin, M. Z., (2007). "Adsorption of phenol from aqueous solutions by water hyacinth ash." ARPN *Journal of Engineering and Applied Sciences*, 2 (2): 121-128.

[17]   Khan, A. R., Tahir, H., Uddin, F. and Uzma, H., (2005). Adsorption of methylene blue from aqueous solutions on the surface of wool fiber and cotton fiber. *Journal of Applied Science and Environmental Management*, 9 (2): 29-35.

[18]   James, A. O., Oforka, N. C., Abiola, O. K. and Ita, B. I., (2009). Corrosion inhibition of mild steel in HCl acid by 2-Benzoylpyridine and pyridoxohydrochloride. *Journal of Chemistry*, 6 (2): 385-394.

[19]   Okafor, P. C., Ebenso, E. E. and Ekpe, U. J., (2010). *Azadirachta indica* extracts as corrosion inhibitor for mild steel in acidic medium, *International Journal Electrochemical Science*, 5: 978-993.

[20]   Obi-Egbedi, N. O., Obot, I. B. and Umoren, S. A., (2012). *Spondias mombin L.* as a green corrosion inhibitor for aluminium in sulphuric acid, *Arabian Journal of Chemistry*, 5: 361-373.

[21]   Martinez, S. and Stern, I., (2002). Thermodynamic characterization of metal dissolution and inhibitor adsorption processes in the low carbon steel/mimosa tannin/sulfuric acid system. *Applied surface science*, 199: 83–89.

[22]   Ikpi, M. E., Udoh, I. I., Okafor, P. C., Ekpe, U. J. and Ebenso, E. E., (2012). Corrosion inhibition and Adsorption Behaviour of Extracts from *Piper guineensis* on mild steel corrosion in Acid media, *International Journal of Electrochemical science*, 7: 12193–12206.

[23]   Le Mehaute, A. and Grepy, G., (1983). "Introduction to transfer and motion in fractal media: the geometry of kinetics", Solid State Ionics, 17 (9-10): 17–30.

[24]   Reinhard, G. and Rammet, U., (1985). In Proceedings of the Proceedings of the 6th European Symposium on Corrosion inhibitors, Ferrara, Italy, p. 831.