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Adsorption Characteristics and Inhibition Effect of *Telfairia occidentalis* Stem Extract on Mild Steel Corrosion in Acidic Medium

Abakedi O. U. [1]*, James M. A. [1], Udongwo A. M. [2]
[1]*Department of Chemistry, University of Uyo, Uyo, Nigeria*
[2]*Department of Chemistry, Akwa Ibom State College of Education, Afaha Nsit, Nigeria*
**Corresponding author, Email address: okonabakedi@uniuyo.edu.ng*

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Abstract: The corrosion inhibitory potential of *Telfairia occidentalis* stem extract (TOSE) on mild steel in 1 M H_2SO_4 solution was investigated by weight loss and hydrogen evolution methods. The weight loss data reveal that at constant temperature, the corrosion rate of mild steel decreases with increase in extract concentration. The inhibition efficiency of TOSE increases with increase in extract concentration but decreases with a rise in temperature. The hydrogen evolution data indicate that the increase in the inhibition efficiency with increase in TOSE concentration is due to a drastic reduction in the hydrogen evolution rate by the extract. The calculated thermodynamic parameters reveal that the corrosion inhibition process is endothermic in nature. Based on a decrease in inhibition efficiency with a rise in temperature as well as a higher activation energy (E_a) in the presence of the extract relative to the blank, physisorption process has been proposed for the adsorption of TOSE on mild steel surface. The surface morphology of the mild steel coupons by SEM analysis confirms that the mild steel surface in the presence of TOSE was smoother compared to that in the blank which was severely corroded. The adsorption of TOSE on mild steel surface obeys the Langmuir adsorption isotherm

1. Introduction

Metals are unavoidably exposed to aggressive environments in some industrial processes. The standard practice is to add corrosion inhibitors to the aggressive media in order to reduce the rate of metal corrosion and hence extend their service life. The traditional corrosion inhibitors in common use are synthesized organic compounds containing heteroatoms like N, O, S and/or P (Abakedi *et al*., 2020; Berisha, 2022; Singaravelu and Bhadusha, 2022; Singaravelu *et al*., 2022; Ashmawy *et al*., 2023). The major drawback to the use of these inhibitors nowadays is their high toxicity and environmentally - unfriendly characteristics (Belghiti *et al.*, 2020; Zarrouk *et al.*, 2013; Bouklah *et al.*, 2004). Fortunately, green corrosion inhibitors have been extracted from biomass (Umoren *et al.*, 2016). Some stem extracts reported as potential corrosion inhibitors for mild steel in acidic medium include *Sida acuta* stem extract (Umoren *et al*., 2016). *Corchorus olitorius* stem extract (Oyewole *et al*., 2021), *Pterocarpus marsupium* stem extract (Lavanya *et al*., 2023), opuntia stem extract (Honarmand *et al*., 2017), *Acacia milotica* stem extract (Mahgoud *et al*., 2019). *Eupartorium adenophora spreng* stem extract (Wong *et* *al.*, 2024) and banana pseudo – stem extract (Honesty *et al.*, 2024). Researches are ongoing in order to find more efficient corrosion inhibitors for mild steel in acidic medium (Hmaimou *et al.*, 2025).

Telfairia occidentalis (commonly called fluted pumpkin) is a staple vegetable in Nigeria. It belongs to the family *Cucurbitaceae*. The leaves and seeds of *T. occidentalis* are edible while the stems are discarded as waste. Preliminary phytochemical screening of *T. occidentalis* stem extract indicates the presence of alkaloids, saponins, tannins, flavonoids, terpenes, glycosides and phenolics (Bliss *et al.*, 2022). Some parts of *T. occidentalis* reported as potential corrosion inhibitors on mild steel in acidic medium include *T. occidentalis* leaf extract (Oguzie, 2005; Nwabanne *et al.*, 2011), *T. occidentalis* rind/pod extract (Akpan *et al*., 2018; Okewale and Adebayo, 2020). The use of *T. occidentalis* stem extract as corrosion inhibitor for mild steel in acidic medium has not been systematically studied (Ananaba and Okonkwo, 2023). The aim of this work is to assess the inhibitory potential of *T. occidentalis* stem extract on mild steel corrosion in acidic medium.

2. Methodology

2.1 Test materials

The mild steel sheet used for this work had the following chemical composition (w/w %): C (0.12), Mn (0.85), S (0.06), P (0.05), Si (0.09) and Fe (98.83). Fresh stems of *Telfairia occidentalis* were collected from a grocery store in Uyo, Nigeria and authenticated by a plant taxonomist in the Department of Botany and Ecological Studies, University of Uyo, Uyo, Nigeria.

2.2 Preparation of Telfairia occidentalis stem extract

Fresh *Telfairia occidentalis* stems were washed with deionized water, cut into small pieces. and oven-dried at 50 °C until constant weight. They were then ground to powder using a grinder. The dried ground sample of *T. occidentalis* stem was macerated with 90% ethanol for three days, with intermittent stirring, at room temperature in a glass trough with cover. The mixture was then filtered. The filtrate was evaporated in a water bath at 40 °C to constant weight, leaving a dark green extract in the beaker. Extract concentrations of 0.5 g/L, 1.0 g/L, 1.5 g/L and 2.0 g/L, respectively, were prepared in 1 M H_2SO_4 solution for both the weight loss and hydrogen evolution studies.

2.3 Weight loss method

Pre – washed and weighed mild steel coupons were suspended by glass hooks and completely immersed in separate 100 ml beakers containing 1 M H_2SO_4 solution (blank) and different concentrations of *T. occidentalis* stem extract (0.5 g/L, 1.0 g/L, 1.5 g/L, and 2.0 g/L) in a thermostatic water bath maintained at 30 °C, 40 °C, 50 °C and 60 °C, respectively. After four (4) hours, the coupons were retrieved from the corrodent, scrubbed with bristle brush under running water. They were then dipped into acetone and air – dried before reweighing. The weight losses of the coupons, in the absence and presence of the extract, were recorded.

The weight loss was used to calculate the corrosion rate, CR (mg cm^{-2} hr^{-1}), using the Eqn 1 (Abakedi *et al.*, 2016):

$$\text{CR}\ (\text{mg cm}^{-2}\text{hr}^{-1}) = \frac{\text{W}}{\text{A.t}} \qquad \textbf{Eqn. 1}$$

where W is the weight loss of mild steel coupon (mg), A is the surface area (cm^2) and t is the immersion time (hours).

The inhibition efficiency, I_{wL} (%), of mild steel was obtained using Eqn 2 (Abakedi *et al.*, 2024):

$$I_{WL}(\%) = \left(1 - \frac{w_1}{w_0}\right) \times 100 \qquad \textbf{Eqn. 2}$$

where w_1 and w_0 are weight losses of mild steel coupons in 1 M H_2SO_4 solution with and without inhibitor, respectively.

2.4 Hydrogen evolution method

The hydrogen evolution tests (via a gasometric assembly) were done as described in previous publications (Abakedi and Asuquo, 2016; Abakedi and Sunday, 2017). The corrodent was 100 ml of 1 M H_2SO_4 solution. About 8 g mild steel coupon was dropped into the 1 M H_2SO_4 solution (blank) and the reaction vessel quickly corked. The volume of H_2 gas evolved from the corrosion reaction was recorded every 60 seconds for 60 minutes. The experiment was repeated using 0.5 – 2.0 g/L *T. occidentalis* stem extract (TOSE) in 1 M H_2SO_4 solution. The inhibition efficiency I_{HE} (%) was evaluated using Eqn. 3 (Abakedi and Sunday, 2017):

$$I_{HE} = \left(1 - \frac{V_1}{V_0}\right) \times 100 \qquad \textbf{Eqn 3}$$

where V_0 and V_1 are the hydrogen evolution rates of mild steel coupons in 1 M H_2SO_4 solution without and with inhibitor, respectively.

2.5 Scanning Electron Microscopy Study

Mild steel coupons (4 cm × 4 cm) were abraded to mirror finish, cleaned and dried. The morphologies of the surfaces of the coupons immersed in 100 ml 1 M H_2SO_4 for four hours without and with 2.0 g/L TOSE were scanned using FEI Nova NanoSEM 230 analyzer.

3. Results and Discussion

3.1 Effect of Telfairia occidentalis stem extract concentration on inhibition efficiency

The effect of *Telfairia occidentalis* stem extract (TOSE) concentration on the corrosion rate of mild steel in 1 M H_2SO_4 solution at 30 °C is shown in Figure 1. It is observed that there is a drastic reduction in the corrosion rate of mild steel in the presence of the extract compared to that of the blank.

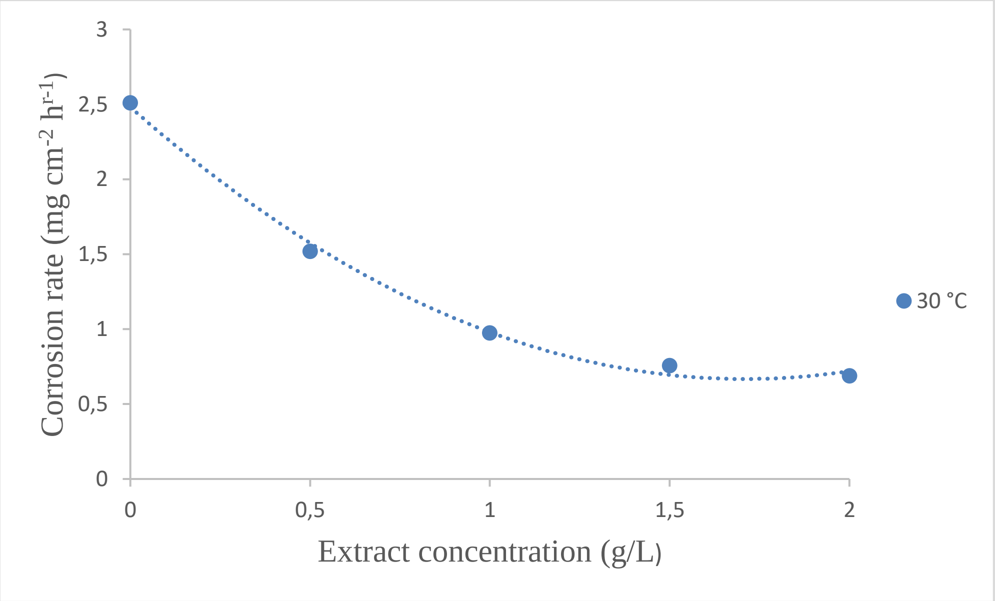


Figure 1: Effect of *T. occidentalis* stem extract concentration on the corrosion rate of mild steel in 1 M H_2SO_4 solution at 30 °C

The resultant effect is an increase in the inhibition efficiency of mild steel in the corrodent, as shown in Figure 2. Figure 2 reveals that at constant temperature, the inhibition efficiency increases with increase in TOSE concentration. The highest inhibition efficiency of 72.56% was obtained at extract concentration of 2.0 g/L at 30 °C. This indicates that TOSE inhibited the corrosion of mild steel in the 1 M H_2SO_4 solution. Additionally, an increase in inhibition efficiency with increase in extract concentration signifies that the adsorption of the extract on mild steel. surface is concentration – dependent.

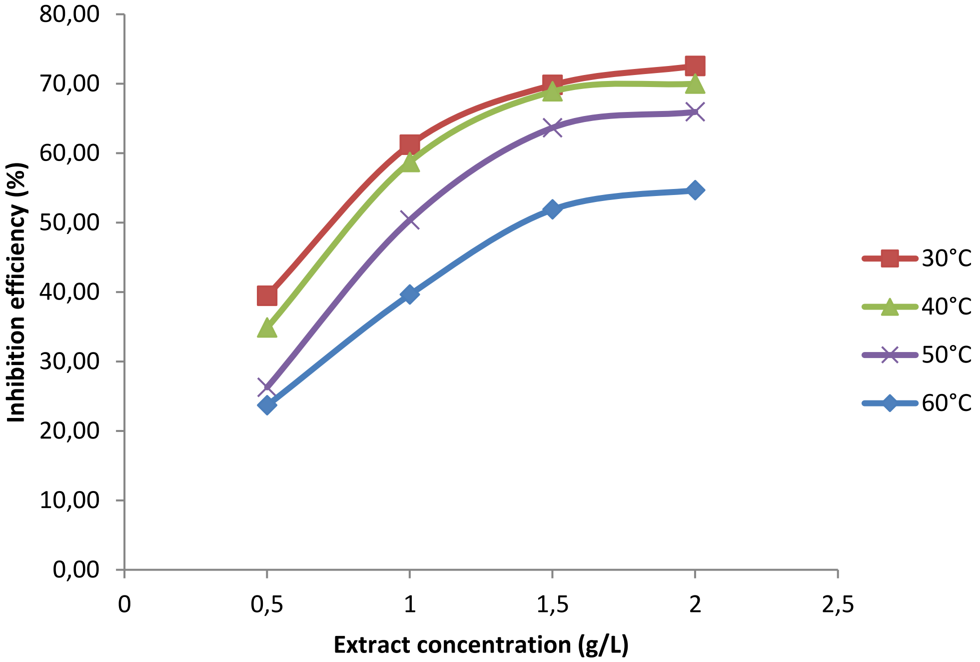


Figure 2: Effect of *T. occidentalis* stem extract (TOSE) concentration on inhibition efficiency of mild steel in 1 M H_2SO_4 solution

3.2 *Hydrogen Evolution Measurements*

The results of the hydrogen evolution test, illustrated in Figure 3 indicate an appreciable reduction in the volume of hydrogen gas evolved in the presence of TOSE relative to the blank. The extract probably adsorbed on the mild steel surface and hindered the evolution of hydrogen gas. The inhibition efficiency by the hydrogen evolution method, presented in Table 1, indicates an increase in inhibition efficiency as TOSE concentration increases. The highest inhibition efficiency by this method was 74.80% at 2.0 g/L extract concentration. The inhibition efficiency by both weight loss and hydrogen evolution methods followed a similar trend, thus indicating that TOSE appreciably inhibited the corrosion of mild steel in 1 M H_2SO_4 solution.

3.3 Effect of Temperature on Inhibition Efficiency

The inhibition efficiency of TOSE was affected by changes in the temperature of the system, as presented in Table 2. A rise in temperature resulted in a decrease in the inhibition efficiency of TOSE on mild steel. A decrease in inhibition efficiency with a rise in temperature indicates that the extract functioned more effectively as an inhibitor at a lower temperature than at a higher temperature. Furthermore, as temperature rises, some extract desorbs from the mild steel surface, hence reducing the surface coverage and inhibition efficiency.

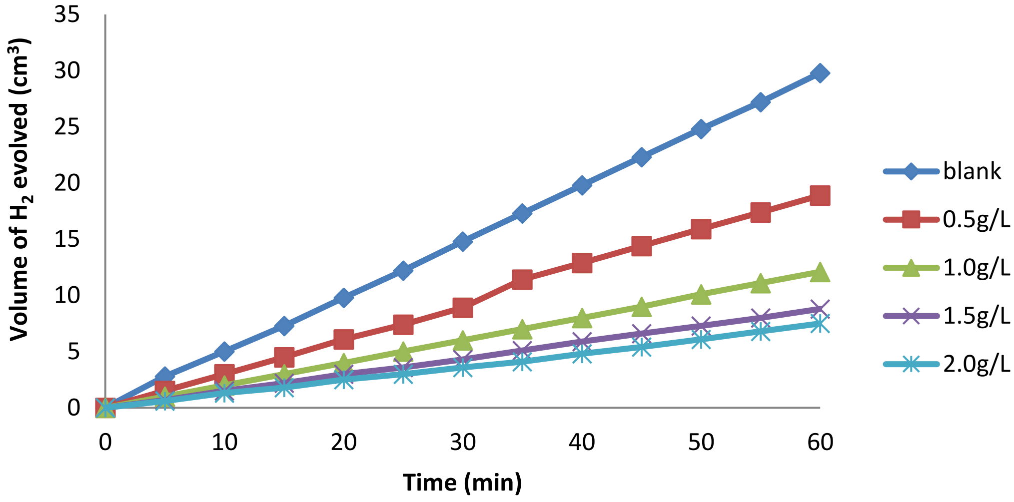


Figure 3: Volume – time curve obtained in the absence and presence of various concentrations of *T. occidentalis* stem extract on mild steel in 1 M H_2SO_4 solution at 30 °C

Table 1: Effect of *T. occidentalis* stem extract concentration on inhibition efficiency of mild steel in 1 M H_2SO_4 solution at 30°C (Hydrogen evolution measurements)

Extract concentration (g/L)	H_2 evolution rate (cm^3/min)	Inhibition efficiency (%)
1 M H_2SO_4 (Blank)	0.496	-
0.5	0.315	36.49
1.0	0.202	59.27
1.5	0.147	70.38
2.0	0.125	74.80

Table 2: Calculated values of corrosion rate and inhibition efficiency for mild steel in 1 M H_2SO_4 in the absence and presence of different concentrations of *T. occidentalis* stem extract at 30 °C – 60 °C

Extract conc. (g/L)	Corrosion rate (mg cm^{-2} hr^{-1})				Inhibition efficiency (%)			
	30 °C	40 °C	50 °C	60 °C	30 °C	40 °C	50 °C	60 °C
Blank	2.5102	5.2078	9.0203	20.8336	-	-	-	-
0.5	1.5195	3.3922	6.6500	15.9016	39.46	34.86	26.28	23.67
1.0	0.9742	2.1492	4.4766	12.5813	61.19	58.73	50.37	39.61
1.5	0.7578	1.6211	3.7438	10.0250	69.81	68.87	63.66	51.88
2.0	0.6891	1.5625	3.0734	8.5484	72.55	70.00	65.93	54.65

The activation energies (E_a) of the corrosion process in the absence and presence of TOSE, respectively, were calculated using the Arrhenius equation (Eqn 4) (Abakedi and Asuquo, 2016):

$$\ln CR = \frac{-E_a}{RT} + \ln A \qquad \textbf{Eqn. 4}$$

where R is the universal gas constant, CR is the corrosion rate; T is the temperature in Kelvin while A is the pre-exponential factor.

The activation energies (E_a) of mild steel corrosion in 1 M H_2SO_4, with and without TOSE, were obtained from the gradients of ln CR vs. 1/T plots (Figure 4), and the results are presented in Table 3. It is observed that the E_a values in the presence of TOSE are higher than the E_a of the blank (57.36 kJ mol^{-1}). An increase in the E_a value in the presence of the extract relative to the blank implies that the extract increased the activation energy barrier of the corrosion reaction, thus slowing down the corrosion process. Additionally, an increase in the E_a value in presence of the extract relative to the blank signifies a physisorption process (Bentiss *et al*., 2007; Ashmawy *et al*., 2023).

The values of enthalpy of activation ($\Delta H°_{ads}$) and entropy of activation ($\Delta S°_{ads}$) were evaluated from an alternative formulation of the Transition State equation (Eqn. 5) Abakedi and Asuquo, 2016):

$$\ln\left(\frac{CR}{T}\right) = \left[\ln\left(\frac{R}{Nh}\right) + \frac{\Delta S^{o}{}_{ads}}{R}\right] - \frac{\Delta H^{o}{}_{ads}}{RT} \qquad \textbf{Eqn. 5}$$

where CR is the corrosion rate, T is temperature in Kelvin, R is the universal gas constant, N is Avogadro's number, A the Arrhenius pre-exponential factor, while h is the Planck's constant.

Linear plots of ln (CR/T) vs. 1/T Figure 5 with gradients of ($-\Delta H°_{ads}/R$) and intercepts of [ln (R/Nh) + $\Delta S°_{ads}/R$] were obtained from which the values of $\Delta H°_{ads}$ and $\Delta S°_{ads}$ were evaluated and presented in Table 3. The positive values of $\Delta H°_{ads}$ both in the absence and presence of TOSE signify that the corrosion process was endothermic. Also, the negative values of $\Delta S°_{ads}$ obtained indicate a decrease in the disorderliness of the system (Hammouti *et al*., 2011).

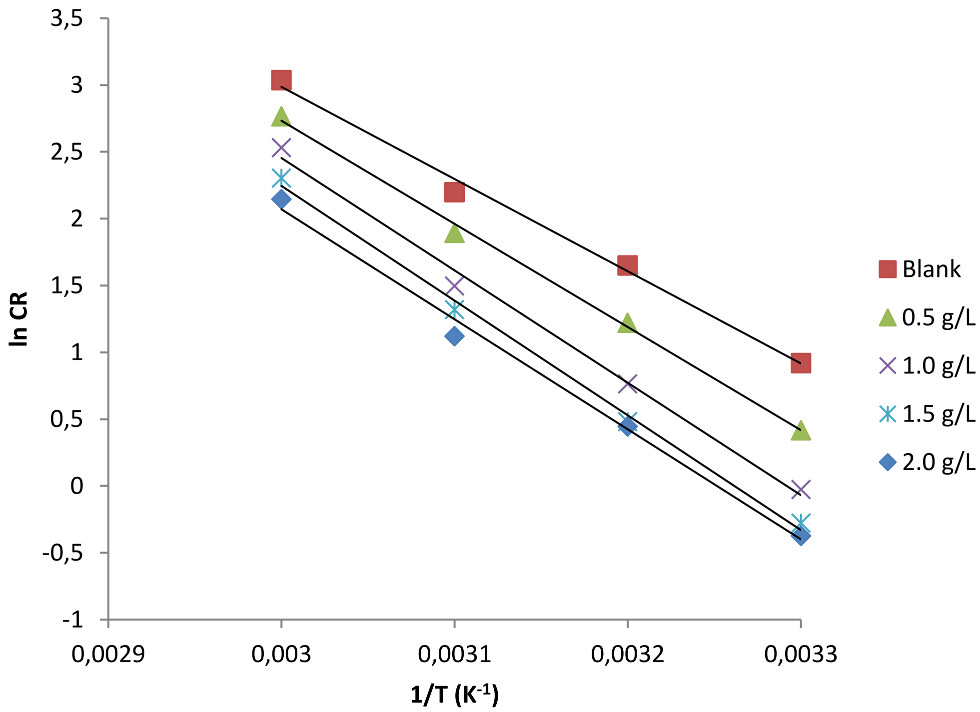


Figure 4: Arrhenius plot for mild steel corrosion in 1 M H_2SO_4 in the absence and presence of TOSE

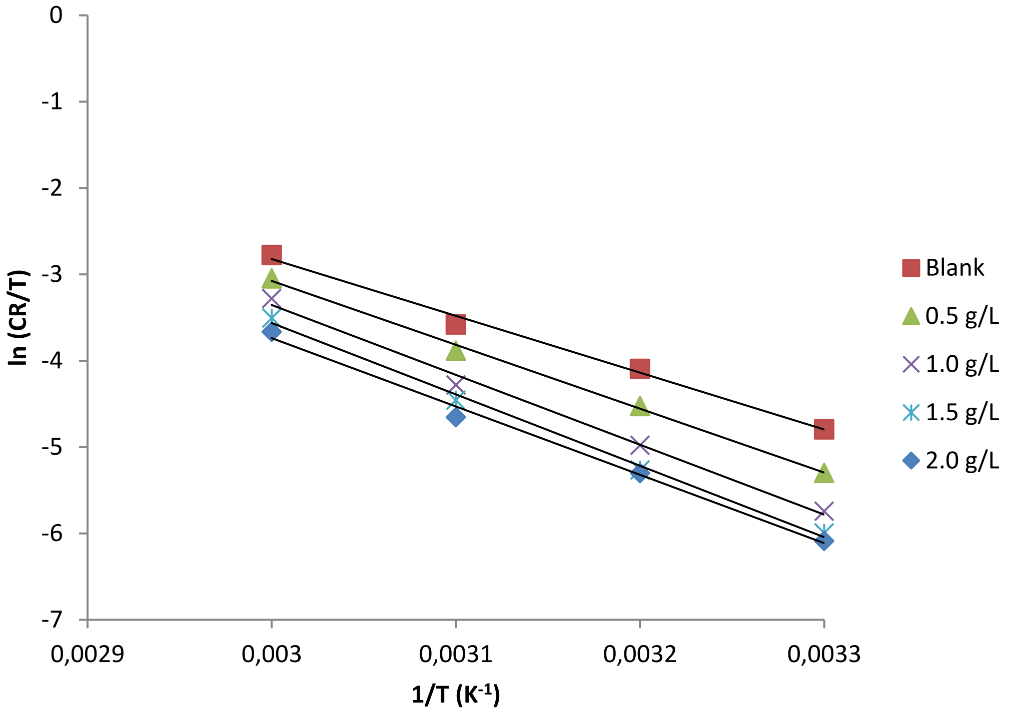


Figure 5: Transition State plot for mild steel corrosion in 1 M H_2SO_4 in the absence and presence of TOSE

Table 3: Calculated values of thermodynamic parameters for mild steel corrosion in 1 M H_2SO_4 in the absence and presence of *T. occidentalis* stem extract

Extract conc. (g/L)	E_a (kJ mol^{-1})	ΔH (kJ mol^{-1})	ΔS (JK^{-1}mol^{-1})
1 M H_2SO_4 **(**Blank)	57.36	54.71	-56.89
0.5	64.16	61.52	-38.56
1.0	69.91	67.28	-23.62
1.5	71.37	68.73	-20.99
2.0	68.44	65.80	-31.25

3.4 Adsorption studies

The adsorption of TOSE on mild steel surface were fitted into several adsorption isotherms. The best fit was obtained with the Langmuir adsorption isotherm defined by Eqn. 6 (Bhuvaneswari *et al*., 2020; Ran *et al*., 2023):

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \quad \textbf{Eqn 6}$$

where θ is the degree of surface coverage, C is the concentration of inhibitor and K_{ads} is the equilibrium constant of the adsorption process.

Linear plots of C/θ vs. C with high R^2 values (Figure 6) confirm that the adsorption of TOSE on mild steel surface obeyed the Langmuir adsorption isotherm. From the intercepts of the graph, values of K_{ads} were obtained and presented in Table 4. Table 4 reveals that the highest value of K_{ads} was obtained at

30 °C. Furthermore, the value of K_{ads} decreases as the temperature rises from 30 °C to 60 °C. A decrease in the value of K_{ads} with increase in temperature indicates that the extract was most strongly adsorbed on mild steel surface at 30 °C. A decrease in the value of K_{ads} as well as a decrease in the inhibition efficiency with a rise in temperature of the system signifies a physisorption process.

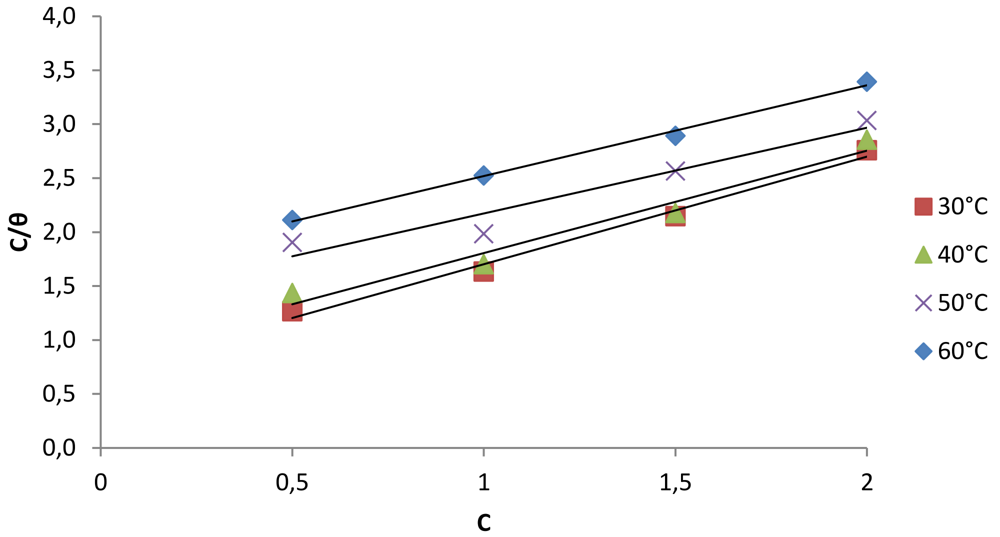


Figure 6: Langmuir isotherm for mild steel corrosion in 1 M H_2SO_4 in the absence and presence of TOSE

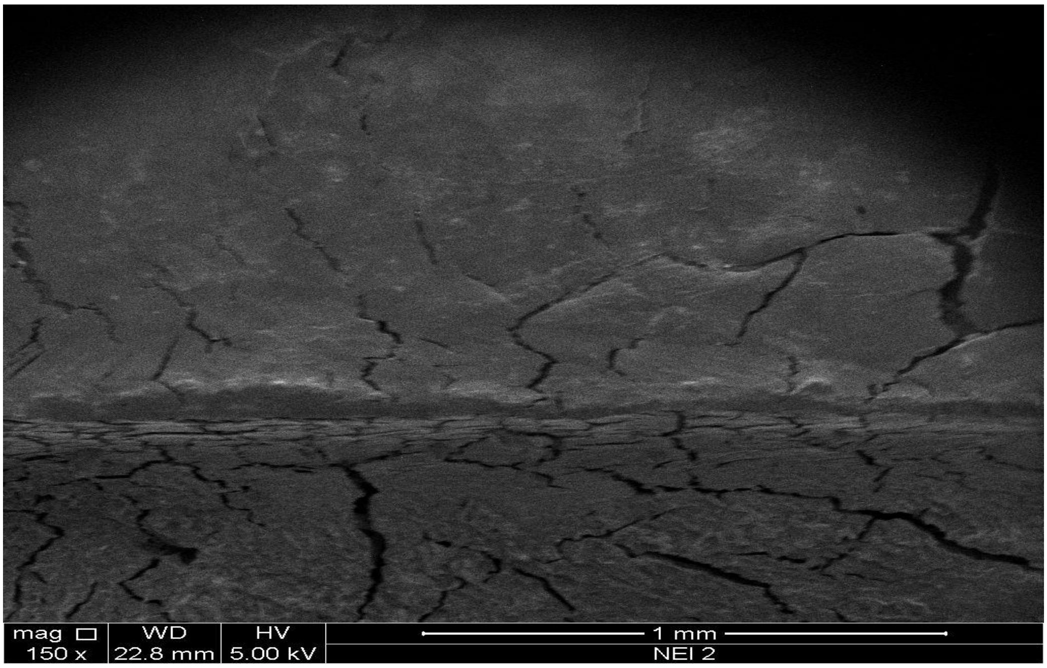
Table 4: Some parameters of the linear regression of Langmuir adsorption isotherm for mild steel corrosion in 1 M H_2SO_4 containing TOSE

Temperature	R^2	n	1/ K_{ads} (g L^{-1})	K_{ads} (L g^{-1})
303 K	0.9884	0.9968	0.7058	1.4168
313 K	0.9639	0.9489	0.8569	1.1670
323 K	0.9339	0.7943	1.3786	0.7254
333 K	0.9960	0.8411	1.6786	0.5957

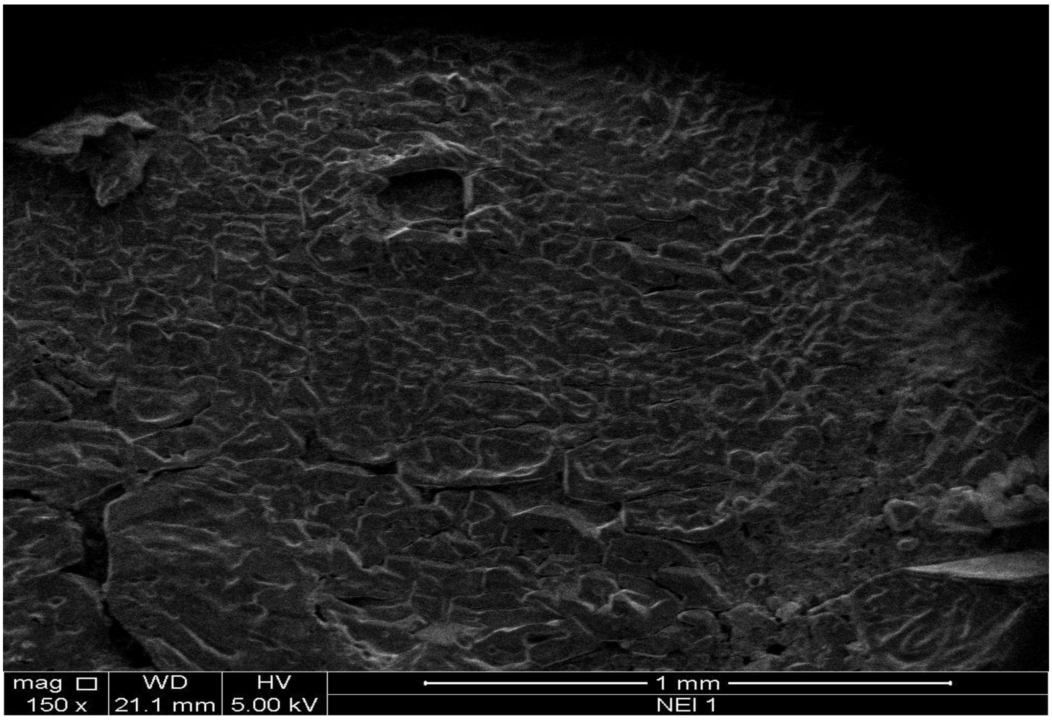
Examination of literature indicated that this natural extract is rich in alkaloids, flavonoids, Saponins, tannins … (Enin *et al*., 2024). These kinds of molecules containing heteroatoms (O, N, S…) as well as aromatic rings are easily adsorbed at the metal surface to create a barrier against the arrival of aggressive ions (H^+) responsible of the degradation of steel in acidic media (Aourabi *et al*., 2021). The inhibition process is generally interpreted by the synergistic intermolecular effect of the various components of the natural extract (Batah *et al*., 2024; Lrhoul *et al*., 2023).

3.5 SEM Analysis

The surface morphology of mild steel coupons in 1 M H_2SO_4 as analyzed by SEM in the absence and presence of 2 g/L TOSE are presented in Figure 7(a and b). Figure 7(a) reveals that mild steel was severely corroded in 1 M H_2SO_4 solution (blank) as the surface is very rough with cracks while Figure 7(b) reveals that mild steel coupon in the presence of 2.0 g/L TOSE is smoother. This signifies that the extract adsorbed onto the mild steel surface and protected it from attack by aggressive ions in solution.



(a)



(b)

Figure 7: Surface morphology of mild steel in 1 M H_2SO_4 in the (a) absence and (b) presence of TOSE

Conclusion

On the basis of this work, the following conclusions could be drawn:

i *Telfairia occidentalis* stem extract (TOSE) appreciably inhibited the corrosion of mild steel in sulphuric acid solution. It exhibits potential as an eco– friendly corrosion inhibitor.

ii The inhibition efficiency increases as the concentration of TOSE increases. However, as the temperature rises, the inhibition efficiency decreases indicating that the inhibition efficiency is temperature – dependent.

iii The calculated thermodynamic parameters indicate that the corrosion inhibition process by TOSE is endothermic in nature, implying absorption of energy during the inhibition process.

iv. The adsorption of TOSE on mild steel surface obeyed the Langmuir adsorption isotherm. The values of K_{ads} indicate that the adsorption of TOSE on mild steel weakens as temperature rises.

v. SEM analyses reveal that TOSE protected the mild steel surface more than the blank, probably by adsorbing on it and preventing attack by aggressive ions in solution.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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