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Corrosion inhibition of carbon steel XC70 in 1M HCl solution using *Balanite Aegyptiaca* extracts as an eco-friendly inhibitor

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Abstract

The corrosion inhibition effect of *Balanites aegyptiaca* leaves extracts on carbon steel XC70 in 1 M hydrochloric acid solution has been studied using gravimetric study and Potentiodynamic polarization method. The plant extracts has proven its ability to stabilize metal corrosion, as FTIR curves confirm that extracts has compounds rich in oxygen atom and aromatic compounds. The results show that the inhibition efficiency increases with increase in extract concentration and decreases with rise in temperature. The inhibition efficiency from weight loss studies was found to be more than 90 % at 50 % volumic concentration while this inhibition efficiency was obtained from Potentiodynamic polarization studies at 150 ppm. We also investigated the effect of temperature on corrosion with and without the optimal concentration in the temperature range of 293 to 373 K and calculated the activation energy, enthalpy, and entropy. The thermodynamic results showed that the plant extract particle's adsorption process on the steel's surface was endothermic and physical in nature. Tafel curve analysis revealed that our green inhibitor worked as a mixed-type inhibitor, bottled up the corrosion processes of steel X70 in hydrochloric acid, and their adsorption was found to follow the Langmuir and Temkin models.

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Keywords: *Balanites aegyptiaca*, Corrosion inhibition, XC70, Tafel, Isotherm adsorption

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1. Introduction

Corrosion is a pervasive and costly phenomenon that results from the interaction between metals and their surrounding environment [1]. a natural problem that is difficult to get rid of [2], This natural process leads to significant material degradation, causing substantial economic losses across various industries annually [3]. Steel is the basic material for building various industries in which strong acids are used as hydrochloric acid and sulfuric acid in various industrial processes such as crude oil refining and petrochemical fittings, this is what causes corrosion in metal structures. Carbon steel, particularly XC70, is widely used in industrial applications such as oil re-

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fining and petrochemical fittings due to its mechanical properties. However, its exposure to aggressive acidic environments, such as hydrochloric acid (HCl), accelerates corrosion, necessitating effective mitigation strategies [2]. To reduce this natural phenomenon, scientists have resorted to the use of industrial inhibitors that are added in small quantities in the corrosive medium surrounding the metal.

Traditionally, industrial corrosion inhibitors have been employed to protect metals by forming protective layers on their surfaces [5]. While these inhibitors are effective, their toxicity, non-biodegradability, and environmental hazards have raised serious concerns [6]. So researchers are working on discovering natural sources from green plants that have high efficiency in preventing metal corrosion in acidic medium Consequently, there is a growing demand for eco-friendly alternatives derived from natural sources, such as plant extracts, which are biodegradable, non-toxic, and cost-effective [7].

Numerous plant extracts have demonstrated promising corrosion inhibition properties, including *Traganum nudatum* [8], *Ginkgo biloba* [9], *Dillenia suffruticosa* [10], *Lawsonia inermis* [11], and *Ambrosia trifida L.* [12]. *Among these*, *Balanites aegyptiaca*, a plant native to arid regions of Africa and South Asia, stands out due to its rich phytochemical composition [13]. This plant has been traditionally used for its medicinal properties, including anti-cancer, anti-diabetic, and antimicrobial effects [14, 15], suggesting its potential as a source of bioactive compounds for corrosion inhibition.

This study investigates the corrosion inhibition efficiency of (*B. aegyptiaca*) leaf extracts on carbon steel XC70 in a 1 M HCl solution using gravimetric (weight loss) and electrochemical (potentiodynamic polarization) techniques. The research aims to evaluate the extract's adsorption behavior, thermodynamic properties, and inhibition mechanisms, contributing to the development of sustainable corrosion inhibitors. The findings align with recent advancements in green corrosion inhibitors, emphasizing their role in environmentally conscious industrial practices [7, 16].

2. Materials and methods

2.1. Sample preparation

In this study X70 carbon steel was used, chemical compositions are noted in Table 1. The carbon steel sample was cut into two shapes, one which is missing of size of $1.9 \times 1.22 \times 0.67$ *cm* and was used in the weight loss method and the other was used as a working electrode in the electrochemical methods and it's surface roof tested $1cm^2$. Before each corrosion test, samples were manually polished with various grades of emery paper (400, 600, 800, 1200, 1500, and 2000), rinsed with distilled water, and dehydrated with acetone at 15 °C.

2.2. Preparation of the test media

To prepare a 1 M HCl solution, we take the mother acidic solution with analytical reagent grade 36% and a density of 1.18 g/cm^3 and added distilled water according to the dilution law to get 1M concentration.

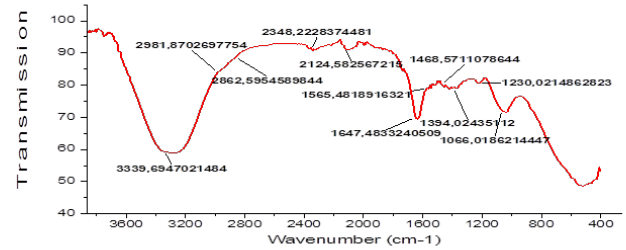

Figure 1. FTIR spectra of *Balanite aegyptiaca* HCl extract.

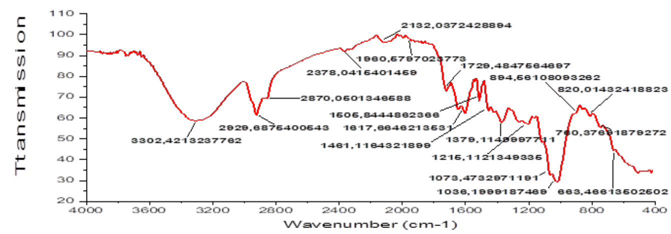

Figure 2. FTIR spectra of TextitBalanite aegyptiaca butanol extract.

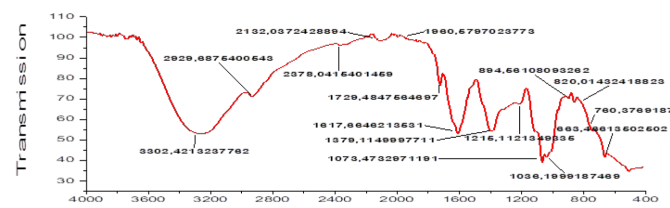

Figure 3. FTIR spectra of TextitBalanite aegyptiaca aqueous extract.

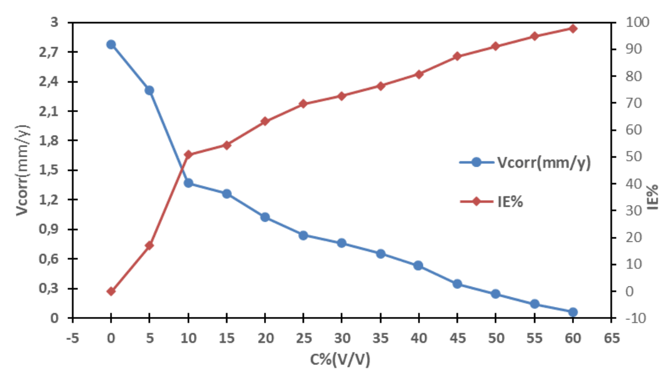

Figure 4. Curves: Corrosion rate and efficiency of carbon steel inhibition in 1M HCl at varied concentrations of B. aegyptiaca extract.

2.3. Preparation of the inhibitor

In southern Algeria (Tamanrasset region), the plant was picked, dried and ground. In this study, two methods were used (weight loss and electrochemical). For weight loss method, 100 g of dry powdered plant leaves were soaked in a 1M HCl solution for 24 hours before being filtered and repeated. The filtrate is collected and stored until it is utilized. after filtering, dif-

Table 1. Chemical composition of carbon steel XC70.

Element	C	P	S	Si	Mn	Cr	Ni	Cu	Al	Nb	V	Ti	Mo	Fe
wt. $\times 10^{-3}$	65	2	1	245	1685	42	26	10	42	67	14	19	5	Residual

Table 2. Corrosion of steel in 1M HCl with different concentrations of B. aegyptiaca extract.

C (v/v) %	Δm (g)	Vcorr (mm/y)	θ	*IE* (%)
0	0.0137	2.78	/	/
5	0.0113	2.31	0.1691	16.91
10	0.0067	1.37	0.5073	50.73
15	0.0062	1.27	0.5441	54.41
20	0.0050	1.02	0.6323	63.23
25	0.0041	0.84	0.6972	69.72
30	0.0037	0.76	0.7267	72.67
35	0.0032	0.66	0.7637	76.37
40	0.0026	0.53	0.8080	80.80
45	0.0017	0.35	0.8744	87.44
50	0.0012	0.25	0.9110	91.10
55	0.0007	0.14	0.9481	94.81
60	0.0003	0.06	0.9777	97.77

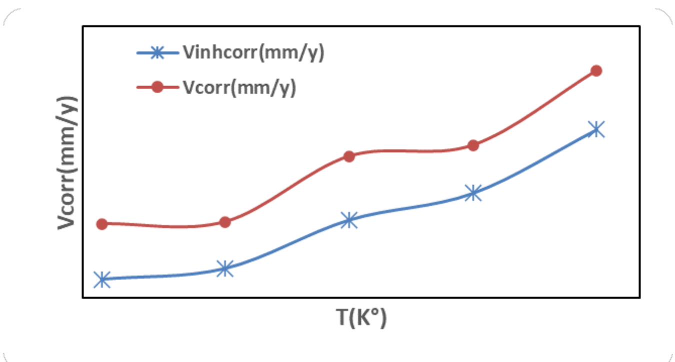

Figure 5. The effect of different temperatures on carbon steel corrosion rates in 1M HCl.

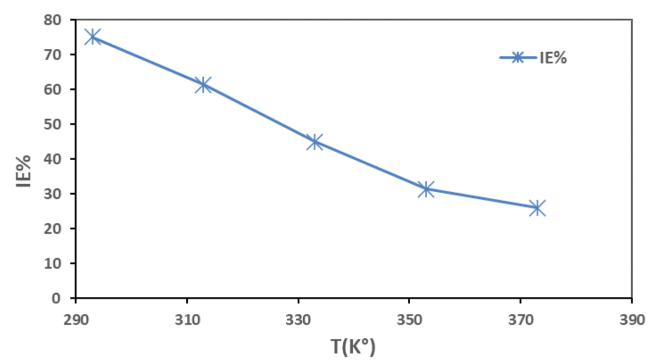

Figure 6. Effect of various temperatures on inhibition efficacy of carbon steel in 1M HCl.

ferent volumetric concentration (ranging from 0 to 60%) were prepared using 1M HCl solution.

For the Potentiodynamic polarization study, the butanol & aqueous extracts of *B. aegyptiaca* plant was used to prepare different concentrations between 30-150 ppm.

2.4. Weight loss measurement

According to Remache *et al.* [4], the steel sample was purified, dried, weighed and measured before and after each experiment. It was immersed for 40 minutes in 100 ml of 1M HCl in the absence and presence of inhibitory solution. Corrosion rate V_{corr}, coverage of surface (θ), and inhibitory efficiency *IE* (%) were determined using equations (1)-(3) respectively:

$$V_{\text{corr}}\,(\text{mm/y}) = \frac{K\,\Delta m}{A\,t\,d}, \tag{1}$$

$$\theta = \left(1 - \frac{V_{\text{corr}}}{V^0_{\text{corr}}}\right), \tag{2}$$

$$IE(\%) = \left(1 - \frac{V_{\text{corr}}}{V^0_{\text{corr}}}\right) \times 100, \tag{3}$$

where: V_{corr} and V^0_{corr} are corrosion rates in the presence and absence of the inhibitor, respectively; $K = 525600$ (constant); Δm: carbon steel weight loss (g); A: metal steel surface area (cm^2); t: exposure period (min); d: steel density (7.8 g·cm^{-3}).

The Arrhenius equation (4) is used to calculate activation energy E_a in the presence and absence of inhibitor, and linearization of equation (4) gives equation (5):

$$V_{\text{corr}} = A\,e^{-\frac{E_a}{RT}}, \tag{4}$$

$$\ln V_{\text{corr}} = \ln A - \frac{E_a}{RT}, \tag{5}$$

where: A is Arrhenius Pre-exponential factor, V_{corr} is corrosion rate, R is a universal gas constant and T is absolute temperature [17].

Table 3. Temperature effect on corrosion rate and inhibition efficiency of carbon steel in 1 M HCl at 60% (v/v) concentration of *B. aegyptiaca* extract.

T (K)	293	313	333	353	373
V_{corr} (mm/y)	3.80	3.90	7.29	7.87	11.73
V_{corr}^{inh} (mm/y)	0.94	1.50	4.01	5.39	8.68
θ	0.7520	0.6148	0.4500	0.3144	0.2598
IE (%)	75.20	61.48	45.00	31.44	25.98

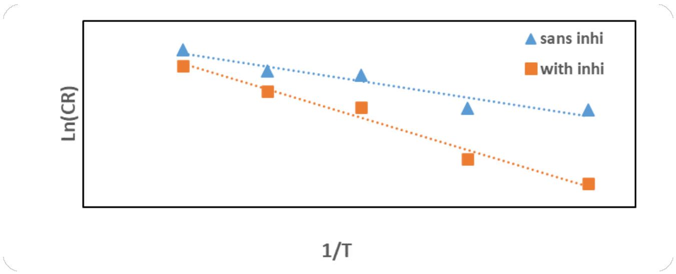

Figure 7. Arrhenius graphs indicate the rate of carbon steel corrosion in 1M HCl with and without the inhibitor.

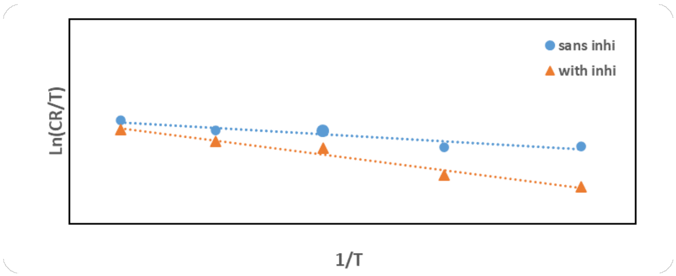

Figure 8. Transition state graphics indicate the corrosion rate of carbon steel in 1M HCl with and without the inhibitor.

Activation enthalpy (ΔH°) and activation entropy (ΔS°) values were obtained from the linearized transition state theory equation (6). The free energy (ΔG°) was determined at different temperatures by equation (7):

$$\ln\left(\frac{C_R}{T}\right) = \ln\left(\frac{R}{Nh}\right) + \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}, \tag{6}$$

$$\Delta G^\circ = \Delta H^\circ - T\,\Delta S^\circ, \tag{7}$$

where h is Planck's constant, and N is Avogadro's number [18].

2.5. Electrochemical test

Potentiodynamic Polarization Method. Potentiodynamic Polarization measurements were analyzed using the Gamry potentio-stat/galvanostat system controlled by the Gamry framework software with three electrodes: a working electrode made of carbon steel XC70 with an active surface area 1cm^2, auxiliary electrode of platinum plate(1cm^2), and the reference electrode was represented by a saturated calomel electrode (SCE). Polarization curves were taken with the scan speed of 5 mV.s^{-1}, in the potential range of -1.5 V to 1.5V. In open circuit, the immersion time of the XC70 plates without and with of various concentrations of *B.aegyptiaca* extracts was 30 min

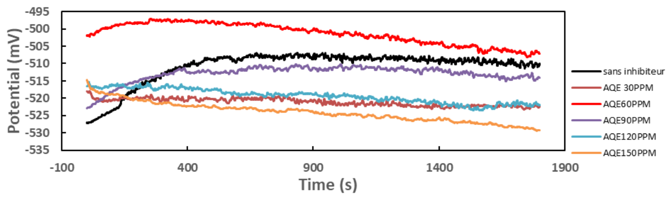

Figure 9. OCP plot with the absence and presence of various concentrations of aqueous extract in 1M HCl solution.

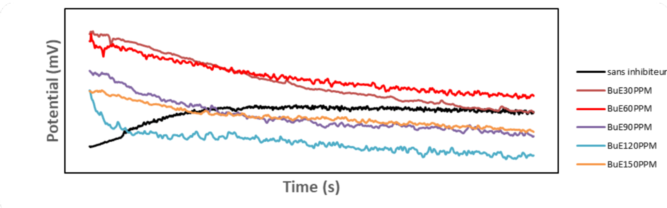

Figure 10. OCP plot with the absence and presence of various concentrations of butanol extract in 1M HCl solution.

at room temperature [19]. According to equation 8 We got the inhibition efficiency (IE%) determined by the Tafel curves [20]:

$$IE(\%) = \left(1 - \frac{i_{corr}}{i^0_{corr}}\right) \times 100, \tag{8}$$

where i^0_{corr} and i_{corr} are the corrosion current densities in the absence and presence of the inhibitor, respectively.

2.6. Adsorption isotherm

In corrosion studies, adsorption on the metal surface is the most crucial topic because it gives information about the electric double layer. The adsorption isotherm is a basic indicator of the interaction between organic inhibitors and the metal surface, which has an inhibitory capability [21]. In order to understand the adsorption phenomenon of the plant extracts on the surface of carbon steel, and to clarify the nature and strength of the adsorption.

The adsorption of the plant extract was tested with three models [22]:

Langmuir:

$$\frac{\theta}{1-\theta} = KC. \tag{9}$$

Rearrangement gives:

$$\frac{C}{\theta} = \frac{1}{K} + C. \tag{10}$$

Table 4. Activation parameters for the dissolution of carbon steel in 1 M HCl with and without the inhibitor.

C% (v/v)	E_a (kJ/mol)	$\Delta H°$ (kJ/mol)	$\Delta S°$ (J/mol·K)	$\Delta G°$ (kJ/mol)				
				293 K	313 K	333 K	353 K	373 K
Blank	13.31	10.58	-198	68.59	72.55	76.51	80.47	84.43
60	26.06	23.32	-165	71.67	74.97	78.27	81.57	84.87

Table 5. Electrochemical parameters of carbon steel in 1M HCl solutions including various concentrations of aqueous extract.

C (PPM)	E*corr* (mV/cm^2)	i*corr* (mA/cm^2)	R*p* (ohm.cm^2)	β_a (mV/Decade)	β_c (mV/Decade)	V*corr* (mpy)	θ	R%
Blank	-444.10	0.484	198.01	432.40	449.90	220.90	/	/
30	-441.20	0.239	247.06	334.90	228.30	109.00	0.50651	50.65
60	-446.30	0.162	348.35	241.60	282.40	74.17	0.66432	66.43
90	-434.80	0.090	306.09	99.90	174.80	41.20	0.81349	81.35
120	-437.50	0.050	309.90	47.96	141.30	22.93	0.89624	89.62
150	-478.50	0.020	658.37	66.30	57.98	9.32	0.95781	95.78

Table 6. Electrochemical parameters of carbon steel in 1M HCl solutions including various concentrations of butanol extract.

C (PPM)	E_{corr} (mV/cm^2)	i_{corr} (mA/cm^2)	R_p (ohm.cm^2)	β_a (mV/Decade)	β_c (mV/Decade)	V_{corr} (mpy)	θ	R%
Blank	-444.10	0.484	198.01	432.40	449.90	220.90	/	/
30	-488.40	0.159	525.66	382.90	385.05	72.51	0.67177	67.18
60	-456.00	0.126	345.33	159.40	268.70	57.51	0.73981	73.98
90	-492.70	0.072	517.18	152.40	195.30	32.84	0.85135	85.14
120	-514.70	0.036	814.28	118.20	155.80	16.38	0.92587	92.59
150	-503.80	0.031	796.01	128.30	99.62	13.98	0.93673	93.67

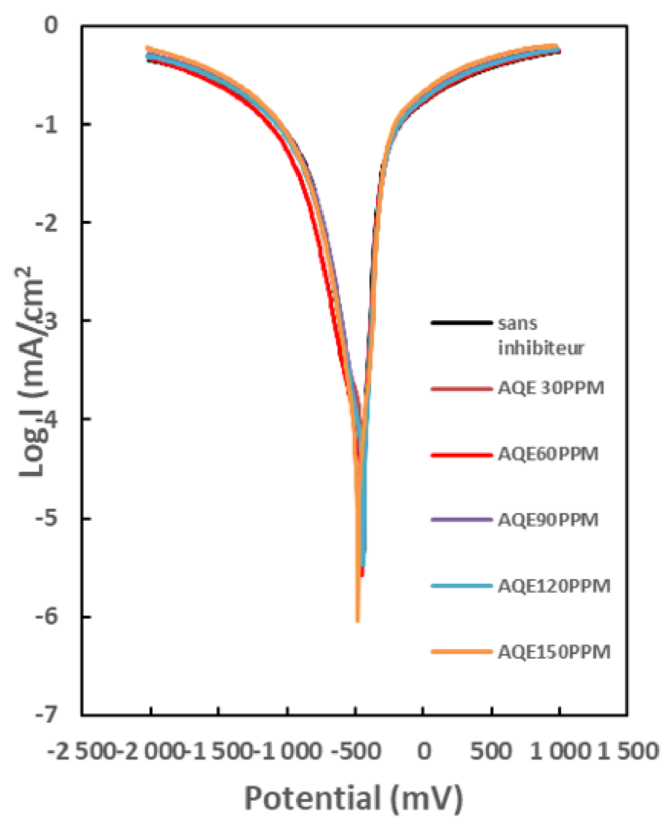

Figure 11. Potentiodynamic polarization curves for carbon steel in 1M HCl with different concentrations of aqueous extract.

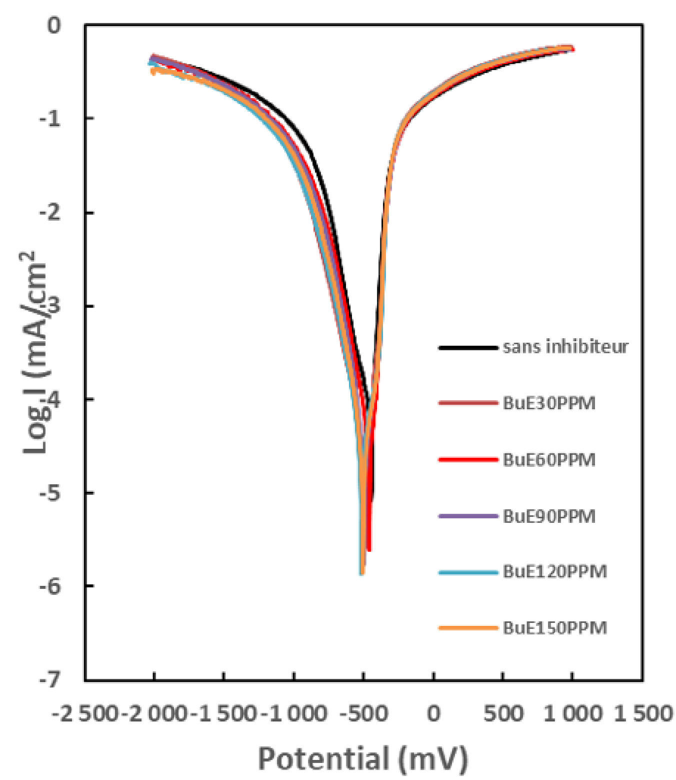

Figure 12. Potentiodynamic polarization curves for carbon steel in 1M HCl with different concentrations of butanol extract.

Temkin:

$$\log\left(\frac{\theta}{C}\right) = \log K - g\theta. \quad (11)$$

Frumkin:

$$\left(\frac{\theta}{1-\theta}\right)e^{-g\theta} = KC. \quad (12)$$

Or in linear form:

$$\log\left(\frac{\theta}{(1-\theta)C}\right) = \log K + g\theta. \quad (13)$$

3. Results and discussion

Characterization of B. aegyptiaca Leaves Extract. Figures 1, 2 and 3 present the FTIR curves of hydrochloric, butanol, and aqueous extracts of *B. aegyptiaca* leaves. The three curves are similar, with a wide peak in the 3300 cm^{-1} range corresponding to O–H stretching vibrations of alcohol or phenol. The band at 2929 cm^{-1}, 2870 cm^{-1}, and 820 cm^{-1} with strong peaks corresponds to the C–H stretching of alkanes. The region at 1729 cm^{-1} shows C=O stretching of acids, the band at 1647 cm^{-1} corresponds to C=O stretching of aldehydes, and 1617 cm^{-1} indicates C=C stretching. The peaks at 1505 cm^{-1} and 1215 cm^{-1} are due to N–O asymmetric stretching and C–O–C stretching, respectively. The bands at 1379 cm^{-1} and 1394 cm^{-1} are due to C–H bending. Other bending vibrations include 760 cm^{-1} (C–H aromatic) and 663 cm^{-1} (C–H bending vibration).

According to the results obtained, B.aegyptiaca leaves extracts has organic components that are oxygen-rich and aromatic rings, which fulfill the basic requirements of a good inhibitor [23].

3.1. Gravimetric study

Weight loss method used as a first step to evaluate the effectiveness of *B.aegyptiaca* extracts in inhibiting carbon steel corrosion.

3.1.1. Effect of concentration

After dipping carbon steel for 40 minutes into 1M hydrochloric acid solution in the absence and presence of plant extract inhibitor. The various corrosion parameters were obtained and listed in Table 2 and Figure 4. The results indicated that the absence of inhibitor led to high corrosion rates. However, when the inhibitor ratio was increased, there was a decrease in the corrosion rate with increase in inhibitor effectiveness. According to the findings, 60 % (v/v) is the optimal concentration for the inhibitor extract, with a maximum inhibition efficiency of 97.77 % obtained. This indicates that the chemical components of this extract was adsorbed on the surface of the metal, occupying the reaction sites [24].

3.1.2. Effect of temperature

After determining the optimal concentration, corrosion was studied at different temperatures (from 293 to 373 K). The results obtained are recorded in Table 3 and Figures 5 and 6. The results showed an increase in corrosion rate with increasing temperatures and at lower values in the presence of inhibitor in the corrosive medium, which resulted in a decrease in inhibition efficiency, where 75% was recorded at 20 degrees. This decrease is due to the increased disintegration of the protective layer as a result of the increased solubility of the formed compounds, it mean we have a physical adsorption [25].

3.1.3. Kinetic and thermodynamic parameters for the inhibition operation

Activation energy (E_a), activation enthalpy ($\Delta H°$), activation entropy ($\Delta S°$), and free energy ($\Delta G°$) were obtained in both the optimal inhibitory and non-inhibitory media at different temperatures. The results are presented in Figures 7– 8 and Table 4. The high activation energy value indicates an increase in the adsorption of the inhibitor on the metal surface [26]. Since the activation energy values are generally lower than 80 kJ/mol, this suggests that the adsorption of *B. aegyptiaca* extract on the carbon steel surface occurs mainly through physical adsorption [27]. The activation enthalpy is higher in the presence of the inhibitor and, being positive, indicates that the dissolution process of carbon steel in HCl solution is endothermic in nature [28]. Negative entropy values in the presence of the plant extract suggest that the process is characterized by association rather than dissociation, implying an increase in disorderliness from the initial interaction phase until the active complex is formed [29]. The free energy reflects the stability of the activated complex. In the presence of the inhibitor, a rise in free energy values with increasing temperature was observed, confirming that the *B. aegyptiaca* extract can adsorb onto the metal surface and form a protective layer.

3.2. Electrochemical method

Open circuit potential. After 30 min immersion of the working electrode in the test solutions, the OCP values under non polarized conditions were obtained, Figures 9-10 show a change in OCP plot in term of period of exposure in the absence and presence of inhibitors. The steady-state values of OCP in the blank solution were lower than the immersion potential (Eocp at t = 0). This means that prior to achieving the steady-state condition, the oxide coating generated by the air must dissolve on the electrode before immersion. The steady-state potential of the test electrodes were transformed to higher positive values by adding inhibitors at varying doses. This represents the passivation of the alloy [30].

Potentiodynamic polarization. For the aqueous and butanol extracts, electrochemical corrosion kinetic parameters like corrosion potential E_{corr}, corrosion current i_{corr}, anodic and cathodic Tafel slopes (βa and βc), corrosion rate V_{corr} and percentage efficiency IE (%) for the corrosion of carbon steel in 1M HCl in the absence and presence of different concentrations of the plant extracts are given in Tables 5 and 6 and it corresponding polarization curve is shown in Figures 11 and 12. Results shows that with increased concentrations of inhibitors there is a decrease in i_{corr} values, even at 150 ppm concentration in the aqueous and butanol extracts there was a decrease in i_{corr} values from 0.484 $mA.cm^{-2}$ to 0.020 $mA.cm^{-2}$ with IE=95.78%, from

Table 7. Isotherm parameters for the weight loss and polarization resistance techniques used to adsorb *B. aegyptiaca* extracts on the surface of carbon steel X70 in 1M HCl solution.

Methods	Isotherm	Equation linear	R^2
Weight loss	Langmuir	$C/\theta = 0.7205C + 0.1881$	0.9456
	Frumkin	$\log[\theta/(1-\theta)C] = 1.1725\theta + 0.2672$	0.6622
	Temkin	$\log(\theta/C) = -0.5469\theta + 0.7872$	0.6774
Polarization resistance	Langmuir (AQE)	$C/\theta = 0.7944C + 0.0386$	0.9950
	Langmuir (BuE)	$C/\theta = 0.9315C + 0.0204$	0.9942
	Frumkin (AQE)	$\log[\theta/(1-\theta)C] = 1.2934\theta + 0.7621$	0.7437
	Frumkin (BuE)	$\log[\theta/(1-\theta)C] = 0.9077\theta + 1.116$	0.5535
	Temkin (AQE)	$\log(\theta/C) = -0.8927\theta + 1.6666$	0.9874
	Temkin (BuE)	$\log(\theta/C) = -1.7794\theta + 2.4882$	0.9312

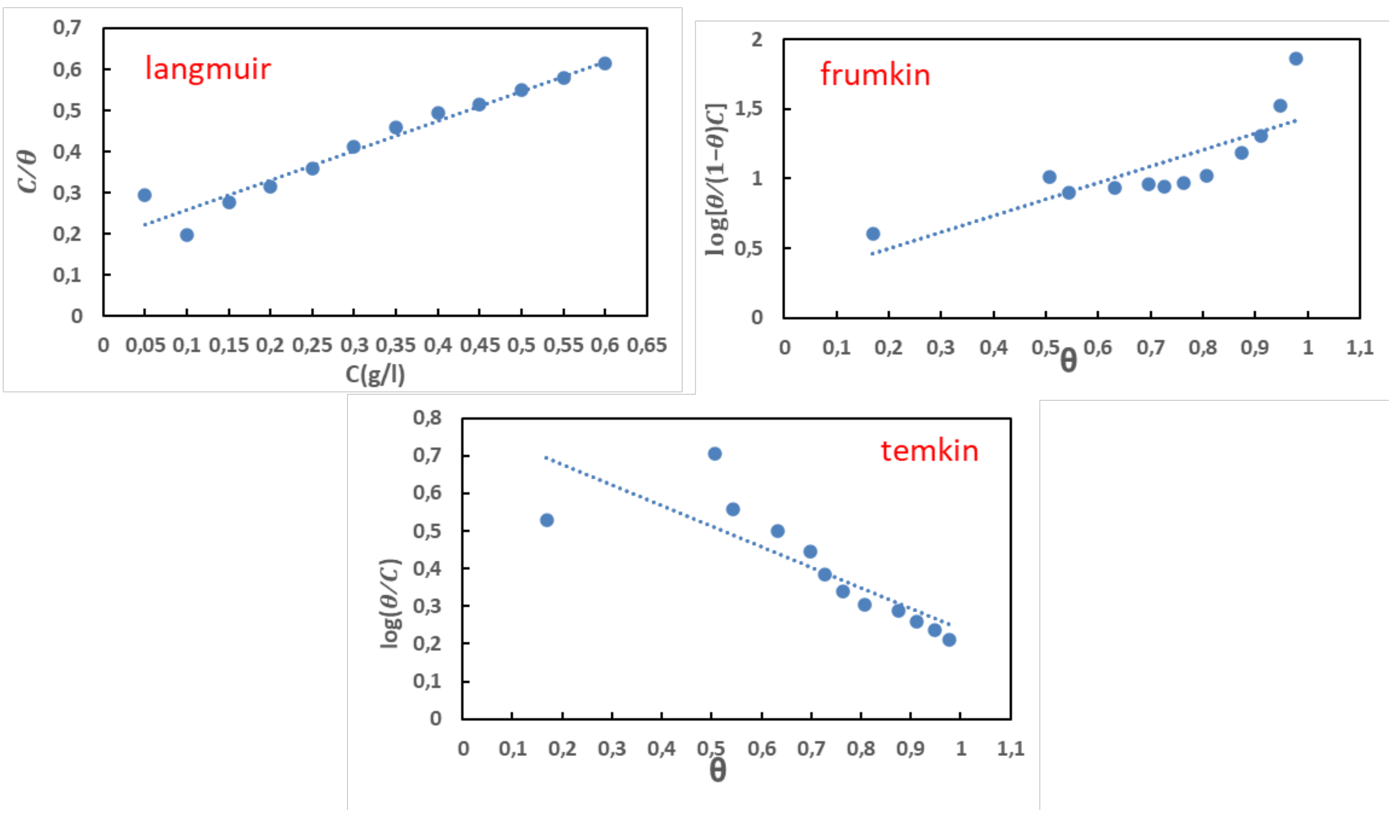

Figure 13. Langmuir, Temkin and Frumkin isotherms for the adsorption of B. aegyptiaca extract on carbon steel X70 in 1M HCl solution by weight loss method.

0.484 mA.cm^{-2} to 0.031 mA.cm^{-2} with IE=93.67% respectively. That proving that the anodic reaction was affected and therefore delayed. At same time, E_{corr} values decreased, suggesting that the Cathodic reaction also was hindered by inhibitory molecules [16].

The B. aegyptiaca leaves extracts showed that it could inhibit anodic-cathodic type in 1M HCl solution by altering both anodic current density and cathodic corrosion potentials. It is certainly a mixed type of HCl 1M acid corrosion inhibitors [31]. The results of this study are consistent with the findings of Abubakar *et al.* [23] and Allaoui *et al.* [32].

Adsorption isotherm. Table 7 and Figures 13-14 shows the isotherm parameters used to adsorb the B. aegyptiaca extracts on carbon steel XC70 surface in1M HCl solution using weight loss and polarization methods. According to R^2 coefficients, in each of these cases, Langmuir isotherm has higher value close to 1 with a linear relationship compared to Temkin and Frumkin isotherm, but Temkin isotherm R^2 value for Polarization resistance method approximate to Langmuir isotherm(R^2> 0.9). also, the adsorption layer has repulsion because the slope values are negative [33]. It means that the inhibitors has been adsorbed on the metal surface with Langmuir and Temkin method by forming a monolayer [34], and being deposited onto the most effective sites [35].

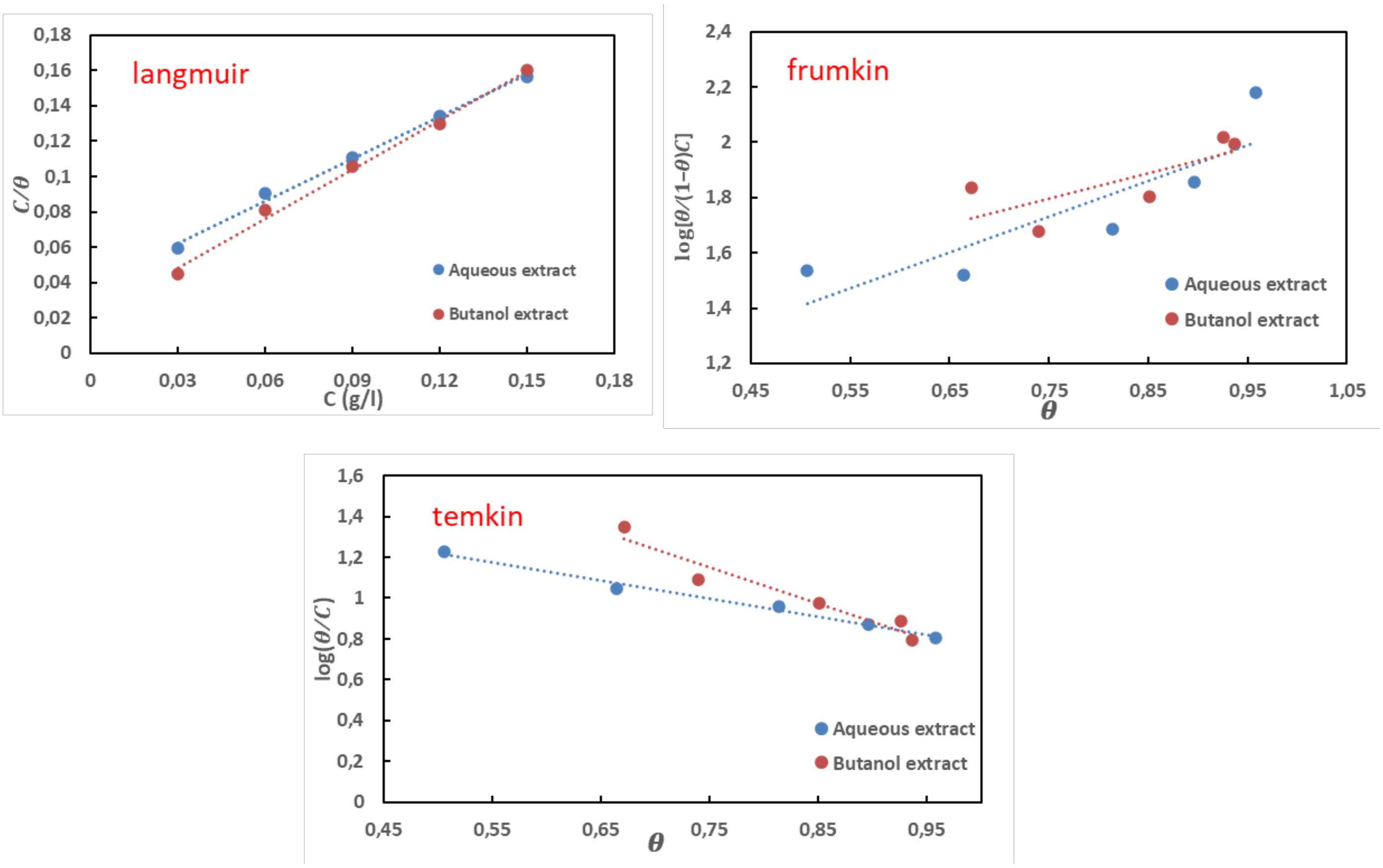

Figure 14. Langmuir, Temkin and Frumkin isotherms for the adsorption of aqueous and butanol extract of B. aegyptiaca plant on carbon steel X70 in 1M HCl solution by polarization resistance method.

4. Conclusion

This study demonstrates that (Balanites aegyptiaca) leaf extracts serve as an effective and eco-friendly corrosion inhibitor for carbon steel XC70 in 1 M hydrochloric acid. Gravimetric and electrochemical analyses revealed inhibition efficiencies exceeding 90% at optimal concentrations (50% v/v for weight loss, 150 ppm for polarization), attributed to the adsorption of oxygen-rich and aromatic compounds onto the steel surface. Inhibition efficiency increased with extract concentration but decreased with rising temperature, suggesting physical adsorption. Thermodynamic parameters (activation energy, enthalpy, entropy) confirmed the endothermic nature of the process, while polarization studies identified the extract as a mixed-type inhibitor. Adsorption followed Langmuir and Temkin isotherms, indicating monolayer formation and site-specific interactions. The findings highlight the potential of (B. aegyptiaca) as a sustainable alternative to toxic industrial inhibitors, combining high performance with environmental safety. Future work should isolate active compounds, test efficacy in other acidic media, and explore industrial scalability. This research advances green corrosion inhibition strategies, aligning with global sustainability goals.

Data availability

No additional data was used beyond those presented in the submitted manuscript.

References

[1] K. Mansouri, N. Hellali, O. Rahim & A. Tabchouche, "Electrochemical and gravimeter study on corrosion inhibition by (methoxymethyl) triphenylphosphonium chloride in acid media H_2SO_4 0.5M", Asian Journal of Research in Chemistry (2022) 1. https://doi.org/10.52711/0974-4150.2022.00001.

[2] M. Allaoui, O. Rahim, B. Labed, I. Bellaoueur & B. Benabed, "Comparison of inhibition and adsorption of a flower extract of *Rumex vesicarius L.* on the corrosion of carbon steel in acid media (1 N HCl and H_2SO_4)", Asian Journal of Research in Chemistry (2023) 175. https://doi.org/10.52711/0974-4150.2023.00029.

[3] G. Belkis, H. S. Abdelkader & R. Oumelkheir, "Evaluation of the inhibitive performance of *Cyperus conglomeratus* leaves extract as a green corrosion inhibitor on mild steel XC70 in acid medium", Corrosion Science and Technology **21** (2022) 171. https://doi.org/10.14773/cst.2022.21.3.171.

[4] M. Remache, M. Rahim, A. Bouhadiba, D. Zouied & H. Chekroud, "Corrosion inhibition effects of celery (Apium graveolens) seeds extract on carbon steel in acid medium", Studies in Engineering and Exact Sciences **5** (2024) e11616. https://doi.org/10.54021/seesv5n2-635.

[5] Z. Xia & X. Zhang, "Study on corrosion resistance of carbon steel in HF/HCl acid mixture in presence of *Lycoris radiata* and *Lycoris chinensis* leaf extract as environmentally friendly corrosion inhibitor", International Journal of Electrochemical Science **17** (2022) 220921. https://doi.org/10.20964/2022.09.20.

[6] R. A. Hameed, G. M. Aleid, D. Mohammad, M. M. Badr, B. Huwaimel, M. S. Suliman, F. Alshammary & M. Abdallah, "*Spinacia oleracea* extract as green corrosion inhibitor for carbon steel in hydrochloric acid solution", *International Journal of Electrochemical Science* **17** (2022). https://doi.org/10.20964/2022.10.31.
[7] P. R. Sivakumar & A. P. Srikanth, "Green corrosion inhibitor: A comparative study", Sadhana - Academy Proceedings in Engineering Sciences **45** (2020) 221017. https://doi.org/10.1007/s12046-020-1283-x.
[8] M. Allaoui, N. Gherraf, O. Rahim, E. Chebouat & M. Gouamid, "Corrosion inhibition of carbon steel in 1M HCl medium using butanol extract of *Traganum nudatum* Del", International Journal of Applied Engineering Research **12** (2017) 6769. http://www.ripublication.com.
[9] Z. Li, S. Xiang, Y. Pan & L. Fu, "*Ginkgo biloba* leaf extract for the synthesis of gold nanoparticles and its application for electrochemical detection of diclofenac", International Journal of Electrochemical Science **17** (2022) 1. https://doi.org/10.20964/2022.10.03.
[10] U. Mamudu, J. Hernandez, S. A. Umoren, M. Sahban & R. Chong, "Investigations of corrosion inhibition of ethanolic extract of *Dillenia suffruticosa* leaves as a green corrosion inhibitor of mild steel in hydrochloric acid medium", Corrosion Communications **15** (2024) 52. https://doi.org/10.1016/j.corcom.2023.10.005.
[11] G. Okore, B. Ejiogu, P. Okeke, K. Amanze, S. Okore, E. Oguzie & C. E. Enyoh, "*Lawsonia inermis* as an active corrosion inhibitor for mild steel in hydrochloric acid", Applied Sciences **14** (2024) 6392. https://doi.org/10.3390/app14156392.
[12] X. Sun, H. Tian, F. Zou, W. Li, Y. Qiang & B. Hou, "Turning waste into treasure: Invasive plant *Ambrosia trifida L.* leaves as a high-efficiency inhibitor for steel in simulated pickling solutions", *Materials* **17** (2024) 3758. https://doi.org/10.3390/ma17153758.
[13] H. Dey & S. Shaili, "Exploring the phytochemical diversity and pharmacological potentials of *Balanite aegyptiaca*: A review", *International Journal of Newgen Research in Pharmacy and Healthcare* **1** (2023) 53. https://doi.org/10.61554/ijnrph.v1i2.2023.34.
[14] R. Kane, Z. Sidoumou, Y. Diagana, N. C. Ayéssou, M. Abderrabba & D. Ben Hassine, "*Balanites aegyptiaca* (L.) Delile (Desert Date Palm), a plant of Mauritanian flora: Fruits biological activities and jam valuation", Food and Nutrition Journal **8** (2024) 301. https://doi.org/10.29011/2575-7091.100201.
[15] A. Usman & R. Ibrahim Ahmad, "A review of the techno-economic potentials of *Balanites aegyptiaca* oil", FUDMA Journal of Science **5** (2021) 101. https://doi.org/10.33003/fjs-2021-0503-652.
[16] S. A. Umoren, M. M. Solomon, I. B. Obot, and R. K. Suleiman, "A critical review on the recent studies on plant biomaterials as corrosion inhibitors for industrial metals", Journal of Industrial and Engineering Chemistry **76** (2019) 91. https://doi.org/10.1016/j.jiec.2019.03.057.
[17] I. Bellaoueur, M. Allaoui, A. Lounas, O. Rahim, N. Gherraf & B. Labed, "Kinetic and electrochemical corrosion inspection of carbon steel X70 in 1M HCl solution by *Senecio hoggariensis* extract as an eco-friendly inhibitor", International Journal of Chemical and Biochemical Sciences **17** (2020) 39. https://iscientific.org/volume-17-2020/.
[18] R. S. Abdel Hameed & M. Abdallah, "Corrosion inhibition of carbon steel in 1 M hydrochloric acid using some pyrazolo[3,4-d]pyrimidone derivatives", Protection of Metals and Physical Chemistry of Surfaces **54** (2018) 113. https://doi.org/10.1134/S2070205118010239.
[19] L. Guerguer, A. Hamdi, A. Ziouche, D. Benbertal, M. A. Belalem & A. Benmoussat, "Influence of surfactant concentration on structural properties and corrosion behaviour of electrodeposited Ni-SiO_2 nanocomposite coatings", International Journal of Materials Research **114** (2023) 175. https://doi.org/10.1515/ijmr-2021-8429.
[20] S. Elhady, H. Inan, M. Shaaban & I. S. Fahim, "Investigation of olive leaf extract as a potential environmentally friendly corrosion inhibitor for carbon steel", Scientific Reports **13** (2023) 17151. https://doi.org/10.1038/s41598-023-43701-x.
[21] S. Sharma, A. S. Solanki, A. Thakur, A. Sharma, A. Kumar & S. K. Sharma, "Phytochemicals as eco-friendly corrosion inhibitors for mild steel in sulfuric acid solutions: A review", Corrosion Reviews **42** (2024) 727. https://doi.org/10.1515/corrrev-2024-0018.
[22] M. A. Deyab, "Mitigation of acid corrosion on carbon steel by novel pyrazolone derivatives", RSC Advances **7** (2017) 45232. https://doi.org/10.1039/c7ra08761f.
[23] M. S. Abubakar & B. Usman, "Investigation of corrosion inhibition potential of ethanol extract of *Balanites aegyptiaca* leaves on mild steel in 1 M hydrochloric acid solution", Moroccan Journal of Chemistry **7** (2019) 82. https://doi.org/10.48317/IMIST.PRSM/morjchem-v7i1.14889.
[24] R. M. Dakhil, T. S. Gaaz, A. A. Al-Amiery & A. A. H. Kadhum, "Inhibitive impacts of *Citrus aurantium* leaves extract on carbon steel in corrosive media", Green Chemistry Letters and Reviews **11** (2018) 559. https://doi.org/10.1080/17518253.2018.1547796.
[25] K. Mansouri, L. Sekhri, O. Rahim, and A. Tabchouche, "A comparative electrochemical study on corrosion inhibition of iron by synthesized tetraphenyl phosphonium iodide in acid media", *Oriental Journal of Chemistry* **32** (2016) 2015. https://doi.org/10.13005/ojc/320428.
[26] S. Kaya, Z. Aouzal, M. Bouabdellaoui, E. A. Bazzaoui, S. Erdoğan & M. Bazzaoui, "Experimental and MDS studies of corrosion inhibition of carbon steel by saccharinate sodium", Surface Innovations **10** (2017) 11. https://doi.org/10.1016/j.surfin.2017.11.003.
[27] D. K. Verma & F. Khan, "Inhibitory effects of marigold leaves extract on the mild steel corrosion in 0.5 M sulphuric acid solution", Chemical and Material Research **7** (2015) 69. https://oai:ojs.localhost:article/25452.
[28] M. Lebrini, F. Robert & C. Roos, "Adsorption properties and inhibition of C38 steel corrosion in hydrochloric solution by some indole derivates: Temperature effect, activation energies, and thermodynamics of adsorption", International Journal of Corrosion **2013** (2013) 139798. https://doi.org/10.1155/2013/139798.
[29] A. A. Ganash, "Theoretical and experimental studies of dried marjoram leaves extract as green inhibitor for corrosion protection of steel substrate in acidic solution", Journal of Dispersion Science and Technology **6445** (2017). https://doi.org/10.1080/00986445.2017.1391096.
[30] X. Xu, A. Singh, Z. Sun, K. R. Ansari, and Y. Lin, "Theoretical, thermodynamic and electrochemical analysis of biotin drug as an impending corrosion inhibitor for mild steel in 15% hydrochloric acid", Royal Society Open Science **4** (2017) 170933. https://doi.org/10.1098/rsos.170933.
[31] R. F. B. Cordeiro, A. J. S. Belati, D. Perrone, and E. D'Elia, "Coffee husk as corrosion inhibitor for mild steel in HCl media", International Journal of Electrochemical Science **13** (2018) 12188. https://doi.org/10.20964/2018.12.29.
[32] A. Dehghani, P. Ghahremani, A. H. Mostafatabar B. Ramezanzadeh, "Plant extracts: Probable alternatives for traditional inhibitors for controlling alloys corrosion against acidic media—A review", Biomass Conversion and Biorefinery **14** (2024) 7467. https://doi.org/10.1007/s13399-022-02893-4.
[33] M. Allaoui, O. Rahim, A. Lounes, L. Dokkar & K. Djabou, "Eco-friendly inhibitors by *Moringa oleifera* leaves extract on the corrosion of carbon steel in 1M hydrochloric acid", Journal Marocain de Chimie Hétérocyclique **19** (2020) 69. https://doi.org/10.48369/IMIST.PRSM/jmch-v19i2.22377.
[34] A. A. Khadom, A. N. Abd & N. A. Ahmed, "*Xanthium strumarium* leaves extracts as a friendly corrosion inhibitor of low carbon steel in hydrochloric acid: Kinetics and mathematical studies", South African Journal of Chemical Engineering **25** (2018) 13. https://doi.org/10.1016/j.sajce.2017.11.002.
[35] A. Dehghani, G. Bahlakeh, B. Ramezanzadeh & M. Ramezanzadeh, "Potential of borage flower aqueous extract as an environmentally sustainable corrosion inhibitor for acid corrosion of mild steel: Electrochemical and theoretical studies", Journal of Molecular Liquids **277** (2019) 895. https://doi.org/10.1016/j.molliq.2019.01.008.