

Evaluation of the Inhibitive Performance of *Cyperus Conglomeratus* Leaves Extract as a Green Corrosion Inhibitor on Mild Steel XC70 in Acid Medium

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The performance and inhibitory action of the aqueous extract of *Cyperus Conglomeratus*'s leaves against corrosion of XC70 steel in a 1M HCl acid medium are studied by the determination of the weight loss, the potentiodynamic polarization curves analysis, and electrochemical impedance measurements (electrochemical techniques). The corrosion inhibitory efficiency of XC70 steel increases with the increasing concentration of the green inhibitor, however, the corrosion rate of the steel decreases. Weight loss measurements show that the maximum percentage corrosion inhibition efficiency is approximately 61.86%, while the analysis of the mixed character polarization curves shows that the inhibitor could achieve an inhibition efficiency of 86.96%. The electrochemical impedance study confirmed that the value of the charge transfer resistance (R_{ct}) increases and the value of the double layer capacity (C_{dl}) decreases with increasing concentration of the aqueous extract of *Cyperus Conglomeratus*'s leaves, thus increasing the inhibition efficiency. The study showed that this aqueous extract acts by adsorption on the metal surface; this adsorption follows the Langmuir isotherm. This research work showed that *Cyperus Conglomeratus* leaves extract acts as an effective and eco-friendly inhibitor on mild steel in an acid medium.

Keywords: *Cyperus Conglomeratus*, Green inhibitor, Weight losses, Electrochemical techniques

1. Introduction

Despite, the plenty of immense technologies that the industrial revolution brought to light lately, its impact on the environment has included the misuse and damage to our ecosystem. Furthermore, because of these outstanding improvements in the tech world nowadays, corrosion became one of the important issues that result in annual losses estimated at millions of dollars. Corrosion is a degradation of a metal by an electrochemical attack or a redox chemical reaction in an aggressive environment, it is a problem experienced by all oil and petroleum facilities, domestic and industrial [1-3]. Corrosion is not only a regular attack on all the surfaces of equipment installed in our industrial kingdom but it can also be a source of waste of raw materials and energy, and thus causes accidents with

serious consequences, causing the pollution of the environment. To combat corrosion there are several methods of protection, protection by coating, galvanizing, and cathodic protection, using rust inhibitors or corrosion inhibitors of different kinds [3-5]. The use of organic and inorganic corrosion inhibitors is one of the most practical methods known so far, the effectiveness of organic inhibitors is related to the presence of polar functions with sulfur, nitrogen, or oxygen atoms in the molecule, heterocyclic compounds, and π electrons. Chromate, dichromate, and nitrite are also found in the most effective inorganic inhibitors, but their carcinogenic properties limit their use [6-8]. Synthetic inhibitors show good anti-corrosive activity, most of them are highly toxic to humans and the environment, toxicity can occur either during the synthesis of the compound or during their application [7,9-11]. This has prompted the search for green corrosion inhibitors. Green corrosion inhibitors are

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biodegradable and do not contain heavy metals or other toxic compounds and so they are environmentally friendly. Oils, aromatic plants extracts, spices, and medicinal plants have an ideal ecological alternative to replace the usual corrosion inhibitors. Those types of green-origin herbal inhibitors are considered a rich source of natural chemical compounds that can be obtained by simple extractions with very high efficiency at a low cost. Moreover, they contain few heavy metals or toxic compounds, and they are biodegradable [1,5]. Green corrosion inhibitors decrease or prevent corrosion by the formation of different types of films in several ways: by the formation of bulky precipitates, by adsorption, and/or by the formation of a passive layer on the metal surface. Most biological products inhibited adsorptive corrosion and formed a thin invisible film [5,11]. *Cyperus Conglomeratus* is a medicinal plant belonging to the *Cyperaceae* family, it is an edible plant from southeastern Algeria, *C. Conglomeratus* is used in several phytotherapeutic applications, and has diversified therapeutic properties as an antimicrobial, diuretic, stimulant, emollient, anthelmintic, and analgesic [12].

The main objective of this study is to determine the phytochemical screening of the aqueous extract of (*Cyperus Conglomeratus*) plant leaves. To explain the constituent effects of the latter on the corrosion behavior of mild steel XC70 in 1 M HCl acidic medium, which could be considered as a natural green corrosion inhibitor, non-toxic, less-expensive, and effective natural corrosion inhibitors from renewable sources. The inhibition effect of this extract was investigated using different analytical tools, such as weight loss measurement and electrochemical techniques (Potentiodynamic polarization and electrochemical impedance spectroscopy).

2. Experimental

2.1 Materials

2.1.1 Preparation of the Leaves Extract of the *Cyperus Conglomeratus*

The extract of the plant's leaves is used as an inhibitor,



Fig. 1. *Cyperus Conglomeratus*

the plant *C. Conglomeratus* belongs to the family Cyperaceae, it grows on the dunes of the valley of Oued Righ. It is a spontaneous plant with a medicinal feature and is used in different applications and has large biomass [12]. The leaves of the plant are collected, dried, and then crushed in the form of a powder of fine particle size, the extract is prepared by maceration of 50 g of the powder in question in 100 mL of distilled water for 24 hours, the extraction will be carried out three times in succession, after filtration and recovery of the extract is added Chloridic acid to prepare a molar stock solution 1 M HCl. The different concentrations were prepared from the stock solution: 0.714%, 2.857%, 4.285%, 5.714%, 8.571%, and 14.285%.

2.1.2 Sample Preparation XC70

XC70 steel is widely used in the oil industry; its chemical composition is shown in Table 1 [4]. A cubic material of size 2.44 cm × 1.86 cm × 1.40 cm was used for the weight loss method and in cylindrical form for electrochemical measurements, the polishing was carried out with the aid of a polisher (P 225 U) then the abrasive paper of decreasing grain size 60-2000, rinsed with distilled water and dried with a clean cloth right after.

2.2 Phytochemical Screening

Phytochemical Screening detects the different active

Table 1. Chemical composition of steel XC70

Element	C	P	S	Si	Mn	Cr	Ni	Cu	Al	Nb	V	Ti	Mo	Iron
Value % (10 ⁻³)	65	2	1	245	1685	42	26	10	42	67	14	19	5	Remain

EVALUATION OF THE INHIBITIVE PERFORMANCE OF *CYPERUS CONGLOMERATUS* LEAVES EXTRACT AS A GREEN CORROSION INHIBITOR ON MILD STEEL XC70 IN ACID MEDIUM

substances present in the aqueous extract of the leaves of the plant *Cyperus Conglomeratus*, we performed many preliminary phytochemical tests [13]. All tests were done three times.

2.3 Weight Loss Measurements

The weight loss measurements were performed on XC70 steel by immersing it in 100 mL of electrolyte in a 1 M HCl solution with and without the addition of different concentrations of the aqueous extract of the leaves of the plant *Cyperus Conglomeratus*. The sample is weighed by an electronic balance before and after immersion. Then, it is washed with distilled water and dried before being reweighed. To determine the optimal conditions and effect of temperature, the tests were repeated with the operating conditions optimized (time and concentration) at 285K, 301K, 308K, 318K, and 338K, with and without the presence of an inhibitor.

The corrosion rate (C_R) was determined by the following formulas [8,11]:

$$C_R \text{ (g/cm}^2\text{min)} = \frac{\text{mass loss in (g)}}{\text{Surface (cm}^2\text{)} \times \text{Time (min)}} = \frac{(m_0 - m)}{S \times t} \quad (1)$$

$$C_R \text{ (mm/year)} = \frac{5256000 \times (m_0 - m)}{S \times t \times d} \quad (2)$$

Where m_0 and m represent the weight of the sample before and after immersion in the solution tested in (g), S is the area of the sample in (cm^2), t the immersion time (min) and d is the density of the steel in (g / cm^3). The inhibition efficiency (IE %) and the surface coverage (θ) were calculated from the equations (3), (4) and (5) [2,10].

$$IE\%(v) = \frac{C_{r0} - C_r}{C_{r0}} \times 100 \quad (3)$$

$$IE\%(w) = \frac{W_0 - W}{W_0} \times 100 \quad (4)$$

$$\theta = \frac{IE\%}{100} \quad (5)$$

C_{R0} and C_R are the corrosion rate in the absence and presence of different concentrations of inhibitor, W_0 and

W show weight loss in the absence and presence of different concentrations of inhibitor. The relationship between the corrosion rate of steel in corrosive media and temperature was used to calculate the activation energy (Arrhenius equation), where C_R is the corrosion rate, R is the gas constant, T the absolute temperature, A the pre-exponential factor and E_a is the activation energy.

$$\text{Log}(C_R) = E_a \left(\frac{-1}{2.303RT} \right) + \text{Log}A \quad (6)$$

The activation enthalpy ΔH_a and activation entropy ΔS_a values were obtained through the linearized transition state theory equation (7) [11].

$$\text{Log}\left(\frac{C_r}{T}\right) = \text{log}\left(\frac{R}{Nh}\right) + \frac{\Delta S_a}{2.303R} - \frac{\Delta H_a}{2.303RT} \quad (7)$$

Where h is Plank constant (6.626176×10^{-34} J·s) and N is Avogadro's number.

2.4 Electrochemical Measurements

The Tafel polarization curves and the Nyquist impedance curves were recorded using an electrochemical analyzer which is a Volta PGZ 301 laboratory potentiostat coupled to a computer equipped with the "Volta Master 4" software. The experiments were performed using a set of three-electrode cells: The XC70 steel specimen was used as a working electrode with an active surface of 1 cm^2 , a pure platinum counter electrode (CE), and a standard calomel electrode (EIS). The Potentiodynamic polarization curves were recorded with a scanning rate of $0.2 \text{ mV} \cdot \text{S}^{-1}$ in a potential range of -750 and -200 mV/SCE at room temperature without and with the addition of various concentrations of 1MHCl solutions of the aqueous extract of the leaves of the plant *Cyperus Conglomeratus* (green inhibitor). Open circuit potential E_{ocp} was measured for 30 min to allow stabilization of the steady-state potential. The inhibitory efficiency $IE_i\%$ is calculated by the relation (8), where I_{0corr} and I_{corr} are the corrosion densities in the absence and presence of different concentrations of inhibitor respectively.

$$IE_i\% = (I_{0corr} - I_{corr}) \times 100 / I_{0corr} \quad (8)$$

Electrochemical impedance spectroscopy (EIS)

Table 2. Phytochemical screening of *Cyperus Conglomeratus*

Compounds	Phenolic compounds	Flavonoids	Tannins	Triterpenes	Steroids	Saponosids	Coumarins	Alkaloids
Results	+	+	+	+	+	+	+	-

measurements were carried out after 30 minutes immersion time of XC70 in corrosive media with and without green corrosion inhibitor, at the corrosion potential -483 mV (E_{corr}), in a frequency range from 100 kHz to 10 mHz with a sinusoidal voltage amplitude applied at the bias potential of 10 mV peak-to-peak peak, the efficacy of the inhibitor ($IE_{R_{ct}}\%$) and the double-layer capacitance (C_{dl}) is determined by the following equations (9), (10):

$$IE_{R_{ct}}\% = (1 - (R_{0ct} / R_{ct})) \times 100 \quad (9)$$

$$C_{dl} = \frac{1}{2\pi f_{max} R_{ct}} \quad (10)$$

Where R_{0ct} and R_{ct} represent the charge transfer resistance, before and after addition of the inhibitor to the corrosion environment, respectively. C_{dl} is the double-layer capacitance, f_{max} is the frequency at the maximum value of the imaginary component of the impedance spectra and R_{ct} is the charge transfer resistance. All electrochemical measurements were studied at 298 K using 350 ml of electrolyte

3. Results and Discussion

3.1 Phytochemical Screening

Phytochemical screening revealed that aqueous extract of the leaves of the plant *C. Conglomeratus* contains many organic compounds (Table 2) such as flavonoids, steroids, tannins, Saponosids, Coumarins, triterpenes, and phenolic compounds. Most of these constituents are known to have good inhibitive action. The inhibitive effect of aqueous extract of the leaves of *C. Conclumeratus* on the corrosion XC70 is confirmed by weight loss and electrochemical techniques. Therefore, it is pertinent to say that the adsorption of these compounds onto the XC70 surface is responsible for the corrosion inhibition effect by reducing the surface area available for corrosion [14,15].

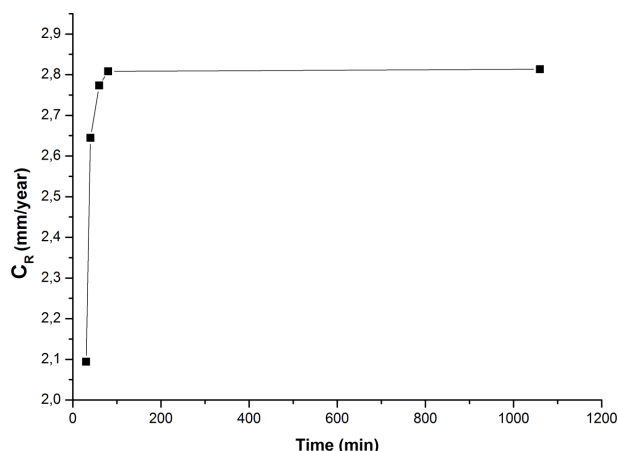


Fig. 2. Variation of corrosion rate with the times of emersion in 1 M HCl

3.2 Evaluation of Anticorrosion Activity by the Weight Loss Method

3.2.1 Optimization of the Immersion Time

To optimize the immersion time of the XC70 steel, speed measurements by the mass loss method were carried out in 1 M HCl for 20 min to 17 hours immersion at 301 K temperature.

Fig. 2 shows that the corrosion rate increases with the increase of the emergence time, 20 min at 17 h of emergence the corrosion rate becomes almost constant between 2.64 - 2.82 mm/year, 40 min present the time of suitable immersion for a better rate of corrosion without inhibitor corresponding to a corrosion rate 2.64 mm/year.

3.2.2 Optimization of the Concentration of the Aqueous Extract

After fixing the concentration of the corrosive medium and choosing the appropriate time of emergence of the XC70 steel, the optimum concentration of the aqueous extract consisting mainly of leaves of the plant *Cyperus conglomeratus* is determined. The corrosion rate of XC70 steel was determined in the absence of the corrosion inhibitor and the presence of the inhibitor at concentrations between 0.714% - 14.28% v/v in 1 M

EVALUATION OF THE INHIBITIVE PERFORMANCE OF *CYPERUS CONGLOMERATUS* LEAVES EXTRACT AS A GREEN CORROSION INHIBITOR ON MILD STEEL XC70 IN ACID MEDIUM

Table 3. Calculated values of corrosion rate and inhibition efficiency for XC70 steel corrosion in HCl 1M without and with different concentrations of the aqueous extract of *Cyperus Conglomeratus's* leaves

C%(V/V)	weight loss	C _R (mm/year)	IE (V) %	Surface coverage (θ)
Blank	0.0034	2.64	0	0
0.714	0.0025	1.952	26.18	0.261
2.857	0.0024	1.861	29.59	0.295
4.285	0.0013	1.008	61.86	0.618
5.714	0.0021	1.637	38.10	0.381
8.571	0.002	1.555	41.18	0.411
14.28	0.002	1.557	41.09	0.410

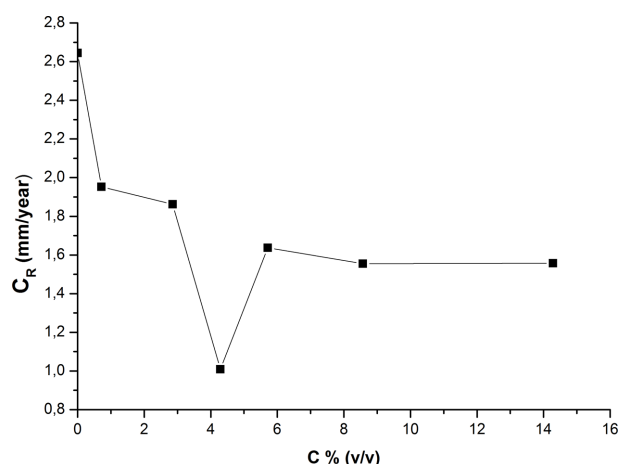


Fig. 3. Variation of corrosion rate with the different concentrations of the aqueous extract of *Cyperus conglomeratus's* leaves in 1 M HCl

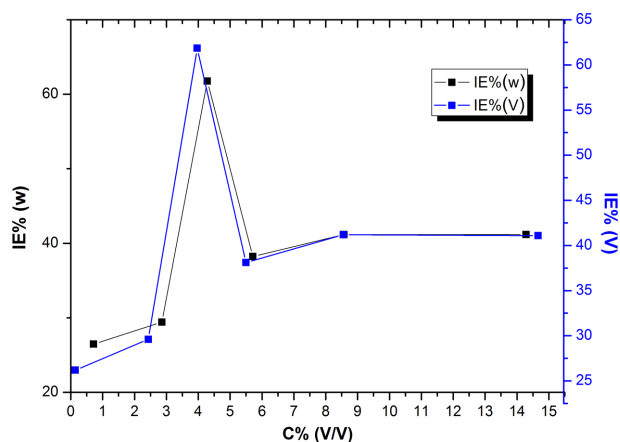


Fig. 4. Variation of inhibition efficiency with different concentrations of the aqueous extract of *Cyperus conglomeratus's* leaves in 1 M HCl

HCl solution for 40 minutes emersion.

From Table 3 and Fig. 3 the rate of corrosion on the XC70 decreases and the inhibitory efficiency increases

with the increase of the inhibitor, 4.28% shows the concentration of the extract where the rate of corrosion is minimal.

Fig. 4 shows the concentration's effect on the aqueous extract of the plant's leaves on the corrosion inhibition efficiency exerted on the XC70 steel, in a 1 M HCl medium, the results of the efficiency of the inhibitor determined by the formulas (3) and (4) are presented by the curves IE_(v) % & IE_(w) % which are almost superimposed and of the same pace, this observation makes it possible to conclude that the type corrosion is localized on the surface. The aqueous extract of the *C. Conglomeratus's* leaves shows a maximum inhibition efficiency of 61.86% in 1 M solution of HCl, at an optimum concentration of 4.28% v/v of the inhibitor causing a minimal rate of corrosion on the XC70 steel. This could be attributed to the adsorption of inhibitory molecules on the active sites of the steel surface and therefore reduce the corrosion process [16]. It is worthy to note that the phytochemical analysis of an aqueous extract of the leaves of the plant *C. Conglomeratus* revealed the presence of heteroatoms containing active constituents (flavonoids, steroids, tannins, Saponosids, Coumarins, triterpenes, and phenolic compounds), therefore there may be a synergism between the molecules accounting for the good inhibition efficiencies [17].

3.2.3 Temperature Effect

In order to study the effect of temperature on inhibitor efficacy and activation energy, experiments were conducted in the 285 - 338K temperature range in the absence and the presence of an optimal concentration

of the inhibitor (4.28%) in 1 M HCl solution for 40 min of XC70 steel spattering. The effect of increasing the temperature on the inhibitor efficacy values is shown in Fig. 5. The results show that the inhibitory efficiency of the extract is maximum (78.9%) at a temperature of 308 K, from this temperature the inhibitor efficacy decreases with the increase of temperature. This is attributed to an increase in the solubility of the protective films and of any reaction products precipitated on the surface of the metal that may inhibit the reaction, also due to an enhanced effect of temperature on the dissolution process of XC70 or the partial desorption of the inhibitor from the metal surface [15,18]. The activation parameters play an important role in understanding the inhibitive mechanism of the inhibitors. The value of the activation energy E_a obtained by linear regression of $\text{Log}(C_R)$ vs. $1/T$ data equation (6) (Fig. 6), is $43.66 \text{ KJ mol}^{-1}$ - $58.07 \text{ KJ mol}^{-1}$ in the absence and the presence of 4.285% of the aqueous extract of the leaves of the plant *C. Conglomeratus*, respectively. The increase in activation energy in the presence of the inhibitor indicates strong inhibitory

action of the extract by increasing the barrier energy for the corrosion process [19]. The activation enthalpy ΔH_a and entropy ΔS_a values in the absence and the presence of 4.285% of the extract were calculated from the results of the temperature studies using equation 7 and Fig.7 [11], they are grouped in Table 4.

The thermodynamic parameters ΔS_a and ΔH_a of

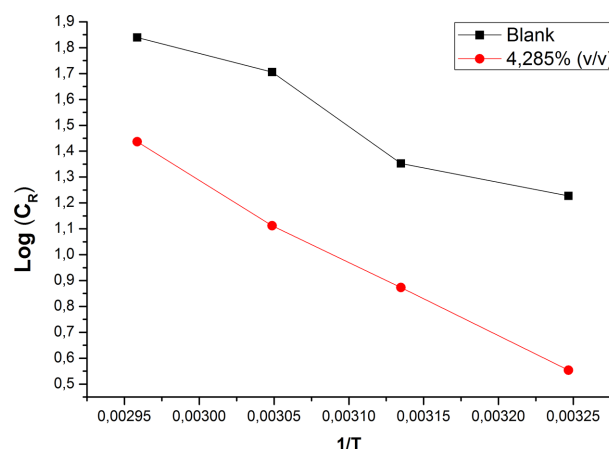


Fig. 6. Arrhenius plot of the corrosion rate for XC70 steel in 1 M HCl in the absence and the presence of the aqueous extract of *Cyperus Conglomeratus's* leaves

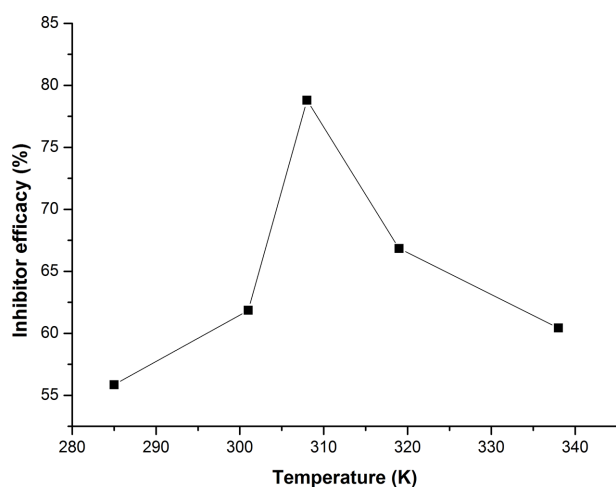


Fig. 5. The variation of inhibitor efficacy with different temperature (K) at optimal conditions

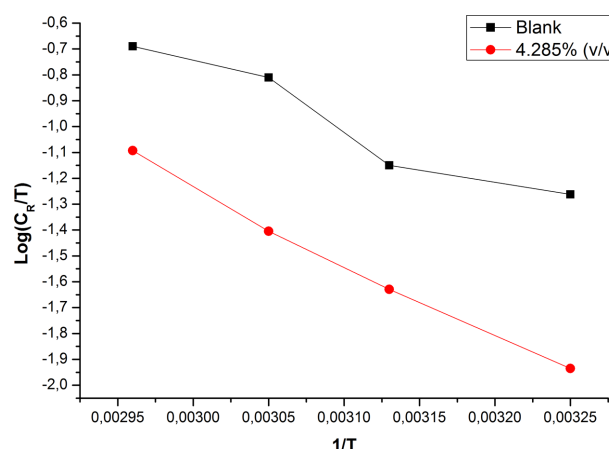


Fig. 7. Transition state plot of the corrosion rate for XC70 steel in 1M HCl in the absence and the presence of the aqueous extract of *Cyperus Conglomeratus's* leaves

Table 4. Thermodynamic parameters in absence and presence of 4.285% of the aqueous extract of *Cyperus conglomeratus's* leaves

C%(v/v)	Activation Energy E_a (KJ mol ⁻¹)	Activation Enthalpy ΔH_a (KJ mol ⁻¹)	Activation Entropy ΔS_a (J mol ⁻¹ K ⁻¹)
Blank	43.66	40.62	-85.12
4.285%	58.07	55.24	-50.13

EVALUATION OF THE INHIBITIVE PERFORMANCE OF *CYPERUS CONGLOMERATUS* LEAVES EXTRACT AS A GREEN CORROSION INHIBITOR ON MILD STEEL XC70 IN ACID MEDIUM

dissolution of XC70 steel in 1 M HCl in the presence of the extract are higher than in the absence of the inhibitor. The positive signs of ΔH_a explain the endothermic nature of the steel dissolution process, as well as the increase of the activation enthalpy with the concentration, which corresponds to a decrease in the dissolution of the metal. The negative values of entropy in the presence of the aqueous extract indicate a decrease in the disorder during the formation of the complex metal/molecules adsorbed in the solution [20].

3.3 Evaluation of Anticorrosion Activity by Electrochemical Measurements

3.3.1 The Polarization Curves of Tafel

The superposition of the Tafel lines for the aqueous leaf extract that it reacts as a corrosion inhibitor is illustrated in Fig. 8, Table 5 shows the electrochemical parameters (corrosion rates, corrosion potentials E_{corr} , densities i_{corr} corrosion, the anodic and cathodic slopes of Tafel b_a and b_c) and the inhibitory efficacy of different concentrations of inhibitor.

The results presented in Table 5 show that the addition of the inhibitor in a corrosive medium led to a decrease in the corrosion current densities as the inhibitor concentration increased, which may be due to the adsorption of the inhibitor on the steel-solution interface. Moreover, in the presence of the inhibitor, the inhibitory efficiency increases with the concentration and reaches approximately 87%, therefore an increase of the polarization resistances and a decrease of the corrosion potentials, Fig. 9 indicates that the corrosion rate on the XC70 decreases with the increase of the inhibitor, it went from 2.943 to 0.383 mm/year for a concentration

of 14.28%.

In order to show the effect of the action of the aqueous leaves extract of the plant *C. Conglomeratus* as a corrosion inhibitor and to determine the effect of the current on the type of corrosion inhibition; the variation of the open circuit potential E_{opc} and the corrosion potential E_{corr} for each concentration of the green inhibitor illustrated in Fig. 10 was followed. The values E_{opc} were obtained after 30 min immersion of the working electrode in the test solutions without polarization, while the E_{corr} values were determined by extrapolation of the Tafel curves (with polarization) during a polarity measurement in the laboratory. The slightest change of E_{opc} in the presence or the absence of the inhibitor is therefore translated, that the aqueous extract of the leaves of the plant *C. Conglomeratus* in the open circuit can delay the oxidation of XC70 and

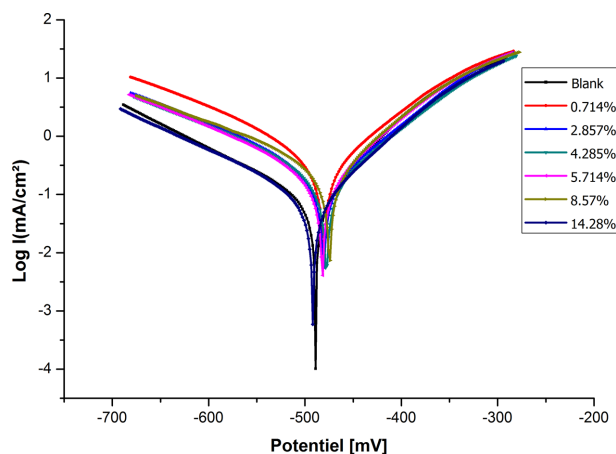


Fig. 8. Tafel polarization curves for the XC70 steel electrode in 1M HCl solution containing various concentrations of the aqueous extract of *Cyperus conglomeratus*'s leaves

Table 5. Electrochemical data derived from Tafel measurements at various concentrations of the aqueous extract of the leaves of the plant *Cyperus Conglomeratus*

C%(V/V)	E_{corr} (mV)	R_p (ohm.cm ²)	i_{corr} (mA/cm ²)	IE _i % (i_{corr})	Cr (mm/year)	b_a (mV)	$-b_c$ (mV)	Surface coverage (θ)
Blank	-482.6	63.92	0.254		2.943	79.8	94.0	
0.714	-482.9	112.02	0.1237	51.29	1.433	71.8	85.1	0.512
2.857	-479.8	118.69	0.1188	53.22	1.377	72.6	89.2	0.532
4.285	-484.2	116.03	0.0925	63.58	1.072	55.6	71.7	0.635
5.714	-476.8	84.65	0.0928	63.46	1.075	43.0	54.0	0.634
8.571	-493.9	244.92	0.0619	75.62	0.7176	68.2	99.1	0.756
14.28	-491.2	217.55	0.0331	86.96	0.3833	37.3	51.5	0.869

the reduction of hydrogen ions to produce hydrogen gas on the surface of the steel, it can therefore be concluded that the inhibitor can react as a mixed type inhibitor without or with the polarization of the working electrode. As the cathodic polarization is the shift of the potential of the cathode to the negative direction and the anodic polarization is the shift of the potential of the anode to the positive direction. The inhibitor could take the function of the cathodic or anodic inhibitor, if the displacement of E_{corr} is greater than 85 mV, however, if the displacement of E_{corr} is less than 85 mV, it can be considered as an inhibitor mixed type. In this research, the values of the corrosion potential vary irregularly concerning the corrosion potential of steel without the

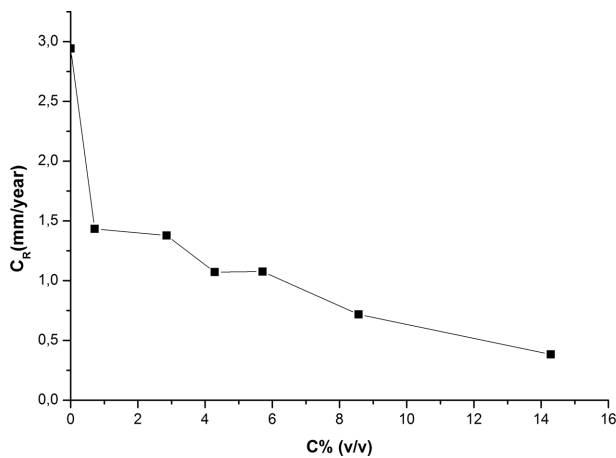


Fig. 9. Variation of corrosion rate with different concentrations of the aqueous extract of *Cyperus Conglomeratus's* leaves by electrochemical method

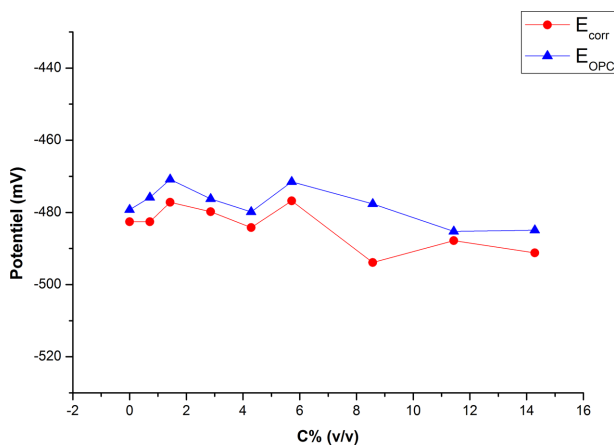


Fig. 10. Variation of the open circuit potential and the corrosion potential with different concentrations of the aqueous extract of *Cyperus conglomeratus's* leaves in 1 M HCl

use of an inhibitor, where the displacement of E_{corr} is less than 20 mV (11.3 mV) for the aqueous extract of the leaves of the plant *C. Conglomeratus* which shows that this green inhibitor reacts as a mixed type inhibitor. Inhibitors of the mixed type are represented by organic compounds with Se, S, N, or O donor atoms instead of having reactive functional groups that cling to the metal [2,21]. The values of b_a and b_c are slightly modified indicating that the inhibition mechanism has appeared by simply blocking available cathode and anode sites from the surface of the steel.

3.3.2 Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy (EIS) is one of the best techniques for analyzing the properties of the electrochemical system and explaining the process of inhibition mechanism, it relies on the measurement of a transfer function following the deliberate disturbance of the electrochemical system studied [22,23]. The Nyquist and Bode diagrams obtained from the EIS measurements for XC70 steel in a 1 M solution of HCl in the absence and the presence of the 298 K inhibitor are shown in Fig. 11 and Fig. 12 respectively. Nyquist curves with and without inhibitor addition represent a semicircle at all concentrations, showing that the charge transfer mechanism is at the inhibitor/steel interface [24,25]. The diameters of the capacitive half-loops increase with the increasing inhibitor concentration, indicating the increase in the inhibition efficiency. This

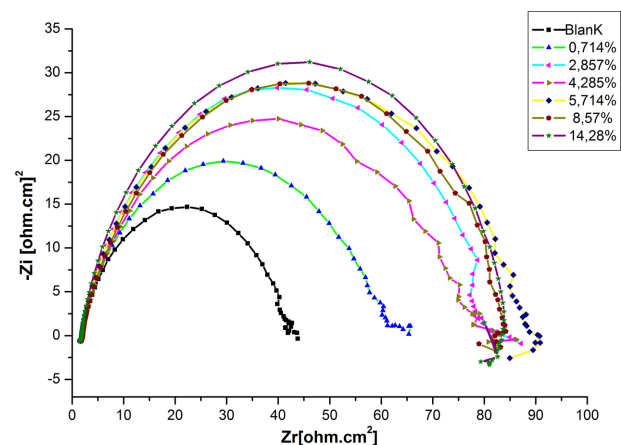


Fig. 11. Nyquist plots recorded for the XC70 steel electrode in 1 M HCl solution containing various concentrations of the aqueous extract of *Cyperus conglomeratus's* leaves

EVALUATION OF THE INHIBITIVE PERFORMANCE OF *CYPERUS CONGLOMERATUS* LEAVES EXTRACT AS A GREEN CORROSION INHIBITOR ON MILD STEEL XC70 IN ACID MEDIUM

observation indicates that the inhibitory layer formed on the surface of the steel could significantly improve its corrosion resistance [26]. The observed depression of the capacitive semicircle due to the frequency dispersion effect can be related to the roughness of the metal surface, the existence of porous layers on the surface, and the adsorption of inhibitor molecules on the surface of steel [27,28]. Nyquist diagrams can be modeled using a simple equivalent electrical circuit, in which case the ideal capacitive behavior is not observed and thus a constant phase element (CPE) is used to account for surface inhomogeneities [29,30]. The representation of the Bode diagrams of 1M HCl solution in the absence and the presence of different concentrations of the inhibitor is illustrated in Fig. 12, in this type of diagram, the module of the impedance $|Z|$ (represented in logarithmic scale) and the phase shift angle is plotted

against frequency, also represented in logarithmic scale.

Only one time constant (CPE) is detected in the Bode plots, this can be attributed to the dispersion of the frequency of the interfacial impedance. Fig. 12 shows that the modulus of the impedance and phase shift angle over the frequency range has been increased with increasing concentrations of the inhibitor, these results are in good agreement with the impedance of the selected equivalent circuit and validate the effective ability to be inhibited by the aqueous extract leaves of the plant *C. Conglomeratus* and the corrosion reaction of XC70 steel is controlled by a process of charge transfer. In this study, the impedance data were analyzed by an electrical equivalent circuit (EEC) for the metal/electrolyte interface consisting of the solution resistance (R_s), charge transfer resistance (R_{ct}), and the double-layer capacitance (C_{dl}) as illustrated in Fig. 13.

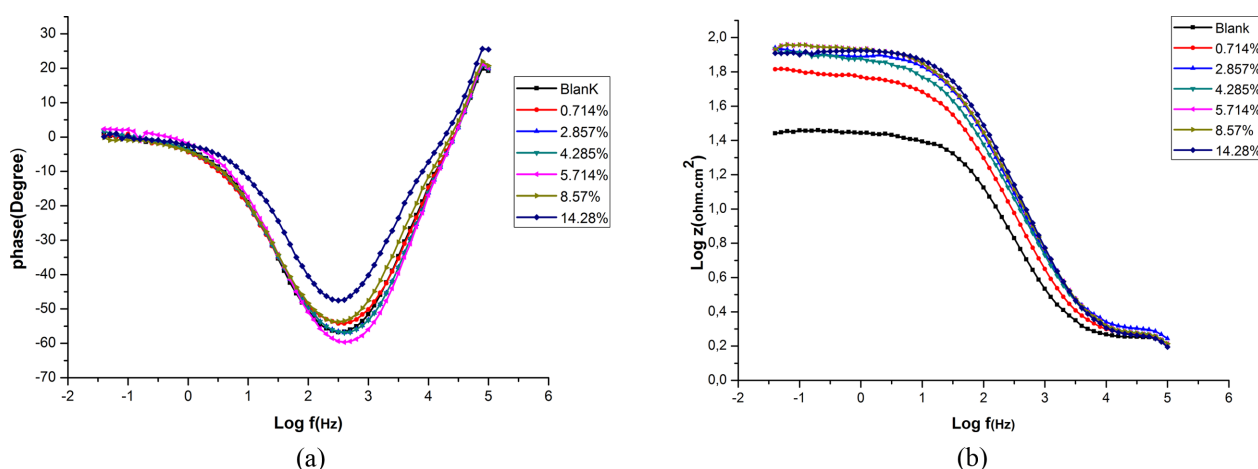


Fig. 12. Bode plots for XC70 steel corroded in without and with various concentrations of the aqueous extract of *Cyperus conglomeratus*'s leaves

Table 6. Characteristic parameters evaluated from the impedance diagram for steel at various concentrations of the aqueous extract of the leaves of the plant *Cyperus Conglomeratus*

C% (V/V)	R_s (ohm.cm ²)	R_{ct} (ohm.cm ²)	C_{dl} (μF/cm ²)	f_{max} (Hz)	Depletion angle (°)	$IE_{R_{ct}}$ %	Surface coverage (θ)
Blank	1.691	26.05	122.1	50.063	-8.94 °		
0.714	1.699	57.22	87.89	31.663	-9.93 °	54.47	0.544
2.857	1.761	79.75	63.05	31.668	-10 °	67.33	0.673
4.285	1.729	71.58	70.25	31.667	-9.27 °	63.6	0.636
5.714	1.798	83.09	60.52	31.666	-10.1 °	68.64	0.686
8.571	1.811	83.43	76.3	25.014	-9.84 °	68.77	0.687
14.28	1.672	83.68	60.09	31.67	-10.2 °	68.87	0.688



Fig. 13. Electrical Equivalent Circuit

The solution resistance (R_s), charge transfer resistance (R_{ct}), and constant phase angle element (CPE), which is related to the double-layer capacitance (C_{dl}), and $IE_{R_{ct}}$ the effectiveness of the corrosion inhibitor of the steel in a corrosive medium are summarized in Table 6.

From Table 6, the R_{ct} values are greater in the inhibited solution than in the uninhibited solution. The charge transfer resistance continues to increase with increasing inhibitor concentrations, they vary between 26.05 - 83.68 $\text{ohm}\cdot\text{cm}^2$. The increase in transfer resistance R_{ct} is due to the formation of a passive protective film on the surface of the steel. Resistance values of the R_s solution are slightly higher in the presence of the corrosion inhibitor, since organic inhibitors generally reduce the dielectric constant of the aqueous solutions, thus increasing their strength [31]. The results obtained show that the inhibitory efficiency becomes greater with the increase in the concentration of the inhibitor, which has an optimum value of 68.87% for a 14.28% inhibitor concentration.

With the addition of the inhibitor, the double layer capacity C_{dl} decreases from 122.1 $\mu\text{F}/\text{cm}^2$ to 60.09 $\mu\text{F}/\text{cm}^2$, this decrease can be attributed to the adsorption of organic molecules on the surface of the steel. In fact, the more the inhibitor adsorbs, the more the thickness of the organic deposit increases, and the capacity of the double layer decreases [29,32]. The decrease in C_{dl} is due to the adsorption of the inhibitor on the surface of the steel, which has the effect of reducing the dielectric constant of the medium, and/or increasing the thickness of the electric double layer [33].

3.4 Adsorption Isotherm

The adsorption of organic molecules provides information on the interaction between the adsorbed molecules themselves as well as their interaction with the surface of the electrode. Measurements were made to evaluate the type and process of adsorption of the aqueous leaves extract of the plant *Cyperus Conglomeratus* on the surface of XC70 steel and find the model best suited to the results obtained by the method of loss mass and electrochemical measurements (polarization curves and EIS). According to the results obtained in Tables 3, 5, and 6, the value of (θ) increases with the addition of the aqueous extract as an inhibitor. Data from the three methods were tested with the Langmuir, Temkin, and Frumkin isotherm (Table 7).

In order to evaluate the adsorption process of the aqueous extract of *C. Conglomeratus's* leaves on the carbon steel surface, Langmuir, Temkin and Frumkin adsorption isotherms were obtained according to the following equations [34,35] :

$$\text{Langmuir: } C_{inh}/\theta = \frac{1}{K} + C_{inh} \tag{11}$$

$$\text{Temkin: } \log \theta/C_{inh} = \log k - \alpha\theta \tag{12}$$

$$\text{Frumkin: } \frac{\theta}{(1-\theta)} \text{Exp}(2\alpha\theta) = k \times C_{inh}$$

$$\text{Its linear form: } \log \theta/(1-\theta)C_{inh} = \log k + \alpha\theta \tag{13}$$

Where θ is the surface coverage ($\theta = \text{IE}\% / 100$), K is the adsorption-desorption equilibrium constant, C_{inh} is the inhibitor concentration and α is the adsorbate interaction parameter.

From Table 7 and Fig. 14, 15 & 16, for the mass loss method; the variation of the C/θ ratio as a function of the inhibitor concentration is linear with a regression coefficient $R^2 = 0.96$ close to unity. This indicates that

Table 7. Isotherms for the adsorption of the aqueous extract of *Cyperus conglomeratus's* leaves on the surface of XC70 steel in 1M

Isothermes	Weight Loss Method		Polarization Method		EIS	
	Equation Linear	R ²	Equation Linear	R ²	Equation Linear	R ²
Langmuir	$C/\theta = 2.362C + 0.635$	0.968	$C/\theta = 1.0624 C + 1.927$	0.974	$C/\theta = 1.431C + 0.291$	0.999
Temkin	$\text{Log}\theta/C = 0.564\theta - 0.728$	0.053	$\text{Log}\theta/C = 2.308\theta + 0.696$	0.704	$\text{Log}\theta/C = 6.415\theta + 3.367$	0.762
Frumkin	$\text{Log}\theta/(1-\theta)C = 0.318\theta - 2.015$	0.002	$\text{Log}\theta/(1-\theta)C = -0.078\theta - 0.042$	0.355	$\text{Log}\theta/(1-\theta)C = -5.269\theta + 3.082$	0.684

EVALUATION OF THE INHIBITIVE PERFORMANCE OF *CYPERUS CONGLOMERATUS* LEAVES EXTRACT AS A GREEN CORROSION INHIBITOR ON MILD STEEL XC70 IN ACID MEDIUM

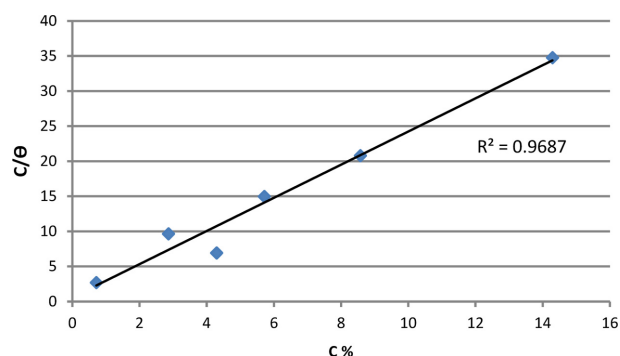


Fig. 14. Langmuir adsorption isotherm of the inhibitor by the loss mass method

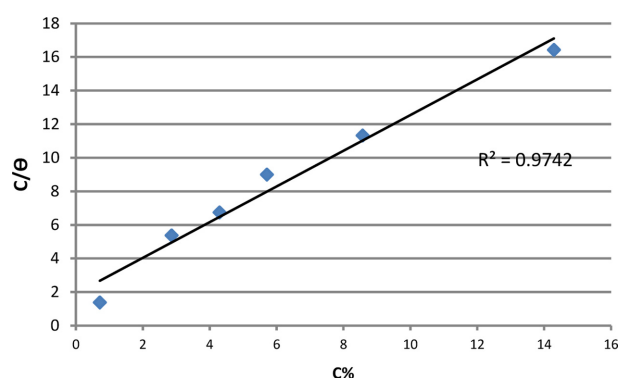


Fig. 15. Langmuir adsorption isotherm of the inhibitor by Tafel polarization method

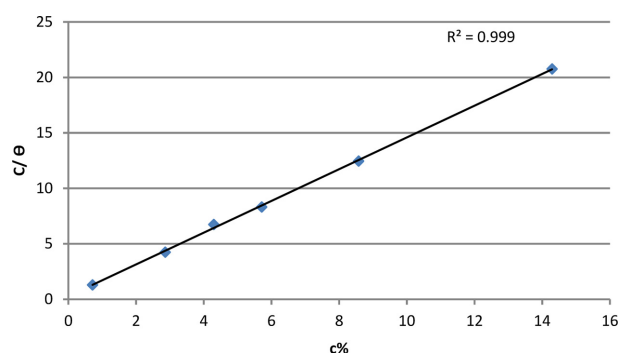


Fig. 16. Langmuir adsorption isotherm of the inhibitor by EIS method

the adsorption of the aqueous leaf extract of the plant *C. Conglomeratus* on the surface of XC70 steel in 1M HCl medium obeys the Langmuir adsorption isotherm. This same behavior is obtained for electrochemical measurements (the polarization method and EIS). Therefore, the aqueous leaf extract of the plant *C. Conglomeratus* extract contains organic compounds

having polar atom (s) and groups also containing heteroatoms which are adsorbed on the metal surface by single layer adsorption, limiting the access of the electrolyte [36]. Inhibitor molecules remain stable when their free energies have been reduced by their adsorption on the steel surface, where they have reacted with ions or molecules close to the surface [37].

4. Conclusion

- This work shows that the aqueous leaf extract of the plant *Cyperus conglomeratus* inhibits corrosion in a 1M HCl solution, as well as the corrosion inhibitory efficiency increases with the concentration of the extract.
- The polarization curves show that the aqueous extract of the leaves of the plant *Cyperus conglomeratus* can react as a mixed-type inhibitor.
- The EIS measurements show that the transfer resistance R_{ct} increases whereas the double layer capacity C_{dl} decreases with the increasing concentration of aqueous extract of the leaves of the plant *Cyperus conglomeratus*, this is due to the adsorption of the inhibitor molecules on the surface of the steel.
- The evaluation of the anticorrosive activity by the three methods confirms the adsorption of the inhibitor molecules while the adsorption model obeys the adsorption of Langmuir.

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