***Capparis Aegyptia* as a green inhibitor for aluminum corrosion in alkaline media**

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Abstract

The study of metal corrosion is of particular importance for the environment, economy and industry. Several methods have been used to control corrosion of metals. However, plant extracts are considered among the best choices as they are environmentally safe, inexpensive and renewable. In this study, the inhibition effect of *Capparis Aegyptia* extract on the corrosion of aluminum in 1 M sodium hydroxide (NaOH) was investigated. Both weight-loss measurements and electrochemical polarization methods were used. The results show that *C. aegyptia* extract is a good corrosion inhibitor. The inhibition efficiency increases with inhibitor (*C. aegyptia* extract) concentration and slightly increases with temperature. The inhibition efficiency reaches a maximum value of 93.8% with the highest extract concentration at 25°C. The adsorption of *C. aegyptia* extract on aluminum surface obeys Langmuir and Temkin adsorption isotherms. The thermodynamic adsorption free energy (ΔG_{ads}^0) value and sign were indicative of the physisorption of *C. aegyptia* extract molecules on the aluminum surface. Moreover, the thermodynamic parameters (ΔH^* , ΔS^* and E_a) of the adsorption process were calculated and discussed. The electrochemical polarization study showed that *C. aegyptia* extract act as a mixed-type inhibitor cathodic and anodic. Moreover, surface morphology was analyzed by scanning electron microscopy (SEM) technique. SEM results provided confirmatory evidence of the improved surface condition, due to the adsorption, for the corrosion protection.

Keywords: *C. aegyptia*, green inhibitor, aluminum, electrochemical polarization, weight loss.

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Introduction

The study of natural products of plant origin as inexpensive, eco-friendly corrosion inhibitors is an essential field of study. The extracts from their leaves, barks, seeds, and roots comprise of a mixture of organic compounds and some have been reported to function as effective inhibitors of metal corrosion [1–3]. The presence of heteroatoms in the structure of inhibitory molecules such as O, N, S; enhance the adsorption process and inhibition efficiency [4, 5]. Recent literature has shown that plant materials, such as *Salvia judica* [6], *Sinapis Alba* [7], *Plumbago Europae* [8], *Mesembryanthemum nodiflorum* [9],

Inula viscosa [10], *Lupinus varius* [11] and *Capparis spinosa* [12, 13] are effective inhibitors for aluminum in alkaline solution. The corrosion inhibition efficiency of this plant's extracts is normally attributed to the presence of complex organic species.

Corrosion of aluminum and its alloys has been a subject of numerous studies due to their importance in the recent civilization. Accordingly, numerous studies concerning the inhibition of aluminum corrosion using organic substances have been conducted [13–16].

Capparis is a flowering plant genus in the family of Capparaceae. These plants are shrubs or lianas and are collectively known as caper shrubs or caper bushes. *Capparis* species occur over a wide range of habitat in the subtropical and tropical zones. The corrosion inhibition efficiency of *Capparis* extract is normally attributed to the presence of complex organic species such as Sterols, flavones, oxygenated heterocyclic constituents, alkaloids, and an isothiocyanate glycoside [17–20].

In the present work, weight loss method and electrochemical polarization methods were used to investigate the inhibition of aluminum corrosion by *C. aegyptia* extract in a 1 M NaOH solution. Weight loss measurement was used to study the effect of inhibitor concentration and temperature on the inhibitor efficiency of *C. aegyptia* extract on the corrosion aluminum. The surface morphology was analyzed by scanning electron microscopy (SEM) technique.

1. Experimental

1.1. Material preparation

Pure aluminum (purity 99.999%) was supplied in the form of a foil of a thickness of 0.5 mm (Aldrich). The experiments were carried out using rectangular aluminum foil specimens (dimensions: length = 3 cm, width = 1 cm and thickness = 0.5 mm). The aluminum specimens were treated by a mixture of H_3PO_4 (85 wt.% in water) and HNO_3 (15 v/v) at 80°C for 30 s, then immersed in HNO_3 solution (50% v/v) at 50°C for 20 seconds, rinsed well in deionized water and placed in alkaline solution (40.0 g NaOH in 1 L deionized water) for one minute. The specimens dried well on-air stream and isolated from the outside atmosphere for further use.

1.2. Preliminary phytochemical screening

The obtained methanolic extract of the *C. aegyptia* plant was subjected to different chemical tests for the detection of different Phyto-constituents using standard procedures [21]. Moreover, the presence of these functional groups was confirmed by recording the FTIR spectra for the crude oil using Bruker Tenson 72 spectrometer.

1.3. Samples preparation and weight loss measurements

The inhibition efficiency of aluminum in the aqueous solution of sodium hydroxide by using *C. aegyptia* extract as an inhibitor was determined by the gravimetric technique. A 50 g of dry *C. aegyptia* powder was refluxed in 250 mL of 1 M NaOH solution for 3 h,

allowed to stand overnight then filtered using Whatman general-purpose filter paper, diam. 90 mm (Aldrich). The weight loss experiments were carried out using the aluminum foil specimens (total exposed area = 6.4 cm²). Specimens were weighed and immersed for different time intervals (1, 2, 4 and 6 hours) at 250°C in 15 ml of 1 M NaOH solutions of the (*C. aegyptia*), and for different concentrations of the extract (40–440 mg/L). After testing, they were rinsed thoroughly with deionized water, dried, and reweighed. The measurements were carried out at 25, 35 and 450°C using a water thermostat controlled to ±0.50°C and weighed using Electronic Semimicro Balance Sartorius 2024 MP6 with the precision of ±0.1 mg. Triplicate determinations were carried out each time.

1.4. Potentiostatic polarization measurements

Potentiostatic polarization studies were carried out using an EG&G (model 264) potentiostat/galvanostat. The current-potential curves were measured using a conventional three-electrode cell. The working electrode was aluminum (a cylindrical rod embedded in Araldite with the exposed surface area of 0.6 cm²); the saturated calomel electrode (SCE) was used as a reference and a platinum foil was used as a counter electrode. Polarization was carried out in alkaline solution in the absence and presence of various concentrations of the inhibitor *C. aegyptia*. The current-potential curves were recorded automatically. The polarization was scanned from a potential of –1000 mV to 0.0 mV (SCE) with a scan rate of 10 mV s^{–1}.

The electrochemical corrosion current density was evaluated using the well-known Stern-Geary equation (Equation 1):

$$I_{\text{corr}} = \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c) \frac{1}{R_p}} \quad (1)$$

where I_{corr} is the corrosion current density; β_a is the anodic Tafel constant; β_c is the cathodic Tafel constant and R_p is the polarization resistance.

Corrosion current density (I_{corr}) was estimated from the intercept of cathodic and anodic Tafel lines and the inhibition efficiency ($I\%$) was calculated by using the following equation (Equation 2) :

$$I\% = (I_{\text{corr}}^* - I_{\text{corr}}) / I_{\text{corr}}^* \quad (2)$$

where, I_{corr} and I_{corr}^* are the corrosion current density with and without the inhibitor, respectively.

1.5. Scanning electron microscopy (SEM)

The surface morphology of the aluminum specimens was examined after polishing and after exposure to 1 M NaOH in the absence and presence of an optimal concentration of

the inhibitor. The instrument used was FEI Inspect F50 scanning electronic microscope (Netherlands) equipped with a Field Emission Gun (FEG).

2. Results and discussion

2.1. Phytochemical analysis

Methanolic extract of *C. aegyptia* is investigated as a possible corrosion inhibitor. As shown in Table 1, the methanolic extract was found to contain flavonoids, Anthraquinones, saponin, tannins, and glycosides. It is well-documented that most of these constituents have excellent inhibitive action [22–26].

Table 1. Qualitative analysis of phytochemical compounds in the methanolic extract of *C. aegyptia*.

Phytochemical tests	Result
Tannins	Positive
Flavonoids	Positive
Anthraquinones	Positive
Saponins	Positive
Glycosides	Positive

2.2. Fourier transform infra-red (FTIR) spectroscopy

IR spectrum was obtained for the extract mixture as shown in Figure 1. Careful inspection of the IR spectra indicate the presence of the following active sites; (i) O–H stretching frequency appears at 3409 cm^{-1} ; (ii) The aromatic stretching frequency appear at 292 cm^{-1} and 2852 cm^{-1} ; (iii) C=O stretching frequency at 1620 cm^{-1} ; (iv) C=C stretching frequency at 1510 cm^{-1} ; (v) CH_2 bending frequency at 1385 cm^{-1} (vi) CH bending frequency at 1272 cm^{-1} (vii) C=C bending frequency at 1059 cm^{-1} .

Figure 1. The IR spectra for the *C. aegyptia* extract.

2.3. Weight loss measurements

2.3.1. Effect of inhibitor concentration

The weight loss of aluminum in 1 M NaOH in the presence and absence of *C. aegyptia* extract as green inhibitor were tested at 25°C, at different immersion times (1 h, 2 h, 4 h, and 6 h), and for different concentrations of the extract (40–440 mg/L). The weight loss was recorded to the nearest ± 0.1 mg. The weight loss of the corrosive solution is given by the following equation (Equation 3);

$$\Delta W = W_i - W_f \quad (3)$$

where W_i and W_f are the weight losses of the aluminum specimens in the presence and absence of the inhibitors, respectively. Figure 2 shows the variation of the weight loss (mg) of Al due to corrosion with the immersion time in 1 M NaOH solution of various concentrations of *C. aegyptia* extract at 25°C, respectively. Weight loss of aluminum was determined, at various time intervals, in the absence and presence of different concentrations of *C. aegyptia* extract. the weight loss values (mg) of Al decreased as the concentration of the inhibitor increased, *IE* the corrosion inhibition increases with increasing the extract concentration. This behavior is expected to occur due to the increase in the surface coverage of the metal with the increase of the extract concentration, thus the aluminum surface is efficiently separated from the medium [24–27].

The percentage inhibition efficiency (*IE*) was calculated using the following equation (Equation 4).

$$\%IE = (w_0 - w_i) / w_0 \quad (4)$$

where w_0 and w_i are weight losses of Al in the absence and presence of the inhibitor. The percentage of inhibition efficiency (*%IE*) of the investigated *C. aegyptia* crud extract (Table 2). These experiments were Carried out at different time intervals and using different concentrations of the inhibitor at 25°C. A careful look at these Table 2 indicates that the inhibition efficiency increases with increasing the extract concentration and time. Generally, the adsorption of inhibitor at metal/solution interfaces can markedly change the corrosion resisting properties of metals. The efficiency of organic molecules as good corrosion inhibitors mainly depends on their adsorption ability on the metal surface. This adsorption can occur through the replacement of water molecules by organic inhibitor molecules [27].

Figure 2. Weight loss variation of aluminum *versus* *C. aegyptia* extracts concentration in 1 M NaOH at 25°C at different immersion period.

Table 2. Inhibition efficiencies of Al in the presence of different concentrations of the inhibitor and at different time intervals at 25°C.

Conc. (ppm)	Inhibition efficiency (%IE)			
	1 h	2 h	4 h	6 h
40	47.1	54.2	62.7	64.9
120	65.3	70.9	74.2	74.8
200	76.9	80.9	81.6	81.8
280	81.1	86.0	86.8	87.4
360	86.4	89.4	91.0	91.6
440	91.6	93.2	93.8	93.8

2.3.2. Effect of temperature

Corrosion rates (CR) of Al are calculated several experiments were carried out using the same parameters except for temperature, which was changed over the range (25, 35, 45°C). The immersion time in these experiments was kept constant also at two hours. The influence of changing the temperature on the corrosion rate of Al in 1 M NaOH solutions is presented in Figure 3, the figure reveals that the corrosion rates increase with an increase in temperature. Usually, increasing the temperature accelerates the corrosion process and hence increases the dissolution rate of the metal. However, when inhibition efficiencies are calculated, the reverse was observed, in which, the inhibition efficiency was increased with the increase of temperature Table 3. It is well documented in the literature that, a decrease in inhibition efficiency with the rise in temperature is frequently interpreted as being suggestive of the formation of an adsorption film of physical (electrostatic) nature. The

reverse effect (our case), corresponding to an increase in inhibition efficiency with a rise in temperature in the presence of inhibitor, suggests a chemisorptions mechanism [27–30].

Table 3 shows the percentage of inhibition efficiencies at various concentrations in 1 M NaOH for 120 min immersion period at different temperatures (25–45°C). The results showed that inhibition efficiency increased as the concentration of inhibitor increases from 40–440 mg/L. The maximum inhibition efficiency of 93.45% was observed at 45°C for 440 mg/L of extract in basic medium. This behavior is most probably due to an increase in the metal surface area covered by the extract.

Figure 3. The variation in the corrosion rate of Al in 1 M NaOH in the presence of *C. aegyptia* crud at various temperatures.

Table 3. Inhibition efficiencies of Al in the presence of different concentrations of the inhibitor at different temperatures at 2 h.

Conc. (ppm)	Inhibition efficiency (%IE)		
	<i>T</i> = 298 K	<i>T</i> = 308 K	<i>T</i> = 318 K
40	30.60	34.12	36.84
120	70.89	71.94	73.60
200	79.51	80.00	81.79
280	85.95	86.41	87.99
360	87.87	88.20	90.01
440	91.77	92.30	93.45

2.4. Kinetic and thermodynamic considerations

By using the Arrhenius law in the temperature range used, a plot of the logarithm of the corrosion rate *versus* the reciprocal of absolute temperature gives straight lines according to Arrhenius equation (Equation 5):

$$R_c = Ae^{\frac{-E_a}{RT}} \quad (5)$$

where R_c is the corrosion rate, A is the constant frequency factor and E_a is the apparent activation energy.

The values of E_a were calculated and summarized in Table 4 for the basic medium. The values of the activation energy decrease as the concentration of *C. aegyptia* extract increases.

The value of activation energy E_a is higher in the uninhibited solution compared to the inhabited ones. Analysis of the temperature dependence of inhibition efficiency as well as comparison of corrosion activation energies in the presence of inhibitor gives some insight into the possible mechanism of inhibitor adsorption. A decrease in inhibition efficiency with the rise in temperature, with the analogous increase in corrosion activation energy in the presence of inhibitor compared to its absence, is frequently interpreted as being suggestive of the formation of an adsorption film of physical (electrostatic) nature. The effect, corresponding to an increase in inhibition efficiency with the rise in temperature and lower activation energy in the presence of inhibitor, suggests a chemisorption mechanism [27–30]. From the foregoing, the trend for the extracts of *C. aegyptia* suggests a predominant effect chemisorption of inhibiting species 1 M NaOH.

Thermodynamic parameters of the corrosion process play an important role in defining the spontaneity of metal conversion into corrosion products. Thermodynamic parameters of activation for corrosion process (enthalpy (ΔH), free energy (ΔG) and entropy (ΔS)) were calculated by using an alternative formulation of the Arrhenius equation is the transition state equation (Equation 6):

$$R_c = \frac{K_b T}{h} e^{\left(\frac{\Delta S^*}{R}\right)} e^{\left(\frac{-\Delta H^*}{RT}\right)} \quad (6)$$

where h is Planck's constant, K_b Boltzmann's constant, ΔS^* is the entropy of activation and ΔH^* is the enthalpy of activation.

Table 4. Corrosion rates (mg/h·cm²) and activation energies at various temperatures in 1 M NaOH.

Conc. (mg/L)	CR (298 K)	CR (308 K)	CR (318 K)	R^2	E_a (kJ/mol)
0	5.992	11.046	25.267	0.989	56.59
40	4.158	7.277	15.958	0.987	52.87
120	1.744	3.100	6.669	0.990	52.75
200	1.228	2.209	4.600	0.993	51.97
280	0.842	1.502	3.033	0.994	50.44
360	0.727	1.303	2.525	0.997	49.02
440	0.493	0.850	1.655	0.994	47.62

According to this equation, a plot of $\log (R_c/T)$ against $(1/T)$ gives a straight line from which the values of ΔH^* and ΔS^* are calculated and listed in Table 5 for a basic medium

Absolute values of enthalpy of activation decreased from 54.03 to 45.06 kJ/mole ongoing from the uninhibited solution to highest inhibitory concentration (440 mg/L) in 1 M NaOH solution, values of enthalpy of activation for the inhibited solutions are lower than that of the uninhibited solution followed by a continuous decrease with the increase of inhibitor concentration, indicating that the inhibitory action in solution occurs via chemical adsorption. However, values of enthalpy in this study are larger than the common physical adsorption heat, but smaller than the common chemical adsorption heat [31, 32], probably meaning that both physical and chemical adsorption take place (*i.e.* comprehensive adsorption). The adsorption heat approached the general chemical reaction heat, the chemical adsorption might occur accompanied by physical adsorption (electrostatic interaction).

The entropy of activation (ΔS^*) in the absence and presence of the inhibitor has negative values. This indicates that the activated complex in the rate-determining step represents an association rather than dissociation, meaning that, a decrease in disordering takes place on going from reactants to the activated complex [33, 34]. The ΔS^* shifts to more negative values (more ordered behavior) with increasing inhibition efficiency and this was more pronounced in the case of NaOH inhibited solutions. This can be explained that the inhibitor species may involve in the activated complex of the corrosion reaction leading to more ordered systems.

Table 5. Enthalpy and Entropy values of the reaction with various concentrations of the *C. aegyptia* extract in 1 M NaOH.

Inhibition conc. (mg/L)	R^2	ΔS^* (kJ/mol·K)	ΔH^* (kJ/mol)
0	0.988	−0.081	54.03
40	0.986	−0.096	50.32
120	0.989	−0.104	50.19
200	0.993	−0.109	49.41
280	0.994	−0.117	47.88
360	0.997	−0.123	46.47
440	0.993	−0.131	45.06

2.5. Adsorption behavior

The adsorption isotherm can be determined if the inhibitor effect is due mainly to the adsorption on a metallic surface (*i.e.* to its blocking). The inhibitory action of *C. aegyptia* extract toward the basic corrosion of aluminum could be attributed to the adsorption of its

components into the aluminum surface. The adsorbed layer acts as a barrier between the metal surface and the aggressive solution leading to a decrease in the corrosion rate.

The values of the amount of inhibitor adsorbed from the solution, Q_{ads} , on the aluminum specimen in the presence of inhibitor are estimated by the following equation (Equation 7):

$$Q_{\text{ads}} = 2.303R \left[\log \left(\frac{\theta_2}{1-\theta_2} \right) - \log \left(\frac{\theta_1}{1-\theta_1} \right) \right] \left[\frac{T_1 T_2}{T_2 - T_1} \right] \quad (7)$$

where R is the gas constant, θ_1 and θ_2 are the degree of surface coverage at temperatures T_1 (324 K) and T_2 (335 K) respectively.

The calculated values of Q_{ads} are found to be ranged from 1.0 to 2.0 kJ mol⁻¹ for basic medium. The positive sign of Q_{ads} indicates an increase in efficiency at high temperatures [6–13].

The experimental data for the tested inhibitor *C. aegyptia* in basic solutions have been applied to different adsorption isotherms. The best correlation among the experimental results from the adsorption of *C. aegyptia* extract on aluminum surface fitted Langmuir adsorption isotherm equation.

The adsorption of *C. aegyptia* extract molecules obeys the Langmuir adsorption isotherm which is expressed by equation (Equation 8):

$$\log \left(\frac{C}{\theta} \right) = -\log K_{\text{ads}} + \log C \quad (8)$$

Where C is the inhibition concentration in terms of ppm and K is the equilibrium constant for the adsorption process of the inhibitor molecules on the metal surface. The plot of the $\text{Log}(C/\theta)$ vs $\log C$ fitted the experimental data for the basic solution as shown in Figure 8.

The equilibrium constants, K_{ads} , for the adsorption of *C. aegyptia* extract on aluminum in basic solution at different temperatures estimated from the regression equation of the linear plot of Figure 4 are summarized in Table 6.

Table 6. Langmuir adsorption parameters for the adsorption of *C. aegyptia* extract on aluminum in the basic medium for 120 min immersion period at different temperatures.

Temperature (K)	K_{ads}	ΔG_{ads} (kJ/mol)	R^2
298	0.018	–0.04	0.9993
308	0.019	–0.12	0.9990
318	0.020	–0.31	0.9995

Figure 4. Langmuir adsorption model on the aluminum surface of *C. aegyptia* extracts in 1 M NaOH solution for 2 hours at different temperatures.

Furthermore, it has been noticed that the value of K_{ads} increases with increasing temperature, indicating that the adsorption of inhibitor molecules on the aluminum surface was favorable at higher temperatures. Such results imply activation that the interactions between the adsorbed molecules and the metal surface become stronger as temperature increased up to 45°C, in this study. This result explains the increase in the inhibition efficiency with increasing temperature. However, the low values reported for the free energy change ΔG_{ads} , confirm the physisorption mechanism of the tested *C. aegyptia* inhibitor on the aluminum surface.

The experimental data for the tested inhibitor has been applied to Temkin adsorption isotherm equation (Equation 9);

$$e^{a\theta} = KC \quad (9)$$

Figure 5 show a plot of θ versus $\log C$ which was made from the above Temkin equation. A linear graph was obtained which confirmed Temkin adsorption isotherm for the adsorption of the extract on the surface of the metal. The fitting was excellent for the basic medium ($R^2 > 0.99$). The K_{ads} and ΔG_{ads} values were evaluated and presented in Table 7.

The relationship between the equilibrium constant K of adsorption and the free energy of adsorption ΔG_{ads} is given by equation (Equation 10);

$$\Delta G_{\text{ads}} = -2.303RT \log(55.5K) \quad (10)$$

Values of free energy of adsorption of *C. aegyptia* crude on the aluminum surface were calculated from the plot of the isotherms in Figure 5 calculated values of ΔG_{ads} are recorded in Table 7 these values are negative. For the basic medium, the values were as

follows; -9.68 , -10.18 and -10.70 kJ/mol at 298, 308 and 318 K, respectively. The values obtained indicate that adsorption of crude is spontaneous and occurs via physical adsorption mechanism. Generally, values of ΔG_{ads} up to -20 kJ/mol (as obtained in this study), while values more negative than -40 kJ/mol signify chemical adsorption [6–13].

Figure 5. Temkin adsorption isotherm plot as θ against $\log C$ for *C. aegyptia* extract at different temperatures for aluminum corrosion in 1 M NaOH.

Table 7. Temkin adsorption parameters.

Temperature (K)	K_{ads}	ΔG_{ads} (kJ/mol)	R^2
298	0.896	-9.68	0.9910
308	0.959	-10.18	0.9910
318	1.029	-10.70	0.9920

2.6. Potentiostatic polarization measurements

The effect of *C. aegyptia* extract on the corrosion behavior of aluminum electrode in 1 M NaOH solution has been studied by polarization measurements. The Tafel plot data are graphed as potential *versus* the logarithm of the measured current as shown in Figure 6.

The electrochemical corrosion parameters including corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic Tafel constant (β_a), cathodic Tafel constant (β_c) and inhibition efficiency ($I\%$) were calculated from the polarization curves of aluminum in the absence and presence of various concentrations of inhibitor in 1 M of NaOH then summarized in Table 8. The data in Table 8 show that the corrosion current density (I_{corr}) is markedly reduced as the concentration of inhibitor increases, which indicates that the *C. aegyptia* has a pronounced corrosion inhibition effect of aluminum in these media.

From the shape of the polarization curve (Figure 6), they are obvious that both anodic and cathodic reactions are inhibited. They are evident from the data shown in Table 8. that as the concentration of the inhibitor increases, the corrosion potential (E_{corr}) is slightly changing. Moreover, the values of both anodic (β_a) and cathodic (β_c) Tafel constants are strongly changed in the presence of the inhibitor (*C. aegyptia*). This confirms the mixed-mode (anodic and cathodic) inhibition action of the *C. aegyptia*.

The anodic Tafel constant (β_a) is greater than the cathodic (β_c) Tafel constant at all inhibitor's concentrations suggesting that the effect of the inhibitors on the anodic polarization is more pronounced than that on cathodic polarization (Table 8).

It was reported that the presence of polyphenol compounds inhibits the corrosion by controlling both the anodic and cathodic reactions

Furthermore, an inspection of Table 8. reveals that; current densities (I_{corr}) decrease considerably by the addition of the extract to the basic solution concerning the blank solution, indicate that the extract retards the rate of corrosion. Also, a significant decrease in the corrosion current (I_{corr}) and corrosion rate accompanied by an increase in the polarization resistance (RP) value, which is evident that the inhibition efficiency increased with extract concentration increased and reaching a maximum at 440 ppm. The obtained values of inhibition efficiency ($I\%$) from polarization studies were in good agreement with those obtained from the weight loss study with a small variation. The results of both weight loss and polarization methods revealed that the *C. aegyptia* provide very good protection to aluminum against corrosion in basic medium. This can be attributed to the relative stability of the *C. aegyptia* film that formed on the surface of aluminum [22, 24].

Figure 6. Polarization anodic and cathodic curves of aluminum in the absence and presence of various concentrations of *C. aegyptia* in 1 M NaOH.

Table 8. Electrochemical corrosion parameters of Aluminum in the absence and presence of various concentrations of inhibitor *C. aegyptia* in 1 M NaOH.

Extract conc (mg/L)	E_{corr} (mV/SCE)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	β_a (mV/dec)	β_c (mV/dec)	R_p (Ohm)	I (%)	CR mm/y
Blank	−149.89	6.546	157	50	4.924	—	71.40
120	−150.1	2.731	116	34	7.499	58.27	57.35
280	−154.8	1.367	94	28	15.24	79.11	14.91
440	−155.9	0.664	48	36	16.73	89.85	7.30

2.7. Scanning electron microscope (SEM)

Figure 7. Scanning electron micrograph of plain aluminum in basic medium (a) aluminum in 1 M NaOH at 25°C (b) aluminum in 1 M NaOH in the presence of 120 ppm *C. aegyptia* at 25°C (c) aluminum in 1 M NaOH in the presence of 440 ppm *C. aegyptia* at 25°C.

Figure 7(a) shows uniform severe corrosion in the absence of inhibitor, and the forming of adherent amorphous corrosion products. The appearance of such corroded areas may be attributed to the dissolution of the alumina layer due to the aggressive attack of OH^- anions and the increased alkalinity of the solution in the vicinity of the surface [7–9]. However, the SEM obtained for aluminum in presence of inhibitor showed that the metal surface is partially covered with inhibitor giving it a reasonable degree of protection and it is obvious that the surface is covered with an inhibitor in presence of sodium hydroxide (Figure 7(b) and (c)). The formation of an adsorbed protective film of the inhibitor molecules on the aluminum surface is also confirmed by scanning electron micrographs in Figure 7(c), which proves that *C. aegyptia* acts as a good inhibitor at basic solutions.

Conclusion

The *C. aegyptia* extract was successfully applied as a corrosion inhibitor on the surface of aluminum in an alkaline solution. The inhibition efficiency increases with an increase in the concentration of the *C. aegyptia* to attain a value of 93.8% in the basic medium at the highest inhibitor concentration 440 ppm at 25°C. Results indicated that the plant extract acts as a good inhibitor in basic media. Besides, it is found that the inhibition efficiency increases with temperature increasing. The values of activation energies (E_a) for the inhibited solutions were less than those of an un-inhibited solution. Interpretations of various thermodynamic, kinetic and electrochemical results indicate the presence of a mixed mechanism for the adsorption of the inhibitor molecules over the aluminum surface. The inhibitor molecules involve both physical and chemical adsorption.

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