Research Article

Opuntia ficus-indica Extract as Green Corrosion Inhibitor for Carbon Steel in 1 M HCl Solution

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The effect of *Opuntia ficus-indica* (Nopal) as green corrosion inhibitor for carbon steel in 1 M HCl solution has been investigated by using weight loss tests, potentiodynamic polarization curves, and electrochemical impedance spectroscopy measurements. Also, scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FT-IR) analysis were performed. The inhibitor concentrations used ranged from 0 to 300 ppm at 25, 40, and 60°C. Results indicated the inhibition efficiency increases with increasing extract concentration and decreases with the temperature, and the inhibitor acted as a cathodic-type inhibitor which is physically absorbed onto the steel surface. In fact, the adsorption of the inhibitor on the steel surface follows the Langmuir adsorption isotherm, indicating monolayer adsorption. The presence of heteroatoms such as C, N, and O and OH groups were responsible for the corrosion inhibition.

1. Introduction

Acid solutions are often used in industry for cleaning, decalizing, and pickling of steel structures, processes which are normally accompanied by considerable dissolution of the metal. Corrosion of metals, however, is considered to be a serious problem in most industries. The new generation of environmental regulation requires the replacement of toxic inhibitors with nontoxic inhibitors. In this context, many alternative ecofriendly corrosion inhibitors have now been developed. A number of organic compounds are known to be applicable as corrosion inhibitors for steel in acidic environments. A big number of scientific studies have been devoted to the inhibitive action of green inhibitors on the corrosion of mild steel in acidic solutions, showing that these extracts could serve as good corrosion inhibitors. For instance, Gopiraman et al. [1] evaluated *Brugmansia suaveolens* and *Cassia*

roxburghii [1] for the corrosion inhibition of mild steel in hydrochloric acid by using weight loss and electrochemical impedance spectroscopy, obtaining inhibitor efficiency values close to 95%. Ji et al. [2] evaluated the use of *Musa paradisiaca* for the corrosion inhibition of mild steel in HCl with the same methods as above plus polarization curves and FT-IR analysis, finding that this extract is absorbed onto the steel surface following a Langmuir type of adsorption isotherm. Similarly, Chauhan and Gunasekaran [3] and Kamal and Sethuraman [4] used *Zanthoxylum alatum* and *Spirulina platensis*, respectively, as corrosion inhibitors for mild steel in HCl. El-Etre [5], Behpour et al. [6], and Abdel Gaber et al. [7] used *Punica granatum*, *Lupinus albus*, and *Ocimum viride* as green corrosion inhibitors of carbon steel in hydrochloric and sulfuric acids, respectively, finding that their efficiency values increased with the inhibitor concentration but decreased with the temperature. Oguzie [8] found similar results but by using

gasometric measurements for mild steel in the same solutions with the use of *Telfairia occidentalis*, *Azadirachta indica*, and *Hibiscus sabdariffa*. Quraishi et al. [9], Al-Turkustani et al. [10], and Vinod Kumar et al. [11] evaluated *Murraya koenigii*, *Medicago sativa*, and *Areca catechu* as ecofriendly inhibitors for mild steel in sulfuric and hydrochloric acids by using weight loss measurements, electrochemical techniques, and surface characterization, finding that they acted as mixed type of inhibitors, with their efficiency increasing with their concentration but decreasing with the testing temperature. Velazquez-Gonzalez et al. [12] used *Rosmarinus officinalis* for the corrosion inhibition of carbon steel in sulfuric acid; Souza et al. [13] evaluated *Ilex paraguariensis* for the corrosion inhibition of carbon steel as well but in HCl, finding that they acted as anodic type of inhibitors, with efficiency values above 80%. Finally, Soltani and Khayatkashani used *Gundelia tournefortii* [14] on mild steel corrosion in 2.0 M HCl and 1.0 M H₂SO₄ solutions by using weight loss measurement, potentiodynamic polarization, and electrochemical impedance spectroscopy techniques. The inhibition efficiency was found to increase with increasing the inhibitor concentration due to the adsorption of the inhibitor molecules on the metal surface.

A number of organic compounds represent this type of inhibition, particularly those containing elements of Groups V and VI of the periodic table, such as nitrogen, phosphorous, arsenic, sulphur, oxygen, and selenium. The efficiency of an organic compound as an inhibitor is mainly dependent upon its ability to get adsorbed on a metal surface [15]. It can then retard the cathodic and/or anodic reaction, thus, reducing the corrosion rate [16]. The stability of the adsorbed inhibitor film on the metal surface depends on some physicochemical properties of the molecule related to their functional groups, aromaticity, the possible steric effects, electronic density of donor atoms, type of corrosive environment, and the nature of the interaction between the π orbital of the inhibitors and the d orbitals of iron [17, 18].

Opuntia ficus-indica is common vegetation in Mexico. The antioxidant activity of the fruit of cactus has been investigated and showed antioxidant components of the fruit such as vitamin C and only negligible amounts of carotenoids and vitamin E [19]. Lee et al. evaluated an ethanol extract of the stem of *Opuntia ficus-indica* to determine the mechanism of its antioxidant activity and found that the OFS extract was characterized as containing a high amount of phenolics (180.3 mg/g), which might be the active compounds responsible for the antioxidant properties of the *Opuntia ficus-indica* extract [20]. Similarly, Galati et al. [21] analyzed the juice of whole fruits of *Opuntia ficus-indica* and determined the contents of ascorbic acid, total polyphenols, and flavonoids and found that the juice showed antioxidant activity probably due to the phenolic compounds that are effective radical scavengers. This study is aimed at investigating the inhibition effect of *Opuntia ficus-indica* extract on mild steel in 1 M HCl solution using weight loss measurements and electrochemical techniques. The inhibitor was investigated and characterized using FT-IR and SEM analysis.

2. Experimental Procedure

2.1. Specimens Preparation. Carbon steel specimens containing C = 0.15%, Mn = 0.70%, P = 0.010%, S = 0.027%, Cr = 0.016%, Ni = 0.12%, Al = 0.006%, Cu = 0.044%, and the balance Fe were cut from a bar with diameter of 1 cm and 1.0 cm long. Specimens were polished successively by using SiC papers of 100, 260, 400, 600, and 800 grades and then thoroughly cleansed with distilled water and then dried with ethanol and kept in a desiccator till their use. Coupons of size 0.7850 cm² were used for electrochemical studies. They were encapsulated in commercial epoxy resin.

2.2. Inhibitor Preparation. 50 g of *Opuntia ficus-indica* fresh was soaked in 100 mL using double distilled water and refluxing the solution for one hour. After cooling, solutions were filtered followed by drying in vacuum oven for one night. The solid extract was used as a corrosion inhibitor.

2.3. Solution Preparation. The corrosive medium was 1 M HCl prepared with 38% analytical grade supplied by Sigma-Aldrich. Double distilled water was used for the preparation of all reagents.

2.4. Weight Loss Measurements. Carbon steel specimens were immersed in 50 mL of 1 M HCl with various extract concentrations (0, 50, 75, 100, 150, 200, and 300 ppm) during 6 hours of exposition. After that, specimens were taken out, washed with double distilled water, degreased with methanol, dried, and weighted accurately. The test was performed in triplicate to guarantee the reliability of results, and the mean value of the weight loss is reported. Tests were performed at room temperature (25°C), 40°C, and 60°C by using a hot plate. Corrosion rates, in terms of weight loss measurements, ΔW , were calculated as follows:

$$\Delta W = \frac{(m_1 - m_2)}{A}, \quad (1)$$

where m_1 is the mass of the specimen before the corrosion test, m_2 is the mass of the specimen after the corrosion test, and A is the exposed area of the specimen. For the weight loss test, inhibitor efficiency (IE) was calculated as follows:

$$IE (\%) = \frac{(\Delta W_1 - \Delta W_2)}{\Delta W_1} \times 100, \quad (2)$$

where ΔW_1 is the weight loss without inhibitor and ΔW_2 is the weight loss with inhibitor. At the end of the experiment, selected specimens were washed with distilled water, dried, and examined for their surface morphology using JEOL-JSM5800LV model scanning electron microscope.

2.5. Electrochemical Techniques. The electrochemical experiments were performed using a typical three-electrode cell. A platinum rod was used as counter electrode and saturated calomel electrode (SCE) as reference electrode under naturally aerated conditions. Polarization curves were recorded at a constant sweep rate of 1 mV/s at the interval from -300

to +200 mV with respect to the E_{corr} value. The values of inhibition efficiency (%) were determined from the following:

$$\text{IE (\%)} = \frac{(I_{\text{corr}_2} - I_{\text{corr}_1})}{I_{\text{corr}_2}} \times 100, \quad (3)$$

where I_{corr_1} and I_{corr_2} are current densities with and without addition of inhibitor, respectively.

Electrochemical impedance spectroscopy studies were carried out using AC signals of 10 mV amplitude for the frequency spectrum from 100 MHz to 100 kHz. The charge transfer resistance values were calculated from the diameter of the semicircles of the Nyquist plots. The impedance studies were studied using Solartron Impedance/Gain-Phase analyzer SI 1260. The corrosion inhibition efficiency (%) was determined by

$$\text{IE (\%)} = \frac{(R_{\text{ct}_2} - R_{\text{ct}_1})}{R_{\text{ct}_2}} \times 100, \quad (4)$$

where R_{ct_1} and R_{ct_2} are the charge transfer resistances in presence and absence of inhibitor, respectively.

2.6. Fast Fourier Transform Infrared Spectroscopy (FT-IR). FT-IR spectra were recorded in a frequency range from 4000 to 700 cm^{-1} for the 1 M HCl + 75 ppm of *Opuntia ficus-indica* solution before and after the corrosion test, by using a Perkin Elmer model equipment.

3. Results and Discussion

3.1. Weight Loss Measurements. The effect of *Opuntia ficus-indica* concentration on the weight loss data for carbon steel in 1 M HCl at the different testing temperatures is given in Figure 1. At 25°C, the lowest weight loss was observed when 75 ppm of inhibitor is added, but an increase in the weight loss was obtained with a further increase in the *Opuntia ficus-indica* concentration. The weight loss increased with increasing the testing temperature up to 40 or 60°C, observing the highest value at 60°C. At these temperatures, a decrease in the weight loss with increasing the inhibitor concentration can be seen, which is due to the absorption of *Opuntia ficus-indica* onto the steel forming a protective film. The change in the inhibitor efficiency values with the concentration at the different testing temperatures is given in Figure 2, where it can be seen that at 25°C the highest inhibitor efficiency, 70%, was obtained when 75 ppm of *Opuntia ficus-indica* was added, and then it decreased with a further increase in the inhibitor concentration. At 40 and 60°C, an increase in the efficiency values with increasing the *Opuntia ficus-indica* concentration was observed, with the highest value of 82% obtained at 60°C with the addition of 300 ppm. This increase in the efficiency values with an increase in the *Opuntia ficus-indica* concentration is due to an increase in the metal surface area covered by the inhibitor.

3.2. Polarization Measurements. Polarization curves for carbon steel at various concentrations of *Opuntia ficus-indica*

FIGURE 1: Effect of *Opuntia ficus-indica* concentration and temperature on the weight loss for carbon steel in 1 M HCl.

FIGURE 2: Effect of *Opuntia ficus-indica* concentration and temperature on the inhibitor efficiency value for carbon steel in 1 M HCl.

extract in 1 M HCl at 25°C are shown in Figure 3. For the uninhibited solution, data display an active behavior without evidence of a passive region, with the anodic current density value increasing as the anodic potential increases, indicating dissolution of the steel. At a potential value of −200 mV, a limiting anodic current density value was found. On the cathodic side, another limiting current density value is found around −350 mV. As soon as 50 ppm of *Opuntia ficus-indica* was added, the corrosion potential (E_{corr}) shifts towards more active values, but both the anodic and especially the cathodic current density values are reduced. The corrosion current density (I_{corr}) also was decreased with the addition of 50 ppm *Opuntia ficus-indica*. With a further increase in the *Opuntia ficus-indica* concentration of 75 ppm, E_{corr} reached its most active value, and the I_{corr} value reached its lowest value. As the concentration of *Opuntia ficus-indica* was higher than

FIGURE 3: Effect of *Opuntia ficus-indica* concentration on the polarization curves for carbon steel in 1 M HCl at 25°C.

TABLE 1: Electrochemical parameters obtained from the polarization curves at 25°C.

C_{inh} (ppm)	β_a (V/dec)	β_c (V/dec)	E_{corr} (V)	I_{corr} (A/cm ²)	IE (%)
0	0.064	0.090	-0.230	$2E-4$	—
50	0.075	0.046	-0.270	$1.93E-05$	90
75	0.084	0.152	-0.305	$1.82E-05$	91
100	0.075	0.123	-0.280	$3.75E-05$	82
150	0.084	0.088	-0.261	$4.01E-05$	81
200	0.092	0.047	-0.220	$4.38E-05$	79
300	0.085	0.162	-0.214	$5.14E-05$	75

75 ppm, E_{corr} was shifting towards the noble direction, and the I_{corr} value increased. In all cases, the cathodic current density was the most affected by the Journal of Spectroscopy addition of *Opuntia ficus-indica*, indicating that this extract reduces both the anodic dissolution of iron and also the cathodic hydrogen evolution and oxygen reduction reactions. Electrochemical parameters for polarization curves at 25°C are given in Table 1, where it can be seen that both anodic and cathodic Tafel slopes were affected by the addition of *Opuntia ficus-indica*, but the latter was significantly affected. These results are indicative of the adsorption of inhibitor molecules on the carbon steel surface. However, since the cathodic Tafel slope was the most affected, these results suggest that *Opuntia ficus-indica* extract can be classified as a cathodic-type corrosion inhibitor.

When the temperature increased up to 40°C (Figure 4), polarization curve in the uninhibited solution did not exhibit a passive behavior, only anodic dissolution and an anodic limit current density at a potential value of -250 mV. For concentrations of 50 and 75 ppm of *Opuntia ficus-indica*, this behavior was only marginally affected, but for concentrations equal to or higher than 100 ppm, the E_{corr} value shifted towards more active values, and both the anodic and specially the cathodic current density values were lowered, decreasing, thus, the I_{corr} value, obtaining the lowest value when 300 ppm

FIGURE 4: Effect of *Opuntia ficus-indica* concentration on the polarization curves for carbon steel in 1 M HCl at 40°C.

FIGURE 5: Effect of *Opuntia ficus-indica* concentration on the polarization curves for carbon steel in 1 M HCl at 60°C.

of *Opuntia ficus-indica* was added, for more than one order of magnitude. A very similar behavior was observed at 60°C (Figure 5), where the corrosion current density value was practically unaffected for concentrations lower than 100 ppm, but for concentrations higher than 100 ppm, the I_{corr} value was decreased with the addition of *Opuntia ficus-indica*, obtaining the lowest value when 300 ppm of inhibitor was added.

3.3. Electrochemical Impedance Spectroscopy Measurements. Nyquist diagrams for carbon steel at various concentrations of *Opuntia ficus-indica* extract in 1 M HCl at 25°C are shown in Figure 6. It can be seen that data describe a single, capacitive-like, and depressed semicircle, with its center at the real axis, indicating a charge transfer controlled process, and it does not change with the addition of *Opuntia ficus-indica*. As the inhibitor concentration increases up to 50 or 75 ppm, the semicircle diameter increased, reaching its highest value and, thus, the lowest corrosion rate, when 75 ppm of *Opuntia*

FIGURE 6: Effect of *Opuntia ficus-indica* concentration on the Nyquist diagrams for carbon steel in 1 M HCl at 25°C.

TABLE 2: Effect of *Opuntia ficus-indica* concentration on the R_{ct} and C_{dl} values obtained from EIS measurements at 25°C.

C_{inh} (ppm)	R_{ct} ($\Omega \text{ cm}^2$)	C_{dl} ($\mu\text{F cm}^{-2}$)	IE (%)
—	159	117.2	—
50	344	98.1	53
75	357	92.2	55
100	257	89.5	38
150	232	98.2	31
200	197	106.1	19
300	174	115.4	8

ficus-indica was added. With inhibitor concentrations higher than 75 ppm, the semicircle diameter decreased, reaching its lowest value and the highest corrosion rate, when 300 ppm of inhibitor was added. Similar results were reported above with polarization curves at 25°C (Figure 3), where the lowest I_{corr} value was obtained with the addition of 75 ppm of *Opuntia ficus-indica*. Either lower or higher inhibitor concentrations increased the I_{corr} value. Electrochemical parameters obtained from Nyquist diagrams are given in Table 2, where it can be seen that the highest charge transfer resistance value, R_{ct} , was obtained when 75 ppm of *Opuntia ficus-indica* was added, and, thus, at this concentration, the highest inhibitor efficiency value was obtained also. It must be noted that, at 100 ppm, the solution has a higher resistance value than those observed at the other concentrations. This might be due to the fact that some corrosion products are dissolved into the solution increasing its resistance, that is, decreasing its conductivity. The double layer capacitance value, C_{dl} , decreased with the addition of *Opuntia ficus-indica*, reaching its lowest value with the addition of 75 ppm. This is due to the absorption of *Opuntia ficus-indica* and the replacement of adsorbed water molecules onto the steel surface [22].

FIGURE 7: Effect of *Opuntia ficus-indica* concentration on the Nyquist diagrams for carbon steel in 1 M HCl at 40°C.

When the temperature increased up to 40°C (Figure 7), Nyquist diagrams displayed a single, depressed, and capacitive-like semicircle with its center in the real axis, indicating that the corrosion process is under charge control, like the test at 25°C, and it is the same when *Opuntia ficus-indica* is added. As soon as *Opuntia ficus-indica* were added, the diameter semicircle starts to increase with its concentration, reaching its highest value and thus the lowest corrosion rate, with the addition of 300 ppm. The semicircle diameters obtained at 40°C were lower than those obtained at 25°C, which indicates an increase in the corrosion rate with an increase in the temperature. However, a higher solution resistance value for an inhibitor concentration of 200 ppm was observed than the rest of the inhibitor concentrations, similar to that observed at 100 ppm at 25°C (Figure 6), which might be due to the fact that some corrosion products are dissolved into the solution increasing its resistance. A very similar behavior was obtained at 60°C (Figure 8), where it can be seen that Nyquist diagrams displayed a single depressed, capacitive-like semicircle, with its diameter increasing with the *Opuntia ficus-indica* concentration. The semicircle diameters at 60°C were lower than those obtained at both 40 and 25°C, indicating that the corrosion rate at 60°C was the highest.

3.4. Adsorption Behavior. To investigate the adsorption behavior of *Opuntia ficus-indica* extract in 1 M HCl solution, several isotherm models were employed, such as Langmuir, Freundlich, Flory-Huggins, Frumkin, and Temkin, but the best fit was obtained for the Langmuir isotherm model as shown in Figure 9, obtained by using the polarization curves data. The Langmuir adsorption could be represented by the following equation:

$$\frac{C_{inh}}{\theta} = \left(\frac{1}{K_{ads}} \right) + C_{inh}, \quad (5)$$

where C_{inh} is the concentration of inhibitor, θ is surface coverage, and K_{ads} is the adsorption constant. The surface coverage

FIGURE 8: Effect of *Opuntia ficus-indica* concentration on the Nyquist diagrams for carbon steel in 1 M HCl at 60°C.

FIGURE 9: Langmuir type of adsorption for carbon steel in presence of *Opuntia ficus-indica*.

(θ) of the inhibitor on the carbon steel surface is expressed by the following equation:

$$\theta = \frac{IE(\%)}{100}. \quad (6)$$

The mechanism of corrosion inhibition may be explained on the basis of adsorption behavior. Basic information on the interaction between the inhibitor and the metal surface can be provided by an adsorption isotherm. The adsorption parameters, such as regression coefficient (R^2), adsorption constant (K), and free energy of adsorption (ΔG), and slope values were obtained by straight line fitting between C/θ (y -axis) and C (x -axis). Figure 10 shows the Langmuir isotherm of the polarization curves method. The most important thermodynamic adsorption parameter is the free energy of adsorption

FIGURE 10: SEM micrograph of carbon steel before the corrosion tests in 1 M HCl solution.

(ΔG). The adsorption constant (K) is related to the standard free energy of adsorption; ΔG is calculated with the following equation:

$$\Delta G = -RT \ln (55.5K), \quad (7)$$

where 55.5 is the water concentration of solution in mol/L, R is the ideal gas constant, and T is the absolute temperature. Table 3 shows the values calculated in the Langmuir isotherm. To convert from ppm to g/L, we have used a conversion factor and assumed that it dissolves in water. To convert ppm to g/L, we must multiply by 0.001:

$$75 \text{ ppm} * 0.001 = 0.075 \text{ g/L}. \quad (8)$$

The result in units ΔG KJ/mol is due to the gas constant $R = 8.3144$ KJ/kmol. The negative values of ΔG indicate the stability of the adsorbed layer on the mild steel surface and spontaneity of the adsorption process. Generally, the magnitude of ΔG around -20 kJ/mol or less negative is assumed for electrostatic interaction that exists between inhibitor and the charged metal surface (physisorption).

3.5. SEM Images. The scanning electron microscope images were recorded to establish the interaction of inhibitor with the metal surface, and they are shown in Figures 10 and 11. Before being exposed to the 1 M HCl solution (Figure 10) as expected, the steel shows no evidence of any corrosive attack. However, for the uninhibited solution at 25°C, Figure 11 revealed that the surface was severely corroded due to the aggressive attack by 1 M HCl. As the temperature increased (Figures 11(c) and 11(e)), the corrosion products become more porous and less protective, and the corrosive attack was more evident. For the solution containing 75 ppm of *Opuntia ficus-indica* at 25°C (Figure 11(b)), micrographs showed a very protective film, without evidence of microporous or cracks, which made this film very protective. However, as the temperature increased (Figures 11(d) and 11(f)), this film becomes less adherent and more porous, leaving some places of the steel unprotected from the environment, with an increase in the corrosion rate.

TABLE 3: Thermodynamical parameters obtained from the Langmuir type of adsorption isotherm.

Temperature (°C)	Slope	R^2	K_{ads} (KJ·mol ⁻¹)	ΔG_{ads} KJ·mol ⁻¹
25	1.380	0.9986	55.50	-19.90
40	0.014	0.9994	71.43	-21.56
60	1.004	0.9997	250	-26.40

FIGURE 11: SEM micrographs of carbon steel corroded in uninhibited 1 M HCl solution at (a) 25, (c) 40, and (e) 60°C, and in 1 M HCl solution + 75 ppm of inhibitor at (b) 25, (d) 40, and (f) 60°C.

3.6. Fourier Transform Infrared Spectroscopy (FT-IR). The FT-IR spectra of the 1 M HCl + 75 ppm of *Opuntia ficus-indica* extract before and after the corrosion tests are shown in Figure 12. A summary of these results is given in Table 4. A careful investigation of the spectra revealed that all the

extracts showed almost similar peaks; however, the intensities decreased after the corrosion test because these compounds reacted with the metal and acid to form corrosion products. Before the corrosion test, two peaks appear at 3118 and 3018 cm⁻¹ which could be attributed to a primary

TABLE 4: Characteristic peaks obtained from FT-IR spectra for 1.0 M HCl + *Opuntia ficus-indica* solution before and after corrosion test.

1.0 M HCl + 300 ppm inhibitor before corrosion test		1.0 M HCl + 300 ppm inhibitor after corrosion test	
Frequency (cm ⁻¹)	Functional group and vibration type	Frequency (cm ⁻¹)	Functional group and vibration type
3118	N-H stretch	3368–3369	N-H stretch
3018	O-H stretch	3189	O-H stretch
1720	C=O stretch	1610	C=O stretch
1627	N-H bending	1588	N-H bending
1394	C-H bending	1394	C-H bending
1222	C-N stretch	1222	C-N stretch
1074	C-O stretch	1074	C-O stretch

FIGURE 12: FT-IR spectra for 1M HCl + 75 ppm of *Opuntia ficus-indica* extract before and after corrosion test.

amide. After the corrosion test, a strong and broad peak at 3000/3400 cm⁻¹ can be attributed to N-H and O-H stretching vibration. Amines (NH₃) and hydroxides (OH) have been reported as good corrosion inhibitor for carbon steel in acidic environments [23–27] due to the formation of passivating corrosion products. A small peak at 1720 cm⁻¹ was observed before the test. Such a peak may be attributed to C=O stretching vibration, and its intensity increased with the addition of the *Opuntia ficus-indica* extract at 1610 cm⁻¹. The absorptions bands at 1627/1588 cm⁻¹ were also observed due to an N-H bond vibration. A peak at 1394 cm⁻¹ was attributed to C-N bond vibration before and after test. A small peak at 1222 cm⁻¹ was observed before and after the test, attributed to C-N stretching vibration. Peaks before and after the corrosion tests at 1074 cm⁻¹ were attributed to C-O stretching vibration. It has been shown [28, 29] that the antioxidant capacity of *Opuntia ficus-indica* is due to the presence of phenolic compounds such as quercetin, kaempferol, mercitin, and isorhamnetin which contain amines as well as OH, C=O, C=N, and C-C groups. Thus, results showed that *Opuntia ficus-indica* extract contains organic molecules that are rich in oxygen and nitrogen atoms as well as aromatic rings, such as phenols, which meet with the fundamental requirements of good inhibitor.

4. Conclusions

Opuntia ficus-indica extract acted as a good corrosion inhibitor for carbon steel in 1M HCl solution. At room temperature, the highest inhibition efficiency was obtained by adding 75 ppm, but at higher temperatures, inhibition efficiency increased with the inhibitor concentration and decreased with increasing the temperature. The change in the free energy brings negative values around -20 kJ/mole which indicates that the adsorption process is spontaneous and is physical adsorption following a Langmuir type of adsorption isotherm. The inhibitor altered both anodic and cathodic Tafel slopes, but the cathodic one was the most affected, which showed the cathodic mode of action of the inhibitor molecule. The increase in R_{ct} values and decrease in C_{dl} values confirm the formation of an insulated protective layer over the mild steel surface, which was supported by SEM images. The corrosion inhibitive effect shown by *Opuntia ficus-indica* extract can be correlated to the presence of heteroatoms in its chemical structure such as C, N, and O which form protective corrosion products.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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