Journal of Basrah Researches (Sciences) **52**(1), 74 (2026)
DOI: https://doi.org/10.56714/bjrs.52.1.6

Electrochemical and surface Analysis of Clove flower buds Extract as a Green Corrosion Inhibitor for N80 Carbon Steel in Acidic Media

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A R T I C L E I N F O

Received 09 August 2025
Revised 27 December 2025
Accepted 02January 2026
Published 30 June 2026

K e y w o r d s :

Corrosion, Plant Inhibitors, Polarisation Curves, Carbon Steel.

Citation: M. M. Jassim, A. S. Abdul Nabi., J. Basrah Res. (Sci.) **52**(1), 74 (2026). DOI:https://doi.org/10.56714/bjrs.52.1.6

A B S T R A C T

The carbon steel corrosion in acidic conditions is one of the most significant problems in petroleum and chemical industries, especially in the process of acidizing and pickling. In this research, corrosion inhibition properties of a water extract of clove flower buds (Syzygium aromaticum) were examined in the case of N80 carbon steel in 1 M hydrochloric acid. It is due to the high phytochemical content of clove extract, consisting of phenolic and nitrogen-based compounds, which are found to induce effective adsorption on metal surfaces and increase corrosion resistance that the use of clove extract is justified. Polarization measurements were used to measure corrosion behavior with various concentrations of inhibitors and temperatures using electrochemical techniques. The scanning electron microscopy analysis of the surface morphology and in situ formation of the inhibitor films were studied and the chemical composition of the extract was determined through the GC-MS analysis. It was shown that clove extract is an efficient mixed-type corrosion inhibitor, which decreases the corrosion current density and rate of corrosion significantly. The greatest inhibition efficiency of 90.01 percent was at an inhibitor concentration of 200 ppm and a temperature of 298 K. The results attest to the fact that extract of clove flower buds offer an efficient and environmentally friendly protection against corrosion on N80 carbon steel in acidic environments as an alternative to using synthetic corrosion inhibitors in a sustainable manner.

1. Introduction

Corrosion is a process that causes materials to deteriorate due to a reaction with chemical or electrochemical substances within the environment, causing a structural and functional failure of metallic components. This effect results in significant economic damages, estimated to be between 1-5 percentage of the gross domestic product of a country in an annulary basis, safety risks and risks of operations [1]. The problem of corrosion is a serious issue in most industries, especially in the petroleum industry like the oil and gas pipelines, storage tanks, and processing units where exposure of the carbon steel to an aggressive acidic environment is very common [4].

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ISSN: 1817-2695 (Print); 2411-524X (Online)
Online at: https://jou.jobrs.edu.iq

There are several techniques such as anodic protection, cathodic protection, protective coating, the choice of material, and corrosion inhibitors that are used to reduce corrosion [5,6]. One such method of protecting the metals in acidic media is the application of corrosion inhibitors which is believed to be one of the most effective and cost effective methods [7]. Corrosion inhibitors operate by slowing down the process of anodic dissolution or cathodic hydrogen evolution or both of the processes even at low concentrations [8]. Most traditional inorganic and synthetic inhibitors are toxic and nonbiodegradable, thus becoming a source of concern in the environment and health [9].

The use of green corrosion inhibitors based on natural sources, especially plant extracts has gained more focus over the last few years. Such inhibitors are non-polluting, biodegradable, cost-effective and easily obtainable which makes them to be attractive compared to traditional inhibitors [10]. The presence of heteroatoms (O, N, S) and π-electron systems that facilitate the adsorption to the metal surface is the primary factor that causes high inhibition efficiency of plant extracts [11]. It is by this adsorption that a protective film is created on the metal surface and lengthens the contacts between the corrosive medium and the metal hence inhibiting corrosion reactions.

Clove flower buds (Syzygium aromaticum) among other medicinal plants explored in the field of green corrosion inhibitors have demonstrated good inhibition power. Clove is widely endowed in phenolic substances and other bioactive active materials that possess high adsorption potential on metal surface [13,14]. These compounds are effective corrosion inhibitors because they generate stable and adhering inhibitor layer by adsorption processes based on physical and chemical processes. The molecular structure of the clove constituents, which comprises aromatic rings and electron-giving functional groups, is very instrumental in enhancing the effect of inhibition specifically in acidic environments [10,11].

Even though a number of studies have documented the corrosion inhibition characteristic of plant extracts, in-depth research on the use of clove extract as a green corrosion inhibitor on N80 carbon steel particularly at different temperatures and concentrations have not been carried out. N80 carbon steel is widely employed in the oil and gas pipes and is easily prone to acid induced corrosion [15]. The current paper will assess the efficiency of clove flower bud extract as a corrosion inhibitor of N80 carbon steel in 1 M HCl solution by using electrochemical polarization as well as kinetic analysis, surface morphology analysis, and compositional characterization to explain how the extract works.

2. Experimental

2.1. Equipment and materials utilized

Distilled water and high-purity special chemicals were utilized for analysis. The chemicals and solvents were purchased from BDH. The filter paper was NEWSTAR (15 cm) from China. Silicon carbide (SiC_2) paper and clove flower bud were obtained from a store. SOC also provided N-80 carbon steel alloy. A gas chromatography-mass spectrometry (GC-MS) MS:5973 provided with a selective grid mass detector was utilized to analyze and identify the chemical components present in the plants in the laboratories of the University of Tehran, Islamic Republic of Iran. DMSO-d6 was utilized as a solvent during these analyses. A Bank Elektronik Intelligent Controls, type M, manufactured in Germany in 2007, was utilized for evaluate the corrosion rate of N80 alloy. A scanning electron microscope (SEM) was utilized at the University of Tehran to study the morphological changes that occurred on the alloy outer shell due to corrosion.

2.2. Alloys Use

This study utilized an N-80 carbon steel alloy, supplied by the Southern Oil Company, which contains the following components in percentage: 0.3% C, 1.2% Mn, 0.05% P, 0.06% S and 98.39% Fe.

2.3. Preparation of Corrosion Solution

The corrosion solution was prepared from concentrated hydrochloric acid (HCl) at a concentration of 1 mol/L using the dilution method.

2.4. Prepare clove flower bud extract

After washing, drying and grinding, 10 gm of clove flower bud powder was weighed and add 300 ml of distilled water to 500 ml beaker. Solution was then heated at 70°C for one hour using a mechanical stirrer. The solution was then left to cool for two hours. After that, the mixture was filtered using filter paper, and the filtrate was collected and dried at 50°C for two days, where a dry powder of the extract weighing 2 gm was obtained. The standard extract is prepared by dissolving 0.5 gm of it in 500 ml of distilled water in 500 ml volumetric flask, to obtain a standard solution with a concentration of 1000 ppm. A series of solutions of varying concentrations are then prepared using the dilution method [15].

2.5. Determining corrosion rate using electrochemical Tafel Plot Extrapolation technique

A corrosion rate measuring device was utilized. The measuring cell consists of three electrodes: the working electrode, to which the carbon steel specimen is attached; the auxiliary electrode, made of platinum; and the reference electrode, a standard calomel electrode. The N80 carbon steel specimens were cut into coupons with an exposed surface area of 5×2×0.4 cm for length , width, and thickness respectvely. Before each experiment, the steel surfaces were mechanically polished successively using silicon carbide (SiC) abrasive papers of grades 120, 300, and 600, rinsed thoroughly with distilled water, degreased with ethanol, and dried in air. Measurement was done with the help of the electrochemical method through the bank Elektronik Intelligent Controls potentiostat (Type M, Germany). The measurements of the polarization were conducted in a potential range of -250 to +250 mV respect to the open circuit potential (OCP) at a scan rate of 10 mV . The reference electrode was a standard calomel electrode (SCE). The cell is then connected to the measuring device, and the required information is entered, such as the initial and final voltage values and the reaction time. The process typically takes 15–20 minutes. When the measurement is complete, the device is turned off, the cell is emptied, and the corrosion rate is thoroughly cleaned. The process is then repeated using a new, clean sample of N80, with Various levels concentrations of the inhibitor (C) in the corrosive medium and at different temperatures (298, 308, 318 K)[16]. Each electrochemical measurement was performed in triplicate (n = 3) under identical experimental conditions, and the reported values represent the average of three independent measurements.
The experimental results are presented as mean values ± standard deviation (±SD) calculated from three independent measurements.

3. Results and discussion

3.1. Chemical detection of the active compounds in clove flower buds (C) extract

A number of qualitative chemical investigations were conducted to identify the active chemical compounds present in the aqueous extract clove flower buds, because these compounds are crucial in preventing corrosion

3.1.1. Phenols Test

It was detected by add (3 ml) of the plant extract to (3 ml) of FeCl3 solution (1%). When the blue-green color appears, it indicates the presence of phenols [17].

3.1.2. Flavonoides Test

It was detected by add (1 ml) of alcoholic KOH (5N) to (1 ml) of the plant extract. When a yellow precipitate appears, it indicates the presence of flavonoids [18].

3.1.3. Tannins Test

It was detected by adding several drops of lead acetate solution (1%) to (5 ml) of plant extract. When a white precipitate appears, it indicates the presence of tannins [18].

3.1.4. Alkaloids Test

It was detected using Wagner reagent. The reagent was prepared by dissolving (2 gm) of KI with (1.3 gm) of I in (100 ml) of distilled water.(2 ml) of the reagent was added to (1 ml) of the extract. When a brown precipitate appeared, it indicated the presence of alkaloids [19].

3.1.5. Saponin Test

This was detected by placing) 20 ml (of the plant extract in a test tube and shaking it vigorously. If abundant foam formed, this indicated that it contained saponins [19].

Table 1. Results of chemical detection of active compounds in aqueous extract of (C)

Number	The compounds	Reagents	Detection guide	the result
1	Phenol	$FeCl_3$ (1%)	white precipitate	+
2	Flavonoides	Alcoholic KOH (5N)	yellow precipitate	-
3	Tannin	$Pb(CH3COO)_2$ (1%)	white precipitate	-
4	Alkaloid	Wagner	brown precipitate	+
5	Saponin	shaking it vigorously	foam appears	+

+= Presence; - = absence

Table 1 summarises the qualitative chemical screening results of the aqueous clove flower bud extract. The findings validate the existence of phenols, alkaloids and saponins and not flavonoids or tannins. Phenolic compounds are important in corrosion inhibition since they could adsorb to the metal surface using oxygen atoms and the pi system. Alkaloids also increase the efficacy of inhibition by contributing to the unpaired electrons of nitrogen atoms to the metal surface. Moreover, the saponins help in formation of protective adsorbed film on the carbon steel surface. It is these phytochemical constituents that accounted to the good performance of the clove extract in corrosion inhibition in the electrochemical studies.

It is necessary to mention that the appearance of siloxane-related compounds in the GC-MS analysis is usually explained by instrumental factors rather than the real components of the plant extract. Siloxanes commonly appear in GC MS studies as a consequence of bleeding of the column or the septum or resistant oil which is made of silicone. Thus, these compounds will not produce the corrosion inhibition property of the clove extract. The inhibition effect as exhibited in this work can largely be credited to the presence of heteroatoms and π-electron systems of the organic compounds that comprise phenolic, nitrogen-containing and fatty acid ester compounds as these are very common in their high adsorption capacity on metal surfaces.

3.2. Mass- Spectrum Extracted Plant (GC - Mass)

(GC-MS) spectra of clove flower buds extract (C) were analyzed, with the aim of identifying the active chemical compounds present in it, which explain the inhibition mechanism exhibited by this extract. The quantitative surface roughness parameters obtained from AFM analysis are

summarized in Table 2.

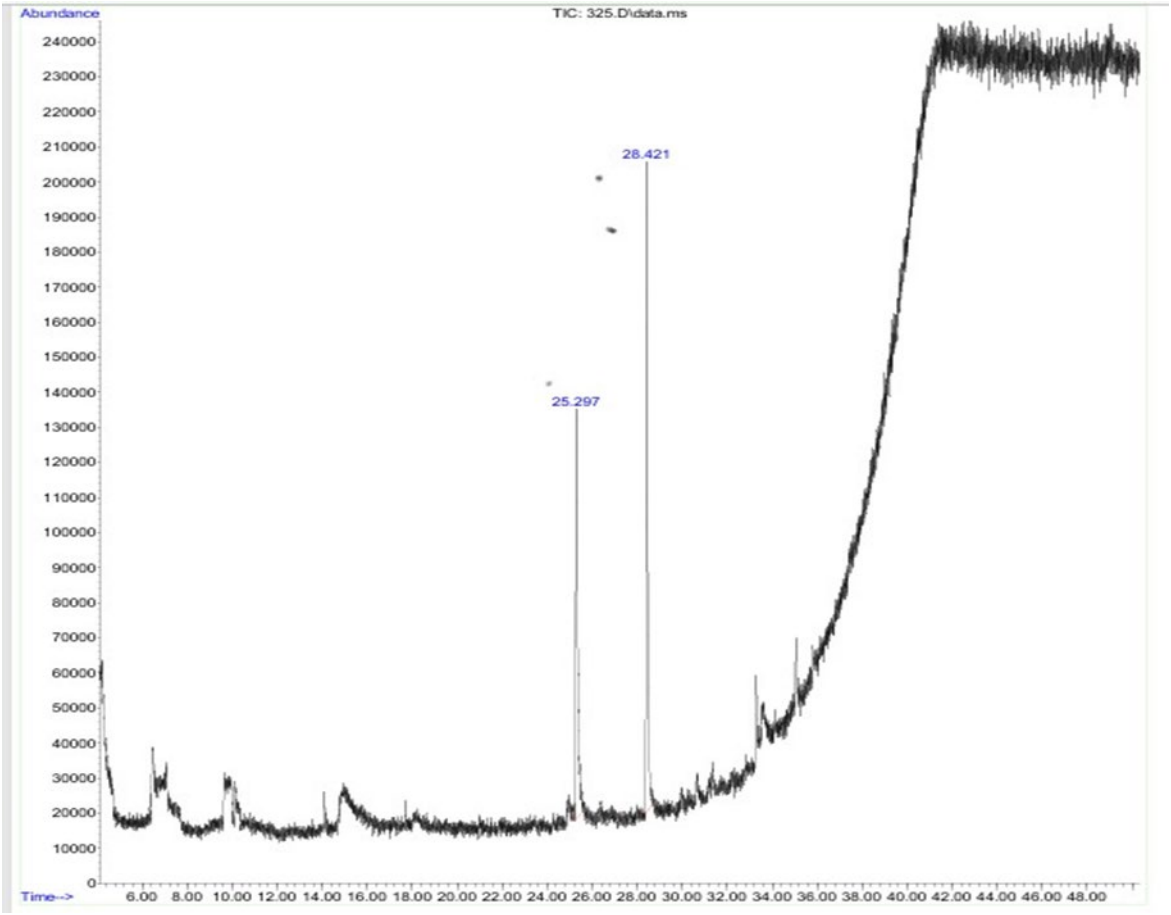

Fig. 1. GCMS spectra of extract C

Table 2. Represents the most important compounds that appeared in the GC-Mass spectrum of extract (C)

NUMBER	RT (min)	Area %	Name	Quality	CAS Number
1	14.101	1.47	Cyclohexasiloxane, dodecamethyl	25	000000-00-0
2	17.723	0.87	3-Methylsalicylic acid,	38	074150-88-2
3	25.298	41.46	Methyl palmitate	99	000112-39-0
4	28.422	46.22	Octadecanoic acid, methyl ester	99	000112-61-8
5	33.283	6.39	2-Ethylacridine	38	000000-00-0
6	35.058	3.58	2-amino-5-isopropylbenzene-1, 4-diol	53	055012-80-1

Table 2 provides quantitative data of AFM outcomes of the surface modification of N80 carbon steel in the presence of clove flower bud extract. Higher values of roughness are associated with the untreated steel surface, which demonstrates that the surface was highly degraded by acid attack. On the contrary, an average roughness and root mean square roughness values are considerably lowered on the steel surface in contact with the inhibitor. This decrease testifies to the creation of a thin and protective adsorbed film on the metal surface. The reduction of the roughness of the surface proves

that the clove extract reduces localized corrosion and restrains the deterioration of the surface. These AFM results are very consistent with the data on the electrochemical and SEM results and indicate the adsorption-based mechanism of clove extract inhibition on the carbon steel surface.

3.3. Study of the efficiency of extract (C) as corrosion inhibitor using the Tafel curve method

The study aimed to assess the effectiveness of the aqueous extract (C) as corrosion inhibitor for N80 in 1 M HCl solution at varying temperature. Experiments were conducted existence and non-attendance the plant inhibitor, and using different extract concentrations. Polarization curves were utilized to evaluate. The study results showed the following:

3.3.1. Polarisation curves (Tafel lines)

The Tafel curves were utilized to study the role of the plant extract for preventing the corrosion of carbon steel. The values of the corrosion current density (Icorr), corrosion potential (Ecorr), cathodic (βc) and anodic (βa) Tafel constants were obtained, as shown in Table (3) and Figures (2-4). We also note that when the plant inhibitor (C) is added at different concentrations, the shape of the Tafel curve there is no significant change, but rather works on reducing reaction occurring at the anode and cathode electrodes almost equally, which indicates that these inhibitors belong to the mixed type. That is, the inhibitors hinder the reaction at the anode electrode (metal dissolution) and delay the emission of hydrogen gas at the cathode electrode [20]. The percentage of inhibition efficiency (IE %) and the area of the part covered by the inhibitor (θ) were calculated from the relations (1) and (2) respectively [21].

$$\text{IE\%} = \frac{I°corr - Icorr}{I°corr} \times 100\% \quad (1)$$

$$\theta = \frac{\%\text{IE}}{100} \quad (2)$$

Where: I°corrr, Icorrr represent the corrosion current densities in the existence and non-attendance of the inhibitor, respectively. The results show that the corrosion current density of the blank solution (HCl) records higher values compared to those recorded when the plant extract) C) was utilized as a corrosion inhibitor, at constant temperature. A decline in corrosion current density was observed as the corrosion Inhibitor levels were elevated at every temperature. This indicates that the inhibitor inhibits corrosion and reduces its severity.

According to electrochemical polarization findings, the inhibition efficiency rises with the increasing concentration of inhibitor. The highest concentration of inhibition efficiency was observed with a concentration of 200 ppm with a maximum value of 90.01 percent in 1 M HCl solution at 298 K. The lowest values of the corrosion current density and corrosion rate were observed at this concentration level, meaning that the protective layer on the surface of the carbon steel was a stable and compact layer. Concentrations below 200 ppm were not associated with a significant further increase in the performance of the inhibition, and therefore they were considered to be providing partial surface coverage. 200 ppm was chosen as the most convenient concentration of the inhibitor to be studied further.

The concentration of the acidic medium was maintained at 1 M HCl during the course of the experiment because this is the concentration of a very hostile environment that is present in industrial acid pickling and oilfield acidization practice. A constant acid concentration enables a sound assessment of the inhibitor activity and makes sure that observed dynamics in corrosion behavior are mainly linked to the level of the inhibitor concentration and not the differences in the strength of the acid.

3.3.2. Corrosion Rate (CR)

The corrosion reaction rate (CR) was calculated in units of Mille-inch penetration per year (mpy) in the non-attendance and existence of the plant extract and at temperatures (318, 308, 298K) using the relationship (3)[22].

$$CR = \frac{0.1288 \times Icorr \times E.W}{\rho} \quad (3)$$

Where:

CR: Corrosion rate (mpy)
Icorr: Corrosion current density in the presence of inhibitor (mA/cm^2)
E.W: Equivalent weight of metal or alloy (W.E Fe = 27.8 gm/mol)
ρ: Density of metal or alloy (ρFe = 7.86 gm/cm^3)

It is evident that the corrosion rate rises sharply when there is no inhibitor. This is due to the dissolution of the metal in the anodic reaction. However, when an inhibitor is present, the corrosion rate decreases because the corrosion current density decreases. This decrease in current means decline in the corrosion rate, and reason is the direct relationship between them, as shown in Equation (3), which seen in Table (3) [23]. Also, the corrosion rate decreases when we raise the inhibitor concentration, provided that the temperature remains constant. If the temperature rises while the concentration remains the same, we see a rises in the corrosion rate. This occurs because the inhibitor cover that adheres to the outer shell (physical adsorption) weakens and disappears with the rise in temperature [24].

3.3.3. Effect of Temperature

The corrosion rate and inhibition efficiency results were compiled based on the data presented in Table (3) and Figure (5) as follow:

A. The corrosion rate rises with growing temperature and decline with growing concentration. as mentioned at end of the previous paragraph.

B. The inhibition efficiency decline with growing temperature when the inhibitor concentration is held constant. Conversely, the % IE rises with growing inhibitor concentration, while the temperature remains constant. This behavior is cautilized by the physical adsorption nature of the inhibitor on the carbon steel outer shell. Lower temperatures are more favorable for this type of adsorption. In contrast, chemisorption exhibits the opposite trend, with inhibition efficiency growing with growing temperature [25]. The inhibition activity measured in the current study is rather comparable with the best performances of other plant based corrosion inhibitors in acidic environments. Past research on plant extracts as green inhibitors of carbon steel has widely reported inhibition efficiencies of about 70 to 95 percent on the basis of the type of extract, concentration, temperature, and acid solution. In this study, the highest inhibition percentage of 90.01 obtained with the use of the clove flower bud extract at 200 ppm in 1 M HCl is quite within this stated range. This comparison proves that clove extract is competitive in corrosion-inhibition performance compared to other plant-based inhibitors, besides having other benefits of being environmental-friendly, cheap, and accessible.

Table 3. shows the findings of the Tafel curves for the corrosion of carbon steel in the existence and non-attendance of the inhibitor (C) at different concentrations in (HCl 1M) solution and within temperatures (298, 308, 318 K).

Temp (K)	Inhibitor Conc	E_{corr} (mV)	C_R (mpy)	I_{corr} (mA/cm^2)	βa (mV/Dec)	βc (mV/Dec)	IE %	Θ

298		-461.9	10.08	22.14	217.9	-174.3	0	0
308	HCl (1M)	-465.2	13.47	29.59	235.5	-196.9	0	0
318		-447.2	17.25	37.88	225.0	-204.3	0	0
298		-445.6	5.76	12.65	118.3	-122.2	42.86	0.42
308	50ppm	-470.8	8.10	17.80	134.2	-125.1	39.84	0.39
318		-469.5	11.01	24.17	151.3	-146.3	36.19	0.36
298		-472.0	3.69	8.11	108.5	-81	63.36	0.63
308	100ppm	-463.2	6.71	14.74	159.8	-58.7	50.18	0.50
318		-473.2	9.26	20.33	120.6	-64.9	46.33	0.46
298		-438.2	1.63	3.58	62.5	-88.2	83.83	0.83
308	150ppm	-449.1	5.17	11.37	84.1	-85.7	61.57	0.61
318		-456.0	7.29	16.01	99.2	-74.3	57.73	0.57
298		-458.0	1.00	2.21	58.3	-53.7	90.01	0.90
308	200ppm	-466.2	3.68	8.10	85.4	-66.1	72.62	0.72
318		-469.1	5.63	12.38	100.0	-80.7	67.31	0.67

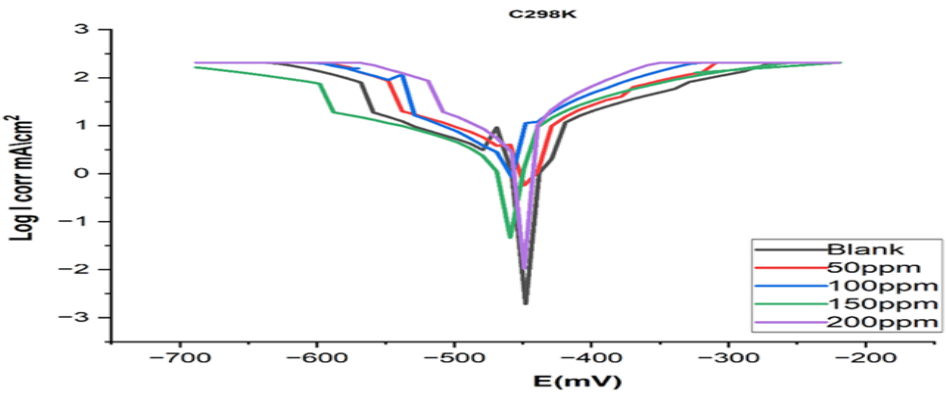

Fig .2. Tafel curves for corrosion of N80 alloy in the existence and non-attendance of inhibitor (C) at different concentrations and a temperature of (298 K).

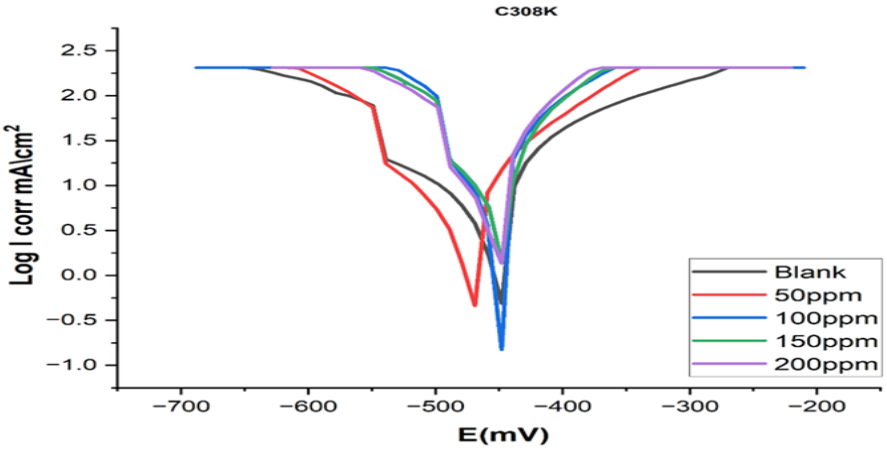

Fig. 3. Tafel curves for corrosion of N80 alloy in the existence and non-attendance of inhibitor (C) at different concentrations and a temperature of (308 K).

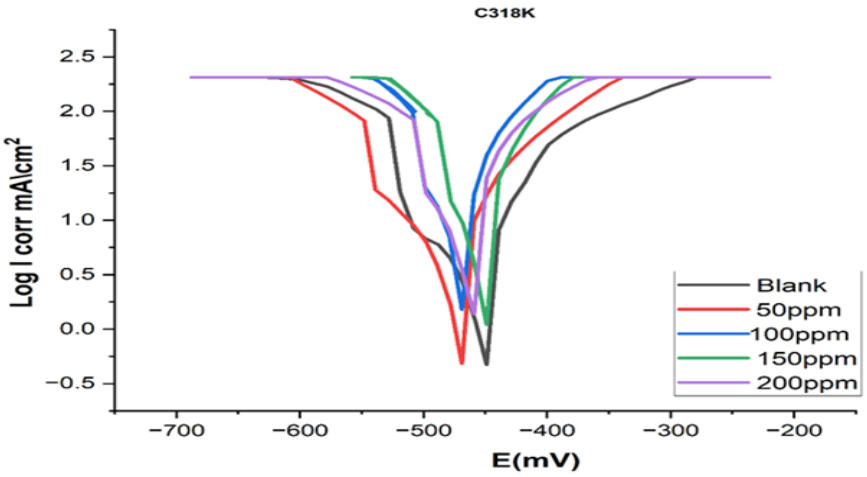

Fig. 4. Tafel curves for corrosion of N80 alloy in the existence and non-attendance of inhibitor (C) at different concentrations and a temperature of (318 K).

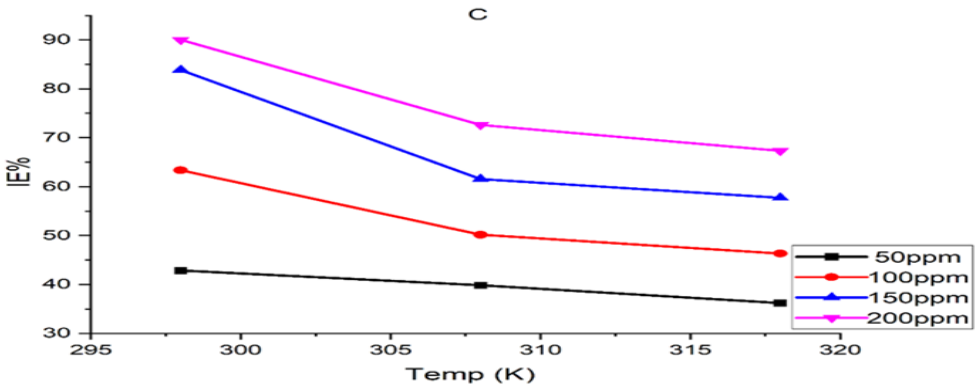

Fig. 5. The correlation between inhibition efficiency and temperature in an acid solution (HCl 1M) with different concentrations of the inhibitor (C) and at temperatures (298, 308, 318 K)**.**

3.3.4. The study focuses on the kinetic variables

The kinetics of corrosion reaction and the influence of temperature on the functioning of carbon steel alloy in the corrosive medium with hydrochloric acid at a concentration of 1 mol\L, in the existence and non-attendance of inhibitors and at different concentrations, were studied. A number of thermodynamic functions related to the adsorption process were determined using the aim of understanding the nature and behavior of adsorption and determining the extent of the inhibitor's interaction with alloy outer shell. The role of temperature in the corrosion rate of carbon steel was examined (298, 308, 318 K), based on the equation (4) [26].

$$\text{Log Icorr} = \log \text{A} - \frac{-\text{Ea}}{2.303\ \text{RT}} \tag{4}$$

Where: Icorr: Corrosion current Density, Ea: Activation energy , T:Temperature, R: Gas constant ,A: Arrhenius constant. When plotting the relationship between the values of Log Icorr versus 1/T, as shown in Figure (6), a straight line is obtained, where the slope of this line represents the value of (Ea/2.303R-), while the part intercepted by the axis represents the value of Log A. Equation (4) is utilized to find (Ea), which is essential for calculating the rest of the kinetic functions.
Based on the transition state equation (5), the kinetic functions of the activated complex resulting from the reaction of the inhibitor with alloy were calculated, namely the (ΔH*) and (ΔS*). These values provide important information about the mechanism of activated complex formation during the corrosion process in acidic medium.

$$\log \frac{\text{lcorr}}{\text{T}} = \log \frac{\text{R}}{\text{Nh}} + \left(\frac{\Delta S*}{2.303}\right) - \left(\frac{\Delta H*}{2.303\text{RT}}\right) \tag{5}$$

Where: N: Avogadro's number, h: Planck's constant. When drawing the relationship between the values of log lcorr/T and 1/T, as shown in Figure (7), a straight line is obtained that represents the slope of (ΔH*/2.303R-) utilized calculate (ΔH*). The cut-off part represents log R/Nh+((ΔS*)/2.303) to find the activation entropy value (ΔS*). Then the values of (ΔG*) are calculated from Equation (6)[27].

$$\Delta G^* = \Delta H^* - T\ \Delta S^* \tag{6}$$

From the results shown in Table (4) (Ea),(ΔH*),(ΔS*) and (ΔG*), we note that the activation energy (Ea) rises in the existence of the inhibitor compared to its non-attendance. The rise in activation energy (Ea) in the presence of the inhibitor relative to the blank indicates that adsorption of the inhibitor molecules causes an energy barrier to the process of corrosion. Moreover, the efficiency of the inhibition decreases with the increase in temperature at a given concentration of the inhibitor; this is usually in accordance with most physical adsorption, whereby the adsorbed layer becomes less stable at a high temperature.The current kinetic parameters do not suffice to conclude on the decisive difference of the physisorption or chemisorption; the adsorption process in this case is characterized as primarily adsorption-mediated with the behavior similar to the example of physical adsorption in the given conditions [28]. The fact that the activation entropy changes are negative values (which means that the activated complex is more organized than the initial one) can be explained by the fact that the inhibitor molecules and solvent species are organized/ associated at the interface of metal/solution in the process of the formation of the activated complex. Though a negative ΔS is an indication that facilitated the further ordering at the interface, it does not on its own determine the nature of adsorption as either physical or chemical [30]. Further adsorption thermodynamic (e.g., ΔG°ads and isotherm fitting) or spectroscopic evidence of chemical bonding would be necessary to determine the adsorption type more conclusively; this is not covered in current study.

Table 4. Values of the kinetic functions ΔG^*, ΔH^*, ΔS^*, Ea in the existence and non-attendance of inhibitor (C) across varying concentrations and within temperatures (318, 308, 298 K)

Comp	Conc (ppm)	Ea ($KJ.mol^{-1}$)	ΔS^* ($KJ.mol^{-1}.K^{-1}$)	ΔH^* ($KJ.mol^{-1}$)	ΔG^* ($KJ.mol^{-1}$)		
					298 (K)	308 (K)	318 (K)
HCl	1M	21.17	-0.15	18.61	63.31	64.81	66.31
C	50ppm	25.51	-0.14	22.95	64.67	66.07	67.47
	100ppm	36.31	-0.11	33.75	66.53	67.63	68.73
	150ppm	59.34	-0.04	56.90	68.82	69.22	69.62
	200ppm	68.24	-0.01	65.68	68.66	68.76	68.86

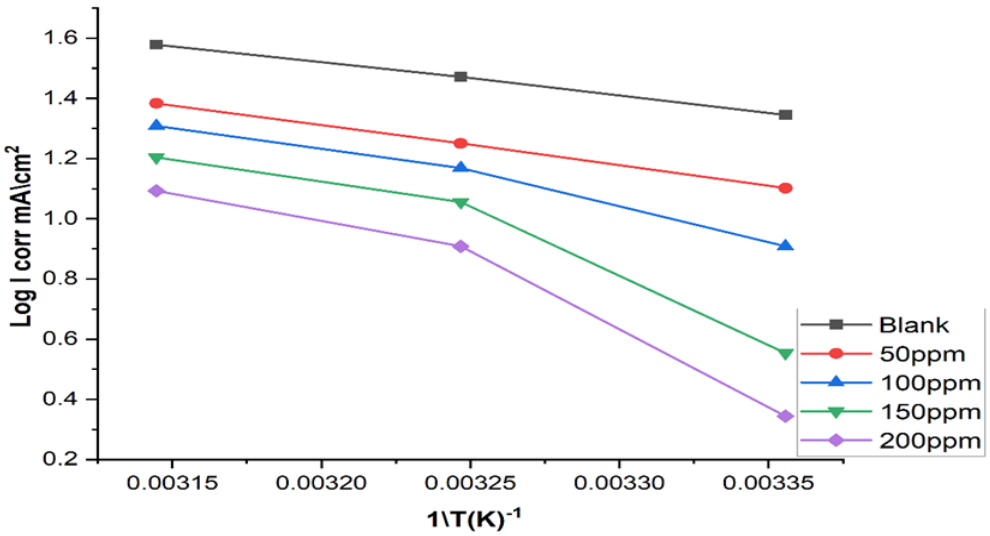

Fig. 6. Arrhenius relationship with the existence and non-attendance of inhibitor (C) at different concentrations and temperatures (318, 308, 298 K)

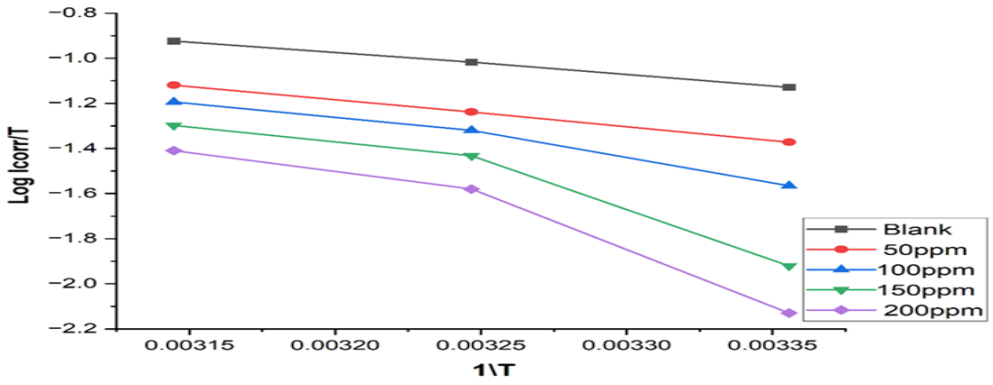

Fig. 7. The relationship between the transition state and the calculation of enthalpy and entropy in the existence and non-attendance of the inhibitor (C) across varying concentrations and temperatures (318, 308, 298 K)

3.4. Morphological Study of the surface of N80 alloy using Scanning Electron Microscopy (SEM) Technique

Studies were conducted using the scanning electron microscope to analyze the morphological changes of the outer shell of N80 alloys, whether in the existence and non-attendance of the inhibitor. Figure 8 shows the scanning electron microscope images of the outer shell of the N80 at the optimal concentration of the inhibitor (200 parts per million) in 1M HCl solution. After immersing the samples for 3 hours at a temperature of 298 K, significant corrosion of the steel outer shell was observed due to the effect of the acid. Conversely, the samples treated with the inhibitor showed a smoother outer shell and fewer holes, indicating the performance of the inhibitor in reducing corrosion [31].

(1) (2) (3)

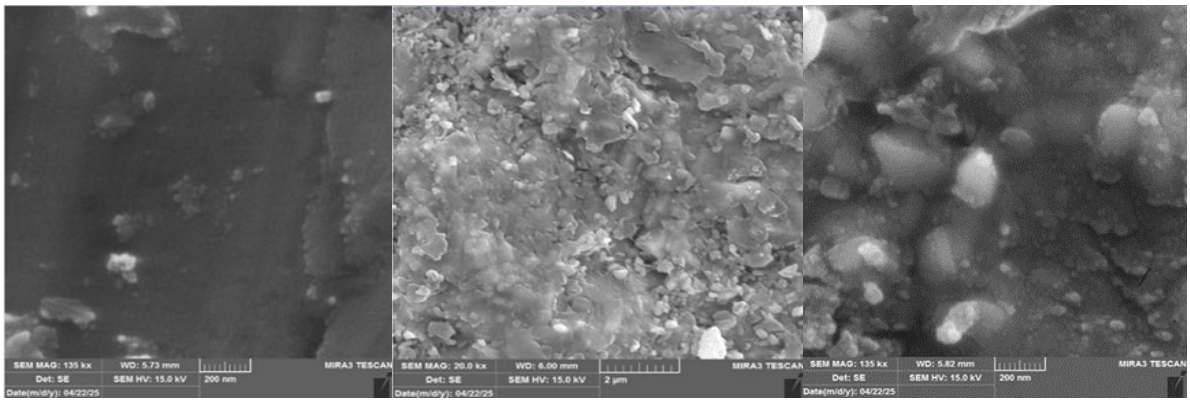

Fig. 8. SEM images of carbon steel outer shells: (1) The alloy is polished only; (2) The alloy is immersed in a 1M HCl solution, (3) The alloy is immersed in the presence of inhibitor (C).

3.5. Mechanism of action of Inhibitor

Plant extracts demonstrate their performance as corrosion inhibitors when utilized in corrosive media. This is due to the presence of organic compounds known for their capacity to prevent corrosion through adsorption upon the metal outer shell, causing the formation an insulating cover. This is because these organic compounds contain atoms with paired electrons and aromatic rings, giving them high inhibitory effectiveness. Diagnostic results indicate that the active compounds in inhibitor often contain atoms such as nitrogen or oxygen, in addition to presence of π-systems. These chemical

structures are among the most prominent potential pathways that explain the inhibition mechanism of these extracts [32].

1- The aromatic ring in the inhibitor molecule is likely to react with atoms on the alloy outer shell, resulting in overlap between the π electrons and the d orbitals of the metal atoms. This overlap results in the formation of a protective cover on the metal outer shell that acts as a barrier to the penetration of corrosive materials, thus contributing to a reduction in the corrosion rate [33]. Figure 9 illustrates this interaction.

2- The plant-based inhibitor has the tendency to adsorb onto the metal substrate, due to its interaction with the lone pairs of electrons present in the nitrogen (N) and oxygen (O) atoms. This interaction results in the formation of either ionic or covalent bonds with the d orbitals, which are either empty or partially filled in the metal, this bonding results in the immobilization of the inhibitor molecules on the metal outer shell, forming an insulating cover. This cover blocks the penetration of corrosive agents to the outer shell, thus limiting the rate of corrosion. [34]. Figure 10 illustrates this effect.

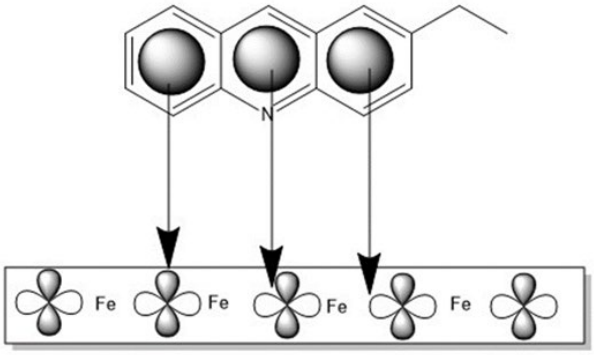

Fig. 9. shows the interaction of the π-bonds in the compound 2-Ethylacridine, one of the inhibitory compounds (C), with the d-orbital.

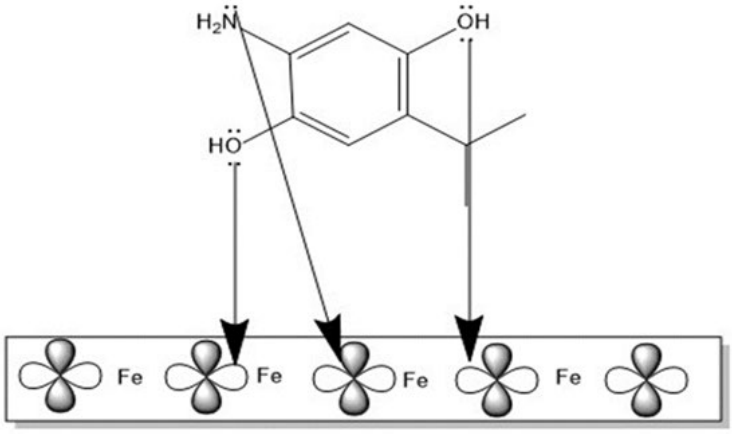

Fig. 10. shows the overlap of the lone pairs of the O and N atoms in the compound 2-amino-5-isopropylbenzene-1,4-diol, one of the inhibitory compounds (C), with the d-orbital.

4. Conclusions

In an acidic environment containing 1 M hydrochloric acid, inhibitor (C) was proven to slow the corrosion process of N80 carbon steel. Electrochemical experiments clearly indicated the effectiveness of (C) as a corrosion protectant. The highest inhibition efficiency was achieved at a concentration of

200 ppm at 298 K. Furthermore, the results showed that the inhibitor efficiency rose as the concentration rised, but declined with rising ambient temperature.

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Journal of Basrah Researches (Sciences) **52**(1), 74 (2026)
DOI: https://doi.org/10.56714/bjrs.52.1.6

التحليل الكهروكيميائي والسطحي لمستخلص براعم زهرة القرنفل كمثبط تآكل اخضر للفولاذ الكربوني N80 في البيئات الحمضية

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معلومات البحث

الاستلام	09 اب 2025
المراجعة	27 كانون أول 2025
القبول	02 كانون ثاني 2026
النشر	30 حزيران 2026

الكلمات المفتاحية

التآكل، مثبطات النباتية، منحنيات الاستقطاب، الفولاذ الكربوني.

الملخص

يُعدّ تآكل الفولاذ الكربوني في الظروف الحمضية من أبرز المشكلات في صناعات البترول والكيماويات، لا سيما في عمليات التحميض والتخليل. في هذا البحث، تمّ فحص خصائص تثبيط التآكل لمستخلص مائي من براعم زهرة القرنفل (Syzygium aromaticum) على فولاذ N80 الكربوني في حمض الهيدروكلوريك بتركيز 1 مولار. يُعزى استخدام مستخلص القرنفل إلى محتواه العالي من المركبات الكيميائية النباتية، التي تتكون من مركبات فينولية ونيتروجينية، والتي وُجد أنها تُحفّز امتصاصًا فعالًا على أسطح المعادن وتزيد من مقاومتها للتآكل. استُخدمت قياسات الاستقطاب لدراسة سلوك التآكل بتراكيز مختلفة من المثبطات ودرجات حرارة مختلفة باستخدام تقنيات كهروكيميائية. كما دُرست مورفولوجيا السطح وتكوين طبقات المثبط في الموقع باستخدام المجهر الإلكتروني الماسح، وتمّ تحديد التركيب الكيميائي للمستخلص من خلال تحليل GC-MS. وقد أظهرت النتائج أن مستخلص القرنفل مثبط تآكل فعال من النوع المختلط، حيث يُقلّل بشكل ملحوظ من كثافة تيار التآكل ومعدل التآكل. بلغت أعلى كفاءة تثبيط 90.01% عند تركيز مثبط قدره 200 جزء في المليون ودرجة حرارة 298 كلفن. وتؤكد النتائج أن مستخلص براعم زهرة القرنفل يوفر حماية فعالة وصديقة للبيئة ضد التآكل على الفولاذ الكربوني N80 في البيئات الحمضية كبديل لاستخدام مثبطات التآكل الاصطناعية بطريقة مستدامة.

Citation: M. M. Jassim, A. S. Abdul Nabi., J. Basrah Res. (Sci.) **52**(1), 74 (2026). DOI:https://doi.org/10.56714/bjrs.52.1.6

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ISSN: 1817-2695 (Print); 2411-524X (Online)
Online at: https://jou.jobrs.edu.iq