

Electrochemical And Surface Analysis of Salvia Officinalis Extract as a Green Corrosion Inhibitor for N80 Carbon Steel in Acidic Media

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Abstract

Corrosion of N80 carbon steel in acidic oilfield environments, particularly in 1 M HCl, causes significant material degradation, reducing pipeline integrity and posing operational risks. Although traditional synthetic inhibitors are effective, they often contain toxic chemicals, underscoring the need for eco-friendly alternatives. In this study, the use of *Salvia officinalis* aqueous extract as a green corrosion inhibitor is explored, offering a sustainable and non-toxic alternative to synthetic inhibitors in corrosive environments.

Tafel polarization, scanning electron microscopy (SEM), and gas chromatography–mass spectrometry (GC–MS) were employed to evaluate the corrosion inhibition performance of *Salvia officinalis* extract at varying concentrations (50–200 ppm) and temperatures (298 K, 308 K, 318 K). The inhibitor demonstrated up to 94.98% efficiency at 200 ppm and 298 K, with significant reductions in corrosion current density (I_{corr}) and corrosion rate (CR). SEM analysis revealed smoother steel surfaces, confirming effective corrosion protection. GC–MS identified key active compounds—including phenols, alkaloids, and terpenes—responsible for the extract's inhibitory effect.

Overall, *Salvia officinalis* aqueous extract acts as a mixed-type inhibitor, substantially reducing corrosion rates and providing a green, sustainable solution for corrosion prevention in industrial applications, particularly within the petroleum industry. Further research is recommended to enhance its performance at higher temperatures.

Keywords: Corrosion, N80 carbon steel, *Salvia officinalis* extract, green corrosion inhibitor, Tafel polarization, SEM, GC-MS, inhibition efficiency.

BACKGROUND:

Corrosion is a widespread problem in the petroleum industry, and most pipelines that transport oil and gas are made of carbon steel, especially N80 alloy. Acidic conditions (high temperatures) as well as environments with the tendency to corrode favor severe physical conditions that increase the corrosion rate, causing damage and danger to the structure and activity. Conventional corrosion inhibitors are effective but may represent hazardous and toxic chemicals and raise concerns about environmental harm, which motivates the creation of more environmentally friendly types. Recent years have attracted more researchers to the idea of utilizing plant-based extracts as alternative, environmentally friendly corrosion inhibitors that tend to promise sustainability without reducing efficacy [1].

Salvia officinalis, commonly known as sage, is an annual plant of the Lamiaceae family that has a variety of bioactive components. They include phenols, flavonoids, and alkaloids, and these compounds have exhibited potential inhibitory effects on corrosion by creating a protective film on metals. *Salvia officinalis* has been of interest as a corrosion inhibitor because it is environmentally safe, cost-effective, and highly available. Furthermore, extracts of plants can also provide long-term corrosion protection in severe industrial environments and can offer an alternative to conventional inhibitors [2].

Acidic environments, particularly 1M hydrochloric acid, are a major risk to the integrity of petroleum pipelines because of the corroding capacity of steel (N80) to acid. This corrosion causes serious material loss, shortens the life of the pipeline, and increases operating risks. Although synthetic inhibitors are usually applied to reduce their presence, their harm to the environment and human life constitutes a significant obstacle. Thus, more sustainable, non-toxic methods are necessary to address the pipeline corrosion in these harsh environments [3].

“This research aims to investigate the electrochemical behavior and surface morphology of N80 carbon steel in the presence of *Salvia officinalis* extract as a green corrosion inhibitor in acidic media. The study will assess the efficiency of the extract at different concentrations and temperatures, using electrochemical techniques like Tafel polarization and surface characterization through scanning electron microscopy (SEM).”

This research is significant because it provides a sustainable solution to corrosion in the petroleum industry by utilizing *Salvia officinalis*, a plant-based extract, as a corrosion inhibitor. The study's findings can contribute to the development of eco-friendly corrosion prevention methods, offering a safer and more cost-effective alternative to traditional synthetic inhibitors. By demonstrating high inhibition efficiency and environmental safety, this research promotes the adoption of green technologies in industrial applications, supporting sustainability and reducing the environmental impact of corrosion inhibitors.

LITERATURE REVIEW

Traditional Inhibitors vs. Green Inhibitors

Metals are vulnerable to corrosion, particularly in hostile areas like petroleum pipelines, and corrosion inhibitors are the most essential. The mitigation of corrosion by traditional synthetic inhibitors has been around for a long time, with examples including chromates, phosphates, and amines [4]. The mechanism of these inhibitors is that they are adsorbed onto the metal surface, forming a protective barrier that shields the metal from attack by corrosive agents. Although such inhibitors are extremely effective, their effects on the environment and the health of the patient are significant. Most of the synthetic inhibitors have toxic chemicals that are harmful to the environment and people, and this raises concerns about sustainability and compliance with regulations [5].

On the contrary, green inhibitors extracted from natural resources such as plant extracts provide a healthier and more sustainable alternative. Such inhibitors are environment-friendly because they are biodegradable, non-toxic, and renewable in most cases. Green inhibitors operate on the same principle as classic varieties, namely adsorption on metal surfaces. However, they are often organic compounds, in particular, those of phenolic, flavonoid, and alkaloid structure, which are rich in plant-derived extracts [6]. Eco-friendliness Industrial trends dictate the increasing necessity of green manufacturing processes, and using green inhibitors is a major course of action leading to sustainable corrosion protection means.

Previous Studies Using Plant Extracts

The use of plant extracts in corrosion inhibition has increased its popularity because it is environmentally friendly and effective. The effectiveness of the compounds on plants has been identified through various research works on preventing the corrosion of metals in various environments. As an illustration, the effectiveness and environmental friendliness of purple rice bran extract were tested as an inhibitor of steel in hydrochloric acid by [7], and its efficiency was ensured by its low concentration. On the same note, the corrosion inhibition study of mild steel by [8], using serine and methionine, discusses the prospect of amino acids as plant inhibitors of corrosion. These research projects affirm that plant extracts may be used as efficacious inhibitors because they adsorb on the metal surface and lower corrosion velocities.

Salvia officinalis (sage) was also studied in its plant extract to investigate its corrosion inhibition properties. Research has revealed that sage harbors bioactive compounds that include phenolic acids, alkaloids, and terpenes, and can explain why it prevents corrosion via metals. These chemicals are highly effective inhibitors in that they adsorb to metal surfaces and thus tenderize them against hostile environments. Furthermore, the high interest in such plant extracts as *Salvia officinalis* is the combination of properties: in addition to protecting against corrosion, they have low toxicity and a minimal impact on the environment, which makes them perfect options to be used in industry [9].

Studies Focusing on N80 Steel in Acid

N80 carbon steel, used in the petroleum industry to construct petroleum pipelines, is likely to experience corrosion in acidic environments, such as hydrochloric acid. Many investigations have been done on the corrosion behavior of N80 steel in such environments to reduce corrosion rates with various inhibitors. An example is that N80 steel has been found to corrode greatly at 1M HCl, and the rate is affected by certain factors, including temperature and the presence of inhibitors, as shown by [10] and [11]. These research findings have proved that the rate of corrosion experienced by N80 steel would be considerably minimized upon the addition of suitable inhibitors, and this has shown the role that corrosion protection plays in the safety of the pipeline networks.

A study done on the effectiveness of plant extracts as inhibitors of N80 steel in acidic media showed some promising results. *Salvia officinalis* extract has been investigated for its ability to increase resistance to corrosion in aggressive conditions. Active constituents present in the extract, e.g., phenols and alkaloids, are adsorbed on the metal surface, which creates a protective coat against corrosive entities. It is a category of green inhibitor that has been found applicable to curb corrosion rates on N80 steel, since, as it has

been previously established, the efficiency of inhibition tends to rise with the concentration of the extract [12].

Electrochemical and SEM Methods in Inhibitor Evaluation

Evaluations of corrosion inhibitors through electrochemical procedures have become quite popular because these methods furnish quantitative, real-time data regarding the corrosion process. Corrosion rates, the effectiveness of inhibitors, and the mechanism of action pathways are routinely determined using the Tafel polarization and “electrochemical impedance spectroscopy (EIS), and linear polarization resistance (LPR)” methods. Especially, Tafel polarization can provide useful data to evaluate vital parameters of the corrosion performance, such as current density of corrosion (I_{corr}), corrosion potential (E_{corr}), and polarization resistance (R_p). The study by [13] contributes to the efficiency of green inhibitors tested by Tafel polarization. It proves that the method allows measuring the decrease in the corrosion current density and interpreting it as an understanding of the mechanism of action.

Scanning Electron Microscopy (SEM) serves as another key instrument when reviewing the morphology of the surface of metal, before and after exposure to inhibitors. “The corrosion products are visualized, and the protective layers are formed on the surface of the metal through SEM. SEM images provided detailed information on structural variations taking place on the surface of N80 steel when corrosion inhibitors were applied.” The morphology of the metal surface can be observed to determine whether the protective film driven by the inhibitor is uniform or localized corrosion is present. As has been established by the studies of [14] and [15], SEM can be usefully applied to evaluate the protective qualities of green inhibitors, as it has been shown that the extracts of plants provide an unbroken layer on the surface of the metal, which acts efficiently in terms of minimizing corrosion.

Experimental Section

2.1 Chemicals and Devices Used

Hydrochloric acid (HCl) in concentrated form was used to prepare the corrosion solution, and all chemicals and solvents were obtained from BDH. Experiments were done using the N80 carbon steel alloy, which was supplied by the Southern Oil Company (SOC). In Table 1, the chemical composition of the alloy is given. The surface analysis was done using Scanning Electron Microscopy (SEM) at the University of Tehran, Islamic Republic of Iran. Gas Chromatography-Mass Spectrometry (GC-MS) of the *Salvia officinalis* extract was also carried out at the University of Tehran to identify the chemical constituents of that extract.

2.2 Alloy Composition

The N80 carbon steel alloy used in this study has the following composition:

- Phosphorus (P): 0.05%
- Sulfur (S): 0.06%
- Manganese (Mn): 1.2%
- Carbon (C): 0.3%
- Iron (Fe): 98.93%

2.3 Preparation of Corrosion Solution

“A 1M hydrochloric acid (HCl) solution was prepared by diluting concentrated HCl with distilled water. This solution was used as the corrosive medium for evaluating the corrosion inhibition performance of *Salvia officinalis* extract on N80 carbon steel.”

2.4 Preparation of *Salvia officinalis* Leaf Extract

“The *Salvia officinalis* leaf extract was prepared by adding 10 grams of dried and ground sage leaves to 300 mL of distilled water in a 500 mL beaker. The mixture was heated to 70°C for one hour using a mechanical stirrer. After cooling for two hours, the solution was filtered through filter paper, and the filtrate was dried at 50°C for two days, resulting in 1.54 grams of dry extract. A standard solution was made by dissolving 0.5 g of the dried extract in 500 mL of distilled water to achieve a concentration of 1000 ppm. Solutions with concentrations of 50, 100, 150, and 200 ppm were prepared by appropriate dilution.”

2.5 Electrochemical Measurements

“Electrochemical measurements were performed using Tafel polarization to determine the corrosion rates and inhibitor efficiency. The setup consisted of a three-electrode electrochemical cell: the working electrode (N80 carbon steel), a platinum auxiliary electrode, and a saturated calomel electrode (SCE) as the reference. The tests were conducted in 1M HCl solution containing varying concentrations of *Salvia officinalis* extract at temperatures of 298 K, 308 K, and 318 K.”

SEM and GC-MS Analysis

The SEM analysis was done at the University of Tehran when the steel samples were allowed to sit in the corrosion solution after 3 hours at 298 K. Strain morphology was examined to note the effectiveness of an inhibitor. The *Salvia officinalis* extract was also analyzed by the GC-MS technique at the University of Tehran to establish the important chemical compounds, mass spectrum data, and retention times that were fitted in the identification of the active ingredients causing corrosion inhibition.

RESULTS AND DISCUSSIONS

The following section shows the findings of the experimental studies conducted to assess the efficiency of *Salvia officinalis* as a corrosion inhibitor on N80 carbon steel. The results are elaborated, comparing experimental data to available literature to draw implications of the research findings.

3.1 Chemical detection of the active compounds in *Salvia officinalis* leaf (S) extract

To obtain the active chemical components that are contained in the aqueous extract of *Salvia officinalis* leaves, a set of qualitative chemical tests was performed. This was carried out because chemical constituents play a major role in inhibiting corrosion.

3.1.1 Phenols Test

The extract made of *Salvia officinalis* was subjected to the ferric chloride (FeCl_3) reagent study of phenolic compounds. In the process, 3 ml of the plant extract was pipetted with due diligence into a clean test tube, and another 2 ml of the recently prepared 1% FeCl_3 solution was added. It was mixed, ensuring that the reaction mixture was swirling slowly. There was also a distinguished blue-green coloration that indicated the presence of phenolic constituents in the extract. The cause of this color change is the complexation between phenol and ferric ions, and indicates the phenolic content present in the literature reports [16].

3.1.2 Flavonoids Test

Potassium hydroxide (KOH) test was used in the determination of the presence of flavonoids in the plant extract. In this analysis, a sterile test tube was used and 1 ml of the *Salvia officinalis* extract combined with 1 ml of 5N alcoholic KOH. Initially, the contents were thoroughly mixed such that there was uniform absorption of the reagent and the plant extract. Within a couple of minutes, a yellow precipitate was obtained, indicating the presence of flavonoid compounds. This response is explained by the formation of flavonoid-alkaline complexes characterized by yellow color and presence in solution. The test would comply with the usual phytochemical screening procedures, and you would get qualitative confirmation of flavonoid quantity [17].

3.1.3 Tannins Test

The presence of tannins was qualitatively identified using lead acetate. In this procedure, a fresh 1% lead acetate solution was prepared, and several drops of it were added to 5 ml of the *Salvia officinalis* extract in a test tube. It swirled the mixture gently to allow interaction. Tannins were present in the sample, as a white precipitate formed. This precipitation is just because insoluble lead-tannin complexes form. This is one of the established parameters used to determine the presence of tannins and is extensively used in phytochemical research to test the presence of astringent polyphenolic substances in plant extracts [18].

3.1.4 Alkaloids Test

It was tested against Wagner reagent, one of the older tests to detect the presence of alkaloids in plant extractions. To 2 g of iodine and 1.3 g of potassium iodide (KI and I₂) was added 100 ml of distilled water. It was done in a test-tube; 1 L of the *Salvia officinalis* extract was added to 2 L of Wagner reagent. This mixture was stirred, and it was immediately noticed that the mixture released a brown precipitate. This indicated that alkaloids were present, as alkaloids are N-containing compounds and give rise to an insoluble iodine complex when placed in the acidic environment provided by the reagent [19].

3.1.5 Saponins Test

Saponins were found in the extract of *Salvia officinalis*: a relatively easy-to-run frothing test confirmed that. Under test, a test tube of 20 ml of plant sample was taken and vigorously shaken for a few seconds, allowing free reagents into the mixture. A stable and voluminous film of foam was produced on the top and persisted for a long time, which confirmed the presence of saponins. Among the causes of such foam is the surfactant nature of the saponin molecules, which reduces the surface tension of the liquid enclosing air bubbles in the liquid. The well-known qualitative test to identify saponin is the froth formation test of plant extracts [20].

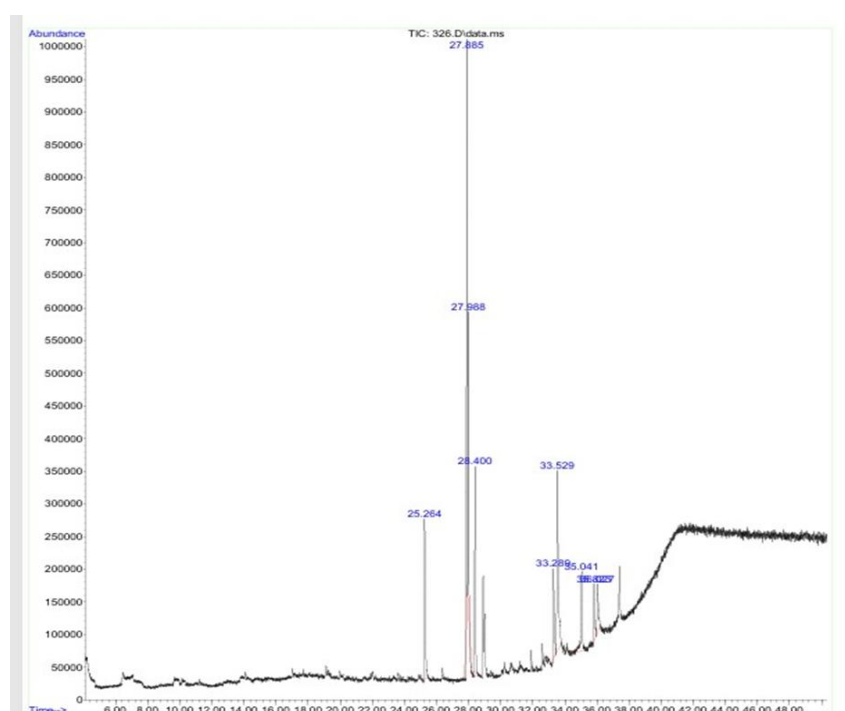
Table :2 Results of chemical detection of active compounds in the aqueous extract of (S)

Number	The compounds	Reagents	Detection guide	The result
1	Phenols	FeCl ₃ (1%)	white precipitate	+
2	Flavonoides	Alcoholic KOH (5N)	yellow precipitate	-
3	Tannins	Pb(CH ₃ COO) ₂ (1%)	white precipitate	+
4	Alkaloids	Wagner	brown precipitate	+
5	Saponin	shaking it vigorously	foam appears	+

+ = presence; - = absence

Table 2 presents the results of the chemical detection of active compounds in the *Salvia officinalis* extract. The presence of phenols, tannins, alkaloids, and saponins was confirmed through specific reagents and corresponding reactions, such as white precipitates for phenols and tannins, brown precipitate for alkaloids, and foam formation for saponins. Flavonoids, however, were not detected. The identified compounds, particularly phenols and alkaloids, are likely responsible for the extract's corrosion inhibition properties, as they can form protective layers on metal surfaces.

The figure
GC-MS



presents a

chromatogram of *Salvia officinalis* extract, displaying key bioactive compounds responsible for its corrosion inhibition properties. The chromatogram shows peaks at various retention times, each corresponding to specific compounds identified in the extract.

Table (3) shows the most important components that appeared in the plant inhibitor (S)

NUMBER	RT (min)	Area%	Name	Quality	CAS Number
1	14.085	0.35	N-Methyl-1-adamantaneacetamide	45	000000-00-0
2	17.027	0.27	Dutadrupine	30	007758-68-1
3	19.118	0.60	Aromadendrene oxide- 2	25	000000-00-0
4	25.267	9.25	Methyl palmitate	99	000112-39-0
5	27.887	20.04	9,12-Octadecadienoic acid, methyl ester	99	002462-85-3
6	27.986	9.90	Oleic acid, methyl ester	99	000112-62-9
7	28.401	10.36	Methyl stearate	99	000112-61-8
8	28.899	4.23	Linoleic acid ethyl ester	98	000544-35-4
9	28.987	3.55	1,15-Hexadecadiene	53	021964-51-2
10	31.893	1.03	1,3-dimethyl-4-azaphenanthrene	35	000000-00-0
11	32.598	0.81	Equilin	55	000096-65-1
12	33.289	5.98	1H-Indole, 3-methyl-	38	000083-34-1
13	33.527	16.25	Benzene, (3-chloroallyl)-	37	006268-37-7

14	35.042	6.73	Pyrrolidine, 1-(9-borabicyclo[3.3.1]non-9-yl)-	15	022516-41-2
15	35.821	3.96	Tryptophane	25	000073-22-3
16	36.028	4.21	Butane, 2-phenyl-3-(trimethylsilyloxy)-	50	000000-00-0
17	37.398	2.49	Cyclotrisiloxane, hexamethyl-	43	000541-05-9

Table 3 lists these compounds, including 9,12-octadecadienoic acid methyl ester (20.04%), which is the most abundant, followed by benzene (3-chloroallyl)- (16.25%) and methyl stearate (10.36%). Other notable compounds include aromadendrene oxide-2, oleic acid methyl ester, and methyl palmitate. These compounds are recognized for their hydrophobic and film-forming properties, which are crucial for forming protective layers on the steel surface and reducing exposure to corrosive agents. The CAS numbers and area percentages in the table indicate the concentration of each compound in the extract. This analysis highlights the active components responsible for the corrosion inhibition performance of *Salvia officinalis*, making it a potential eco-friendly inhibitor for industrial applications.

“Table (4) shows the results of the polarization curves for the corrosion of carbon steel in the presence and absence of the inhibitor (S) at different concentrations in an acid solution (HCl) with a concentration of (1M) and at temperatures (298, 308, 318 K).”

Temp (K)	Inhibitor Conc	E_{corr} (mV)	C_R (mpy)	I_{corr} (mA/cm ²)	β_a (mV/Dec)	β_c (mV/Dec)	%IE	θ
298	Blank HCl (1M)	-461.9	10.08	22.14	217.9	-174.3	0	0
308		-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	50ppm	-443.7	4.67	10.26	90.7	-99.7	53.65	0.53
308		-456.5	7.30	16.04	101.5	-91.3	45.79	0.45
318		-489.0	10.72	23.55	141.5	81.4	37.82	0.37
298	100ppm	-452.3	3.22	7.08	77.0	-85.6	68.02	0.68
308		-473.6	6.11	13.42	140.2	-141.0	54.47	0.54
318		-486.5	9.13	20.05	147.1	-93.5	47.06	0.47
298	150ppm	-453.2	0.99	2.18	66.5	-137.3	90.15	0.90
308		-479.4	3.66	8.05	126.6	-187.2	72.62	0.72
318		-472.0	6.84	15.03	108.9	-99.1	60.32	0.60
298	200ppm	-462.1	0.50	1.11	58.4	-73.2	94.98	0.94
308		-440.7	2.45	5.40	61.0	-66.9	81.75	0.81

318		-480.0	5.18	11.38	104.0	-74.4	69.95	0.69
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The data of polarization curves belonging to N80 carbon steel at different temperatures and concentrations with and without *Salvia officinalis* extract (S) are demonstrated in Table 4. The IE% improves at bigger concentrations of the extract to a point of 94.98% at 200 ppm and 298 K, showing good resistance to corrosion. At increased temperatures (308 K and 318 K), there is a lesser efficiency of inhibition, because of waning adsorption strength. The corrosion rate (CR) and corrosion current density (I_{corr}) reduce tremendously with an increase in the inhibitor concentration, which ascertains the protective capacity of the extract. The results report on the temperature-dependent properties of the extract, determining its effectiveness at low temperatures and the necessity to improve stability under high temperatures.

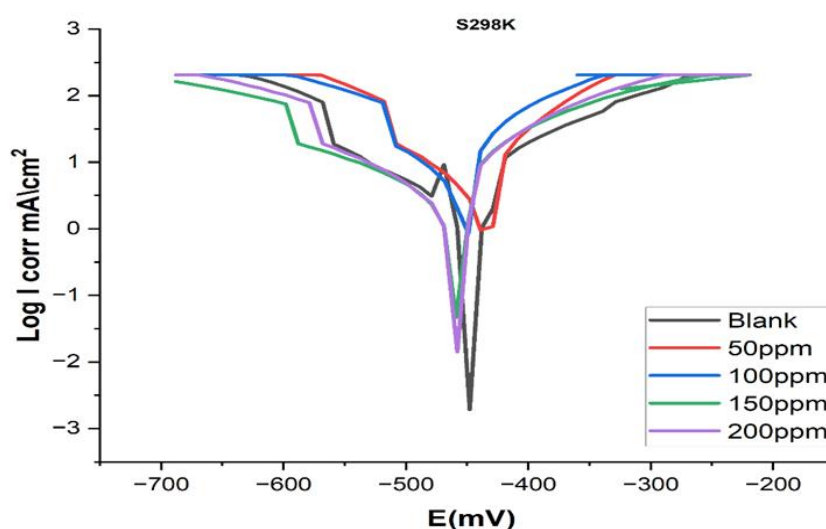


Figure (2): “Polarization curves for corrosion of N80 alloy in the presence and absence of inhibitor (S) at different concentrations and a temperature of 298 K.”

The figure presents polarization curves of the corrosion of N80 carbon steel in the presence and absence of *Salvia officinalis* extract in concentrations of 50, 100, 150, and 200 ppm at a temperature of 298 K. The graphs indicate that when the inhibitor concentration increases, the corrosion current density (I_{corr}) decreases, indicating that the inhibitor can reduce corrosion. The corrosion potential (E_{corr}) also indicates a shift toward less negative values when there is an increase in the concentrations of the inhibitor, as indicated by the curves, which show a decrease in the degree to which metal is dissolved as well as the evolution of hydrogen. This trend cements the fact that *Salvia officinalis* is efficient in alleviating corrosion in 1 M HCL and the extract contains considerable inhibition in high concentration.

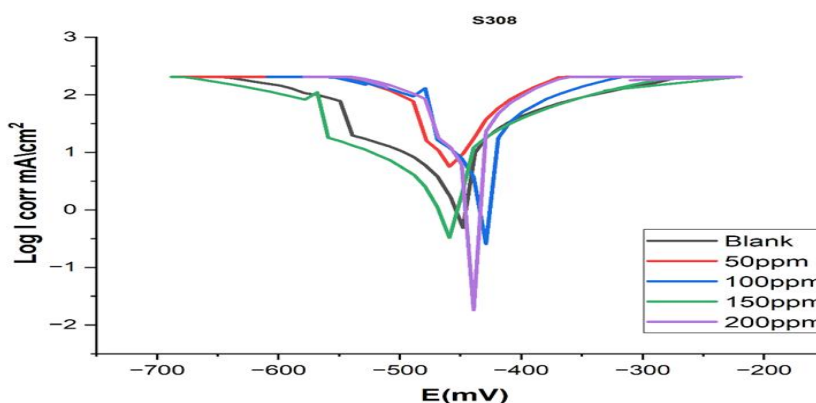


Figure (3): “Polarization curves for corrosion of N80 alloy in the presence and absence of inhibitor (S) at different concentrations and a temperature of 308 K.”

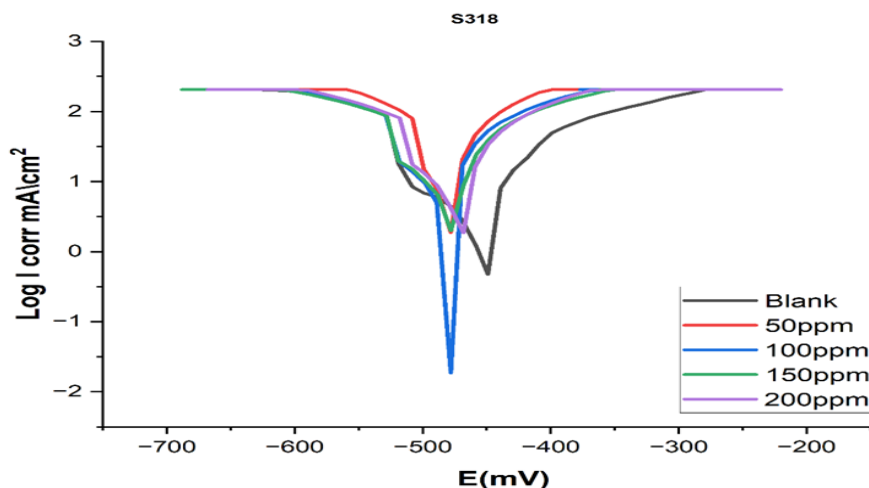


Figure (4): “Polarization curves for corrosion of N80 alloy in the presence and absence of inhibitor (S) at different concentrations and a temperature of 318 K.”

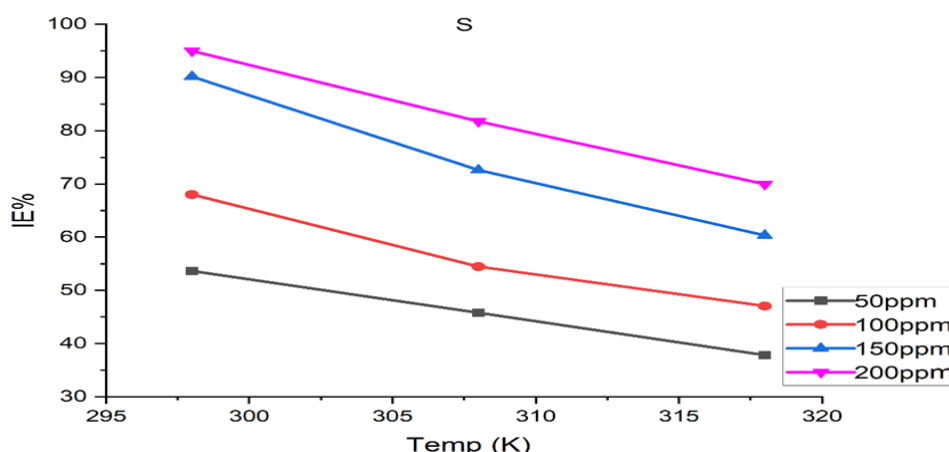


Figure (5): “The relationship between inhibition efficiency and temperature in an acid solution (HCl 1M) with different concentrations of the inhibitor (S) and at temperatures (298, 308, 318 K).”

“In a corrosive environment with 1 M hydrochloric acid, the kinetics of the corrosion process and the impact of temperature on the behavior of N80 alloy were investigated both with and without inhibitor (S) present at different concentrations. Kinetic functions for the adsorption process were computed to elucidate the characteristics and behavior of adsorption, as well as to ascertain the bonding strength between the inhibitor and the alloy surface. The influence of temperature on the corrosion rate of carbon steel was assessed at different temperatures (298, 308, 318 K) using the Arrhenius equation (4)” [21].

$$\text{Log } I_{\text{corr}} = \text{log } A - \frac{-E_a}{2.303 RT} \quad (4)$$

Where: “ I_{corr} : Corrosion current density, E_a : Activation energy, T : Temperature, R : Gas constant ($8.3143 \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$), A : Arrhenius constant. When plotting the relationship between the values of $\text{Log } I_{\text{corr}}$ versus $1/T$, as shown in Figure 6, a straight line is obtained, where the slope of this line represents the value of $(E_a/2.303R)$. In contrast, the part intercepted by the axis represents the value of $\text{Log } A$. Equation (4) is used to find the activation energy (E_a), 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 the 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 an acidic medium.”

$$\log \frac{i_{corr}}{T} = \log \frac{R}{N_h} + \left(\frac{\Delta S^*}{2.303} \right) - \left(\frac{\Delta H^*}{2.303RT} \right) \quad (5)$$

Where: N: “Avogadro’s number ($6.022 \times 10^{23} \times \text{mol}^{-1}$), h: Planck’s constant ($6.626 \cdot 10^{34}$ J.S). When plotting the relationship between the values of $\log i_{corr}/T$ versus $1/T$, as shown in Figure 7, a straight line is obtained where the slope of the line represents the relationship ($\Delta H^*/2.303R$), which is used to calculate the activation enthalpy (ΔH^*). The part cut from the axis, which represents $\log R/N_h + (\Delta S^*)/2.303$, is used to find the activation entropy value (ΔS^*). After calculating the values of (ΔH^*) and (ΔS^*), the values of (ΔG^*) are found from equation (6)[22].”

$$\Delta H^* - T \Delta S^* = \Delta G^* \quad (6)$$

“According to the results in Table 5 (E_a), (ΔH^*), (ΔS^*), and (ΔG^*), the activation energy (E_a) rises when the inhibitor is present compared to its absence. The elevation in activation energy is ascribed to the development of a thin layer of inhibitor molecules adsorbed on the alloy surface, establishing a physical (electrostatic) barrier that obstructs or diminishes charge interaction and transfer from the alloy surface, thereby constraining the corrosion process. This aligns with the reduction in inhibition efficacy as temperature increases, suggesting that the inhibition process initiates with physical adsorption on the alloy surface, followed by chemical adsorption [23]. Positive activation enthalpy (ΔH^*) values signify that the corrosion reaction is endothermic. ΔH^* values are shown to rise with an increase in inhibitor concentration. Negative entropy values (ΔS^*) signify ordered (less random) binding of inhibitor molecules to the metal surface via adsorption [24]. Elevated and positive values of standard Gibbs free energy (ΔG^*) signify that the corrosion response is non-spontaneous, suggesting substantial inhibitory efficacy against the corrosion of carbon steel [25].”

Table (5): Values of the kinetic functions ΔG^* , ΔH^* , ΔS^* , E_a in the existence and non-attendance of the inhibitor (S) at different concentrations and at different temperatures (318, 308, 298 K).

Comp	Conc	E_a (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
S	50ppm	32.75	-0.12	30.19	65.95	67.15	68.35
	100ppm	41.10	-0.09	38.54	65.36	66.26	67.16
	150ppm	76.33	-0.05	73.78	88.68	89.18	89.68
	200ppm	92.03	0.009-	89.47	92.15	92.24	92.33

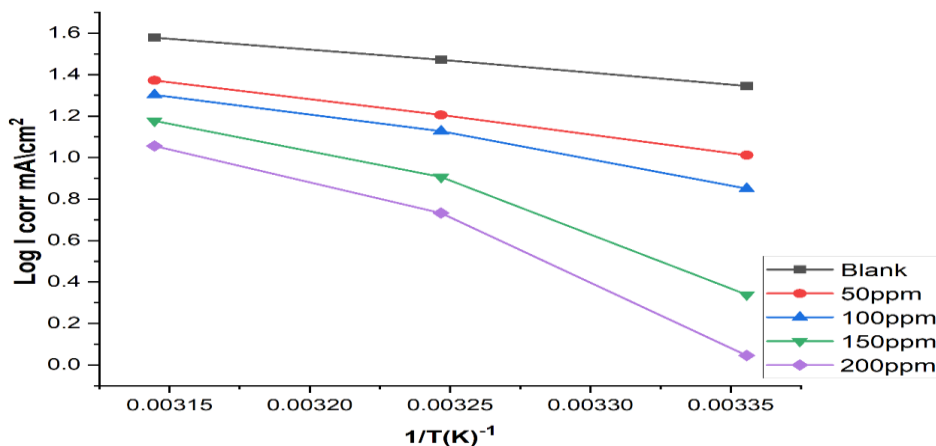


Figure (6): Arrhenius relationship with the existence and non-attendance of inhibitor (S) at different concentrations and temperatures (318, 308, 298 K)

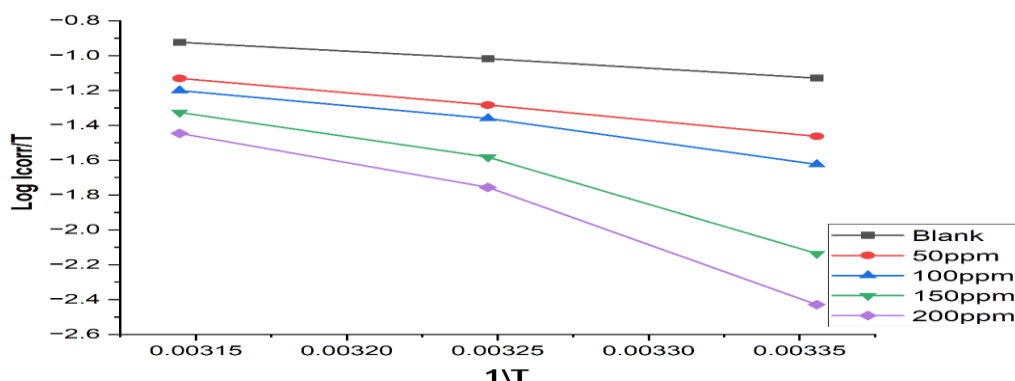


Figure (7): The relationship between the transition state and the calculation of enthalpy and entropy in the existence and non-attendance of the inhibitor (S) at different concentrations and temperatures (318, 308, 298 K).

Research was performed utilizing a scanning electron microscope to examine the morphological alterations of the surface of N80 alloys, both in the presence and absence of the inhibitor. Figure 8 presents scanning electron microscopy pictures of the surface of carbon steel N80 at the ideal inhibitor concentration of 200 parts per million in a one molar hydrochloric acid solution. Following a 3-hour immersion of the samples at 298 K, notable corrosion of the steel surface was detected due to the acid's influence. In contrast, the samples treated with the inhibitor exhibited a smoother surface and fewer voids, demonstrating the inhibitor's efficacy in mitigating corrosion, which is ascribed to the protective layer formed on the alloy surface by adsorption [26].

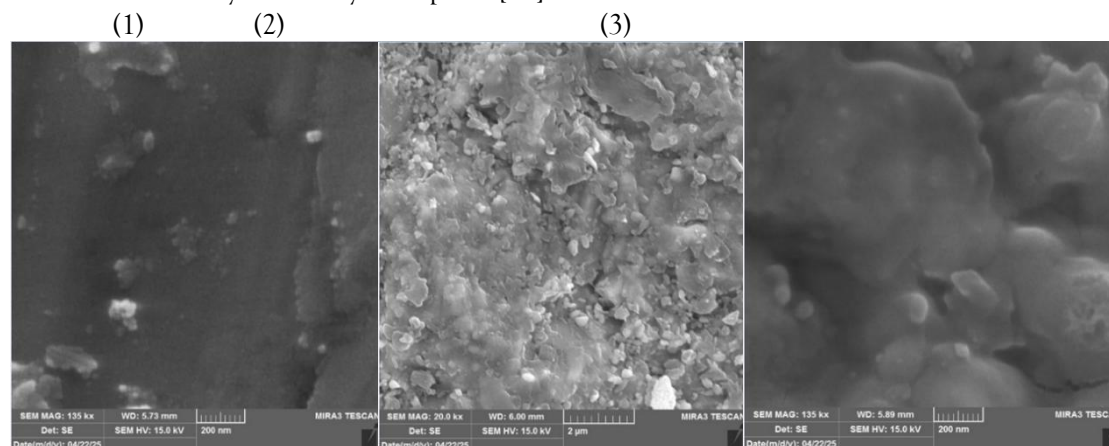


Figure (8): “SEM images of carbon steel surfaces: (1) The alloy is polished only, (2) The alloy is immersed in a 1M HCl solution, (3) The alloy is immersed in the presence of inhibitor (S).”

“Plant extracts exhibit efficacy as corrosion inhibitors in corrosive environments. This results from the presence of organic chemicals that hinder corrosion by adsorbing onto the metal surface, thereby generating an insulating layer. This is due to the presence of paired electrons and aromatic rings in these chemical molecules, which confer significant inhibitory efficacy. Diagnostic results reveal that the active chemicals in the inhibitor frequently comprise atoms such as nitrogen (N) or oxygen (O), alongside the existence of π -systems inside the aromatic rings. These chemical structures represent significant potential avenues for elucidating the inhibitory mechanism of these extracts [27].”

1. “The aromatic rings of the inhibitor engage with the metal surface atoms via an overlap of the π electrons in the inhibitor and the d orbitals of the metal. This interaction results in the creation of a protective layer on the metal surface, inhibiting the ingress of corrosive substances and so lowering the corrosion rate [28], as illustrated in Figure 9.”

2. “The plant inhibitor adheres to the metal surface via the interaction of unpaired electrons in the nitrogen (N) and oxygen (O) atoms with the vacant or nearly occupied d-suborbitals of the metal. This contact leads to the establishment of bonds that may be covalent, ionic, or derived from van der Waals forces, which facilitate the adhesion of the inhibitor molecules to the metal surface. Consequently, a protective layer is established that inhibits the corrosive media from contacting the metal surface, hence diminishing the corrosion rate [29], as illustrated in Figure 10.”

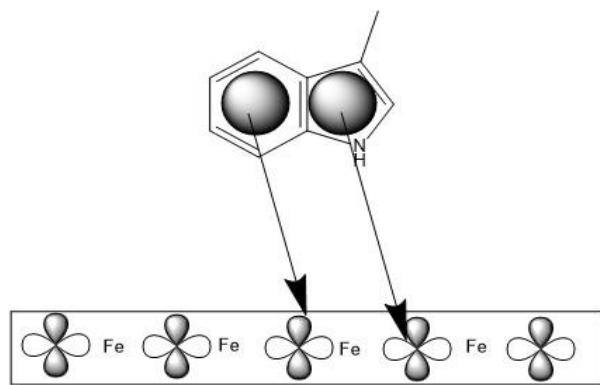


Figure (9) shows the interaction of the π -bonds of the aromatic rings in the compound 3-Methyl-1H-indole, one of the inhibitory compounds (S), with the d-orbitals of iron.

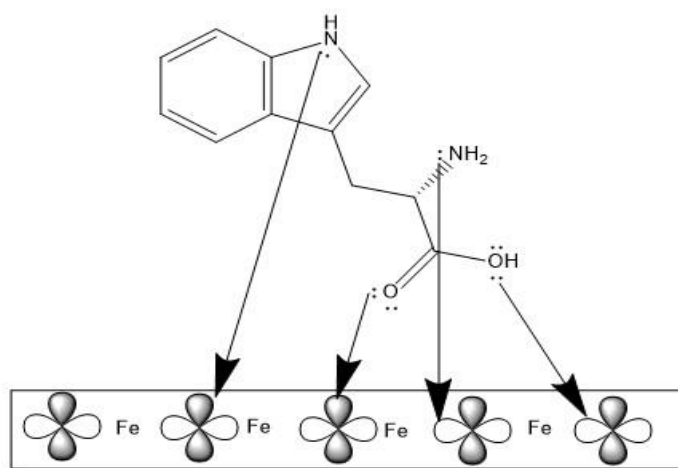


Figure (10) shows the overlap of the free electron pairs of the oxygen and nitrogen atoms in the compound Tryptophane, one of the inhibitory compounds (S), with the d-orbitals of iron.

DISCUSSION

The study on *Salvia officinalis* as a corrosion inhibitor for N80 carbon steel in 1M HCl highlights the effectiveness of the plant extract in mitigating corrosion, with a significant decrease in corrosion rate and corrosion current density observed at higher inhibitor concentrations. This aligns with previous research that shows plant-based inhibitors, particularly those containing phenols, alkaloids, and terpenes, can effectively form protective layers on metal surfaces, reducing corrosion in aggressive environments [11]. The polarization curves (Table 4) further support this by demonstrating that the inhibitor reduces both anodic and cathodic reactions, confirming its mixed-type inhibition behavior. The SEM analysis provided clear evidence of surface protection, with a smoother surface observed in the presence of the inhibitor, indicating reduced corrosion damage.

In terms of temperature dependency, the study found that inhibition efficiency decreased with increasing temperature, which is consistent with findings in the literature. Physical adsorption of the inhibitor molecules weakens at higher temperatures, reducing the inhibitor's protective effect [21]. This temperature dependence suggests that while *Salvia officinalis* is effective at lower temperatures, further research into improving temperature stability, perhaps through chemical adsorption or the use of nano-enhanced additives, is needed to enhance its effectiveness at higher temperatures [23].

The GC-MS result represented the 9,12-octadecadienoic acid methyl ester, methyl stearate, and oleic acid methyl ester to be present in large proportions in the extract, which are characterized by their hydrophobic and film-forming qualities. These results align with those of research findings indicating that fatty acid esters and terpenes can help create a hydrophobic barrier on a metal surface to protect against corrosion

[14]. Such results on the adsorption mechanism are also evidenced by the activation energy (E_a) calculations (Table 5) and the Arrhenius relationship (Figure 6) that show an increased value of E_a at lower temperatures, which points to an increase in interactions between the inhibitor and the metal surface.

Conclusively, the present work contributes to the emerging literature on the use of plants as inhibitors for the protection of corrosion in industry in a sustainable manner. *Salvia officinalis* extract has several advantages and has shown great efficacy, especially at lower temperatures, which makes it a very promising alternative to synthetic inhibitors with an eco-friendly base. It has not been well studied in high-temperature conditions. It thus needs further research to make it viable for use in aggressive conditions such as the petroleum pipeline over prolonged periods.

CONCLUSION

In this study, the efficiency of *Salvia officinalis* extract used as a green inhibitor of corrosion in N80 stainless steel in the presence of 1M HCl is determined. The extract with optimum concentrations greatly decreased the rate of corrosion, and the corrosion current density was reduced very efficiently, with its greatest efficiency being 94.98% in 200 ppm, at a temperature of 298 K. The polarization curve and SEM analysis proved that the extract could create protective layers on the metal surface, which is why it can be used as an alternative to traditional inhibitors, given its environmental friendliness, particularly under severe industrial cases.

Limitations

The limitation of the study is that it considers only short test immersion and under limited controlled conditions, which may not give a complete picture of a corrosion situation in the real world. Moreover, the inhibitor has limited applications under high temperatures since it is temperature sensitive. Reproducibility may also be influenced by the variation in the extract composition caused by environmental and preparation factors, and no long-term stability in complex industrial environments was tested.

Recommendation

Further studies aim to prepare a more stable and effective *Salvia officinalis* extract at high temperatures, possibly via chemical adsorption or the inclusion of nano additives. Long-term performance testing beyond the laboratory in environments such as multi-component corrosive environments is needed. Also, economic feasibility studies and scalability tests will guide the viability of commercializing this extract as an inhibitor against corrosion. Diversification of the study by adding additional plant-based inhibitors is possibly a better alternative in enhancing the protection against corrosion.

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