

## ***Spinacia oleracea* Extract as Green Corrosion Inhibitor for Carbon Steel in Hydrochloric Acid Solution**

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There is a great environmental demand for using the eco-friendly save corrosion inhibitor for metals and alloys. Green corrosion inhibitors are safe for the environment and have low cost and are easily applicable in many industrial fields. In this respect, the plant Extract of fresh *Spinacia oleracea* (SPINOLE) was used as a green corrosion inhibitor for carbon steel in a 1.0 M hydrochloric acid corrosive environment. In a 1.0 M hydrochloric acid-corrosive environment, carbon steel was employed using (SPINOLE) as a green corrosion inhibitor. The effectiveness of the produced (SPINOLE) extract at various concentrations (100-500ppm) was assessed using chemical and electrochemical techniques. The impact of temperature and the isotherm of adsorption were investigated. It was discovered that the effectiveness of the extract's ability to stop corrosion diminishes when the temperature is raised and increases with extract concentration. Adsorption of extract elements onto the steel surface without changing the reaction process is what causes the inhibition, and this adsorption complies with the Langmuir adsorption isotherm model. Data on potentiodynamic polarization show that the plant extract inhibitor is mixed-type. The plant extract improves polarization resistance and inhibition performance by adhering to the metal/electrolyte interface, according to potentiodynamic polarization data. The cathodic reaction is delayed when inhibitor molecules are added to an aggressive medium, which results in a negative shift in the open circuit potential. In addition to mass loss, atomic absorption spectroscopy(AAS) was utilized as an indirect gravimetric method. The data from both methods are in good agreement with one another and with electrochemical methods.

**Keywords:** Green inhibitor; potentiodynamic polarization; corrosion; plant extract; gravimetric. AAS; Adsorption.

## 1. INTRODUCTION

Corrosion is an electrochemical process associated with every use of metals and alloys in the environment. When metals come into contact with their surroundings, chemical or electrochemical reactions occur between the metal and its surroundings. As a result, corrosion occurs when the refined metal transforms to a more chemically stable state such as oxide, hydroxide, or sulfide. This interaction has an impact on the structures and properties of several materials [1-9].

Corrosion is a continuous problem as it is a thermodynamically possible process of negative free energy. The damage by corrosion results in a high cost of maintenance in many industrial fields including boilers, water tanks, infrastructure, and petroleum pipelines [1-4]. Steel is considered a backbone of heavy industries highly affected by corrosion in acidic, alkaline, and marine environments [1-13]. Two methods are extremely widespread among the various categories available to control corrosion. The first is to alter the metal's electrode potential, while the second is to alter the metal's nature. The second category can be achieved through metal coating or material selection for a specific job, although this is not always permitted because it modifies the work's qualities and nature [13]. In this case, changing the environment, which can be accomplished through the use of corrosion inhibitors [13], maybe a preferable option. Many applicable methods were used for the control of the metallic corrosion process namely, painting and coating, galvanization, anodic and cathodic protection, and corrosion inhibitors. Many organic and inorganic materials were studied as corrosion inhibitors containing surfactants, polymeric materials, and heterocyclic compounds [5-13]. However, most of the used materials in this field are toxic or expensive ore used hazard organic synthesis in its preparation, which makes its application in environment id hazard due to warnings and prohibitions. Nowadays the environmental prohibition of using a hazardous chemical in an industrial application is important, due to the toxic effect of traditional corrosion inhibitors of high cost. There is a great environmental demand for using the eco-friendly save corrosion inhibitor for metals and alloys. For that reason, scientific efforts are continuous for searching for eco-friendly corrosion inhibitors known as green corrosion inhibitors. Green corrosion inhibitors, also known as environmentally friendly and potentially non-toxic corrosion inhibitors, have been produced over the previous decade as a result of corrosion inhibition research [1-4]. The use of green corrosion inhibitors is of great attention, green corrosion inhibitors used in the last decades are drug materials in expired and non-expired forms [14-19], modified plastic waste materials [20-22], Nanomaterials [23-27], and plant extract [28-31]. Beginning with R. S. Abdel Hameed's study published in 2009 [14], studies on the inhibitory effects of expired pharmaceuticals in metal corrosion processes have been emphasized. After this research, many expired drug materials were used as inhibitors for metallic corrosion in a corrosive environment and the trial in this field continues [14-19]. Plastic waste and its modified product are recently used as corrosion inhibitors for metals in an aqueous corrosive environment [20-31]. Green corrosion inhibitors made of nanomaterials are commonly used [32-36]. Toxic chemicals are commonly utilized as reducing and stabilizing agents in traditional Nanomaterials synthesis methods, which are difficult to run and exceedingly ecologically unfriendly [28-31]. As a result, the development of an environmentally benign Nanomaterials synthesis process has recently gotten a lot of attention. Low cost, environmental friendliness, sustainability, and ease of

operation are all advantages of using plant extracts as reductants and stabilizers to produce metal nanoparticles. Furthermore, the-synthesized metal nanoparticles are safer, more stable, and more uniform in size than their traditional counterparts are. In the field of metal nanoparticle synthesis, green preparation methods have become a research hotspot. Plant extracts were used on a large scale for the green synthesis of nanoparticles, and *Cannabis sativa* (hemp plant) was used as a stabilizing media for the green synthesis of silver nanoparticles [28-31]. Plant extracts as corrosion inhibitors are beneficial from a green chemistry standpoint in a number of ways, including a) avoiding the toxic effects of natural inhibitors on humans, b) reducing the amount of energy and the organic solvent which used in the synthesis of the traditional corrosion inhibitors, and finally, c) leaving no waste materials [28-31]. Literatures reveals the extract of flowers, plants, leaves, fruits, and seeds have enough active compounds to inhibit the corrosion of metals and alloys when in corrosive media [28-31]. In the previous reported studies [48-50], oil extracted from the leaves of *Eruca sativa* used as an inhibitor for steel in acidic environment and achieved maximum corrosion inhibition of 95% [48]. Ethanolic extract of *Avocado* as Eco-friendly corrosion Inhibitor for 201 Stainless Steel corrosion in Acidic Environment exhibit 93% inhibition efficiency [49].. In the current research, carbon steel in a 1.0 M hydrochloric acid corrosive environment was treated with an extract of *Spinacia oleracea* (SPINOLE) as a green corrosion inhibitor. The effectiveness of different quantities of the produced (SPINOLE) extract as a corrosion inhibitor was assessed using chemical and electrochemical techniques. The effect of temperature and adsorption isotherm were studied.

## 2. EXPERIMENTAL PART

### 2.1 Plant Materials and Chemicals

*Spinacia oleracea* leaves, fresh. As a product of Hail green veggies, it was collected from the market in Hail city. All analytical-grade reagents were purchased and utilized without further purification. For aqueous extraction and the manufacture of the corrosive solution, double distilled water was employed. The corrosive solution in this investigation is aggressive 1.0 M hydrochloric acid with a pH of 0.0, which is made from analytical grade 37 percent HCl (Sigma Aldrich) mixed with double-distilled water, titrated against 1.0 M Na<sub>2</sub>CO<sub>3</sub>, and then diluted to the desired pH. To ensure repeatability, each experiment was performed in aerated stagnant solutions and duplicated at least three times under the exact same circumstances. The average of the three replicated values was then used for data processing. Table 1 shows the gravimetric composition of the steel materials used in this study. It has a similar chemical make-up to the petroleum pipelines' carbon steel construction.

**Table 1.** shows the gravimetric composition of the steels employed.

The constituent Elements	Manganese	Silicon	Zinc	Sulfur	Phosphorus	Carbon	iron
Percent composition Weight (%)	0.517	0.201	0.315	0.009	0.007	0.157	Nearly equal 99

## 2.2. Preparation of Leaf Extract.

The following process was used to make aqueous *Spinacia oleracea* leaves and stems extracts: fresh *Spinacia oleracea* leaves and stems were gathered and cleaned with tap water first, then distilled water rinsed until all impurities were removed under running water. Following that, the fresh leaves were weighted, chopped into little bits, and added to a beaker with 200 cc of distilled water. After 30 minutes of constant stirring at 50°C, the liquid was then allowed to cool at ambient temperature [28–31]. The mixture was centrifuged for 20 minutes at 81 G-force while being filtered using Whatman 42 filter paper. To be used later, the extract (Figure 1) was created and kept in the refrigerator.



**Figure 1.** Aqueous *Spinacia oleracea* leaves and stem extracts were employed in a 1.0 M HCl corrosive environment as a green corrosion inhibitor for carbon steel.

## 2.3. Open circuit potential measurement

The potential of a carbon steel electrode in 1.0 M HCl solution was measured at 30 °C against a saturated calomel electrode (SCE) in the absence and presence of varying amounts of the inhibitor used. All measurements were taken with the Multi-tester until the steady-state potentials were reached.

## 2.4. Potentiodynamic polarization measurements.

The radiometer analytical, Volta master for all electrochemical measurements are used in the tests (PGZ301, DYNAMIC ELS VOLTAMMETRY). The counter electrode is made of platinum wire. Calomel is used as a reference electrode because it is uniform and to which all potential is assigned. A

steel cylindrical electrode (1 cm<sup>2</sup> in area) is also used as a working electrode. To abrade and clean it, silicon carbide abrasive sheets of grades 600, 1000, 1200, 1500, and 2000 are used. After that, the electrode was rinsed with distilled water, degreased with ethyl alcohol, cleaned with water, and dried so that it could be used as a functioning electrode. This protocol was followed before each experiment. The working electrode was immersed in the corrosive solutions for 50 minutes. The electrochemical scanning is done at a 1 mV/s. scan rate. Using the following mathematical equation [31-36], the inhibition efficiency percent I.E. was computed.

$$\% \text{ I.E.} = ( [ I - I_0 ] / I ) \times 100 \quad (1)$$

Where I and I<sub>0</sub> represent the corrosion current densities in the absence and presence of inhibitors, respectively. Using the values of the cathodic and anodic Tafel slopes obtained from the Tafel plot, the corrosion potential (E<sub>corr</sub>), corrosion current (I<sub>corr</sub>), and Tafel constants (a & c) were computed and tabulated.

### 2.5. Electrochemical Impedance measurements

In the electrochemical studies, a three-electrode assembly with calomel as a reference electrode, platinum wire as a counter electrode, and carbon steel specimens with an exposed surface area of 1 cm<sup>2</sup> as a working electrode were used. At an open circuit potential, impedance responses were measured (frequency range: 10-100 KHz, 5mV amplitude). All tests and measurements were carried out at room temperature in an unstirred or motionless environment. The inhibitory efficiency was calculated using charge-transfer resistance, which is represented as R<sub>p</sub> in the impedance data of Nyquist plots [31-36].

The inhibition efficiency was calculated using charge-transfer resistance, which was labeled as R<sub>ct</sub> in the impedance data of the Nyquist plots, as follows[31-36]:

$$\% \text{ I.E.} = [ ( R_{ct} - t_0 ) / R_{ct} ] \times 100 \quad (2)$$

R<sub>ct</sub> is the charge transfer resistance with an inhibitor, while R<sub>ct</sub><sup>0</sup> is the charge transfer resistance without an inhibitor.

### 2.6. Weight Loss measurement

Using various grades of emery sheets, low carbon steel coupons with dimensions of 4.0 x 2.0 x 0.2 were scraped away. It was cleaned further by immersing it in an acetone bath for 10 minutes. It was then washed and dried gently with a towel. Weight measurements were taken using a four-digit analytical balance. These carbon steel coupons were immersed in various inhibitor solutions (100, 200, 300, 400, and 500 ppm) in 1.0 M HCl for 7 hours at temperatures ranging from 303 to 333 degrees Celsius. To ensure that the results and computations were consistent, the trials were repeated three times. From these, the average weight loss was calculated. For each new reading, a freshly prepared inhibitor solution was used. The following are the calculations used to investigate the inhibition parameters.

Corrosion inhibition efficiencies (percent I.E.) were calculated using the following equation [31-36] based on weight/mass loss (mg) in the presence (M) and absence (M<sub>0</sub>) of the corrosion inhibitor:

$$\% \text{ I.E.} = [ ( M_0 - M ) / M_0 ] \times 100 \quad (3)$$

For calculating the corrosion rate, the following equation was used:

$$CR = 87.6 \times [ (\Delta M) / (A \times t \times \rho) ] \quad (4)$$

Where CR is the corrosion rate in mm/year, M is the weight/mass loss of low carbon steel (mg), A is the coupon's exposed surface area in cm<sup>2</sup>, t is the exposure time (hr), and ρ is the density of mild steel in g/cm<sup>3</sup>. The surface coverage fraction was calculated as θ using the following equation [39-50]:

$$\theta = [ (M_0 - M) / M_0 ] \quad (5)$$

The surface coverage values acquired using the weight loss approach were graphically fitted to various isotherms, and the fit that provided the best results was determined by the value of the regression coefficient with the highest value.

### 2.7. Atomic absorption Spectroscopy (AAS) measurements

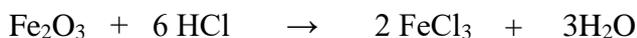
The number of iron ions in corrosive solutions was quantified using atomic absorption spectroscopy in the absence and presence of the medications used as corrosion inhibitors (AAS). The concentration of ferric ions passing into the solution was determined using Varian Spectra AA 220 atomic absorption spectroscopy. We dissolved the corrosive medium in aqua regia to determine the amount of iron ions in the solution when the inhibitor was absent and present [41, 42].

## 3. RESULTS AND DISCUSSION

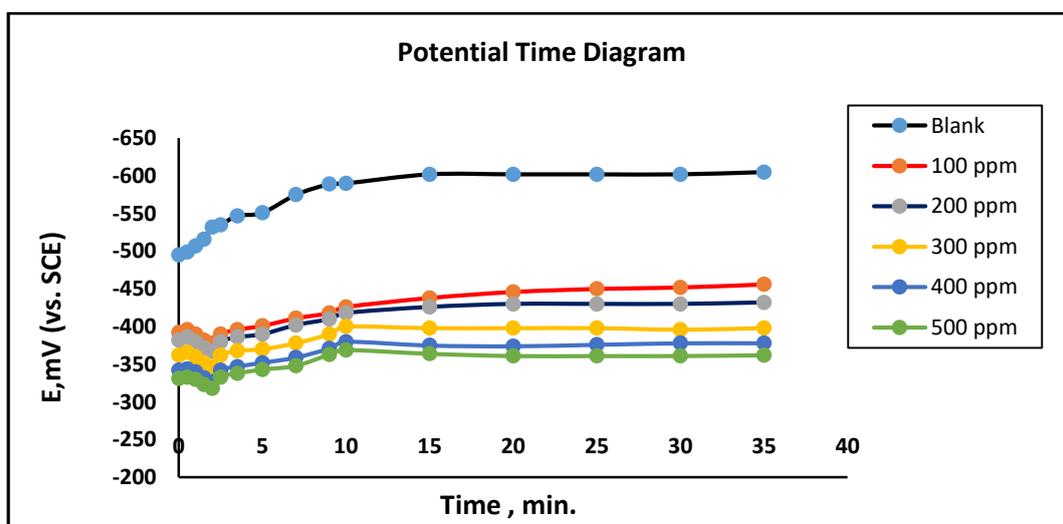
The development of green materials to minimize corrosion has been prompted by severe environmental legislation and growing ecological consciousness among scientists. Chemical inhibitors have been restricted due to environmental concerns and, more recently, environmental restrictions. These inhibitors may induce reversible (temporary) or irreversible (permanent) damage to organ systems, such as the kidneys or liver, as well as disrupt a biochemical process or an enzyme system at a specific location in the body. Toxicity can reveal itself during the compound's production or during its application. The use of some natural compounds as corrosion inhibitors is motivated by the known dangers of most synthetic corrosion inhibitors. Plant extracts are becoming increasingly popular since they are environmentally friendly, affordable, widely available, and renewable sources of resources. Plant products are organic in nature, and several of their constituents, including as tannins, organic and amino acids, alkaloids, and pigments, have been shown to restrict growth. Furthermore, they can be extracted using simple, low-cost procedures. In this present work, the plant Extract of fresh *Spinacia oleracea* symbolized here as (SPINOLE) was used as a green corrosion inhibitor for carbon steel in a 1.0 M hydrochloric acid corrosive environment. Chemical and electrochemical techniques were used to evaluate the corrosion inhibition performance of different concentrations (100 -500ppm) of the prepared (SPINOLE) extract. The effect of temperature and adsorption isotherm was studied. Electrochemical techniques used to evaluate the corrosion inhibition efficiency of the plant extract are open circuit potential, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS) measurements. In addition, the chemical techniques used which id direct gravimetric (mass loss) and indirect gravimetric which is atomic absorption spectroscopy (AAS) measurement.

### 3.1. Open Circuit Potential Measurements

The potential of carbon steel electrodes immersed in 1.0 M HCl solution as a function of immersion time is shown in Figure 2 in the absence and presence of green inhibitor *Spinacia oleracea* plant extract (SPINOLE) green corrosion inhibitors. The potential of a steel electrode immersed in 1.0 M HCl solution (blank curve) clearly moves to a higher negative potential first, resulting in a short step. According to the following chemical equation [31-35]:



Following this, a new oxide film forms within the solution, shifting the potential back to a more noble direction until a steady-state potential was reached. When inhibitor molecules are added to the aggressive medium, the cathodic reaction is slowed, resulting in a negative shift in the open circuit potential [31-35].



**Figure 2:** Shows the potential-time curves for carbon steel submerged in 1.0 M HCl in both the presence and absence of the green inhibitor *Spinacia oleracea* plant extract (SPINOLE).

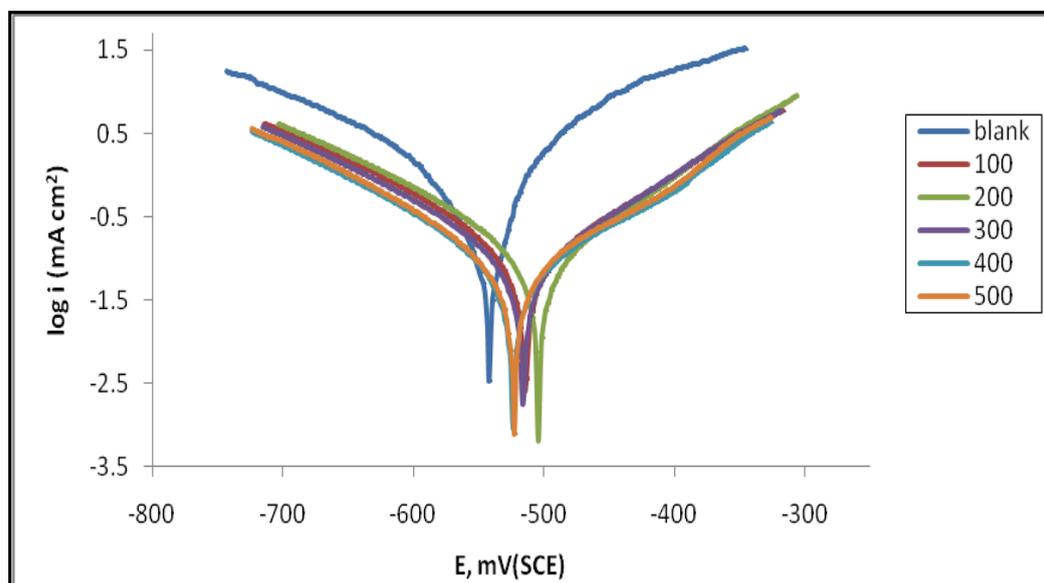
### 3.2. Potentiodynamic Polarization Measurements

The components of the corrosion inhibition process that alter the anodic/cathodic process are investigated using potentiodynamic polarization curves. Table 2 provides a list of the parameters that were approximated. It has been demonstrated that the plant extract from *Spinacia oleracea* (SPINOLE) has great biocompatibility, is nontoxic, and may produce a surface coating by adhering to the surface of steel. Inhibitors can change the course of corrosion by slowing it down. The corrosion current density and potential are determined by the point at which the anodic and cathodic curves converge. In the presence of an inhibitor,  $E_{\text{corr}}$  tends toward value when compared to blank, but no discernible change has been found (Figure 3). As a result, the *Spinacia oleracea* plant extract (SPINOLE) primarily functions as an anodic inhibitor and has an anodic impact.  $I_{\text{corr}}$  values dropped as drug inhibitor

concentrations rose, demonstrating that the presence of inhibitors causes a shield to form on the low carbon steel surface, impeding electrochemical reactions [31–36].

**Table 2.** Potentiodynamic characteristics for Low carbon steel corrosion in 1.0 M HCl at 303 k with and without various dosages of the green inhibitor *Spinacia oleracea* plant extract (SPINOLE).

Solution type	<i>Spinacia oleracea</i> Extract concentration ppm	$i_{corr}$ mA cm <sup>-2</sup>	$-E_{corr}$ mV (SCE)	$\beta_a$ mVdec <sup>-1</sup>	$\beta_c$ mVdec <sup>-1</sup>	$\theta$	% I.E.
Blank solution	Free	1.23	485	103	122	---	---
Inhibitor solution <i>Spinacia oleracea</i> plant extract (SPINOLE)	100	0.21	547	123	143	0.829	82.9
	200	0.19	558	131	149	0.845	84.5
	300	0.15	559	142	157	0.878	87.8
	400	0.12	563	149	162	0.902	90.2
	500	0.11	569	156	169	0.911	91.1



**Figure 3.** Potentiodynamic polarization curves of steel with various concentrations (100,200,300, 400, and 500 ppm) of *Spinacia oleracea* plant extract (SPINOLE) green inhibitor at 30 OC in 1.0 M HCl solution.

### 3.3. Electrochemical impedance Spectroscopy, EIS

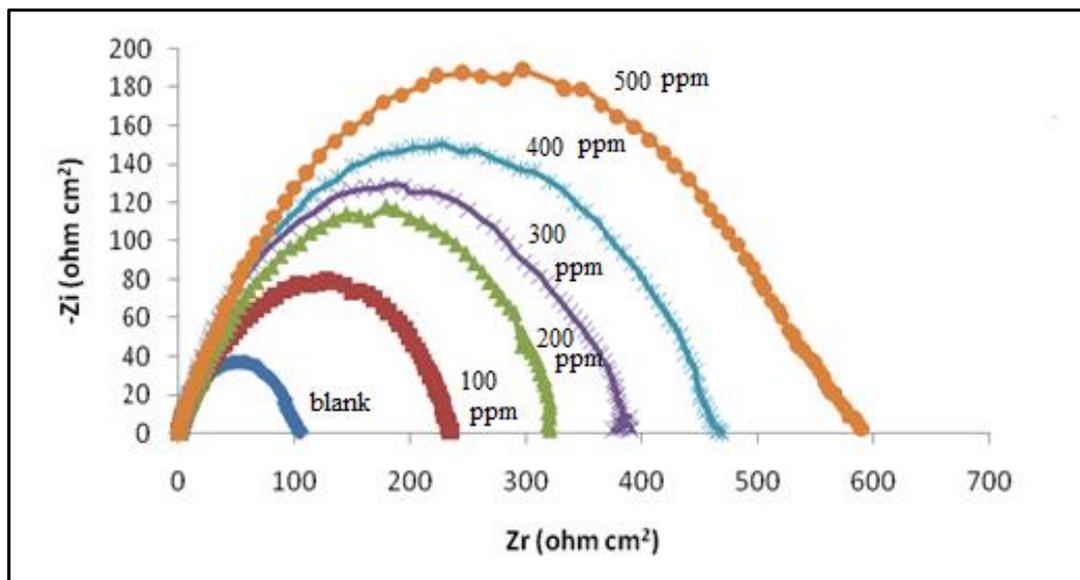
For researching corrosion and inhibitory mechanisms, electrochemical impedance spectroscopy, or EIS, is a very precise instrument. At different concentrations of *Spinacia oleracea* plant extract (SPINOLE) green inhibitor, corrosion inhibition was examined using electrochemical impedance

spectroscopy (EIS) with and without inhibitor. The results for the impedance diagram characteristic parameters are displayed in Table 3.  $R_{ct}$ , a metric of electron transmission across a contact, is found to be inversely proportional to the corrosion rate. A semicircle fitting method was used to calculate the electrochemical impedance characteristics. A single time constant is seen as a flawless semicircle in Nyquist plots. Impedance tests provide information about surface resistance, capacitance, a substance's ability to inhibit corrosion, and the characteristics of the inhibition process. Frequency dispersion of interfacial impedance, which is connected to non-homogeneity of the surface and metal roughness [31–36], is blamed for deviations from perfectly circular forms. Our analysis yielded a pattern, but it wasn't a complete semicircle. This may be related to the presence of an inhibitor that entirely diverts attention away from the semicircle. Single semicircles in the Nyquist plot are moved in lockstep with the x-actual axis's impedance (Figure 4). As the concentrations of plant extract grew, so did the impedances. Furthermore, the impedance profiles remained constant across all concentrations. By lowering the pace of corrosion, inhibitors can alter the process. Furthermore, because of the inhibitor corrosion, the rate-controlling mechanism can be determined to be a reaction-controlled mechanism [31-36].

$R_{ct}$  values increase as inhibitor concentrations rise. As a result, the charge transfer mechanism controls the majority of the corrosion response. Furthermore, an increase in inhibitor concentration leads to a decrease in  $C_{dl}$  values due to the inhibitor's increased surface coverage. This is due to an increase in inhibitory efficiency. The decline in  $C_{dl}$  value could be explained by a lower local dielectric constant and/or a thicker electric double layer on the carbon steel surface [31-36]. A lower local dielectric constant and/or a thicker electric double layer on the carbon steel surface could explain the decrease in  $C_{dl}$  value [31-36].

**Table 3.** Demonstrates the electrochemical impedance parameters of the corrosion of carbon steel in 1.0 M HCl with and without varying dosages of *Spinacia oleracea* plant extract (SPINOLE) green inhibitor at 303 k.

Solution type	<i>Spinacia oleracea</i> Extract concentration ppm	R1 (Ohm/cm <sup>2</sup> )	Rct (Ohm/cm <sup>2</sup> )	Cdl μF cm <sup>-2</sup>	θ	% I.E.
Blank solution	Free	1.72	18.54	1.63	---	---
Inhibitor solution <i>Spinacia oleracea</i> plant extract (SPINOLE)	100	8.7	113	9.7	0.836	83.6
	200	9.6	125	10.3	0.852	85.2
	300	10.5	134	10.9	0.862	86.2
	400	11.7	191	11.7	0.903	90.3
	500	12.4	245	12.4	92.4	92.4



**Figure 4.** Shows the Nyquist plots for a carbon steel electrode with varying quantities of the green inhibitor *Spinacia oleracea* plant extract in 1.0 M HCl at 30 °C (SPINOLE).

### 3.4. Weight loss measurements

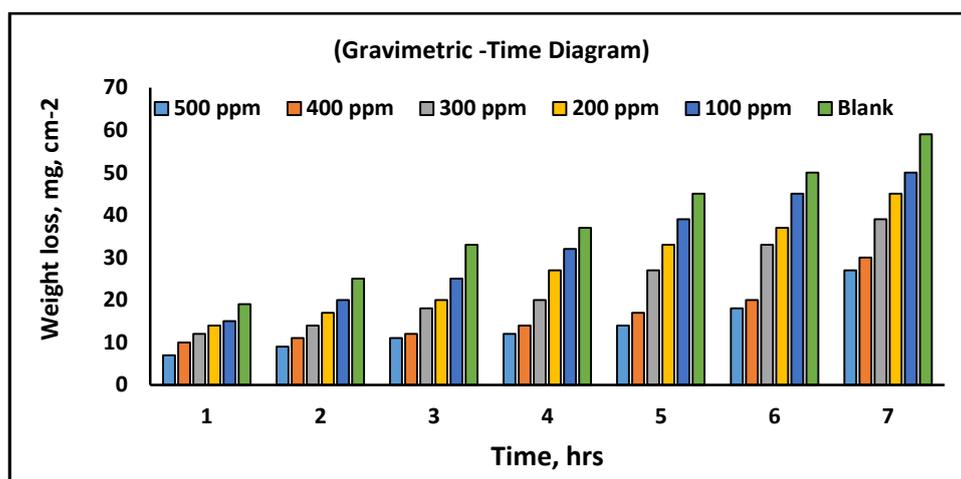
#### 3.4.1. Effect of inhibitor concentration.

Weight loss (mass loss) measurements were used as a direct gravimetric measurement for the evaluation of the *Spinacia oleracea* plant extract (SPINOLE) as a green corrosion inhibitor for steel materials subjected to 1.0 M HCl corrosive environment. The effect of both the *SPINOLE* extract concentration and temperatures was studied. Weight loss measurements based on the direct measurement of metal sample weight before and after immersion in the corrosive solution the different loss in weight are used to calculate the corrosion rate and corrosion parameter using the mathematical formula equations (3-5) part 2.6 mentioned in the experimental.

The inhibitor employed was *Spinacia oleracea* plant extract, abbreviated as SPINOLE, in five different concentrations: 100, 200, 300, 400, and 500pp. A corrosive environment is produced by a 1.0 M HCl solution. The weight of steel samples before and after immersion in a corrosive environment without and with inhibitor for 7 hours is calculated using the average of three readings. Using the calculated mass loss, the corrosion rate, surface coverage, and corrosion inhibition effectiveness were all determined. The results of the weight loss measurements are summarized in Table 4. The maximum inhibition efficiency obtained in the present study is 93% using 500 ppm from studies SPINOLE extract, this value within the range obtained in the reported previous studies [48-50]. The inhibition may be due to the Vito chemicals that exist in the natural extract. In a 1.0 M hydrochloric acidic corrosive environment, the *Spinacia oleracea* (SPINOLE) plant extract green inhibitor acts as a good corrosion inhibitor for steel. Increased immersion duration resulted in a significant increase in corrosion rate, but increased inhibitor concentration resulted in a significant drop in corrosion rate. As the concentration of SPINOLE extract inhibitor rises, the efficacy of corrosion inhibition rises as well (figure 5).

**Table 4.** Shows the statistics and characteristics of the weight loss for low carbon steel corrosion at 303 k in 1.0 M HCl with and without *Spinacia oleracea* (SPINOLE) extract as a green inhibitor.

Solution type	<i>Spinacia oleracea</i> Extract concentration ppm	Corrosion Rate (mmpy x 10 <sup>-3</sup> )	θ	% I.E.
Blank solution	Free	10.3	---	---
Inhibitor solution <i>Spinacia oleracea</i> plant extract (SPINOLE)	100	1.8	0.825	82.5
	200	1.5	0.854	85.4
	300	1.2	0.883	88.3
	400	0.8	0.922	92.2
	500	0.7	0.932	93.2

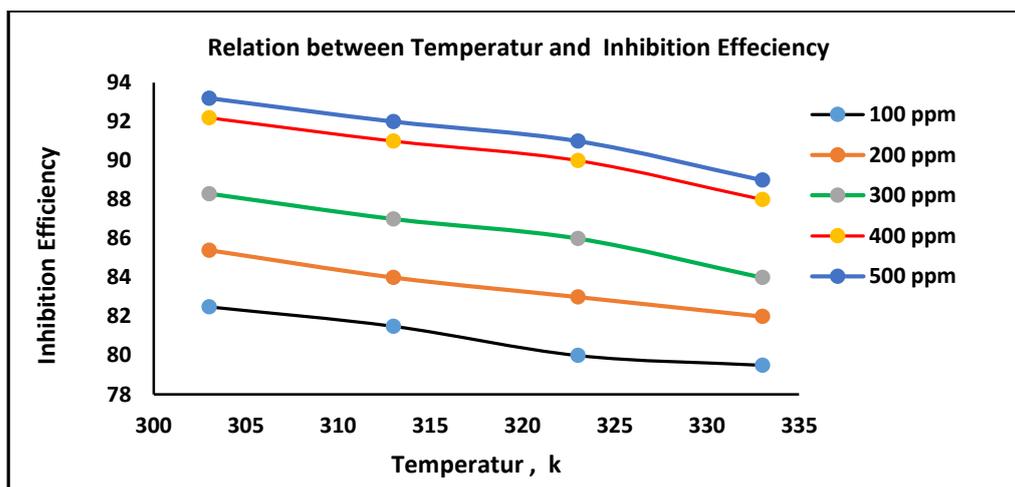


**Figure 5.** In the presence and absence of the green inhibitor *Spinacia oleracea* plant extract (SPINOLE), weight loss of carbon steel in milligrams per second in a corrosive solution of 1.0 M HCl was measured.

3.4.2. Effect of temperature.

To comprehend the mechanism of corrosion inhibition and gauge the kinetic thermodynamic parameters of the corrosion process, weight loss was carried out at 303, 313, 323, and 333 k.

Figure 6 shows the connection between temperature and corrosion inhibition effectiveness. The samples with different concentrations were heated to a range of 303 K to 333 K during the course of a 7-hour immersion period. As the temperature rises, it is evident that the inhibitory efficiency reduces. This might be as a result of increased solution agitation shifting the adsorption-desorption balance in favor of desorption and away from adsorbed inhibitors. As a result, both the ability of the inhibitor to be adsorbed on the metal surface and the roughening of the metal surface due to enhanced corrosion may be damaged. This shows that adsorption is a physical process. The inhibitory efficiency diminishes with increasing temperature, likely as a result of a reduction in the amount of molecules adsorbed on the carbon steel surface [31–36]



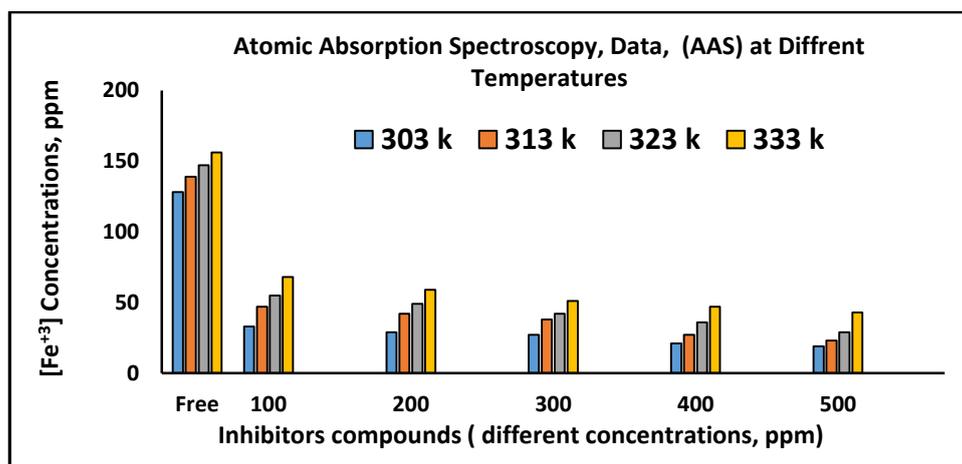
**Figure 6.** Displays data from measurements of weight loss and the effect of temperature on the % I.E. of carbon steel in 1.0 M HCl in the presence of different dosages of *Spinacia oleracea* plant extract (SPINOLE) as a green corrosion inhibitor.

### 3.5. Atomic absorption spectroscopy measurements (AAS)

Atomic absorption spectroscopy, a quick and precise method, is used to measure a variety of metal cations in aqueous, acidic, and alkaline solutions. Numerous benefits of AAS methods include their simplicity, low cost, quickness, and applicability to both research and industry applications. In the industrial and environmental areas, atomic absorption is used for raw material inspection, product evaluation, final product inspection, and environmental analysis. AAS, which is regarded as an indirect measurement, was used to estimate the concentration of iron ions in the corrosive solution that results from the corrosion of steel in an acidic environment. The amount of ferric ions generated in the solution was precisely quantified using atomic absorption spectroscopy. Society may incur costs due to the corrosion of steel structures or other components, and the qualities of the corroding material can be identified [41,42]. In this study, ferric ions  $\text{Fe}^{+3}$  generated by steel corrosion in an acidic HCl corrosive environment were quantified by atomic absorption spectroscopy. The findings of the AAS, which showed that lowering the ferric ion concentration in the corrosive solution decreased the inhibitor concentration, are shown in Table 5 and Figure 7. As a function of corrosion rate, ferric ions were modeled in this study, suggesting that a rise in ferric ion concentration causes an increase in corrosion rate and vice versa. Inhibitors added to *Spinacia oleracea* plant extract (SPINOLE) have an impact on both the concentration of ferric ions and the corrosion process. When compared to data obtained utilizing weight reduction as a chemical technique, the data in table 5 and figure 7, which were produced using AAS, match up nicely. This shows that SPINOLE plant extract has a good inhibitory effect and inhibits steel corrosion in an acidic environment according to analytical and chemical investigations.

**Table 5.** Demonstrates the impact of ferric ions concentrations on green inhibitor concentrations of *Spinacia oleracea* plant extract (SPINOLE) using the AAS method (data taken at 303-333 k).

Solution type	<i>Spinacia oleracea</i> Extract concentration ppm	Ferric ions [Fe <sup>+3</sup> ] Concentrations, ppm			
		303 k	313 k	323 k	333 k
Blank solution	Free	128	139	147	156
Inhibitor solution <i>Spinacia oleracea</i> plant extract (SPINOLE)	100	33	47	55	68
	200	29	42	49	59
	300	27	38	42	51
	400	21	27	36	47
	500	19	23	29	43



**Figure 7.** Shows the impact of ferric ions concentrations on green inhibitor concentrations of *Spinacia oleracea* plant extract (SPINOLE) using the AAS method (data taken at 303-333 k).

3.6. Adsorption Studies.

The adsorption process is influenced by the charge, the nature of the metal surface, its electronic properties, the reaction temperature, the presence of electro-repelling or electro-donating groups in derivatives, and the electrochemical potential at the interface of the solution, solvent adsorption, and other ionic species. Weight loss information was used to calculate the values of surface coverage ( $\theta$ ) at various inhibitor concentrations and to explain the best-fit isotherm for the adsorption process. The results are most closely modeled by the Langmuir adsorption isotherm [32-36]. According to the following equation [32–36], the Langmuir adsorption isotherm best fits the results:

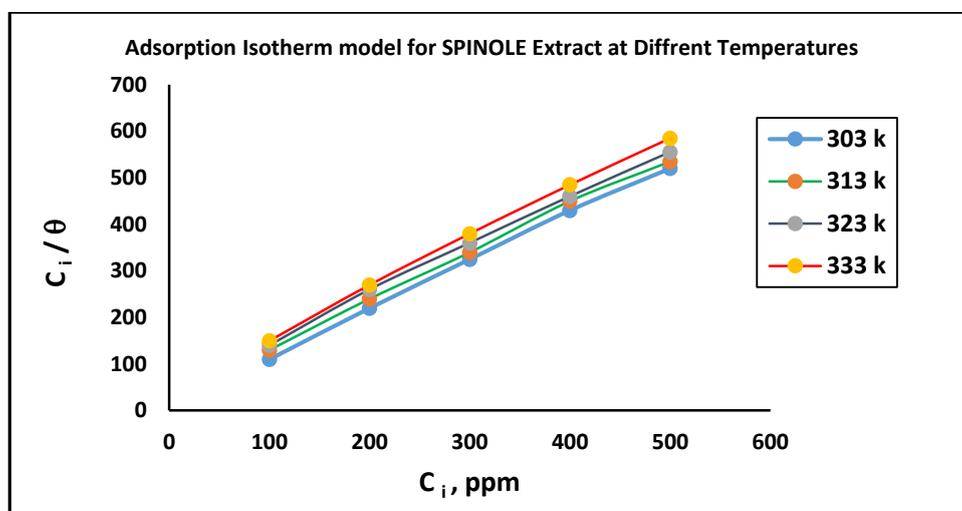
$$\frac{C_i}{\theta} = \frac{1}{K_{ads}} + C_i \tag{6}$$

Where  $K_{ads}$  and  $C_i$ , respectively, represent the equilibrium constants of the *Spinacia oleracea* plant extract (SPINOLE) concentration and the adsorption process [37-41].

$C_i/\theta$  against  $C_i$  was plotted, and the result was a straight line, as seen in figure 8. The intercept of the line with a roughly unit slope value is  $1/K$ . Using the formula [32-36], the standard free energy of adsorption  $G^\circ_{ads}$  is derived.

$$K_{ads} = \frac{1}{55.5} \exp\left(\frac{-\Delta G}{RT}\right) \tag{7}$$

Where  $T$  is the absolute temperature,  $R$  is the gas constant, and 55.5 moles of water are present in the majority of the solution per liter.  $K_{ads}$  is the adsorption equilibrium constant.  $\Delta G^\circ_{ads}$  has been determined to be  $-37.9$  kJ/mol. When  $\Delta G^\circ_{ads}$  is negative, it means that molecules of plant extract are adhering to the metal surface spontaneously [41–48]. The measured value of  $\Delta G^\circ_{ads}$ , however, is about similar to the  $-40$  kJ/mol threshold value required for chemical adsorption, suggesting that this is the mechanism of adsorption [37–48]. The examined inhibitory substances function by adsorbing the molecules responsible for corrosion at the metal/solution interface. Additionally, it is claimed that the development of a solid organic molecule complex with the metal atom has drawn a lot of interest [41–48]. The adsorption and inhibition may be due to the Vito chemical found in the plant extract constituents.



**Figure 8.** shows the computed weight loss data for the *Spinacia oleracea* plant extract (SPINOLE) green inhibitors on carbon steel in 1.0 M HCl solution.

#### 4. CONCLUSION

The following conclusions were drawn in light of the experimental findings and theoretical calculations:

- 1- The plant extract (SPINOLE) from *Spinacia oleracea* may be employed as a nontoxic (green) corrosion inhibitor. Although it is safe for humans to consume, especially in the modest amounts utilized, it has a significant negative effect on steel's technical, economic, and environmental aspects.
- 2- By adding more SPINOLE extract, the corrosion inhibition efficiency increased until it reached 500 ppm, when it was 93% effective. Raising the inhibitor concentration resulted in a decrease in the concentration of ferric ions ( $Fe^{+3}$ ), as seen by atomic absorption spectroscopy (AAS) data.

- 3- The calculated corrosion inhibition efficiency in the present study is (93%) on average which is within the average reported efficiency in the previously reported studies.
- 4- According to the potentiodynamic polarization data, the corrosion potential ( $E_{\text{corr}}$ ) values are continuously declining (negative values), indicating that the utilized SPINOLE extract is inhibited in a mixed-type way but in anodic zone.
- 5- The electrochemical Impedance spectroscopy (EIS) data demonstrate that the charge transfer mechanism is the primary governing factor in the steel dissolution process. The size of the semicircle increases proportionally to the inhibitor concentration.
- 6- It was found that steel corrosion prevention was caused by the adsorption and adherence of inhibitor particles (a SPINOLE extract component) to the steel surface, where they created an inert protective layer.
- 7- The Langmuir adsorption curves were identified to follow the growth of a single layer of SPINOLE extract component on the surface of steel metal.
- 8- All of the findings concurred that *Spinacia oleracea* plant extract (SPINOLE) might be used as carbon steel green inhibitors in an acid media. The inhibition of the plant extract (SPINOLE) is due to the Vito chemical constituent in the plant extract.
- 9- The addition of inhibitor molecules to an aggressive medium causes the cathodic process to be retarded, which results in a negative shift in the open circuit potential.
- 10- As inhibitor concentrations grow,  $R_{\text{ct}}$  values climb as well. As a result, the majority of the corrosion reaction is managed by the charge transfer mechanism. Due to the inhibitor's enhanced surface coverage, a rise in inhibitor concentration also causes a decrease in  $C_{\text{dl}}$  values. An improvement in inhibitory effectiveness is to blame for this. The decline in  $C_{\text{dl}}$  value could be explained by a lower local dielectric constant and/or a thicker electric double layer on the surface of carbon steel.

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