Synergistic Temperature Effect on The Acid Corrosion Inhibition of API 5L Grade B Steel Using Eichhornia Crassipes Leaf Extract

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Abstract

Corrosion is the deterioration of material properties, particularly metals, due to chemical reactions with the surrounding environment. One of the effective methods to mitigate corrosion is the addition of inhibitors. Organic inhibitors are considered environmentally friendly, cost-effective, and renewable. In this study, an extract of water hyacinth leaves (Eichhornia crassipes) was used as an organic inhibitor. The material tested was API 5L Grade B steel in 1 M HCl solution as the corrosive medium, with testing temperatures of 30 °C, 40 °C, 50 °C, and 60 °C, and inhibitor concentrations ranging from 500 mg to 2500 mg. The corrosion behavior was evaluated using Potentiodynamic Polarization (PDP), Electrochemical Impedance Spectroscopy (EIS), and Weight Loss (WL) methods. The results showed a significant reduction in the corrosion rate of API 5L Grade B steel in 1 M HCl solution when the water hyacinth extract inhibitor was added. In the PDP test, the corrosion rate for the sample without inhibitor reached 107.4 mm/year, while the lowest inhibition efficiency was 1.25% and the highest inhibition efficiency was 97.85%, observed at 50 °C with an inhibitor concentration of 2500 mg. This represents the maximum efficiency among all tested concentrations and temperatures.

Keywords: API 5L; Corrosion; Eichhornia crassipes; Organic inhibitor; Water hyacinth.

1. Introduction

The metallic materials, particularly steel, play a crucial role in the advancement of the industrial world. Steel is widely used in the production of various functional and essential products, such as household appliances, workshop tools, and the manufacturing of different types of engines for motor vehicles, ships, aircraft, and pipelines. Steel pipes are commonly found in the oil and gas industry, with API steel pipes being one of the widely used types. In industrial applications, these pipes frequently come into direct contact with surrounding fluids such as water, oil, air, gas, and various chemicals, leading to corrosion of the steel pipes. These pipelines are often made from carbon steel and low-grade alloy steel, that are susceptible to corrosion attack by acidic processes inside the pipelines and their electrochemical interactions with the environment [2].

Rust, commonly known as corrosion, refers to the degradation or deterioration of metals due to redox reactions between the metal and substances in its environment, resulting in unwanted compounds, commonly referred to as rust in everyday terms. Corroded metal offers no benefits and instead leads to losses in many sectors. Although corrosion in steel cannot be completely stopped or eliminated, it can be inhibited or slowed down. Several methods are commonly applied to reduce the corrosion rate, including painting, cathodic protection, sacrificial anodes, oil coating, tin plating, galvanizing, chromium plating, and the use of corrosion inhibitors, the way of structural support, they do shield other materials so that they can maintain their strength and integrity. The primary purpose of protective coating is to shield corrosive structural elements from the environment [4]. In the industrial sector, corrosion prevention commonly employs cathodic protection methods, in which pipelines are connected to sacrificial anodes made of metals with a smaller electrode potential. However, this method is often less effective due to its complex maintenance requirements and high costs. For more efficient corrosion protection, inhibitors are widely used.

An inhibitor is a substance or compound that effectively protects metals from corrosion in their environment. There are two main types of inhibitors: inorganic (synthetic) inhibitors and organic (green) inhibitors. Inorganic inhibitors are derived from chemicals, pharmaceuticals, and other inorganic substances containing various compounds with free electron pairs, such as urea, tungstate, molybdate, imidazoline, silicate, nitrite, borate, phenylalanine, arsenate, chromate, phosphate, and amine compounds. Conversely, organic or green inhibitors are obtained from plants or seeds, typically those containing tannins, organic acids, amino acids, and alkaloids known to possess corrosion-inhibiting properties. Green inhibitors are environmentally friendly, non-toxic, cost-effective, renewable, and sustainable, making them an attractive alternative [2]. Furthermore, biomass waste such as lime peel (*Citrus aurantifolia*) has been explored as a renewable inhibitor. Research on API 5L Grade B steel in acidic mediums demonstrates that active compounds in these extracts effectively cover corrosion-active centers as concentration increases, providing a stable protective layer [14]. Eichhornia crassipes leaves were collected from Lake Abaya in the southern region of Ethiopia, East Africa, in March 2018 [18]. Eichhornia crassipes is a floating aquatic plant, usually grows in shallow freshwater ponds, lakes, and rivers. It grows vigorously within 15–20 days and forms a dense, floating mat, over the surface of water bodies [17].

Papaya leaves as a raw material of organic inhibitors are used, while the corrosive medium is a 1 M HCl solution. Based on the polarization test, the corrosion rate absence inhibitor was 21.43 mm/year. This corrosion rate decreased to 0.4 mm/year. Highest efficiency generated by 97%. This efficiency occurs in the presence of 2.5 mL concentration of corrosion solutions. In the polarization testing, it showed that the inhibitory mechanism that occurs cathodic dominant [10]. Occurred inhibition mechanism was in the form of inhibitor adsorption process on metal surface that allegedly preceded by physical adsorption followed by chemical adsorption. Chemical adsorption is conceivable since metal surface scoping elevates as the increasing of inhibitor concentration, nhibition efficiency and adsorption behavior of an inhibitor film on the steel surface is tested via the electrochemical method and theoretical calculation to establish the adsorption model [11]. The effectiveness of corrosion inhibition was examined by electrochemical techniques and scanning electron microscopy. In 1 M H_2SO_4, the effectiveness of the inhibitor (200 mg/L) was 99.2% (from PDP measurements) or 99.1% (from EIS measurement).

The Langmuir isotherm model was used to examine the adsorption behavior of the extract. The negative and low Gibbs free energy values supported that the inhibitor was adsorbed on the surface of API 5L Grade B material [12]. The raw materials used by mango skin peel with mango leather extract concentration are improved so that the optimized efficiency is more optimal. The tests that have been done in this research are polarization test, electrochemical test, and SEM. The extract concentration used was 2-6 mL, while the corrosion solution used was HCl 1 M. From the measurement results, it was found that the corrosion rate decreased to 1.774 mm/year. The highest efficiency inhibitory result is 81.77% [13].

This study focuses on the use of a green inhibitor derived from water hyacinth leaves (*Eichhornia crassipes*), referencing previous research on AISI 1030 steel and the application of water hyacinth extract as an organic inhibitor for API 5L Grade B steel in 1 M HCl solution [1]. Unlike prior studies, the present research examines API 5L Grade B steel pipes under practical conditions that reflect environmental temperature variations. The investigation evaluates the influence of temperature (30 °C, 40 °C, 50 °C, and 60 °C) and inhibitor concentrations (500 mg, 1000 mg, 1500 mg, 2000 mg, and 2500 mg) on the corrosion behavior of API 5L Grade B steel.

2. Method

2.1 Research Methods

This study employed two main approaches Literature Study and Experimental Work, **for t**he literature study was carried out using references from journals, theses, and textbooks related to corrosion, organic inhibitors, material applications in the oil and gas industry, and testing methods such as Electrochemical Impedance Spectroscopy (EIS), Potentiodynamic Polarization (PDP) [6], and Scanning Electron Microscopy (SEM).Experimental Work is the experimental phase consisted of EIS, PDP, and weight loss (WL) tests at varying temperatures of 30 °C, 40 °C, 50 °C, and 60 °C, along with surface characterization using SEM.

2.2 Research Procedure

The extracts of water hyacinth (*Eichhornia crassipes*) were prepared and assessed, for mild steel corrosion inhibition. The inhibitive effect has been investigated by electrochemical impedance spectroscopy and potentiodynamic polarization techniques.[8]. This research aimed to evaluate the effects of temperature and concentration variations of green inhibitors derived from *Eichhornia crassipes* (water hyacinth) leaf extract on the corrosion rate of API 5L Grade B steel in a 1 M HCl solution . Steel specimens were prepared in two dimensions: 10 × 10 × 4 mm for electrochemical tests (PDP and EIS) and 30 × 30 × 4 mm for weight loss tests. All specimens were ground and cleaned to remove any corrosion products prior to testing. The protection of steel, aluminum, and copper in 1 M HCl medium was examined using electrochemical polarization tests to assess inhibition efficiency, also scanning electron microscopy (SEM) to analyze the surface of metals [7]. The corrosive medium, 1 M HCl, was prepared by diluting 82.8 mL of 37% HCl with distilled water to a total volume of 1 liter. The experiments were conducted at temperatures of 30 °C, 40 °C, 50 °C, and 60 °C, with inhibitor concentrations of 500, 1000, 1500, 2000, and 2500 mg to determine the influence of temperature and dosage on corrosion behavior.

Application of green corrosion inhibitors, which reduce corrosion rates to the appropriate level with low environmental impact, is one of the emerging key approaches of controlling corrosion in modern society [9]. The green inhibitor was produced by macerating 800 g of dried water hyacinth leaf powder in methanol for 7 × 24 hours. The leaves were separated from stems, washed, sun-dried, oven-dried to remove moisture, ground into powder, macerated, filtered, and evaporated until a concentrated extract was obtained. Three test methods were employed. PDP, following ASTM G5–94 and ASTM G102–89, was used to determine corrosion current density (I_{corr}) and corrosion rate through Tafel analysis. EIS, in accordance with ASTM G106–89, was performed to evaluate polarization resistance and inhibition mechanisms by fitting impedance data to equivalent electrical circuit models. Weight loss tests determined the corrosion rate in mils per year (MPY) by comparing the initial and final weights of specimens immersed in 1 M HCl at 50 °C, both with and without inhibitor additions. The computational picture aligns closely with the electrochemical metrics (PDP/EIS) and gravimetric results, indicating that the quantum-chemical properties of DIMC correlate strongly with its measured inhibition efficiency for LCS in acidic chloride media, in agreement with prior structure–activity relationships for organic inhibitors [16].

PDP and EIS measurements were conducted using a CorrTest instrument with Electrochemical & Corrosion Studio v5.2 software. Weight loss tests involved immersing API 5L Grade B steel specimens in 1 M HCl at 50 °C for specified intervals, followed by cleaning and re-weighing to determine mass loss due to corrosion. Data obtained from all three methods were analyzed to determine the inhibition efficiency of the water hyacinth extract and to elucidate its mechanism in reducing the corrosion rate of API 5L Grade B steel under varying temperatures and inhibitor concentrations. Corrosion inhibitors are widely used in industry to reduce the corrosion rate of metals and alloys. Corrosion inhibitors adsorb onto metallic surfaces and insulate them from deterioration. Plants abundant in nature offer a cost-effective replacement for toxic chemical inhibitors on the market. The current research used the potentiostatic polarization technique at room temperature to explore the inhibitory impact of water hyacinth extract on the corrosion of low-carbon steel specimens in a 3.5% NaCl solution [3].

3. Results and Discussion

3.1 Potentiodynamic Polarization Test Results

The significance of using electrochemical methods is that the corrosion process is continuously monitored over the period of the relatively brief exposure time. The electrochemical characterization of materials is frequently carried out using the potentiodynamic polarization (PDP) method. [5]. Based on tests conducted on twenty-four samples with an immersion time of 15 minutes, using temperature variations of 30 °C, 40 °C, 50 °C, and 60 °C, as well as inhibitor concentration variations of 0 mg, 500 mg, 1000 mg, 1500 mg, 2000 mg, and 2500 mg, and employing the CorrTest machine along with Electrochemical & Corrosion Studio version 5.2, the resulting data are presented in Tables 1-4.

Table 1. Inhibition Efficiency of PDP at 30 °C

Inhibitor concentration	Temperature	βa	βc	i0	E0	Corrosion rate	Residual	%IE
(mg)	°C	(mV)	(mV)	Amps/cm²	(Volts)	(mm/a)		
0	30	92,554	186,58	0,00067494	-0,52069	7,836	9,32E-06	
500		115,92	144,72	0,0006662	-0,51328	7,7345	9,79E-07	0,012953037
1000		89,12	98,761	0,00020527	-0,49673	2,3831	9,39E-06	0,695877999
1500		91,365	139,14	0,00019477	-0,5034	2,2612	1,48E-07	0,711434405
2000		69,938	104,56	0,0001107	-0,4857	1,2852	3,69E-06	0,835987749
2500		68,688	124,44	0,00012467	-0,48004	1,4474	3,21E-07	0,815288412

Table 2. Inhibition Efficiency of PDP at 40 °C

Inhibitor concentration	Temperature	βa	βc	i0	E0	Corrosion rate	Residual	%IE
(mg)	°C	(mV)	(mV)	Amps/cm²	(Volts)	(mm/a)		
0	40	210,49	530,24	0,0033567	-0,53792	38,971	3,67E-06	
500		125,41	127,9	0,0002909	-0,52738	3,3773	3,19E-06	0,913338123
1000		127,17	148,33	0,00014669	-0,51743	1,7031	4,25E-08	0,956298273
1500		84,973	149,87	0,00019468	-0,48752	2,2602	3,24E-06	0,942003028
2000		60,77	124,79	0,0001249	-0,48632	1,45	3,22E-06	0,962792846
2500		124,57	145,38	0,00019876	-0,52156	2,3075	4,18E-08	0,950219394

Table 3. Inhibition Efficiency of PDP at 50 °C

Inhibitor concentration	Temperature	βa	βc	i0	E0	Corrosion rate	Residual	%IE
(mg)	°C	(mV)	(mV)	Amps/cm²	(Volts)	(mm/a)		
0	50	307,51	1070,3	0,0092512	-0,53082	107,4	1,51E-05	
500		121,96	144,46	0,00038864	-0,5308	4,512	2,2444-06	0,957988827
1000		166,1	137,01	0,00033713	-0,53216	3,914	1,47E-06	0,963556797
1500		116,45	113,65	0,00026738	-0,54624	3,1043	9,17E-08	0,971095903
2000		92,613	118,51	0,00023206	-0,49877	2,6942	1,74E-05	0,974914339
2500		124,57	145,83	0,00019876	-0,52156	2,3075	4,18E-08	0,978514898

Table 4. Inhibition Efficiency of PDP at 60 °C

Inhibitor concentration	Temperature	βa	βc	i0	E0	Corrosion rate	Residual	%IE
(mg)	°C	(mV)	(mV)	Amps/cm²	(Volts)	(mm/a)		
0	60	214,8	390,58	0,0047253	-0,52544	54,86	7,87E-07	
500		239,68	192,01	0,00077623	-0,54611	9,0119	1,17E-07	0,835729129
1000		163,56	157,55	0,00048496	-0,52972	5,6303	9,49E-09	0,897369668
1500		120,27	112,48	0,00059734	-0,53268	6,9351	2,43E-06	0,87358549
2000		160,23	142,88	0,0003428	-0,5408	3,9799	1,02E-08	0,927453518
2500		127,87	125,78	0,00043864	-0,52928	5,0926	6,48E-07	0,907170981

The highest corrosion rate was obtained at 0 mg inhibitor concentration at 40 °C, with a value of 38.971 mm/year, while the lowest corrosion rate was observed at 2000 mg inhibitor concentration at the same temperature, with a value of 1.45 mm/year. The highest inhibition efficiency (%IE) was achieved at 2500 mg inhibitor concentration at 50 °C, reaching 97.85%, whereas the lowest inhibition efficiency with inhibitor addition was recorded at 500 mg concentration

at 30 °C, with a value of 1.30% and a corrosion rate of 7.7345 mm/year. The trend of inhibition efficiency is illustrated in Figures 1 (a-b), where the lowest point is at 500 mg inhibitor concentration at 30 °C (1.30%), and the highest point is at 2500 mg at 50 °C (97.85%). From the graph, no critical concentration point can be determined, as no higher efficiency has been observed beyond the 2500 mg inhibitor concentration.

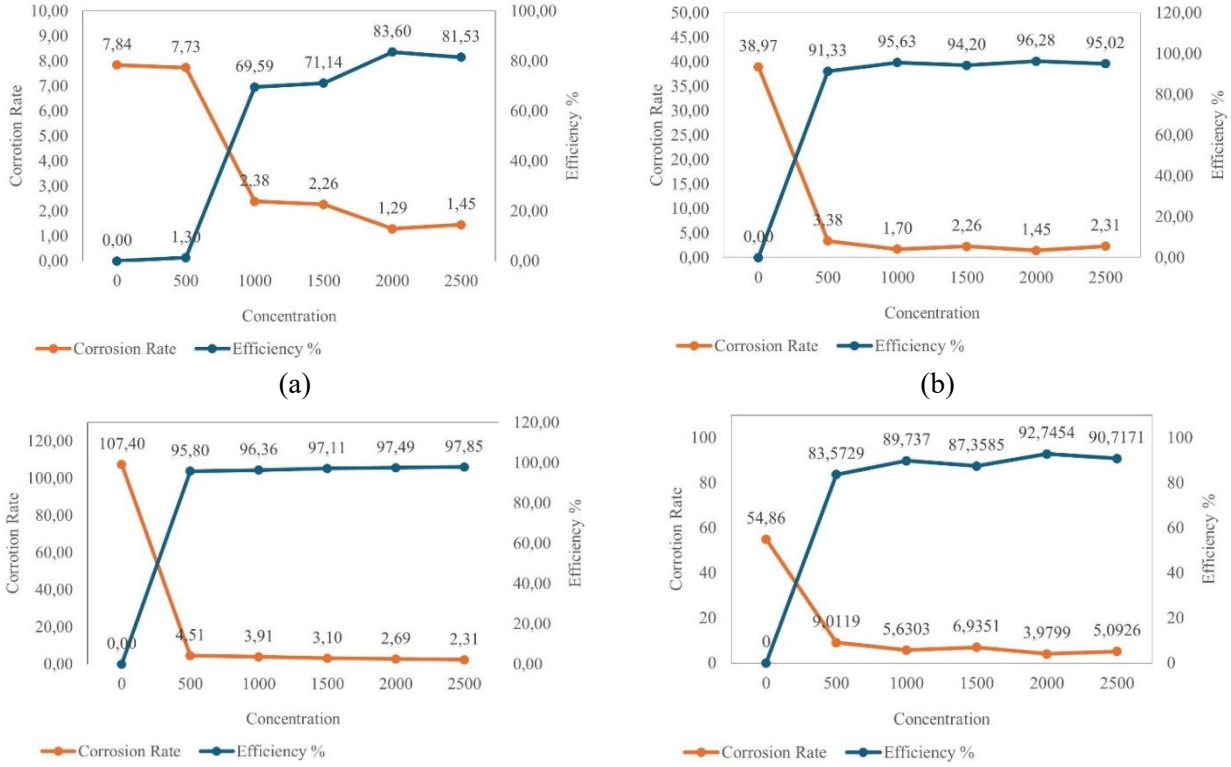
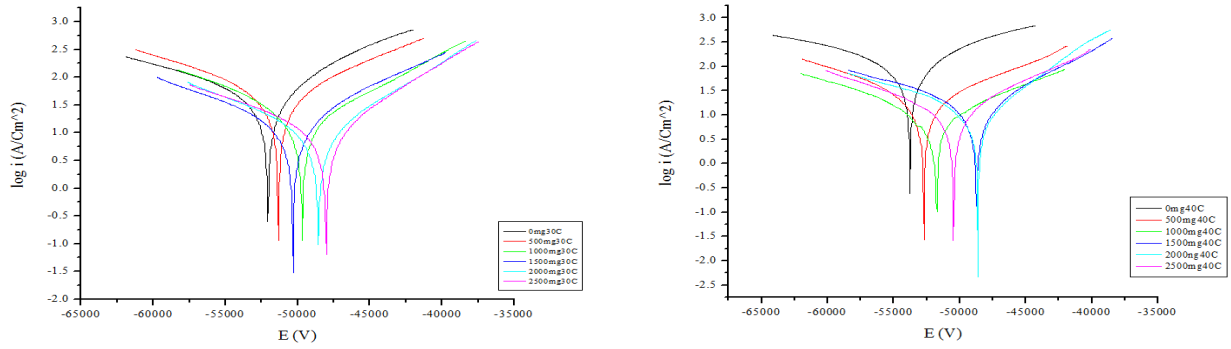
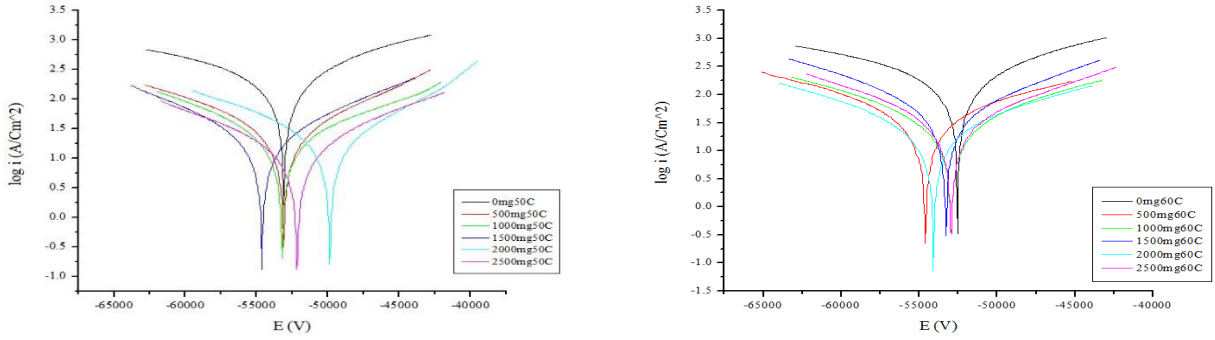


Figure 1. Inhibition Efficiency Graph of Potentiodynamic Polarization (PDP) and Corrosion Rate At (a) 30 °C, (b) 40 °C, (c) 50 °C, and (d) 60 °C

The trend of the corrosion rate can be observed in Figure 1 (a-d), where the lowest point is found at an inhibitor concentration of 2000 mg at 40 °C, and the highest point at 0 mg (without inhibitor) at the same temperature. From the data obtained using Electrochemical & Corrosion Studio version 5.2, as shown in Figures 2 (a-d), the water hyacinth leaf extract inhibitor exhibits a mixed-type behavior (both anodic and cathodic). The sample without inhibitor, represented by the black curve, is positioned at the top, indicating the highest corrosion rate, while the sample with an inhibitor concentration of 1500 mg, represented by the brown curve, is at the bottom, indicating the lowest corrosion rate.



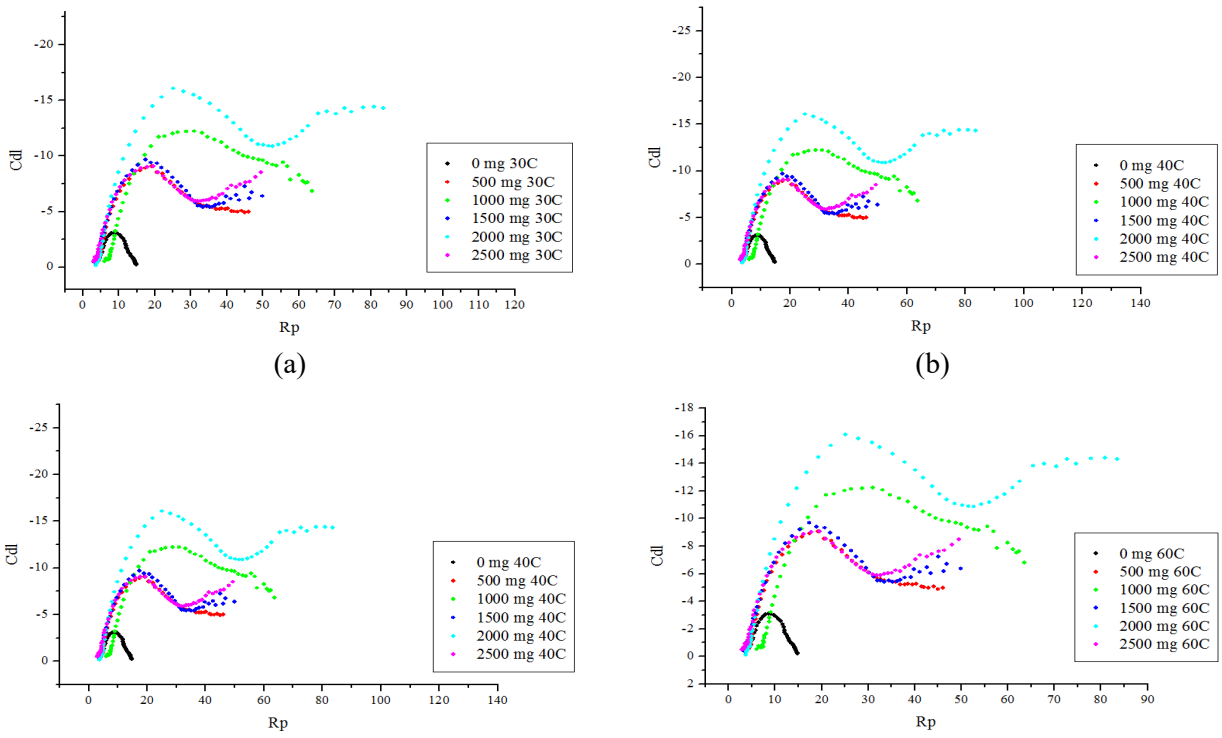


(c) (d)

Figure 2. Nyquist Plot of Potentiodynamic Polarization (PDP) at (a) 30 °C, (b) 40°C, (c) 50°C, and (d) 60 °C

3.2 Electrochemical Impedance Spectroscopy (EIS) Testing Result

The Electrochemical Impedance Spectroscopy (EIS) test with the addition of the organic inhibitor derived from water hyacinth (Eichhornia crassipes) leaf extract produced the following impedance plots:



(a) (b)

(c) (d)

Figure 3. Nyquist Plot of Electrochemical Impedance Spectroscopy (EIS) at (a) 30 °C, (b) 40°C, (c) 50°C, and (d) 60 °C

The Nyquist plots obtained from the Electrochemical Impedance Spectroscopy (EIS) tests provide key parameters related to polarization resistance, solution resistance, and double-layer capacitance. Electrochemical Impedance Spectroscopy (EIS) in various research and technological sectors. The text has been organized in 17 sections starting with basic knowledge on sinusoidal signals, complex numbers, phasor notation, and transfer functions, continuing with the definition of impedance in electrical circuits, the principles of EIS, the validation of the experimental data, their simulation to equivalent electrical circuits, and ending with practical considerations and selected examples on the utility of EIS to corrosion, energy related applications, and biosensing [15]. As shown in the representative plots, at 0 mg inhibitor concentration (depicted by the lowermost black semicircle), the impedance between the steel surface and the corrosive solution is relatively small. Upon the addition of water hyacinth (Eichhornia crassipes) leaf extract at concentrations ranging from 500 mg to 2500 mg, the impedance values increase, indicating that the inhibitor effectively hinders the corrosion current flowing from the electrode surface to the electrolyte. In this

condition, the impedance between the steel surface and the solution is primarily capacitive, implying that the corrosion process is controlled by charge transfer. However, there is no doubt that the electrochemical impedance spectroscopy (EIS) is still one of the most useful techniques around the world for metal corrosion control and monitoring. Corrosion has long been recognized as one of the most expensive problems that concerns many industries and government agencies, because is a steel destructive phenomenon due to their chemical interaction with the aqueous environments and takes place at the interface metal/electrolyte producing an electrical charge transfer or ion diffusion process [20].

The inhibition mechanism of the water hyacinth leaf extract inhibitor can be further interpreted from the impedance values derived from Nyquist plots using Electrochemical & Corrosion Studio v5.2 software. By applying an equivalent electrical circuit model, the impedance or resistance values were determined, as shown in the circuit diagram in Figure 4.

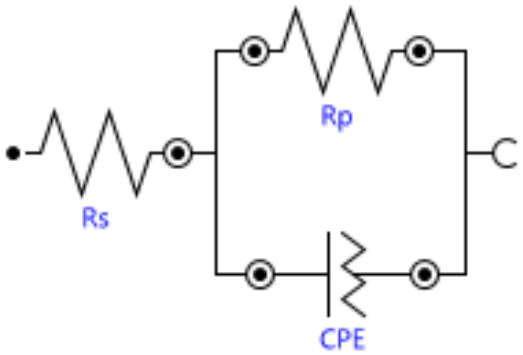


Figure 4. Equivalent Circuit Diagram

Based on the equivalent circuit elements described above, the Nyquist plot results and the corresponding resistance values were obtained. After conducting the tests, the findings are summarized in Table 5.

Tabel 5. Equivalent Circuit Impedance Values with Eichhornia crassipes Extract Inhibitor at 30 °C

Inhibitor concentration	Temperature (°C)	CPE-T	CPE-P	Rp	Rs	%IE
0	30	0,00064373	0,68405	31,08	3,773	
500		0,0012153	0,69191	77,2	5,051	0,597409326
1000		0,00084783	0,5938	74,42	4,35	0,582370331
1500		0,00066952	0,6093	47,27	4,735	0,342500529
2000		0,00031744	0,72426	61,04	4,612	0,490825688
2500		0,00050329	0,6657	75,17	4,973	0,586537182

Table 6. Equivalent Circuit Impedance Values with Eichhornia crassipes Extract Inhibitor at 40°C

Inhibitor concentration	Temperature (°C)	CPE-T	CPE-P	Rp	Rs	%IE
0	40	0,00060797	0,738	19,88	1,27	
500		0,00050906	0,68253	54,19	3,448	0,633142646
1000		0,00090637	0,55197	96,25	12,11	0,793454545
1500		0,00055255	0,6594	75,06	4,713	0,735145217
2000		0,00036436	0,70813	59,48	4,893	0,609353508
2500		0,00045063	0,67363	55,64	2,938	0,642703091

Table 7. Equivalent Circuit Impedance Values with Eichhornia crassipes Extract Inhibitor at 50°C

Inhibitor concentration	Temperature (°C)	CPE-T	CPE-P	Rp	Rs	%IE
0	50	0,00067402	0,6873	12,12	3,882	
500		0,00045496	0,67529	52,6	5,794	0,769581749
1000		0,00055813	0,67425	50,12	2,92	0,758180367
1500		0,00012015	0,5724	44,93	3,358	0,752503895
2000		0,00039578	0,72547	47,95	3,266	0,747236705
2500		0,00040999	0,69309	63,62	3,796	0,80949387

Table 8. Equivalent Circuit Impedance Values with Eichhornia crassipes Extract Inhibitor at 60°C

Inhibitor concentration	Temperature (°C)	CPE-T	CPE-P	Rp	Rs	%IE
0	60	0,0011577	0,60643	10,69	3.682	
500		0,00057615	0,67768	30,6	4,114	0,650653595
1000		0,00085117	0,64226	45,91	6,727	0,767153126
1500		0,00068205	0,67361	32,24	3,55	0,668424318
2000		0,00036858	0,70636	52,1	4,062	0,794817658
2500		0,0006242	0,65124	31,91	3,261	0,664995299

The sample without an inhibitor exhibits a significantly lower resistance compared to the samples with the addition of the inhibitor. The highest resistance was obtained at 40 °C with a concentration of 1000 mg, yielding a resistance efficiency of 0.79345454545 mg, while the lowest resistance among the inhibited samples was recorded at 60 °C with a concentration of 500 mg, with an efficiency of 0.65065359477 mg. The trend of inhibition efficiency across temperatures from 30 °C to 60 °C can be observed in the following figure 5.

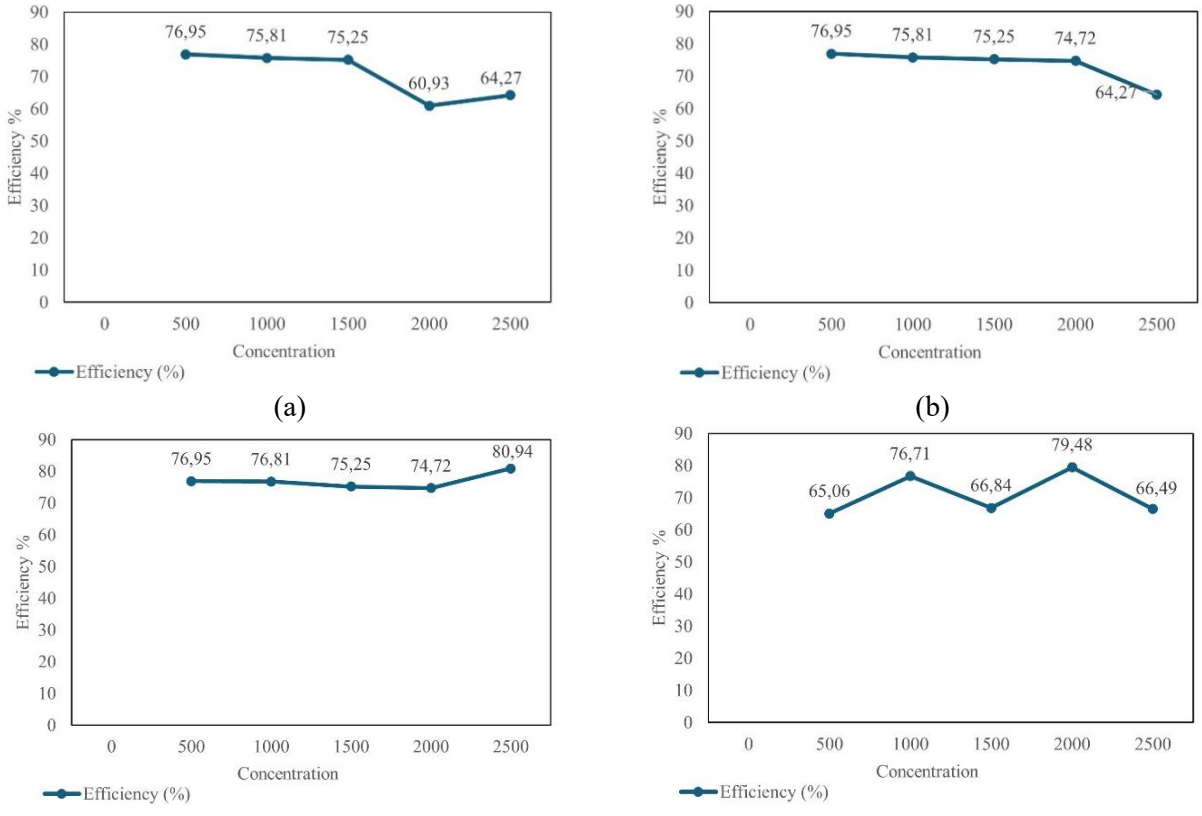


Figure 5. EIS plots for API 5L Grade B steel in 1 M HCl solution at various temperatures: (a) 30°C, (b) 40°C, (c) 50°C, and (d) 60°C.

The graph shows the lowest inhibition efficiency at 30 °C with a concentration of 1500 mg, while the highest inhibition efficiency occurs at 50 °C with a concentration of 2500 mg.

3.3 Weight Loss Test Results

The weight loss test was conducted to determine the corrosion rate and inhibition efficiency. weight loss analysis is the simplest of all corrosion available testing techniques and the longest-established method of corrosion measurement in plants and equipment. The consideration of many factors, such as test purpose, physical parameters and exposure time, are necessary to gain relevant corrosion data using weight loss techniques. [19]. This test utilized the optimal efficiency parameters obtained from the potentiodynamic polarization experiments at a temperature of 50 °C, with inhibitor concentrations of 500 mg, 1000 mg, 1500 mg, 2000 mg, and 2500 mg. The experiments were performed over immersion periods of 4–6 hours, both with and without the addition of the inhibitor. The results of the weight loss tests are presented in the following table 9.

Table 9. Inhibition Efficiency of Weight Loss at 50 °C

Inhibitor concentration	Time	Wo (gram)	Wi (gram)	Wo-Wi (gram)	CorrRate	%IE
0	4	26,885	26,635	0,25	0,305511	0,00 %
	5	26,885	26,57	0,315	0,307955	
	6	26,885	26,504	0,381	0,310399	
500	4	27,266	27,191	0,075	0,091653	70,00%
	5	27,266	27,174	0,092	0,089942	70,79%
	6	27,266	27,156	0,11	0,089617	71,13%
1000	4	26,58	26,513	0,067	0,081877	73,20%
	5	26,58	26,499	0,081	0,079188	74,28%
	6	26,58	26,481	0,099	0,080655	74,01%
1500	4	27,614	27,536	0,078	0,095319	68,80%
	5	27,614	27,514	0,1	0,097763	68,25%
	6	27,614	27,497	0,117	0,095319	69,29%
2000	4	26,564	26,531	0,033	0,040327	86,80%
	5	26,564	26,522	0,042	0,041061	86,66%
	6	26,564	26,514	0,05	0,040735	86,87%
2500	4	28,808	28,764	0,044	0,05377	82,40%
	5	28,808	28,757	0,051	0,049859	83,80%
	6	28,808	28,748	0,06	0,048882	84,25%

From the table, it can be observed that the highest inhibition efficiency was achieved at the 6-hour immersion time with an efficiency of 86.88%. The inhibition efficiency increased from 2000 mg to 2500 mg concentration and then decreased.

4. Conclusions

Based on the experimental results obtained to determine the corrosion rate, inhibition efficiency, and inhibition mechanism of API 5L Grade B steel in 1 M HCl solution with six different inhibitor concentrations, the following conclusions can be drawn: The variation of temperature significantly affects the corrosion rate of steel when using the organic green inhibitor extracted from water hyacinth (Eichhornia crassipes). This effect was observed through Potentiodynamic Polarization (PDP), Electrochemical Impedance Spectroscopy (EIS), and Weight Loss (WL) tests.

In the PDP test, the highest corrosion rate was 38.971 mm/year at 40 °C with 0 mg inhibitor concentration, while the lowest corrosion rate was 1.45 mm/year at 40°C with 2000 mg inhibitor concentration. In the WL test, the highest

corrosion rate was 0.310399 mm/year at 2000 mg inhibitor concentration with 6 hours of immersion, and the lowest corrosion rate was 0.040327 mm/year at the same concentration with 4 hours of immersion. In the PDP test, the highest inhibition efficiency was 97.85% at 50 °C with 2500 mg inhibitor concentration, and the efficiency decreased by 1.29% at 30 °C with 2000 mg concentration. In the EIS test, the highest charge transfer resistance efficiency was 80.94% at 50 °C with 2500 mg inhibitor concentration, and the lowest was 34.25%. In the WL test, the maximum inhibition efficiency was 86.87% at 2000 mg inhibitor concentration with 6 hours of immersion, and the minimum efficiency was 68.25% at 1500 mg concentration with 5 hours of immersion.

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References

[1] M. R. Al-Hadeethi, K. D. Khalil, and H. M. Abd El-Lateef, "Adsorption characteristics and thermodynamic study of new green inhibitors for carbon steel protection in 1 M HCl," *Journal of Molecular Liquids*, vol. 418, p. 126782, 2025.

[2] A. O. Ijaola, P. K. Farayibi, and E. Asmatulu, "Superhydrophobic coatings for steel pipeline protection in oil and gas industries: A comprehensive review," *J. Nat. Gas Sci. Eng.*, vol. 83, p. 103544, 2020.

[3] F. H. Kamil *et al.*, "Corrosion Behaviour, Kinetic and Thermodynamic Studies of Water Hyacinth Extract as a Corrosion Inhibitor for Low-Carbon Steel," *Iraqi J. Ind. Res.*, vol. 11, no. 3, pp. 35–47, 2024.

[4] C. M. Hussain, C. Verma, J. Aslam, R. Aslam, and S. Zehra, "Corrosion protective coatings," in *Handbook of Corrosion Engineering: Modern Theory, Fundamentals and Practical Applications*, 2023, pp. 283–321.

[5] R. Aslam, "Potentiodynamic polarization methods for corrosion measurement," in *Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring: Advances, Challenges and Opportunities*, 2023, pp. 25–37.

[6] ASTM G102-89, *Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements*, ASTM International, West Conshohocken, PA, 2021.

[7] N. Arrousse *et al.*, "Corrosion protection studies of different alloys in 1 M HCl by benzimidazole derivative: Combined molecular dynamic simulations/DFT," *J. Environ. Chem. Eng.*, vol. 11, no. 3, p. 109642, 2023.

[8] M. A. Omran, M. Fawzy, A. E. D. Mahmoud, and O. A. Abdullatef, "Optimization of mild steel corrosion inhibition by water hyacinth and common reed extracts in acid media using factorial experimental design," *Green Chem. Lett. Rev.*, vol. 15, no. 1, pp. 216–232, 2022.

[9] A. Zakeri, E. Bahmani, and A. S. R. Aghdam, "Plant extracts as sustainable and green corrosion inhibitors for protection of ferrous metals in corrosive media: A mini review," *Corros. Commun.*, vol. 5, pp. 25–38, 2022.

[10] G. A. Nugroho, A. Pradityana, N. Husodo, M. Mursid, G. D. Winarto, and F. T. Putrandi, "Mechanism of Papaya Leaf as Organic Inhibitor in Corrosion Process," AIP Conf. Proc., vol. 1983, p. 050017, 2018.

[11] F. Wang, Z. Zhang, S. Wu, J. Jiang, and H. Chu, "Effect of Inhibitor on Adsorption Behavior and Mechanism of Micro-Zone Corrosion on Carbon Steel," *Materials (Basel)*, vol. 12, no. 12, p. 1901, 2019.

[12] A. Pradityana, F. Khosfirah, P. I. Santosa, and W. B. W. Nik, "Corrosion Analysis of Renewable Inhibitor Citrus aurantifolia Peels Extract for API 5L Grade B Steel in Acid Solution," Int. J. Corros. Scale Inhib., vol. 13, no. 1, pp. 397–410, 2024.

[13] A. Pradityana, Subowo, A. Anzip, D. M. E. Soedjono, E. Widiyono, and R. Prayogi, "Inhibition Mechanism on Mango Peels as Organic Inhibitor in 1 M HCl Solution," AIP Conf. Proc., vol. 1983, p. 050018, 2018.

[14] P. R. Roberge, *Handbook of Corrosion Engineering*. New York, USA: McGraw-Hill, 2000.

[15] A. C. Lazanas and M. I. Prodromidis, "Electrochemical Impedance Spectroscopy—A Tutorial," *ACS Meas. Sci. Au*, vol. 3, no. 3, pp. 162–193, 2023.

[16] S. A. M. Ali, M. E. Salem, M. A. A. Mahmoud, M. Alsarrani, M. Abdel-Megid, H. A. El Nagy, and A. Z. Ibrahim, "Acid-phase protection of low-carbon steel by DIMC: evidenced by WL/PDP/EIS and density-functional modeling," *RSC Adv.*, vol. 15, no. 55, 2025.

[17] L. V. Hublikar, S. V. Ganachari, N. Raghavendra, V. B. Patil, and N. R. Banapurmath, "Green synthesis silver nanoparticles via Eichhornia Crassipes leaves extract and their applications," *Curr. Res. Green Sustainable Chem.*, vol. 4, p. 100149, 2021.

[18] T. S. Saligedo, G. G. Muleta, T. W. Tsega, and K. T. Tadele, "Green Synthesis of Copper Oxide Nanoparticles Using Eichhornia Crassipes Leaf Extract, its Antibacterial and Photocatalytic Activities," *Curr. Nanomater.*, vol. 8, pp. 58–68, 2023.

[19] B. El Ibrahimi and E. Berdimurodov, "Weight loss technique for corrosion measurements," in *Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring: Advances, Challenges and Opportunities*, 2023, pp. 81–90.

[20] A. M. Ruiz, H. H. Hernández, J. M. Hernández, R. Orozco-Cruz, *et al.*, "Electrochemical Impedance Spectroscopy (EIS): A Review Study of Basic Aspects of the Corrosion Mechanism Applied to Steels," in *Electrochemical Impedance Spectroscopy*, 1st ed., A. M. Ruiz, Ed. London, UK: IntechOpen, 2020.