

Comparative Analysis of Aqueous Corrosion Inhibition of Copper *Leucas aspera* leaf extract in acidic solutions

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ABSTRACT

Weight loss electrochemical techniques and SEM analysis were used to examine the corrosion inhibition effect of an aqueous extract of *Leucas Aspera* (ALA) leaves for copper in 1M HCl and 0.5M H₂SO₄ solutions. The extract worked as a superb and efficient inhibitor in the acidic media, according to the results. The efficiency of inhibition is somewhat increased by the presence of an inhibitor. As the concentration of ALA on both acids rises from 0.25 to 1.25 v/v, so does its inhibitory efficiency. In both acid media, the corrosion inhibition effect was also observed to be influenced by immersion time. An increase in temperature reduces the inhibitor's effectiveness. The trend of inhibitory efficiency with temperature has been used to propose the mechanism of physical adsorption. The ALA adsorption on mild steel surfaces follows the Freundlich adsorption isotherm in HCl solutions, but in H₂SO₄ solutions, it follows the Langmuir adsorption isotherm. The extract acts as a cathodic mixed type inhibitor on both acids, according to polarization curves. The data obtained from PDP measurements and EIS were determined to be in good agreement. It was found and highlighted that there was a good link between the inhibitor ingredients and the inhibition efficacy in both acids.

Key words: aqueous extract, acidic solutions, corrosion inhibition, copper, EIS, SEM-EDXS.

1. INTRODUCTION

Although copper is known to be susceptible to corrosion in aggressive media, it is immune to the corrosion of the environment and many chemicals. In these situations, it is imperative to use copper corrosion inhibitors; otherwise, no passive protective layer can be relied upon. "Physicochemical interaction between a metal and its environment which results in changes in the properties of the metal and which may often lead to impairment of the function of the metal, the environment, or the technical system of which these forms a part" is the definition of corrosion [1–2]. Generally speaking, corrosion inhibitors are substances that,

when given to an environment in modest concentrations, successfully lower the rate at which a metal exposed to that environment corrodes. Regretfully, a large number of widely used corrosion inhibitors that are still in use today pose health risks.[3–4]. Numerous studies have been conducted using extracts from natural plant parts such as seeds, fruits, leaves, and flowers as corrosion inhibitors in an effort to develop an inexpensive, environmentally safe, and non-toxic natural substance that could be used for acidization and acid pickling of metals in acid media [5–9].

Due to their great inhibitory efficacy and several economic and environmental advantages, plant extracts have gained a lot of interest lately as natural corrosion inhibitors. Numerous plant extracts have been employed as effective corrosion inhibitors for metals up to this point. Complex organics such as tannins, alkaloids, nitrogenous bases, carbohydrates, and proteins, as well as degradation products [10], which typically contain polar organic compounds with nitrogen, sulfur, or oxygen atoms, as well as those with links of double, triple, or conjugated aromatic rings in the molecular structures, which are the main centers of adsorption [11–15], are typically responsible for the performance inhibition of plant extracts. The extracts' components coat the metal surface in a protective layer, halting corrosion. Some research groups have reported using naturally occurring chemicals to successfully prevent metal corrosion in alkaline and acidic conditions [16–21].

Therefore, the goal of the current investigation on *Leucas Aspera* (ALA) aqueous leaf extract was to examine the adsorption and inhibitive qualities on copper in 1M HCl and 0.5M H₂SO₄ media utilizing surface analysis, weight loss, polarization, and electrochemical impedance spectroscopy (EIS) techniques. This plant's leaf extract has been effectively utilized to stop mild steel from corroding in HCl media [22]. According to the literature currently available, no extract from any portion of *Leucas Aspera* (LA) has been applied to metal corrosion inhibition experiments.

2. EXPERIMENTAL

2.1 Specimen preparation

The weight loss investigation utilized a Cu specimen measuring 1×5×0.24 cm and having an area of 12.98 cm², whereas the electrochemical study used a specimen with an exposed area of 0.9785 cm². The specimen's surface was physically polished using emery paper of various grades (600, 1000, 1500, and 2000), which were then progressively cleaned with double-distilled water, degreased with acetone, and kept in a desiccator for use. Copper's

chemical makeup is utilized as follows: (wt. %) Zn = 6.473%, Sn = 0.057%, Fe = 0.037%, Pb = 0.014%, and Cu = 93.41%.

2.2 Extract preparation

Five and 0.25 grams of dried and powdered *Leucas Aspera* leaves were refluxed for three hours at 60 degrees Celsius in 100 milliliters of distilled water, 1M HCl, and 0.5M H₂SO₄ to create the aqueous and acid extracts, respectively. After cooling to room temperature, the solutions were filtered and put away. Care was made to maintain the acid concentration as steady as possible during the extract extraction process. The extracts were prepared using distilled water and analytical-grade HCl and H₂SO₄.

2.3 Weight loss method

For one hour, the pre-weighed and pre-cleaned Cu specimens in triplicate were suspended in 100 ml of test solution including and excluding inhibitor at varying ALA concentrations in 1M HCl and 0.5M H₂SO₄. The samples were then removed, cleaned with purified water, dried, and weighed. The percentage inhibition efficiency (% IE) was computed using the weight loss data. The tests were conducted for several variables, including the inhibitor's concentration (0.25, 0.50, 0.75, 1.00, 1.25 v/v), temperature fluctuations (303–333K), corrosive media (HCl and H₂SO₄), and immersion times (1, 5, 48, 72 hours). The following formulas were used to determine the corrosion rate (CR), surface coverage (θ), and inhibition efficiency percentage (%IE).

$$CR \text{ (mpy)} = (K\Delta W) / \rho A t \quad \text{-----} \quad (1),$$

$$IE = (W(b) - W(i) / W(b)) \times 100 \quad \text{-----} \quad (2),$$

$$(\theta) = (W(b) - W(i) / W(b)) \quad \text{-----} \quad (3),$$

where W(b) and W(i) are the values of weight loss without and with inhibitor, respectively, ΔW is the weight loss in grams, ρ is the density of the coupon in g cm⁻³, A is the area of the coupon in cm², and t is the exposure period in hours.

2.4 Electrochemical method

CHI Instruments' electrochemical analyzer (model 608D) was used to conduct electrochemical measurements. A copper specimen served as the working electrode in the three-electrode cell assembly used for the studies. The reference electrode was saturated calomel, while the auxiliary electrode was a platinum wire mesh. Using a 0.02V sine wave as the excitation signal, AC impedance experiments were carried out at the resting potential in the frequency range of 10,000–1 Hz. The Nyquist plots were used to determine the R_{ct} and C_{dl} values. The following formula was used to determine the percentage IE.

$$(\%IE) = (R_{ct} \text{ (i)} - R_{ct} \text{ (b)}) / R_{ct} \text{ (i)} \times 100 \quad \text{-----} \quad (4),$$

where $R_{ct}(b)$ is the charge transfer resistance in the absence of inhibitor and $R_{ct}(i)$ is the charge transfer resistance in the presence of inhibitor.

2.5 Polarization method

At a scan rate of 0.01 V Sec.⁻¹, potentiodynamic polarization investigations were conducted in the potential range of -0.3 to 0.2 V. Tafel plots were used to extract the electrochemical data, including corrosion potential (E_{corr}), corrosion current density (I_{corr}), and anodic and cathodic slopes (b_a and b_c). The formula was then used to calculate the percentage of IE.

$$(\%IE) = (I_{corr}(b) - I_{corr}(i)) / I_{corr}(b) \times 100 \text{ -----(5),}$$

where $I_{corr}(b)$ is the corrosion current density in the absence of inhibitor and $I_{corr}(i)$ is the corrosion density in the presence of inhibitor.

2.6 SEM Surface Morphology

SEM-EDXS (ZEISS Sigma microscope 5th version) was used to take pictures of fresh, inhibited, and uninhibited copper samples to examine the impact of the inhibitor on the corrosion phenomenon of copper. Following a 72-hour immersion in the blank solutions of 1 M HCl and 0.5 M H₂SO₄ with and without 1.25 v/v ALA extract at 25°C, the precleaned specimens were rinsed with distilled water, allowed to dry in warm air, and then submitted for surface analysis using a SEM.

3. RESULTS AND DISCUSSION

3.1 Weight loss method

Table 1 shows the weight loss, corrosion rate (CR), and inhibition efficiency (% IE) of copper in 1 M HCl and 0.5 M H₂SO₄ with and without ALA at room temperature for varied immersion durations (1-72 hr) at different concentrations. These data clearly show that the inclusion of plant extracts at concentrations at all immersion times up to 72 hours boosts inhibition efficiency and decreases corrosion rate. This is because the inhibitor's adsorbed layer reduces the rate of corrosion by acting as a barrier between the copper metal surface and the acid solution. Even after a prolonged immersion period of 72 hours, the greatest inhibitor concentration of 1.25 v/v is found to have a %IE of 78.69 in 1M HCl and 85.55 in 0.5 M H₂SO₄. More inhibitor molecules are adsorbed on the copper surface in both acid media by blocking more corrosion active sites, as indicated by the increase in % IE with increasing inhibitor concentration. The increased percentage of inhibitor molecules deposited on the metal surface over time may account for the improved IE [23].

Conc. of ALA (v /v)	1M HCl							
	1 hr		5 hr		48 hr		72 hr	
	CR (mpy)	(%)IE	CR (mpy)	(%)IE	CR (mpy)	(%)IE	CR (mpy)	(%)IE
Blank	378.59		383.21		378.57		411.02	
0.25	266.14	29.7	258.72	32.48	251.11	33.66	247.53	39.77
0.50	254.89	32.67	247.59	35.39	227.44	39.92	221.86	45.02
0.75	191.17	49.5	175.42	54.22	153.05	59.57	145.01	64.71
1.00	168.68	55.44	161.71	57.80	122.27	67.7	111.82	72.79
1.25	119.95	68.31	97.85	74.46	89.65	76.31	87.56	78.69
Blank	0.5 M H ₂ SO ₄							
	1870.49		1679.74		1126.98		1054.83	
0.25	899.61	51.9	610.51	63.65	352.61	68.71	328.04	68.9
0.50	712.21	61.92	549.79	67.26	297.05	73.64	271.11	74.29
0.75	682.22	63.52	468.84	72.08	256.88	77.2	244.78	76.79
1.00	603.5	67.73	414.87	75.3	221.14	80.37	202.85	80.76
1.25	461.06	75.35	268.32	84.02	173.07	84.64	152.36	85.55

Table 1. Effect of concentration of ALA on the corrosion of copper in 1 M HCl and 0.5 M H₂SO₄ from weight loss method

3.2 Effect of temperature

Weight loss measurements were conducted at temperatures between 303 and 333 K with and without ALA at varying concentrations for a one-hour immersion period in order to assess the type of ALA adsorption and activation parameters of the copper corrosion process in 1M HCl and 0.5M H₂SO₄ medium. The results are displayed in Table 2. Because of the physical adsorption mechanism, it is evident that when the temperature is raised, the percentage of IE drops from 68.31 to 48.79 in HCl and from 75.35 to 63.10 in H₂SO₄ medium.

For different concentrations of the chosen inhibitor ALA in 1 M HCl and 0.5 M H₂SO₄ medium, Fig. 1 and 2 illustrate how the percentage IE changes with temperature. At all concentrations, the inhibitory efficiency dropped as the temperature rose. This could be because when the temperature rises, the inhibitor's adsorption on the alloy surface decreases, increasing the rate of corrosion since more metal is exposed to the acid [24]. The Arrhenius plot's slope was used to determine the activation energy (E_a) for the Cu corrosion process at various inhibitor doses.

(log CR vs. $1/T$) (Fig. 3& 4),

where the slope is $E_a/2.303 R$, CR is corrosion rate, R is gas constant, and T is the temperature in absolute scale. These values are enumerated in Table .3.

An inhibited solution has greater E_a values than an uncontrolled one. The adsorption of leaf extracts on the copper surface prevents the activation site of the copper specimen from corroding, as indicated by the increasing activation energy value with extract concentration. As a result, the rate of corrosion decreases as the extract concentration rises. Additionally As the temperature rises, the rate of corrosion decreases because the adsorbed molecule desorbs. This is a sign of the inhibitor molecules' spontaneous adsorption on the copper surface and is explained by physisorption [25–26]. The inhibitor molecules' adsorption on active sites is what causes the inhibited system's activation energy to rise.

Conc. of ALA (v/v)	1M HCl							
	303 K		313 K		323 K		333 K	
	CR (mpy)	(%)IE	CR (mpy)	(%)IE	CR (mpy)	(%)IE	CR (mpy)	(%)IE
Blank	378.59		461.06		738.45		775.93	
0.25	266.14	29.7	363.6	21.13	685.97	7.1	742.19	4.34
0.50	254.89	32.67	356.1	22.76	588.51	20.3	670.97	13.52
0.75	191.17	49.5	311.12	32.52	523.59	29.09	554.77	28.5
1.00	168.68	55.44	232.4	49.59	382.34	48.22	476.05	38.64
1.25	119.95	68.31	176.17	61.79	371.09	49.74	397.33	48.79
Blank	0.5 M H ₂ SO ₄							
	303 K		313 K		323 K		333 K	
	CR (mpy)	(%)IE	CR (mpy)	(%)IE	CR (mpy)	(%)IE	CR (mpy)	(%)IE
Blank	1870.49		2181.61		2312.81		2560.21	
0.25	899.61	51.9	1083.31	50.34	1315.71	43.11	1585.6	38.06
0.50	712.21	61.92	1075.81	50.68	1150.78	50.24	1405.68	45.09
0.75	682.22	63.52	850.9	60.99	907.13	60.77	1128.29	55.92
1.00	603.5	67.73	775.93	64.43	835.91	63.85	1075.81	57.97
1.25	461.06	75.35	611	71.99	824.66	64.34	944.61	63.1

Table 2. Effect of temperature on the corrosion of copper in 1 M HCl & 0.5M H₂SO₄ with ALA

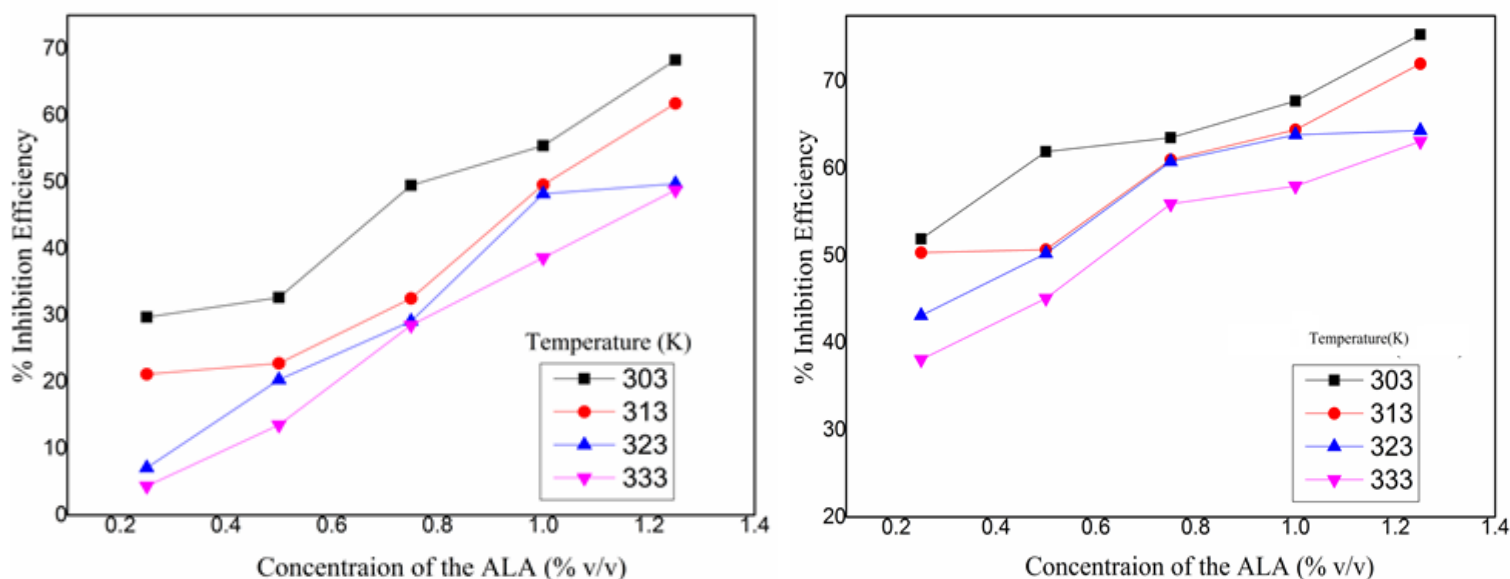


Fig.1&2. Effect of temperature on the corrosion of copper in 1 M HCl and 0.5M H₂SO₄ with ALA

3.3 Adsorption isotherm

The adsorption isotherm provides a clear explanation of the nature of the interaction between the inhibitor and the metal surface. Various adsorption isotherms were used to test the surface coverage values derived from the weight loss approach. The Freundlich isotherm provided the best fit among the different adsorption isotherms that were evaluated in the temperature range of 303–333 K in 1M HCl. Because the surface might not be homogeneous and interactions between the adsorbed molecules might have occurred, there is a departure from the Langmuir equation. Additionally, multilayer adsorption in many layers may occur. When these deviations happen, the adsorption process follows the Freundlich isotherm. This isotherm shows that the equation relates the concentration (C) to the amount of a material adsorbed (θ).

$$\theta = kC^n \text{ ----- (6),}$$

The plot of $\log \theta$ versus $\log C$ is a straight line with “n” as slope value and is shown in Fig. 7. The free energy of adsorption ΔG_{ads} for various concentrations of inhibitor at different temperatures was calculated using the following equation:

$$\Delta G_{ads} = -RT \ln K \text{ ----- (7),}$$

where $K = \theta / C_{inh} (1 - \theta)$, θ is surface coverage, C_{inh} is the concentration of inhibitor, and the constant value of 55.5 represents the concentration of water in solution. Table 3's

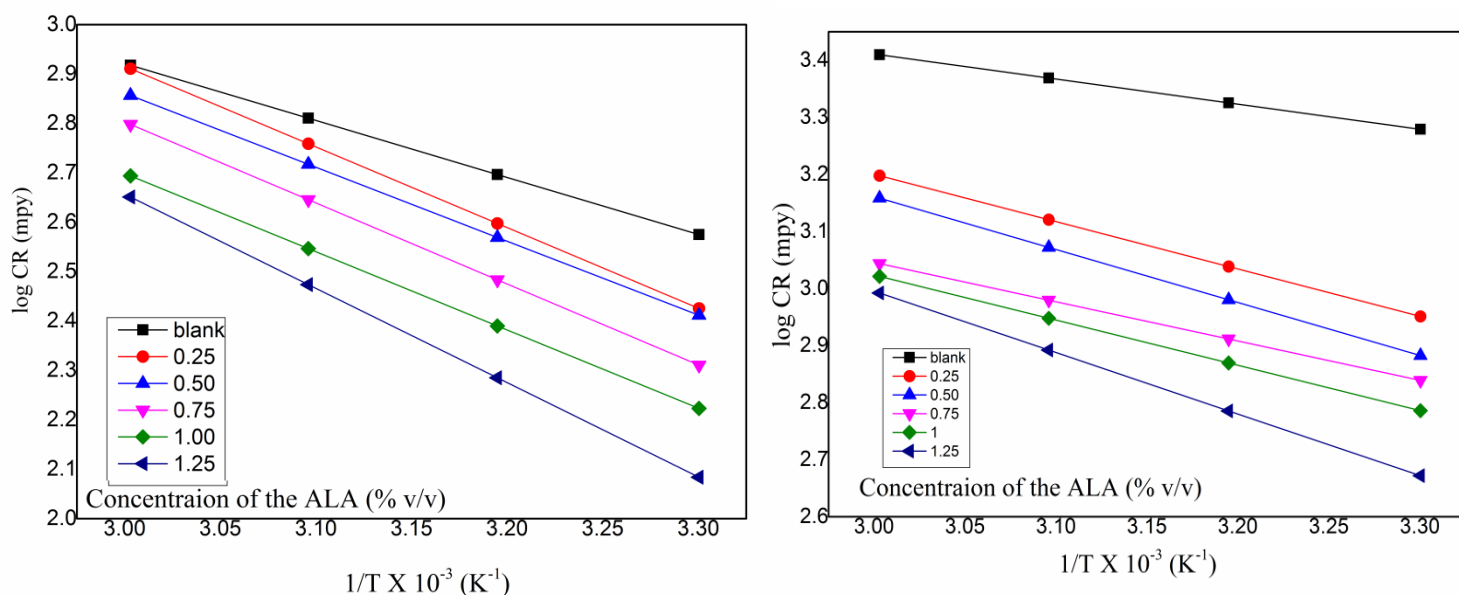
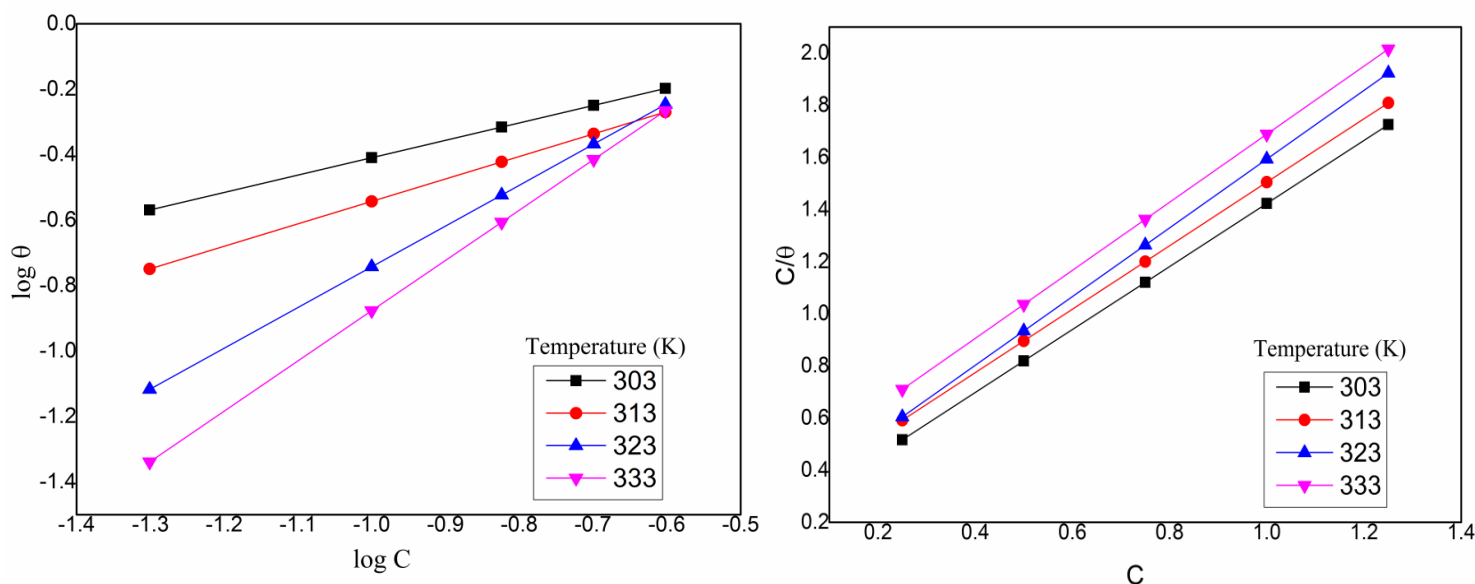
analysis makes it evident that a value of ΔG_{ads} less negative than -20 kJ mol^{-1} indicates physisorption, whereas a value more negative than -40 kJ mol^{-1} indicates chemisorption [27].

The adsorption of inhibitor molecules on the metal surface is an exothermic process, as indicated by the negative value of ΔH_{ads} . When an inhibitor is present, ΔS_{ads} values are found to be positive. This suggests that a reduction in disorder is occurring from reactants to the activated complex, and that the synthesis of the activated complex is the rate-determining step that represents association rather than dissociation [28].

A suitable isotherm has been constructed using the surface coverage (θ) values at various concentrations (C) of ALA in 0.5M H_2SO_4 medium in the temperature range of 303-333 K. The Langmuir, Freundlich, Tempkin, Frumkin, El-awady, and Flory-Huggins isotherms were all tried to suit the experimental results. A straight line was produced when $\log C/\theta$ was plotted against concentration. The correlation coefficient is close to unity, indicating that the experimental data fit the Langmuir adsorption isotherm (Fig. 6) quite well.

S.No.	Conc. of ALA (v/v)	E _a (kJ mol ⁻¹)	-ΔG _{ads} (kJ mol ⁻¹)				-ΔH _{ads} (kJ mol ⁻¹)	ΔS _{ads} (kJ mol ⁻¹)
1M HCl								
1	Blank	22.08	-	-	-	-	-	-
2	0.25	31.24	12.14	10.20	8.26	6.32	70.95	0.1941
3	0.50	28.67	10.33	9.57	8.82	8.07	33.17	0.0754
4	0.75	31.39	10.69	10.14	9.59	9.04	27.33	0.0549
5	1.00	30.33	11.11	10.77	10.44	10.10	21.32	0.0337
6	1.25	36.54	11.85	11.30	10.75	10.19	28.57	0.0552
0.5 M H ₂ SO ₄								
1	Blank	8.41	-	-	-	-	-	-
2	0.25	15.89	14.47	14.24	14.01	13.78	21.46	0.0230
3	0.50	17.78	13.34	13.06	12.79	12.51	21.65	0.0274
4	0.75	13.20	12.73	12.74	12.76	12.78	12.25	0.0016
5	1.00	15.17	12.46	12.38	12.30	12.22	14.91	0.0081
6	1.25	20.63	12.83	12.53	12.23	11.94	21.82	0.0297

Table3. Values of activation energy and thermodynamic parameters for the corrosion of copper with and without different concentrations of ALA

Fig. 3&4. Arrhenius plots for the corrosion of copper in 1 M HCl and 0.5M H₂SO₄ with ALAFig.5&6. Freundlich and Langmuir adsorption isotherm for the corrosion of copper in 1 M HCl and 0.5M H₂SO₄ with ALA

3.4 Electrochemical method

Electrochemical experiments were used to examine the corrosion behaviour of copper in 1 M HCl and 0.5 M H₂SO₄ solutions with and without varying amounts of ALA. Table 4 and Figs. 7(a) and (b) present the impedance data derived from Nyquist plots for the systems indicated previously. All of the systems under study have impedance diagrams that are not perfect semicircles. The roughness and inhomogeneity of the electrode surface cause the frequency dispersion, which is responsible for the imperfect semicircle (depressed

semicircle). This demonstrates how the inhibitor molecules' adsorption on the copper metal surface results in the development of a surface protective coating that lowers the metal's corrosion active sites and increases its resistance to corrosion [29].

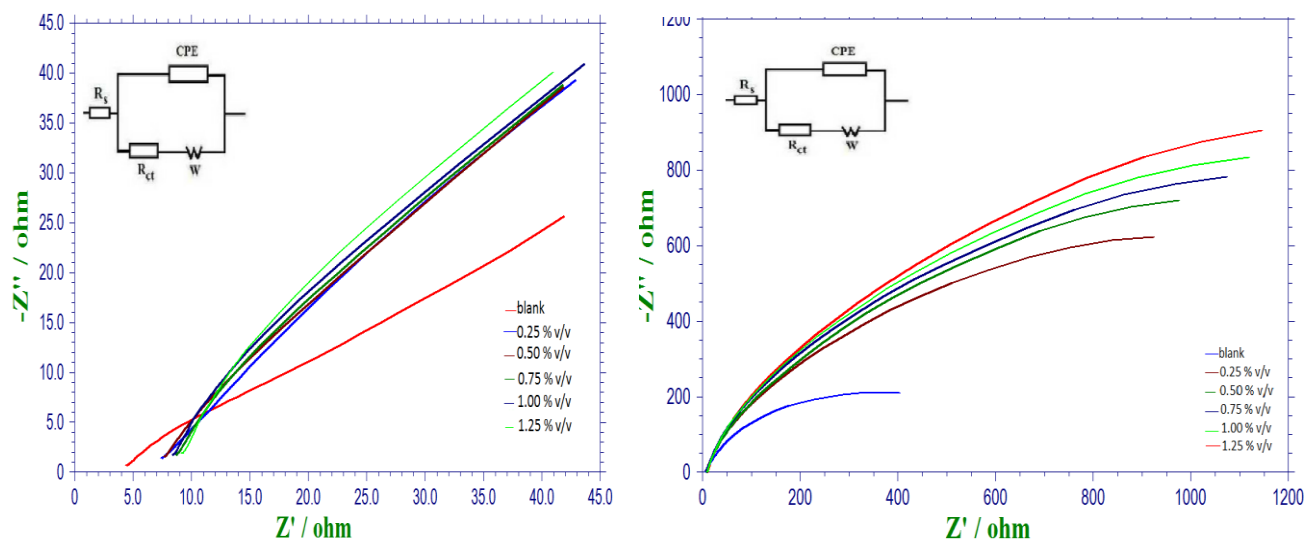
Several circuits have been tested to obtain a more exact fit for the experimental data, and the simple Randles equivalent circuit yields the best accuracy. Table 4 and Figures 8(a) and (b) provide the Randles equivalent circuits utilized for impedance experiments. where C_{dl} is the double-layer capacitance, R_{ct} is the charge transfer resistance, and R_s is the solution resistance. Table 4 lists the electrochemical parameters of R_{ct} , C_{dl} , and %IE in 1 M HCl and 0.5 M H_2SO_4 with and without ALA. The table makes it clear that when the inhibitor concentration rises, so do the C_{dl} values and R_{ct} values. The reason for the rise in R_{ct} in the presence of ALA is that the more inhibitor molecules push out the water molecules at the double-layer interface, which causes the charge to go from the solution to the metal surface. The local dielectric constant drop and/or the electrical double layer's increased thickness are the causes of the rise in C_{dl} values in the presence of the various ALA concentrations when compared to the blank solution. This implies that inhibitor molecules are adsorbing at the metal/solution contact. Direct adsorption can be placed due to donor-acceptor interactions between the metal atoms' unoccupied d orbital and the lone pair of electrons, or π electrons in ALA [30].

The electrochemical parameters, such as corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic slope (ba), and cathodic slope (bc) were obtained from Tafel plots. The percentage of IE is tabulated in Table.4 and Fig. 8 (a) & (b) explain the representative Tafel plots of the corrosion inhibition studies on copper with different concentrations of ALA. The current potential relationships for copper corrosion in 1 M HCl and 0.5 M H_2SO_4 with different concentrations of ALA were examined through polarization measurements. The anodic and cathodic branches of the polarization curves were linearly extrapolated to determine the Tafel slopes. Using the Stern-Geary equation, which is provided below, the corrosion current (I_{corr}) was computed from the slope of the polarization curve (ba and bc) and linear polarization resistance R_p :

$$I_{corr} = [babc / 2.303(ba + bc)] \times (1/R_p) \text{ ----- (8),}$$

According to the polarization data in Table 4, the inhibitor's addition changes both the ba and bc values, indicating that it slows down the hydrogen evolution reaction and lessens the metal's anodic dissolution. This demonstrates the inhibitor's mixed nature. As inhibitor concentration rises, the I_{corr} values fall, indicating that the inhibitors have a larger surface coverage [31–32].

Conc.of ALA (v/v)	PDP						EIS	
	1M HCl							
	ba mV dec ⁻¹	bc mV dec ⁻¹	(- Ecorr) mV sec ⁻¹	I _{corr} * 10 ⁻⁴ Amp cm ⁻²	% IE	R _{ct} Ωcm ²	C _{dl} Fcm ⁻²	IE
Blank	67.82	337.72	266.9	0.3736	-	41.45	0.001139424	-
0.25	75.98	307.31	225.2	0.2501	33.05	137.1	0.0002792144	69.7
0.50	78.46	305.81	228.3	0.2182	41.59	479.1	9.327397*10 ⁻⁵	91.34
0.75	78.80	305.06	228.9	0.1623	56.55	664.8	4.844681*10 ⁻⁵	93.76
1.00	77.24	283.44	227.1	0.1536	58.88	679	3.001529*10 ⁻⁵	93.89
1.25	76.96	290.95	228.3	0.1457	61.00	785	3.991411*10 ⁻⁵	94.71
0.5 M H ₂ SO ₄								
Blank	127.95	209.90	119.5	0.1599	-	596	5.570854* 10 ⁻⁵	-
0.25	126.71	203.12	117.6	0.1475	7.75	1451	5.930235* 10 ⁻⁵	58.92
0.50	173.85	264.06	125.0	0.1216	23.95	1665	2.264369* 10 ⁻⁵	64.20
0.75	167.56	252.46	131.1	0.1073	32.89	1770	5.055394* 10 ⁻⁵	66.32
1.00	145.39	224.71	142.2	0.0840	47.46	1900	2.168907* 10 ⁻⁵	68.63
1.25	152.29	252.07	147.1	0.0766	52.09	2062	2.115848* 10 ⁻⁵	71.09

Table4.Electrochemical parameters for the corrosion of copper in 1 M HCl and 0.5 M H₂SO₄ at different concentrationsFig. 7(a)&7(b). Nyquist plots for the corrosion of copper in 1 M HCl and 0.5 M H₂SO₄ with various concentrations of ALA

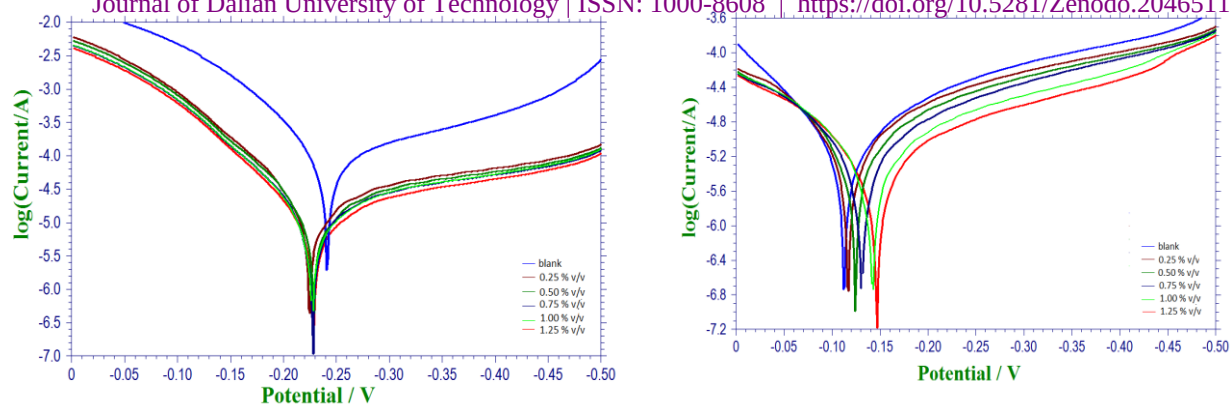


Fig. 8 (a)& 8(b).Tafel plots for the corrosion of copper in 1 M HCl and 0.5M H₂SO₄ with various concentrations of ALA

3.5 Surface Morphology

3.5.1 SEM analysis

Figure 9 (a, b) displays the SEM images of the pure Cu samples subjected for 72 hours in 1 M HCl & 0.5M H₂SO₄ with 0.25 g/L of ALA. Analysis of those figures reveals that the presence of an inhibitor reduces damage to the Cu surface, and the image illustrates how the adsorbed bioactive species on the metal surface create protective coatings.

3.5.2 EDXS analysis

Figures 10 (a and b) display the EDXS images of the inhibited copper specimens, while Table 5 compiles the analytical results. Cu, O, Si, Zn, and Cl are present in both specimens, while 0.5M H₂SO₄ also contains C and S. The inhibited copper specimen had a larger proportion of copper, according to a comparison of the data. This shows that the inhibitor molecules have adhered to the copper surface, stopping the metal ions from dissolving in the hostile media.

HCl medium	Composition (%)					
	Cu	O	Si	Zn	Cl	
Copper in 1M HCl	80.70	8.92	3.17	5.24	1.97	
Copper in 1M HCl+ ALA	87.92	5.42	1.98	2.90	1.78	
H ₂ SO ₄ medium	Composition (%)					
	Cu	O	Si	Zn	C	S
Cu in 0.5M H ₂ SO ₄	68.85	13.10	2.31	6.17	8.26	1.30
Cu 0.5M H ₂ SO ₄ +ALA	86.63	2.50	0.18	4.25	6.44	

Table 5.EDXS analysis results of the copper specimen in 1M HCl& 0.5M H₂SO₄ in the absence and presence of ALA

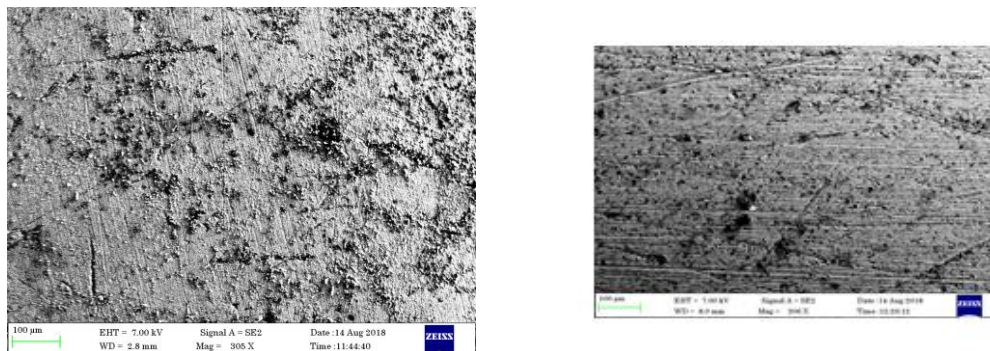
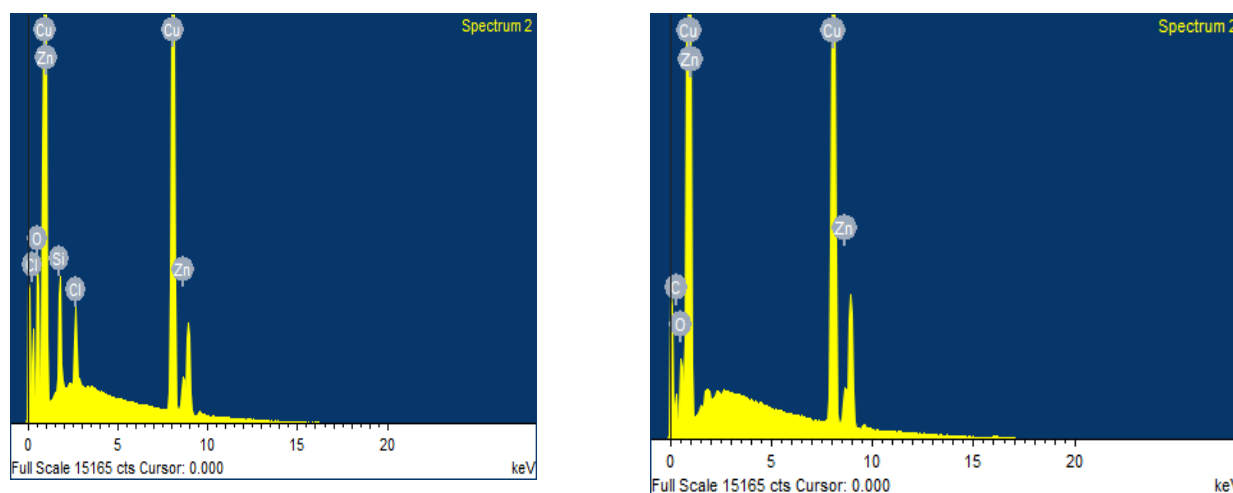


Fig.9(a)&9(b) SEM image of copper sample exposed for 72 h in 1 M HCl and 0.5M H₂SO₄ with ALA



Figs.10(a)&10(b) The EDXS image of the copper sample exposed for 72 h in 1 M HCl and 0.5M H₂SO₄ with ALA

4. CONCLUSIONS

- *Leucas aspera* extract is an effective natural corrosion inhibitor for copper in 1 M HCl and 0.5 M H₂SO₄ solutions.
- Inhibition efficiencies from electrochemical tests and weight loss measurements show strong agreement.
- Negative ΔG_{ads} values indicate spontaneous adsorption of the inhibitor on the copper surface.
- E_a and ΔH_{ads} values support the adsorption mechanism, while positive ΔS_{ads} values suggest an association-type activated complex.
- The extract follows the Freundlich adsorption isotherm in 1 M HCl and the Langmuir adsorption isotherm in 0.5 M H₂SO₄.
- EDXS results confirm adsorption of inhibitor molecules on the copper surface.
- Polymerization studies show that *Leucas aspera* extract acts as a mixed-type corrosion inhibitor.

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