

Kinetic, Thermodynamic, adsorption and electrochemical studies for Corrosion Behaviour of Aluminium AA6063 Alloy in Ethanolic Extract of *Lawsonia alba* Lam. Leaves

Rekha Nair

Professor, Department of Chemistry, Poornima College of Engineering, Jaipur, Rajasthan (India),

Abstract - Corrosion behavior of Aluminium AA6063 alloy was tested in 0.5 N HCl in presence of various concentration of ethanolic extract of *Lawsonia alba* Lam. Leaves. The inhibition efficiency was evaluated by chemical and electrochemical methods. Inhibition efficiency was found to increase with increase in concentration of ethanolic extract of *Lawsonia alba* Lam. Leaves. Kinetic, thermodynamic and adsorption studies were made. Kinetic studies shows that the mechanism follows first order kinetics. Thermodynamic studies for the inhibitor-metal interactions clearly indicate that adsorption of ethanolic extract of *Lawsonia alba* Lam. Leaves extract on AA6063 in acid medium follows Langmuir adsorption isotherm. The nature of adsorption was evaluated as physical adsorption. The Potentiodynamic polarization results confirm that ethanolic extract of *Lawsonia alba* Lam. Leaves extract act as mixed inhibitor.

Keywords: Aluminium, *Lawsonia alba* Lam. Leaves, weight loss method, Polarization, Kinetic, Thermodynamic, adsorption Parameters.

I. INTRODUCTION

Corrosion of metals is one of the major problems faced by industries. Some of the industrial processes like acid cleaning, pickling and descaling processes increase the corrosion problems. One of the best options to reduce corrosion is use of corrosion inhibitors. Corrosion inhibitors such as chromium (III) and cerium (IV) oxides, cerium (III) chloride, benzotriazole, 2-mercaptobenzothiazole and some of the monosaccharide derivatives are used in industries to reduce the corrosion rate of metals in aggressive environment. But most of them are toxic to human and environment. The environmental issues of these toxic corrosion inhibitors are of global concern and have attracted lots of investigation and researches. Use of natural products of plant origin as eco-friendly and inexpensive corrosion inhibitor is one of the practical methods used now a days [1-11]. Plant products are biodegradable, readily available, low cost and renewable resources. Many plant extracts and some essential oils are already been studied as good corrosion inhibitor. These contain compounds having hetero atoms such as O, N and S which are active centers for adsorption on the metal surface. The inhibition efficiency depends on the mechanical, structural and chemical characteristics of the adsorption layers formed under particular conditions.

The present investigation was aimed to evaluate the anti-corrosive property of ethanolic extract of *Lawsonia alba* Lam. leaves on acid corrosion of aluminium alloy (AA6063) using chemical and electrochemical methods. Thermodynamic and kinetic parameters were calculated from the experimental data obtained. The inhibition action of ethanolic extract of *Lawsonia alba* Lam. leaves was satisfactorily explained by chemical as well as thermodynamic methods. The inhibitive property of ethanolic extract of *Lawsonia alba* Lam. leaves was found to be very encouraging and it is recommended that it may be used as *green inhibitor* for acid corrosion of aluminium to replace conventional inorganic / organic inhibitors which are not only expensive but also toxic to living beings. Literature survey reveals that ethanolic extract of *Lawsonia alba* Lam. leaves are found to be rich in organic compounds like, gallic acid (GA), lawsone (2-hydroxy-1,4-naphthoquinone), 1,4-naphthoquinone, mannitol, tannic acid (TA), glucose, resin, alkaloids, stigmasterol, luteolin etc.. Most among these compounds are antibacterial, fungicide, antioxidants and compounds like lawsone, GA and TA are also known to possess anti-corrosive property [12-14].

II. MATERIALS AND METHODS

The anti corrosive property of the ethanolic extract of *Lawsonia alba* Lam. Leaves at its various concentrations on Aluminium AA6063 alloy was investigated in 0.5N HCl at 303 ± 1 K during 24h immersion period. Weight loss methods and electrochemical methods were used for the analysis of corrosion inhibition measurements. All the chemicals, acids and reagents were of analytical grade and bidistilled water was used for the preparation of the solutions. All the experiments were performed in duplicate to check the reproducibility of the results. Average value of weight loss was considered for measurements.

A. WEIGHT LOSS METHOD

1. *Preparation of Sample Coupons of Aluminium AA6063 Alloy:* Aluminium AA6063 alloy is 98% pure (other constituents are Si 0.20-0.6%; Fe 0.35%; Cu 0.10%; Mn 0.10%; Mg 0.45-0.90%; Zn 0.10%; Ti 0.10%). The test coupon is mechanically Press cut having dimensions of 3 cm X 2 cm X 0.15 cm with a hole of 0.12 mm diameter near the upper

edge for the purpose of hanging. The coupons were carefully examined for rough edges and surface smoothening treatment was carried out before each experiment.

2. Preparation of Test solutions and plant extract: To prepare plant Extract, room temperature dried *Lawsonia alba* Lam. Leaves are finely powdered and soaked in ethanol. Extraction is carried out using Soxhlet extractor as per standard Procedures. The mass of *Lawsonia alba* Lam. Leaves extract was assessed to be 2.80 g/L of plant compounds. 100 ml of the test solution (0.5 N HCl) was taken in 6 different 250 ml beakers numbering S-0, S-1, S-2, S-3, S-4 and S-5. *Lawsonia alba* Lam. Leaves extract was added in these five beakers (S-1 to S-5) in the order of increasing concentrations so as to have 0.028, 0.056, 0.084, 0.112 and 0.140 g/L respectively. No extract was added to the beaker S-0, the first beaker.

Corrosion behavior of Aluminium AA6063 alloy was evaluated at different exposure period till 24 hours. Evaluation of the various corrosion parameters from weight loss measurements, such as, Corrosion rate (mmpy) ρ_{corr} , Inhibition Efficiency (IE %), Rate constant (K) for corrosion process, etc. were carried out. The evaluations of thermodynamic and kinetic parameters were carried out with the experimental data.

B. ELECTROCHEMICAL METHODS

Electrochemical measurements were recorded in a Potentiostat/Galvanostat/Frequency Response Analyzer AUTO302 with FRA2 module AUTOLAB controlled by a PC. The standard three electrode cell assembly was used for the study. The working electrode was the square cut aluminium coupon (0.25cm^2) which was in contact with the test solution. The reference electrode and counter electrode were saturated calomel electrode and glassy carbon respectively. All the experiments were performed at room temperature. The electrochemical parameters R_p , i_{corr} , and E_{corr} , associated with polarization measurements for the test metal (AA6063) were simultaneously recorded.

III. RESULTS AND DISCUSSION

A. WEIGHT LOSS MEASUREMENTS

Corrosion behavior of AA6063 in 0.5 N HCl was studied at $303 \pm 1\text{K}$ for various concentrations of ethanolic extract of *Lawsonia alba* Lam. Leaves at various immersion time periods. From the results, the corrosion parameters, like corrosion rate (ρ_{corr}) (in mmpy), percentage inhibition efficiency (IE %), fractional surface coverage (θ), adsorption equilibrium constant (K_{ad}) etc. were evaluated and tabulated in Table-1.

Analysis shows that, with the increase in concentration of Ethanolic Extract of *Lawsonia alba* Lam. Leaves there is a decrease in corrosion of Aluminium AA6063. The graph of experimental data, viz., the corrosion rate, (ρ_{corr}) (in mmpy), vs exposure time, t (h) percentage inhibition efficiency (IE %) etc. at various concentrations of Ethanolic Extract of *Lawsonia alba* Lam. Leaves were also drawn.

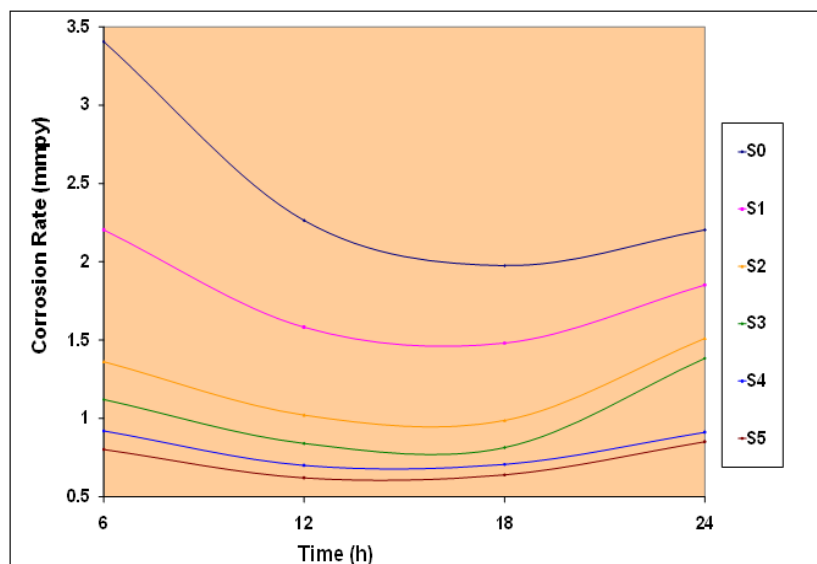


Fig.1 Corrosion Rate (ρ_{corr}) (in mmpy) vs Time(h) (at 24h & $303 \pm 1\text{K}$)

A general decrease in corrosion rates (with inhibitor) was also observed with the immersion time as well as increasing concentration of Ethanolic Extract of *Lawsonia alba* Lam. Leaves. At higher concentration of Ethanolic Extract of *Lawsonia alba* Lam. Leaves (0.140 g/L), corrosion rate was observed to be almost independent of immersion time (Fig.1). With the increase in immersion time, there was a slight decrease in the IE (%) of Ethanolic Extract of *Lawsonia alba* Lam. Leaves; but at higher concentration (0.140 g/L), IE (%) behaves almost independent of immersion time (Fig. 2) (Table-I).

Immersion Time (h)	Ethnanolic Extract of Lawsonia alba Lam. Leaves Concentration (g/L)	Corrosion Parameters				
		Weight loss (mg)	Corrosion Rate (ρ_{corr}) (mmpy)	Inhibition Efficiency (IE %)	Fractional Surface Coverage (θ)	Adsorption Equilibrium Constant (K_{ad})
6	S-0 0.000	8.5	3.4046	-	-	-
	S-1 0.028	5.5	2.2030	35.294	0.3529	19.4770
	S-2 0.056	3.4	1.3618	60.000	0.6000	26.7857
	S-3 0.084	2.8	1.1215	67.058	0.6705	24.2250
	S-4 0.112	2.3	0.9212	72.941	0.7294	24.0668
	S-5 0.140	2.0	0.8010	76.4705	0.7647	23.2135
12	S-0 0.000	11.3	2.2631	-	-	-
	S-1 0.028	7.9	1.5821	30.088	0.3008	15.3644
	S-2 0.056	5.1	1.0213	54.867	0.5486	21.7023
	S-3 0.084	4.2	0.8411	62.831	0.6283	20.1231
	S-4 0.112	3.5	0.7009	69.026	0.6902	19.8918
	S-5 0.140	3.1	0.6208	72.566	0.7256	18.8879
18	S-0 0.000	14.8	1.9760	-	-	-
	S-1 0.028	11.1	1.4820	25.000	0.2500	11.9047
	S-2 0.056	7.4	0.9880	50.000	0.5000	17.8571
	S-3 0.084	6.1	0.8144	58.783	0.5878	16.9762
	S-4 0.112	5.3	0.7076	64.189	0.6418	15.9976
	S-5 0.140	4.8	0.6408	67.567	0.6756	14.8758
24	S-0 0.000	22.0	1.46	-	-	-
	S-1 0.028	18.5	1.23	15.909	0.1591	6.7521
	S-2 0.056	12.9	0.86	41.363	0.4136	12.4092
	S-3 0.084	11.0	0.734	50.000	0.5000	11.9047
	S-4 0.112	9.1	0.606	58.636	0.5864	12.3299
	S-5 0.140	8.5	0.566	61.363	0.6136	11.1721

Table: I. Corrosion Parameters of Acid Corrosion of AA 6063 without and with different Concentrations of Ethanolic Extract of Lawsonia alba Lam. Leaves for Various Immersion Time (h) at temperature $303 \pm 1\text{K}$.

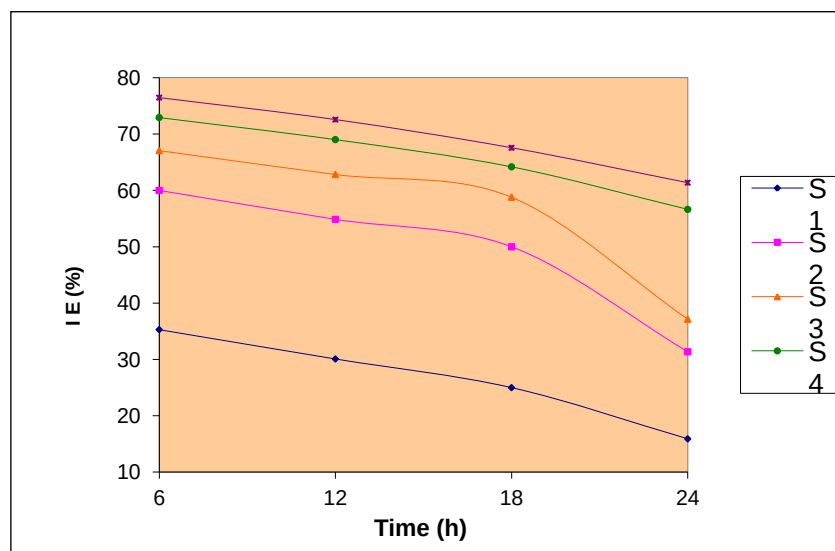


Fig 2. Inhibition Efficiency (%) vs Time (h) (at 24h & $303 \pm 1\text{K}$)

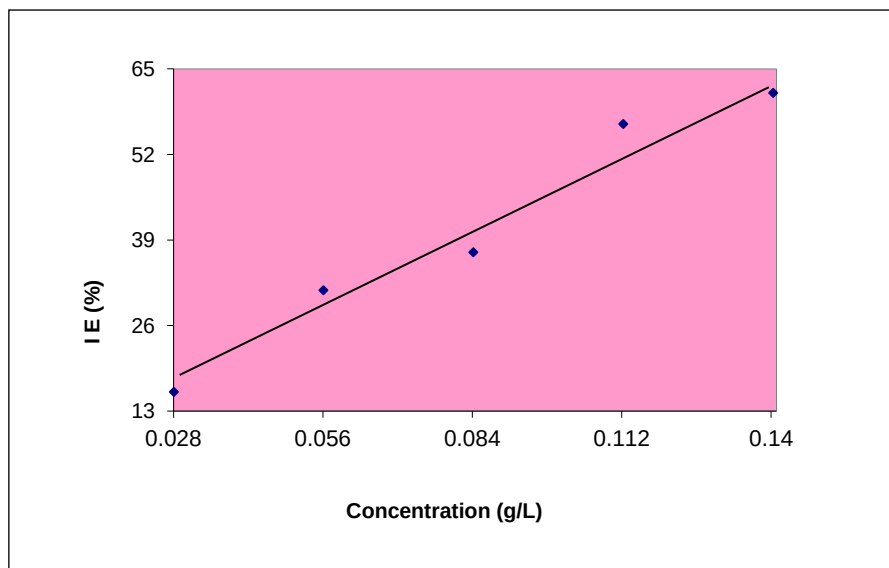


Fig.3 Inhibition Efficiency (%) vs Concentration of Leaf Extract (g/L) (at 24h & 303 ± 1K)

The inhibition efficiency of Ethanolic Extract of Lawsonia alba Lam. Leaves was found to increase as a function of its concentration (Fig. 3). This behavior may be attributed to the increase of the surface area covered by the adsorbed molecules of Ethanolic Extract of Lawsonia alba Lam. Leaves with an increase in its concentration. The active ingredients (such as, lawsone [2-hydroxy-1,4-naphthoquinone], 1,4-naphthoquinone, mannitol, GA, TA, etc.) present in henna, constituting approximately 18 % by weight of its powdered dry leaves, have good adsorption tendency [15-16] and can easily be adsorbed on the corroding metal giving rise to such protective efficiency.

With increase in exposure time Inhibition Efficiency, IE (%) was found to decrease for all concentrations of plant extract. The highest Inhibition Efficiency was observed for 0.140 g/L concentration of Ethanolic Extract of Lawsonia alba Lam. Leaves with a minimum corrosion rate in the study of 24 h exposure time period.

B. KINETIC / THERMODYNAMIC TREATMENT OF WEIGHT LOSS RESULTS

Assuming the corrosion rate of aluminium against the concentration of Ethanolic Extract of Lawsonia alba Lam. Leaves obeys the kinetic relationship [17-20]:

$$\log \rho_{\text{corr}} = \log k + B \log C$$

where, k is the rate constant and equals to ρ_{corr} at inhibitor concentration of unity; B is the reaction constant which in the present case is a measure for the inhibitor effectiveness and C is the concentration of Ethanolic Extract of Lawsonia alba Lam. Leaves in g/L. Fig. 4 illustrates the plot of $\log \rho_{\text{corr}}$ vs $\log C$ at 303 ± 1K. The straight lines substantiate that kinetic parameters (k and B) can be calculated by using the above equation.

The negative slopes of the lines depicts that the rate of corrosion process is inversely proportional to Ethanolic Extract of Lawsonia alba Lam. Leaves concentration, meaning that Ethanolic Extract of Lawsonia alba Lam. Leaves becomes more effective with increasing its concentration. So when the change of ρ_{corr} with the inhibitor concentration becomes steep (high negative value for constant B) it reflects good inhibitive properties for the studied inhibitor.

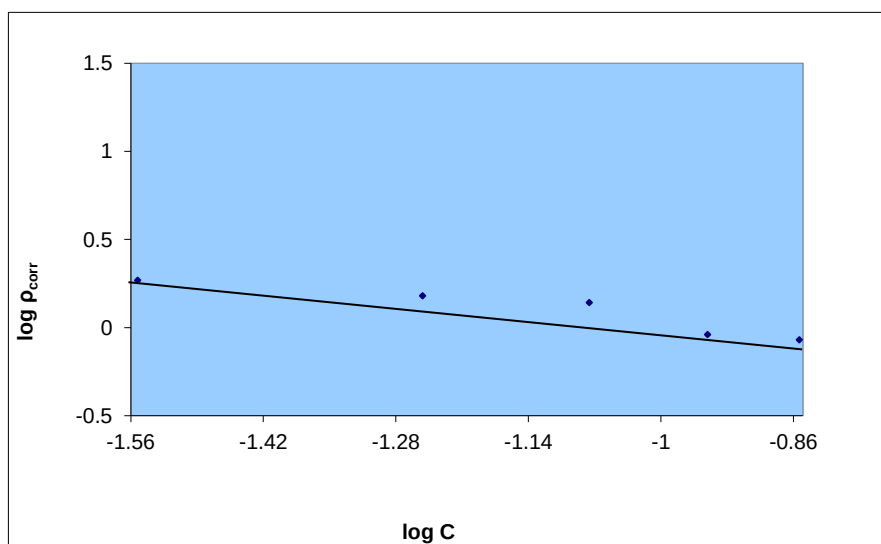


Fig. 4 $\log \rho_{\text{corr}}$ vs $\log C$ (at 24h & 303 ± 1K)

Corrosion reaction is an overall reaction in which both solid and liquid phases are consumed. It is therefore difficult to apply most of the principles of the chemical kinetics to corrosion reaction. A plot of the log of the measured weight of the aluminium after post treatment ($\log W_f$) against time (t) helps to explain the kinetics of the corrosion of aluminium in 0.5 N HCl in the corrodent and corrodent-inhibitor system. It is formulated [17-20] as:

$$\log W_f = \log W_o - Kt$$

where, W_f and W_o are the weights post treatment of coupons and initial weight before immersion respectively; K is the rate constant for corrosion process; and t is the immersion time (h). Fig 5 depicts the plot of logarithm of the weight of AA6063 after treatment ($\log W_f$) against time (t) at $303 \pm 1K$. A linear variation was observed in absence and presence of Ethanolic Extract of Lawsonia alba Lam. Leaves, thus confirming a first order kinetics.

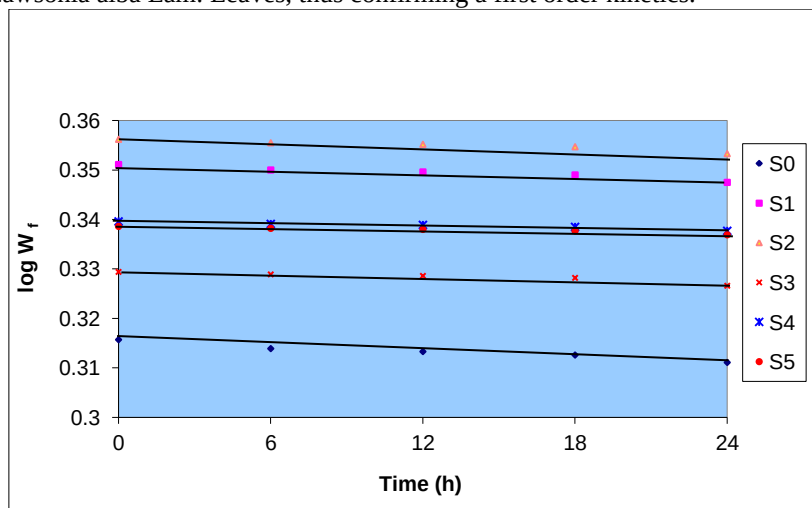
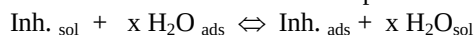


Fig.5. $\log W_f$ vs Immersion Time (h)

C. ADSORPTION ISOTHERMS

The primary step in action of inhibitors in acid solution is generally agreed to be adsorption on to the metal surface, which is usually oxide free in acid solutions. The adsorption of an inhibitor species, on metal surface in aqueous solutions should be considered a place exchanger reaction and the process can be expressed as:



where x, the size ratio, is the number of water molecules displaced by one molecule of inhibitor during adsorption process. In this process Bockris *et. al* [20] have assumed that water molecules dipoles have to be oriented and their orientation depends on the metal charge adapting the suitable adsorption isotherm. When the equilibrium of the process is reached, it is possible to obtain different expressions of the adsorption isotherm plots, and thus the degree of surface coverage $\{\theta = \text{IE} (\%) / 100\}$ can be plotted as a function of the concentration of the inhibitor under test.

It is widely acknowledged that adsorption isotherm provides useful insights into the mechanism of corrosion inhibition. The surface coverage, θ , was calculated. It is necessary to determine empirically which adsorption isotherm fits best to the surface coverage data in order to use the corrosion rate measurements to calculate the thermodynamic parameters pertaining to inhibitor adsorption. The obtained values of θ were fitted to different isotherm models including Langmuir, Frumkin, Temkin, Freundlich etc.

The Langmuir isotherm was found to fit well in the present case of inhibitor (i.e. Ethanolic Extract of Lawsonia alba Lam. Leaves), which is based on the assumption that all adsorption sites are equivalent and that particle binding occurs independently from nearby sites being occupied or not and also that the adsorbed molecule decreases the surface area available for the cathodic and anodic reactions to occur [15-16]. The adsorption equilibrium constant, K_{ad} , is expressed as:

$$K_{\text{ad}} C = \theta / (1 - \theta)$$

where C is the concentration of Ethanolic Extract of Lawsonia alba Lam. Leaves in g/L; θ the fractional surface coverage and K_{ad} is the adsorption equilibrium constant. By and large, the adsorption equilibrium constant (K_{ad}) was found to be large at higher concentrations of Ethanolic Extract of Lawsonia alba Lam. Leaves, hence it is inferred that higher concentration of Ethanolic Extract of Lawsonia alba Lam. Leaves is essential for maximum adsorption to form unimolecular layer. Also, the inhibitor species were attached to the corroding metal surface without lateral interaction between the adsorbed species.

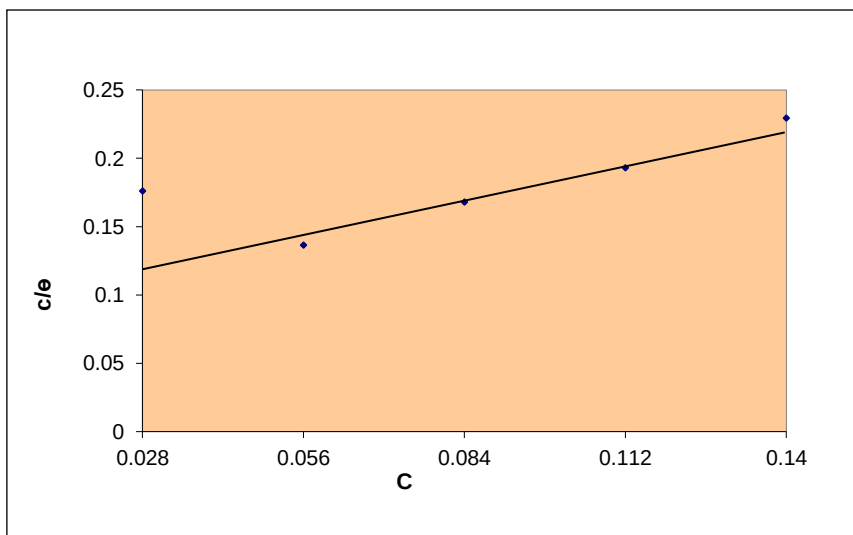


Fig. 6: Langmuir Adsorption Isotherm

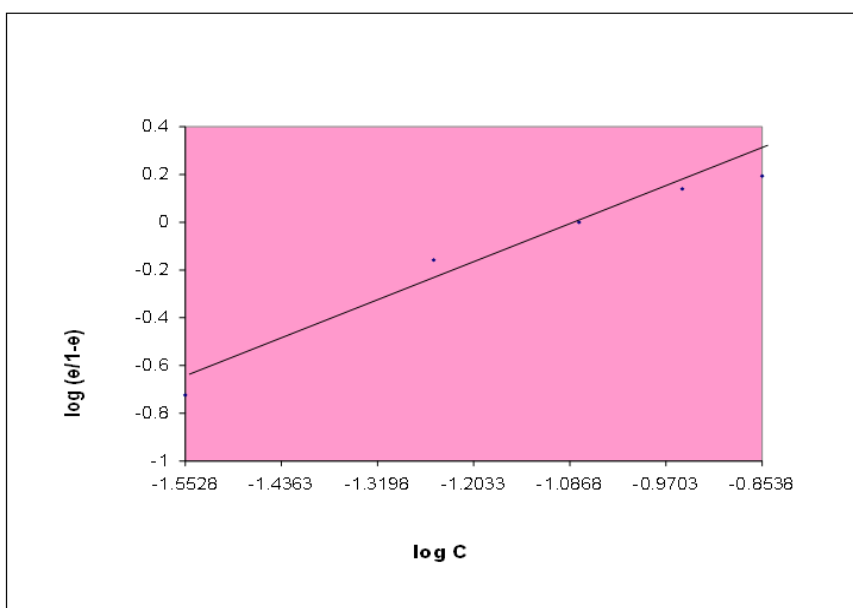


Fig.7 Thermodynamic Kinetic Model

The Langmuir adsorption isotherm can be rearranged to obtain the following mathematical formulation:

$$C/\theta = (1/K_{ad}) + C$$

A linear relationship was observed on plotting C/θ as a function of C , with a slope of almost equal to unity, and the value of the intercept is the reciprocal of K_{ad} [17-20]. Curve-fitting of the data according Langmuir thermodynamic-kinetic model at $303 \pm 1K$ is shown in Fig 6. The linear dependence of $\log \theta / (1 - \theta)$ as a function of $\log C$ is depicted by Fig 7.

The K_{ad} is related to the free energy of adsorption ΔG as:

$$K_{ad} = (1/C_{solvent}) \exp^{(-\Delta G/RT)}$$

where $C_{solvent}$ represents the molar concentration of the solvent (in case of water it is 55.5 mol/dm^3); R = universal gas constant $R = 8.314 \text{ JK}^{-1}\text{mol}^{-1}$; and T = temperature (K).

The values of thermodynamic functions are very approximate because the inhibition efficiency is dependent on time, and so is the surface coverage (θ). Moreover, the adsorption on isotherm used is only valid at low surface coverage, i.e. at low inhibitor concentrations. Also maintaining the temperature constant throughout experiment is not practically feasible. The fact that all thermodynamic functions are relative may be a result of strong adsorption of inhibitors on the surface of the electrode.

D. ELECTROCHEMICAL MEASUREMENTS

All electrochemical measurements were carried out with AUTOLAB frequency response analyzer (FRA) coupled to an AUTOLAB potentiostat connected to a computer. Corrosion current densities (i_{corr}) and corrosion potential (E_{corr}) were evaluated from the intersection of the linear anodic and cathodic branches of the PC as Tafel plots and the results were tabulated in Table-II. Linear polarization graphs were also plotted and analyzed for corrosion. Prior to each experiment, the surface pre-treatment of the working electrode was performed, as mentioned in the chemical method. For each run, a freshly prepared test solution as well as cleaned set of electrodes was used. All experiments were performed at temperature $303 \pm 1K$.

Anodic and cathodic polarization curves of AA6063 in 0.5 N HCl solutions devoid of and containing different concentrations of Ethanolic Extract of Lawsonia alba Lam. Leaves, were recorded. Beginning the experiments at cathodic potentials ensured that any oxide layer present prior to the start of the experiments was reduced. Figures 8-10 show the potentiodynamic polarization curves for aluminium in absence and presence of Ethanolic Extract of Lawsonia alba Lam. Leaves.

The electrochemical parameters R_p , i_{corr} , and E_{corr} , associated with polarization measurements for the test metal (AA6063) were simultaneously recorded. The values for electrochemical parameters, such as, corrosion potential (E_{corr}), corrosion current density (I_{corr}), R_p (Ω/cm^2), corrosion rate (mmpy) and IE (%) were tabulated in Table-II. On reviewing the observed results, it can be concluded that Ethanolic Extract of Lawsonia alba Lam. Leaves possesses anti-corrosive property for aluminium in aggressive solution.

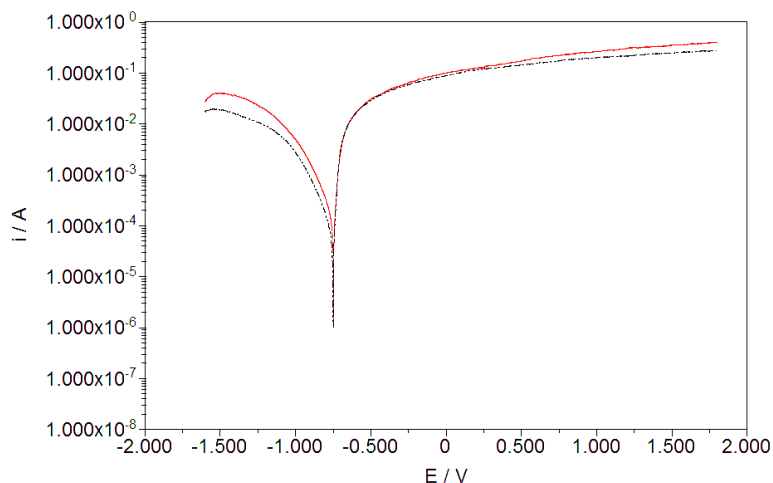


Fig. 8 Tafel Plot for Aluminium AA 6063 in Absence (Red Curve) and Presence of Ethanolic Extract of Lawsonia alba Lam. Leaves (0.140g/L) (Black Curve in 0.5 HCl

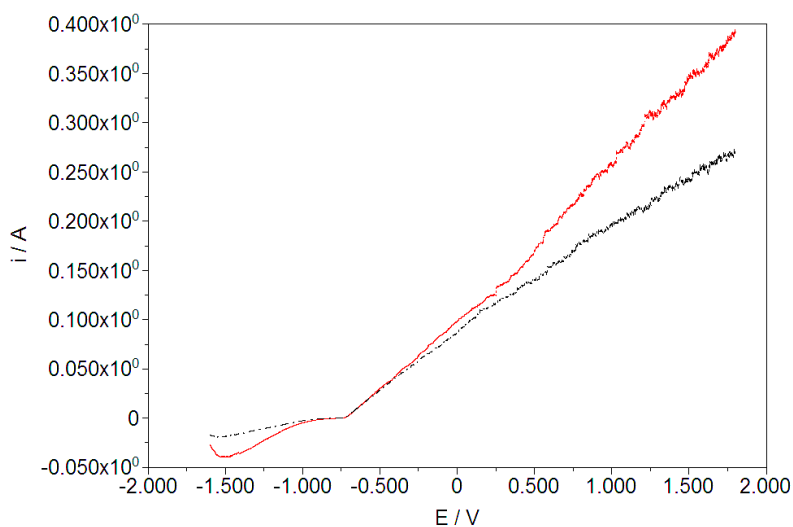


Fig. 9 Polarization Curves for Aluminium AA 6063 in Absence (Red Curve) and Presence of Ethanolic Extract of Lawsonia alba Lam. Leaves (0.140g/L) (Black Curve in 0.5 HCl

The potentiodynamic polarization curves exhibit Tafel-type behavior (Fig. 8) and illustrates that addition of Ethanolic Extract of Lawsonia alba Lam. Leaves (0.140 g/L) to the corrosive solution reduces the cathodic corrosion current density. A very negligible change in the anodic current density was observed with the addition of Ethanolic Extract of Lawsonia alba Lam. Leaves. The Tafel lines remain almost unchanged upon addition of Ethanolic Extract of Lawsonia alba Lam. Leaves. This observation suggests that Ethanolic Extract of Lawsonia alba Lam. Leaves is a mixed type of inhibitor and its molecules adsorb on the metal surface simply by blocking the active sites on the metal surface. [15,16,21].

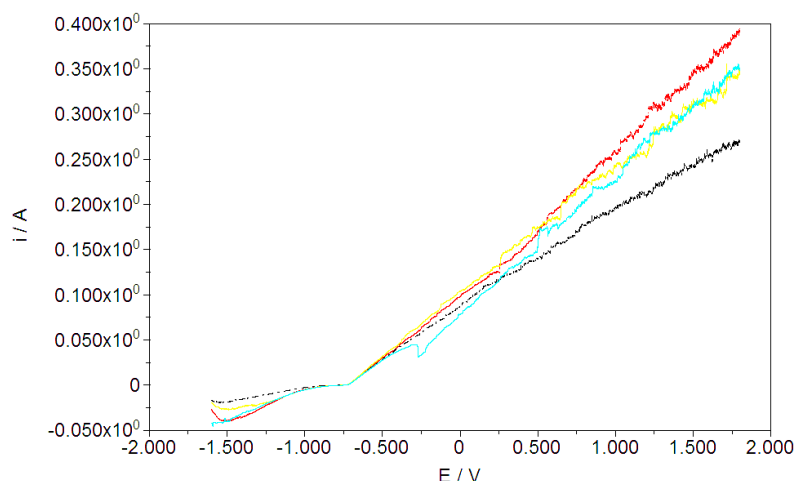


Fig. 10 Polarization Curves for Aluminium AA 6063 in Absence (Red Curve) and Presence of Different Concentrations of Ethanolic Extract of Lawsonia alba Lam. Leaves (0.084–0.140 g/L) [Cyan, Green, Black] in 0.5 HCl

Ethanolic Extract of Lawsonia alba Lam. Leaves concentration (g/L)	E_{corr} (mV)	I_{corr} (mA/cm ²)	R_p (Ω/cm ²)	I E (%)	Corrosion rate (mmpy)
0.000	-749	10.23	79.47	—	1.809×10^{-3}
0.084	-745	7.16	97.19	41.78	0.078×10^{-3}
0.112	-737	9.53	47.04	22.52	1.454×10^{-3}
0.140	-751	6.819	210.71	44.56	1.152×10^{-3}

Table: II. Electrochemical Parameters Of AA6063 In 0.5 N HCl Without and With Different Concentrations of Ethanolic Extract Of Lawsonia Alba Lam. Leaves.

Observations from Fig.9 and 10 and Table-II reveal that the addition of Ethanolic Extract of Lawsonia alba Lam. Leaves, in general, shifts the corrosion potential to less active direction (i.e. the positive values). However, this shift is very negligible; suggesting that adsorption of Ethanolic Extract of Lawsonia alba Lam. Leaves is at both the active sites and Ethanolic Extract of Lawsonia alba Lam. Leaves to be a mixed inhibitor. The data also reveal that corrosion current density, I_{corr} , decreased considerably and R_p values increased with respect to inhibitor concentrations. This suggests the inhibitive effect of Ethanolic Extract of Lawsonia alba Lam. Leaves towards AA6063 in acid medium. The I E (%) was observed to increase as the extract concentration is increased.

IV. CONCLUSIONS

- The Ethanolic Extract of Lawsonia alba Lam. leaves found to act as an inhibitor for corrosion of AA6063 in 0.5 N HCl media and metal dissolution was found to be inhibited to an acceptable degree.
- The values for the thermodynamic parameters for the inhibitor-metal interactions clearly indicate that adsorption of Ethanolic Extract of Lawsonia alba Lam. leaves on AA6063 in acid medium follows Langmuir adsorption isotherm.
- The nature of the adsorption of Ethanolic Extract of Lawsonia alba Lam. leaves on metal surface was evaluated as physisorption.
- The potentiodynamic polarization results confirm the corrosion inhibition by Ethanolic Extract of Lawsonia alba Lam. Leaves and is a mixed type inhibitor.
- On the basis of potentiodynamic investigations, it was found that Ethanolic Extract of Lawsonia alba Lam. Leaves behaves as mixed type of inhibitor for acid corrosion of AA6063 and mainly acts by blocking the active sites of AA6063.

REFERENCES

- [1] Punita Mourya, Sitashree Banerjee, M. M. Singh, "Corrosion inhibition of mild steel in acidic solution by *Tagetes erecta* (Marigold flower) extract as a green inhibitor", *Corros. Sci.*, vol. 85, pp. 352-363, Aug. 2014.
- [2] C. Kamal, M. G. Sethuraman, "*Spirulina platensis* – A novel green inhibitor for acid corrosion of mild steel", *Arabian Journal of Chemistry*, vol. 5, pp. 155-161, April 2012.
- [3] Sunday Aribio Sunday, J. Olusegun Leonard, J. Ibhadiyi Akinlabi, Oyetunji Davies, O. Folorunso, "Green inhibitors for corrosion protection in acidizing oilfield environment", *Association of Arab Universities for Basic and Applied Sciences*, vol. 24, pp. 34-38, Oct. 2017
- [4] Rekha N Nair, Green Corrosion Inhibitors for mild steel in acidic medium, *IJMTER*, vol.4, pp. 216-221, Dec. 2017

- [5] Rekha N Nair, Kharia Nemichand, I K Sharma, P S Verma and Alka Sharma, "Corrosion Inhibition Study of Aluminium in Acid Media by Mango (*Mangifera indica*) Leaves as Eco- Friendly Inhibitor" *J. Electrochem. Soc. India*, vol. 56, pp. 41-47, 2007
- [6] Alka Sharma, P S Verma, I K Sharma, and Rekha N Nair, "Energy Conservation through Combating Metal-Corrosion by Means of Natural Resources", *Proc. World Acad. Sci. Eng. Technol.*, vol. 39, pp. 745-753, 2009
- [7] Rekha N Nair, Shashi Sharma, I K Sharma, P. S. Verma, Alka Sharma, "Inhibitory Efficacy of Piper nigrum Linn. Extract on Corrosion of AA1100 in HCl", *RASYAN J. Chem.*, vol. 3, pp. 783-795, 2010
- [8] Shashi Sharma, Prassan Pratihar, Rekha N Nair, P S Verma, Alka Sharma, "Influence of Ion-Additives on Inhibitory Action of Extract of Trigonella Foenum Graceums seeds for AA6063 in Acid Medium", *RASYAN J. Chem.* Vol. 5, pp. 16-23, 2012
- [9] Rekha N Nair, Monika, Guddi Choudhary, Arpita Sharma, Alka Sharma, "Effect of elevation in temperature on inhibitory action of *Murraya koenigii* leaves on acid corrosion of AA6063, *IJST*, 4(4) (July-August 2014) 976-989.
- [10] Alka Sharma, Rekha N Nair, Arpita Sharma, Guddi Choudhury, "Combating Aluminium Alloy Dissolution by employing *Ocimum Tenuiflorum* leaves extract" *IJST*, vol.2, Dec. 2012.
- [11] C. Kamal, M. G. Sethuraman, "*Spirulina platensis* – A novel green inhibitor for acid corrosion of mild steel", *Arbian Journal of Chemistry*, vol. 5, pp. 155-161, April 2012.
- [12] S. Endrini, A. Rahmat, P. Ismail, T Yun Hin; "Anticarcinogenic Properties and Antioxidant Activity of Henna (*Lawsonia inermis*)" *J Med Sci.* vol. 2, pp. 194-197, 2002.
- [13] Botros R. Mikhaeil, Farid A. Badria, Galal T. Maatooq, Mohamed M. A. Amer, in: "Antioxidant and Immunomodulatory Constituents of *Henna* leaves", *Z. Naturforschung, C: J. Biosci.*, vol. 59, pp. 468-476, 2004.
- [14] K. S. Parikh, K. J. Joshi, in: "Use of Henna & Babul: Picking Inhibitors for Mild Steel in 5% Hydrochloric Acid", *Chem. Eng. World*, vol. 39, pp. 64-68, 2004.
- [15] A. Hamdy, Nour sh. El-Gendy, "Thermodynamic, adsorption and electrochemical studies for corrosion inhibition of carbon steel by henna extract in acid medium" *Egyptian Journal of Petroleum*, vol.22, pp. 17-25, June 2013.
- [16] Dharmendra Kumar, Vinay Jain, Beena Rai, "Unravelling the mechanisms of corrosion inhibition of iron by henna extract: A density functional theory study", *Corros. Sci.*, vol. 142, pp. 102-109, Sept. 2018
- [17] Laidler KJ, *Reaction Kinetics*, 1st ed., vol.1, Pergamon Press: New York, 1963
- [18] P. W. Atkins, J. de Paula, in: *Physical Chemistry*, Oxford University Press: NY, 2002
- [19] P. W. Atkins, in: *Chemisorbed and Physisorbed Species, A Textbook of Physical Chemistry*, University Press Oxford: NY, 1980, 936-938
- [20] J. O' M. Bockris and A. K. N. Reddy, in: *Modern Electrochemistry - Electrodics in Chemistry, Engineering, Biology, and Environmental Science*, 2nd ed., Kluwer Academic / Plenum Publishers: New York, 2B (2000).
- [21] M. Faustin, A Mciuk, P. Salvin, C. Roos, M. Lebrini, "Corrosion inhibition of C38 steel by alkaloids extract of *Geissospermum laeve* in 1 M hydrochloric acid: Electrochemical and phytochemical studies", *Corros. Sci.*, vo. 92, pp. 287-300, Mar. 2015.