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Research paper

Corrosion inhibition of aluminum in 2M HCL using chromolaena odorata leaf extract

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Abstract

Metal corrosion in acidic conditions, especially aluminum, poses major challenges to the industry and leads to great fiscal loss and safety problems. The development of green corrosion inhibitors has sparked growing interest due to their low toxicity and biodegradability in pursuit of sustainable results. In this research article, we analyze Chromolaena odorata leaf extract as a corrosion inhibitor on aluminum in 2.0 M hydrochloric acid using the weight loss method. The extract shows good inhibitory performance, and inhibition effectiveness increased with concentration. The extract reached a maximum efficiency of 99% at 5% v/v concentration. Adsorption of phytochemicals such as flavonoids and alkaloids onto the aluminum surface, which likely reduces corrosion. The adsorption behavior conformed to the Langmuir isotherm, indicating monolayer adsorption on the metal surface. These findings suggest that Chromolaena odorata can serve as a green alternative to conventional synthetic corrosion inhibitors.

Keywords: *Adsorption; Aluminum Corrosion; Chromolaena Odorata; Green Corrosion Inhibitors; Weight Loss Method.*

1. Introduction.

Corrosion degrades metal through an electrochemical reaction that aggressive environmental conditions instigate. In most cases, such corrosion leads to severe structural impairment, high maintenance costs, and downtime that converts to lost revenue, particularly in an industrial setting. Aluminum, with its low density and good electrical conductivity, generally resists corrosion in neutral environments. Hence, it often serves as the metal of choice in such applications. However, its durability decreases significantly in acidic environments, often found in processes such as cleaning, pickling, descaling, and refining. Therefore, aluminum components require protection in these operations. Corrosion inhibitors are among the most common practical approaches to mitigate corrosion. Such materials are thought to act by adsorbing onto the metal surface, thereby interfering with corrosion processes. Inorganic and synthetic organic inhibitors, though relatively effective, are mostly toxic and harmful to the environment, for example, phosphates and chromates [1 - 3].

Therefore, with increasing environmental awareness, developing alternatives that are safer and do not harm the environment is pressing. The development of natural plant-based inhibitors has been an area of increasing interest. Such materials are biodegradable, renewable, relatively cheap, and environmentally safe [4 - 6]. Recent reviews in Green Chemistry and the Journal of Cleaner Production further reinforce this trend, highlighting the effectiveness and sustainability of plant-based and amino acid-derived inhibitors in acid media [7], [8]. Researchers have actively explored various plant extracts as green corrosion inhibitors for metals in acid media. Studies have reported effective inhibition performance from Azadirachta indica, Ziziphus jujuba, Lawsonia inermis, and Musa paradisiaca, among others [9 - 12]. These plants owe their protective effects to phytochemicals such as polyphenols, which adsorb onto metal surfaces and hinder corrosion reactions. Despite this progress, there remains a lack of direct comparative studies that evaluate the efficiency and mechanism of different plant extracts under similar conditions. This gap highlights the need for further investigation into underexplored candidates like Chromolaena odorata in specific corrosive environments.

Phytochemicals in plant extracts adsorb onto metal surfaces, actively inhibiting corrosion reactions. One such extract is Chromolaena odorata, otherwise known as Siam weed, an invasive species very rich in biologically active compounds. Traditionally recognized for its medicinal properties, it possesses antimicrobial and antioxidant activities [13], [14]. The corrosion-inhibiting ability of Chromolaena odorata is attributed to the presence of flavonoids, alkaloids, saponins, and tannins. The inhibition is likely due to adsorption of phytochemicals, which can reduce corrosion by impeding the metal's interaction with aggressive ions. [15 - 17]. Even though ample studies have been carried out regarding the anticorrosive properties of this plant in various media, research on its application in hydrochloric acid media for aluminum protection remains limited [18], [19]. This study evaluates Chromolaena odorata leaf extract as a corrosion inhibitor for aluminum immersed in 2.0 M HCl solution. Furthermore, the adsorption behavior of the extract on aluminum is investigated to elucidate its inhibition mechanism, highlighting its potential as a sustainable corrosion inhibitor for industrial use.

2. Materials and methods

2.1. Preparation of extract solution

Fresh leaves of Chromolaena odorata were gathered, thoroughly washed, and left to dry in the shade for seven days. Once fully dried, the leaves were ground into a fine powder. The preparation of the extract involved heating 4 grams of the powdered material under reflux with 200 mL of ethanol at 78°C for one hour. The filtered solution served as the stock for preparing various concentrations of the corrosion inhibitor. [20], [21].

2.2. Preparation of aluminum coupons

Aluminum sheets cut into coupons, with dimensions 2cm × 3cm × 1mm. The coupons were polished with fine-grade emery paper, degreased with ethanol, dried in acetone, and weighed before immersion in test solutions [22], [23].

2.3. Preparation of electrolyte

A standard solution of hydrochloric acid was prepared to a 2M concentration. Using percentage by volume, varying volumes of the 2M stock solution were mixed with appropriate volumes of the inhibitor stock solution and brought up to the 100 mL mark.
The varied volumes of the inhibitor extracts: (%v/v): 3 mL, 5 mL, 10 mL, 15 mL, and 20 mL.
The varied acid volume (%v/v): 97 mL, 95 mL, 90 mL, 85 mL and 80 mL.
The acid was standardized to a 2M concentrated solution by dissolving a specific volume of the acid in 1 dm3 of water. The specific volume of the acid was calculated using the formula below:

$$\text{Volume} = \frac{\text{molar mass x concentration x 100}}{\text{\%purity x density}} \quad (1)$$

where the molar mass, desired concentration, % purity, and density of the acid are used to determine the exact volume required [24], [25]. The expression is explained as;
Molar mass of the acid,
Concentration required/concentration to be standardized (2)
% purity of the stock acid,
Density/specific gravity of the stock acid (3)

3. Results and discussion

3.1. Weight loss method

The method involved immersing pre-weighed aluminum coupons in an electrolyte composed of 2M hydrochloric acid and different concentrations of Chromolaena odorata extract, with a total volume of 100 mL. The experiment took place at room temperature, and the beakers remained open throughout the test duration. Snapshots captured different exposure stages over 12 hours, with immersion intervals of three hours. Observations made at three-hour intervals showed physical changes in the metal coupons and the electrolyte. After every three-hour immersion, the coupons were withdrawn from the solution and gently scrubbed under running water with a stiff brush to eliminate surface residues. The cleaned coupons were then rinsed with ethanol, dried using acetone, and reweighed. These measurements were recorded as the final weights for each time interval [26 - 28]. Weight loss was calculated as the difference between the initial mass before immersion and the mass after each three-hour interval.

Table 1: The Weight Loss of Aluminium Coupons in Hydrochloric Acid with and Without Chromolaena Odorata Extract After 3 Hours, 6 Hours, 9 Hours and 12 Hours

	Sample	Inhibitor concentration (v/v%)	Initial weight (W_o)	Final weight (W_1)	Weight loss	Inhibitor concentration (%IE)
After 3 hours	Control c1	Control	2.8322	2.6230	0.2092	
	A1	1	2.5419	2.5065	0.0354	83
	A2	2	2.6323	2.6054	0.0269	87
	A3	3	2.5303	2.5142	0.0161	92
	A4	4	2.7036	2.6933	0.0103	95
	A5	5	2.8113	2.8091	0.0022	99
	Control c1	Control	2.6433	2.0813	0.5620	
	A1	1	2.7036	2.3137	0.1059	81
After 6 hours	A2	2	2.5938	2.4987	0.0941	83
	A3	3	2.8662	2.7935	0.0727	87
	A4	4	2.7017	2.6512	0.0505	91
	A5	5	2.5422	2.5214	0.0211	96
	Control c1	Control	2.5001	2.1190	0.3811	
	A1	1	2.6301	2.4941	0.1360	64
	A2	2	2.6616	2.5435	0.1181	69
After 9 hours	A3	3	2.5938	2.4872	0.1066	72
	A4	4	2.7077	2.6209	0.0868	77
	A5	5	2.5656	2.4899	0.0757	80

	Control c1	Control	2.8143	2.3898	0.4245	
	A1	1	2.7311	2.5529	0.1782	58
After 12 hours	A2	2	2.7727	2.6162	0.1565	63
	A3	3	25992	2.4512	0.1480	65
	A4	4	2.7377	2.6104	0.1273	70
	A5	5	2.6061	2.4958	0.1103	74

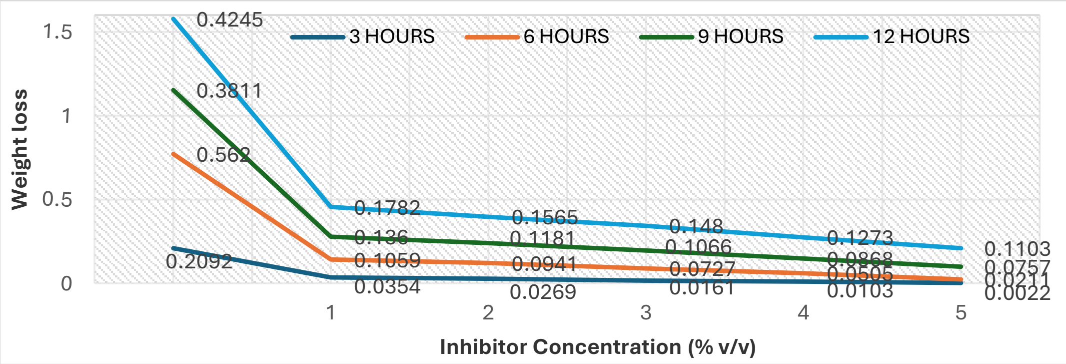

Fig. 1: Plot of Weight Loss Against Chromolaena Odorata Concentration After 3 Hours, 6 Hours, 9 Hours, and 12 Hours.

3.2. Corrosion rate

Table 1 and Figure 1 show that the inhibitor concentration increases and the corrosion rate decreases. Therefore, Chromolaena odorata leaf extract provides protective effects on aluminum. The results showed that the corrosion rate dropped significantly when coupons were immersed in solutions containing the extract compared to those without it. This behavior is commonly attributed to the adsorption of phytochemical compounds onto the metal surface, which may form a protective barrier that limits the metal's exposure to corrosive agents and slows metal dissolution [29 - 31]. However, further surface analysis is required to confirm the exact inhibition mechanism.

Table 2: Inhibitor Concentration, Inhibitor Efficiency, and Surface Coverage After 3 Hours, 6 Hours, 9 Hours, and 12 Hours

Time	Concentration (C, %v/v)	Efficiency (%)	Surface coverage (θ)	C/θ
	1	83	0.83	1.2048
	2	87	0.87	2.2989
	3	92	0.92	3.2609
After 3 hours	4	95	0.95	4.2105
	5	99	0.99	5.0505
	1	81	0.81	1.2346
	2	83	0.83	2.4096
	3	87	0.87	3.4483
After 6 hours	4	91	0.91	4.3956
	5	96	0.96	5.2083
	1	64	0.64	1.5625
	2	69	0.69	2.8986
	3	72	0.72	4.1667
	4	77	0.77	5.1948
After 9 hours	5	80	0.80	6.2500
	1	58	0.58	1.7241
	2	63	0.63	3.1746
	3	65	0.65	4.6154
After 12hours	4	70	0.70	5.7143
	5	74	0.74	6.7568

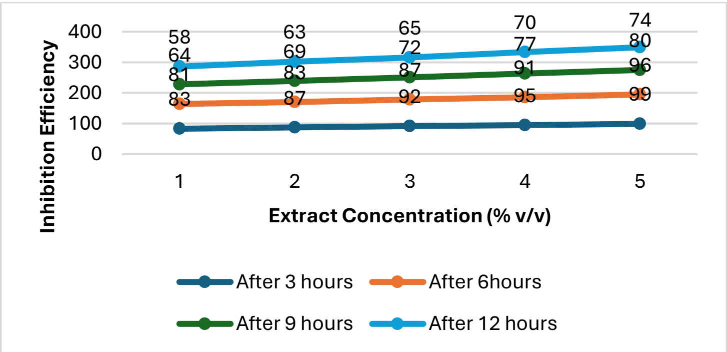

Fig. 2: Plot of inhibition efficiency against Chromolaena odorata extract concentration after 3 hours, 6 hours, 9 hours, and 12 hours.

3.3. Inhibition efficiency

Inhibition efficiency reflects the ability of the extract to inhibit metal corrosion. As shown in Table 2 and Figure 2, increasing the concentration of Chromolaena odorata extract raised the inhibition efficiency. This trend suggests that higher extract concentrations promote greater adsorption of active molecules onto the metal surface, strengthening the protective barrier. Furthermore, the improved efficiency correlates with reduced weight loss, confirming the extract's role as an effective green corrosion inhibitor [32 - 34].
We calculated inhibition efficiency (%I) using the equation:

$$\%I = \frac{W_o - W_1}{W_o} \times 100 \tag{4}$$

Where.
W_o is the uninhibited weight loss.
W_1 is the inhibited weight loss

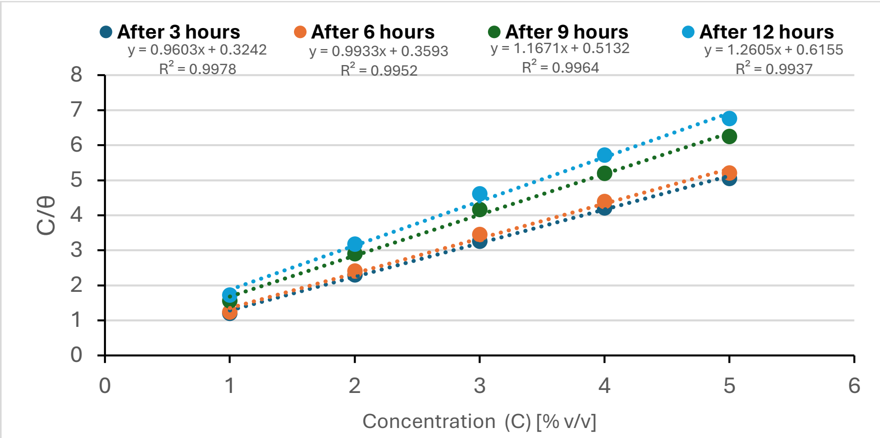

Fig. 3: Langmuir adsorption isotherm plots of C/θ against C after 3 hours, 6 hours, 9 hours, and 12 hours.

3.4. Adsorption mechanism

The adsorption inhibition of aluminum by Chromolaena odorata extract appears to be associated with the adsorption of the extract's constituents onto the metal surface. Adsorption data in Table 2 and Figure 3 show that the inhibitor obeys the Langmuir adsorption isotherm, indicating monolayer adsorption of inhibitor molecules onto specific sites on the aluminum surface without interactions between adsorbed species [35 - 37]. The Langmuir isotherm is represented by the equation:

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C$$

Where C is the inhibitor concentration and θ is the surface coverage, while $K_{ads}It$ is the adsorption equilibrium constant that reflects the strength of the adsorption process. This model assumes uniform adsorption sites and equal adsorption energy for each molecule. To determine Langmuir parameters, surface coverage (θ) was calculated using the inhibition efficiency (%I) at varying inhibitor concentrations (C). A plot of C/θ versus C yielded a linear fit with a slope near 1 and a high correlation coefficient (R^2 ranging from 0.9937 to 0.9978), supporting that the adsorption follows the Langmuir isotherm. The Langmuir fit suggests that surface coverage increases linearly with concentration up to saturation, where each inhibitor molecule occupies a distinct site. This leads to the formation of a monolayer film that may acts as a barrier between the aluminum surface and the corrosive medium. The observed high inhibition efficiencies further suggest strong adsorption and effective corrosion resistance [38], [39].

3.5. Time-Dependent Inhibition Behavior

The inhibition efficiency of Chromolaena odorata leaf extract decreased with increased immersion time, as shown in Table 2. This decline may result from the gradual desorption or degradation of the protective film formed by the phytochemicals on the aluminum surface. Over time, acidic conditions may weaken the metal–inhibitor interaction, leading to partial or complete desorption of the adsorbed molecules [40], [41]. In addition, bioactive compounds such as flavonoids, alkaloids, and tannins may degrade or undergo chemical changes under prolonged acidic exposure, limiting their long-term effectiveness. These compounds are biodegradable and susceptible to modification in low pH environments [42]. These findings highlight the need for further research on the long-term stability of the inhibitor film. Advanced surface analysis techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) could help examine the film's composition and morphological changes over time, providing insights into its degradation and surface interaction behavior [43], [44].

3.6. Phytochemical Composition of Chromolaena odorata

The corrosion inhibition observed with Chromolaena odorata leaf extract can be attributed to its high phytochemical content, as supported by adsorption studies. Phytochemical analyses in earlier research have revealed the presence of flavonoids, alkaloids, tannins, saponins, and phenolic compounds in the plant. It is believed that such bioactive compounds may adsorb chemically or physically on the metal surface, potentially forming a protective layer that hinders corrosion [45]. These compounds are thought to adsorb onto the metal surface, forming a protective film that may reduce interaction with the acidic environment. Flavonoids and tannins likely donate lone electron pairs through hydroxyl and aromatic groups, facilitating adsorption. Alkaloids may contribute via nitrogen groups, enhancing coordination bonding with metal atoms [46]. Saponins are reported to lower surface tension, which could improve extract wetting and surface coverage.

These phytochemicals may act synergistically to create a stable protective barrier on the aluminum surface [47], [48]. This synergy is believed to arise from the combination of different functional groups, such as hydroxyl, nitrogen, and aromatic rings, which contribute to varied and complementary adsorption interactions. The effectiveness demonstrated in this study suggests that these bioactive constituents form durable films that significantly hinder aluminum corrosion.

4. Conclusion

Chromolaena odorata extract was found to effectively inhibit the corrosion of aluminum coupons in 2 M HCl, with a minimum inhibition efficiency increasing alongside extract concentration and decreasing over prolonged exposure. These results confirm its potential as a sustainable corrosion inhibitor. Given its high efficiency, Chromolaena odorata extract shows promise for use in corrosion-prone environments such as the petroleum and marine industries. To advance its application, further studies should assess its performance in other acid media like H_2SO_4, validate the inhibition mechanism using electrochemical methods such as potentiodynamic polarization and electrochemical impedance spectroscopy, and investigate long-term stability. Exploring industrial scalability and synergistic effects with other natural inhibitors will also be valuable for practical implementation.

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Conflict of research

The author declares that there are no conflicts of interest regarding the publication of this research.

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