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ORIGINAL RESEARCH ARTICLE

Factor Interactions Governing Aluminium Corrosion Inhibition by *Sida acuta* Leaf Extract: Response Surface Methodology and Gravimetric Study

Okpanachi Clifford Baba[1]*, Ameh Ekwu Mark[2], Onoyima Christian Chinweuba[3], Ekwoba Lucky[2], Larayetan Rotimi[2], Abalaka Edwin[2] and Ejukwa Emmanuel[2]
[1]Department of Industrial Chemistry, Federal University of Applied Sciences, Kachia, Kaduna State, Nigeria
[2]Department of Pure and Industrial Chemistry, Prince Abubakar Audu University, Anyigba, Kogi State, Nigeria
[3]Department of Chemistry, Nigeria Police Academy, Wudil, Kano State, Nigeria

ABSTRACT
The growing demand for environmentally benign corrosion inhibitors has intensified research into plant-based alternatives to toxic synthetic chemicals. This study evaluated the corrosion-inhibition performance of Sida acuta leaf extract on aluminum in 0.1 M H_2SO_4 using gravimetric techniques and optimizing via Response Surface Methodology (RSM). A Box–Behnken design investigated the combined effects of immersion time (24–168 h), temperature (20–60 °C), and inhibitor concentration (1–7 % v/v) on inhibition efficiency (IE). Experimental IE values ranged from 46.86% to 88.83%, indicating strong dependence on operational conditions. High efficiencies were observed at short exposure times and mild temperatures, including 82.17 % at 24 h, 20 °C, 4 % v/v, and 80.76 % at 24 h, 40 °C, 7 % v/v, with the highest experimental IE (88.83 %) at 96 h, 20 °C, 7 % v/v, reflecting rapid adsorption and protective film formation. The RSM model predicted a maximum IE of 88.81 % at 24 h, 20 °C, and 7 % v/v, indicating optimal protection under low-temperature, moderate-exposure conditions. Extended immersion and elevated temperatures reduced protection, with minimum IE values of 50.56 % and 46.86 % at 168 h, 60 °C, 1 % v/v. Fit summary statistics confirmed the linear model as most suitable (sequential $p < 0.0001$; adjusted $R^2 = 0.7586$; predicted $R^2 = 0.5895$), while sequential sum of squares highlighted significant linear effects ($F = 17.76$, $p < 0.0001$) and negligible contributions from interaction ($F = 0.6638$, $p = 0.5930$) and quadratic terms ($F = 0.2166$, $p = 0.8819$), with the cubic model being significant but aliased. ANOVA further identified immersion time ($F = 33.96$) and temperature ($F = 15.15$) as dominant factors, though the significant lack-of-fit suggests caution in over interpreting predictions. Overall, *Sida acuta* leaf extract demonstrates strong potential as a sustainable green inhibitor, particularly under short-term, low-temperature conditions.

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INTRODUCTION
Corrosion continues to challenge materials engineering, compromising structural integrity and causing significant economic losses, particularly for metals like aluminium, which is widely used in aerospace, automotive, and packaging industries due to its low density, mechanical strength, and natural passivation (Alrasheedi *et al.*, 2024; Liu *et al.*, 2024). In aggressive environments, especially acidic or chloride-rich media, the protective oxide layer on aluminium deteriorates, leading to localized corrosion and accelerated material degradation (Adamu & Salisu, 2024; Habibu et al., 2023; Ibrahim et al., 2023).

Plant-based inhibitors have emerged as environmentally benign alternatives to conventional synthetic chemicals (Badeji, 2025; Ogueji et al., 2023; Ogueji & Ugwumba, 2024), offering renewable, non-toxic, and cost-effective solutions (Fouda *et al.*, 2024). Phytochemicals such as tannins, flavonoids, alkaloids, and phenolics can adsorb onto metal surfaces via π-electron donation, hydrogen bonding, and metal–ligand interactions, forming protective films that hinder both anodic and cathodic corrosion processes (Sheydaei, 2024; Okonji and Lawal, 2025). While numerous studies report the efficacy of extracts from plants such as Carica papaya and Azadirachta indica for steel and aluminum (Ait Bouabdallah *et al.*, 2024), the application of *Sida acuta* leaves remains underexplored.

Importantly, most prior studies focus on inhibition efficiency at fixed conditions, without systematically evaluating how immersion time, temperature, and inhibitor concentration interact to influence corrosion

Correspondence: Okpanachi Clifford Baba. Department of Industrial Chemistry, Federal University of Applied Sciences, Kachia, Kaduna State, Nigeria. ✉ cliffordokpanachi@yahoo.com.
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performance. Here, the novelty lies not only in using *Sida acuta* as a green inhibitor of aluminum in an acidic medium, but also in employing Response Surface Methodology (RSM) to quantify the combined effects of process parameters and optimize conditions for maximal protection.

This approach allows identification of synergistic and antagonistic interactions among variables, providing predictive models that can guide practical application. In this study, *Sida acuta* leaf extract was evaluated for its corrosion-inhibition efficiency on aluminum in 0.1 M H_2SO_4, with immersion time, temperature, and extract concentration systematically varied. By integrating experimental gravimetric analysis with RSM-based statistical modeling, the work highlights both the inhibitory potential of *Sida acuta* and an optimization framework for process, advancing knowledge of sustainable, cost-effective, and eco-friendly corrosion mitigation strategies.

METHODOLOGY

2.1 Materials

All reagents were analytical grade and used as received. Laboratory glassware included beakers, volumetric flasks, measuring cylinders, spatulas, stirring rods, retort stands, a manual analytical balance, and a hot plate. Chemicals for preparation and treatment included concentrated H_2SO_4 (98%), ethanol, acetone, and distilled water.

2.2 Sample Collection and Preparation

Fresh *Sida acuta* leaves were collected from Anyigba, Kogi State, Nigeria, rinsed with distilled water, shade-dried for five days, milled into fine powder, and stored in airtight containers.

2.3 Plant Extract Preparation

40 g of powdered leaves were Soxhlet-extracted with 180 mL of ethanol for 4 h. The extract was concentrated and filtered, then used as the stock solution for inhibitor preparation. All % v/v concentrations are relative to this stock (e.g., 7 mL stock in 100 mL corrosive solution = 7% v/v).

2.4 Phytochemical Screening

Standard qualitative methods were used to detect alkaloids, tannins, flavonoids, and saponins.

2.5 Aluminum Coupon Preparation

Rectangular aluminum coupons (2 × 2 × 0.2 cm) with a central 0.2 cm hole were polished, degreased with acetone, rinsed with distilled water, air-dried, and stored in a desiccator. Initial mass was recorded. The effective exposed surface area excludes the drilled hole.

2.6 Test Solution Preparation

0.1 M H_2SO_4 was prepared by diluting 5.43 mL of concentrated acid into 500 mL of distilled water, cooled to ambient temperature, then made up to 1 L. Solutions were homogenized and stored in labeled containers.

2.7 Experimental Design and Gravimetric Procedure

Corrosion inhibition experiments used a Box–Behnken Design (BBD) in Design-Expert v13 with three factors: immersion time (24 –168 h), temperature (20–60 °C), and inhibitor concentration (1–7% v/v). 17 experimental runs were performed, each in triplicate (n = 3). The replicate center-point runs (runs 1, 5, 12, 15, and 17) were included to estimate pure error and assess model lack of fit (Table 1). Gravimetric weight loss measurements were used to calculate corrosion rate and inhibition efficiency, using the corrected coupon surface area. ANOVA and 3D response surfaces were used to evaluate main, interaction, and cube effects.

2.8: Weight Loss (Gravimetric) Measurements and Response Surface Methodology

Gravimetric measurements were used to assess the corrosion-inhibition performance of Sida acuta leaf extract on aluminum under total-immersion conditions. Aluminum coupons were immersed in 0.1 M H_2SO_4 solutions, both without an inhibitor and with varying concentrations of the extract, acting as a green corrosion inhibitor. The experiments were designed using a Box–Behnken design to systematically evaluate the combined effects of immersion time, temperature, and inhibitor concentration. Immersion periods ranged from 24 to 168 h, extract concentrations ranged from 1 to 7 v/v %, and temperatures were maintained at 20–60 °C using a thermostatically controlled water bath to ensure stable and reproducible conditions.

At the completion of each immersion period, the coupons were withdrawn, rinsed thoroughly with distilled water, gently polished with fine-grade emery paper to remove corrosion products, degreased with acetone, and air-dried before final weighing. Weight loss was determined as the difference between the initial and final masses, and inhibition efficiency (IE%) was calculated using standard gravimetric equations.

The obtained experimental data were analyzed using Response Surface Methodology (RSM) implemented in Design-Expert software (Version 13). This approach enabled quantitative evaluation of the individual and synergistic effects of the process variables on corrosion rate and inhibition efficiency. Three-dimensional response surface plots and regression models were generated to identify optimal inhibition conditions and to assess the predictive reliability and robustness of the developed model.

Weight loss was calculated by finding the difference between the weight of each coupon before and after immersion;

$$\Delta W = W_b - W_a \quad (1)$$

Where W_b is the weight before immersion, Wa is the weight after immersion.

Inhibition efficiency was calculated as

$$IE\% = \frac{Wo - W1}{Wo} \times 100 \quad (2)$$

Where W_1 and W_o are the weight loss values in the presence and absence of the inhibitor, respectively, IE% is the inhibition efficiency.

Table 1: Experimental Range of the Independent Variables, With Factor Levels for the Inhibition of *Sida acuta* leaf Extract on Aluminium in 0.1M H_2SO_4 Solution

Independent Variable	Symbols	Range and Levels		
		-1	0	+1
Time of Exposure (h)	X_1	24	96	168
Temperature of the solution (°C)	X_2	20	40	60
Inhibitor concentration in the extract (v/v)	X_3	1	4	7

RESULTS AND DISCUSSION

3.1 Box–Behnken Response for the Inhibition Efficiency of *Sida acuta* Leaf Extract

The corrosion inhibition performance of *Sida acuta* leaf extract on aluminium was evaluated across varying immersion times (24–168 h), temperatures (20–60 °C), and extract concentrations (1–7 v/v). The data (Table 2) revealed that inhibition efficiency is strongly dependent on both the extract concentration and the operational temperature. High efficiencies were observed at short immersion times, with peak values of 82.17% (24 h, 20 °C, 4 v/v) and 80.76% (24 h, 40 °C, 7 v/v), indicating rapid adsorption of the phytochemical constituents onto the aluminium surface and the formation of an effective protective film (Mungwari, 2024).

As the immersion period extended, inhibition efficiencies decreased markedly, reaching 56.87% (168 h, 40 °C, 1 v/v) and 50.56% (168 h, 60 °C, 1 v/v), suggesting partial desorption and gradual degradation of the protective layer under prolonged exposure (Nesane *et al*., 2023). Temperature exerted a notable influence on performance: low to moderate temperatures (20–40 °C) maintained high surface coverage and inhibition, while higher temperatures (60 °C) consistently reduced efficiency (e.g., 52.63% at 96 h, 1 v/v), reflecting the thermal sensitivity of the adsorbed phytochemicals (Abu Orabi *et al*., 2024).

Extract concentration also played a critical role in corrosion mitigation. Increasing the extract content enhanced surface coverage, as evidenced by the maximum inhibition of 88.83% observed at 96 h, 20 °C, and 7 v/v. Conversely, lower concentrations (1 v/v) were less effective, particularly under high-temperature and long-duration conditions.

3.2 Main Effects For Inhibition Efficiency By *Sida Acuta* Leaf Extract

3.2.1 Effect of Time

Figure 1 presents the influence of immersion time on the inhibition efficiency of *Sida acuta* leaf extract for aluminium in acidic medium. The inhibition efficiency decreased progressively with increasing exposure time. At the initial stages of immersion, high efficiency values were recorded, indicating rapid adsorption of phytochemical constituents onto the aluminium surface. With prolonged immersion, however, a gradual decline in efficiency was observed, suggesting reduced stability of the protective film over time (Motawea, 2025).

Table 2: Design Matrix and Response for the Inhibition Efficiency by the *Sida acuta* Leaf Extracts

Run	Time (h)	Temp (°C)	Conc. (v/v)	Inhibition Efficiency (%)
1	96	40	4	67.74
2	168	60	1	50.56
3	24	40	7	80.76
4	24	60	4	72.39
5	96	40	4	67.74
6	96	60	1	52.63
7	24	20	4	82.17
8	24	40	1	75.48
9	96	60	7	64.31
10	168	60	4	58.35
11	96	20	7	88.83
12	96	40	4	67.72
13	96	20	1	70.35
14	168	20	4	61.87
15	96	40	4	67.74
16	168	40	1	56.87
17	96	40	4	67.72

This reduction can be attributed to the desorption of adsorbed inhibitor molecules due to changes at the metal–solution interface. Prolonged exposure increases the kinetic energy of inhibitor molecules, weakening the intermolecular forces responsible for adsorption and reducing surface coverage (Ezzat and Mabrouk, 2024).

Additionally, extended immersion facilitates competitive adsorption by aggressive ions such as H^+ and SO_4^{2-}, which disrupt the organic film and accelerate its degradation.

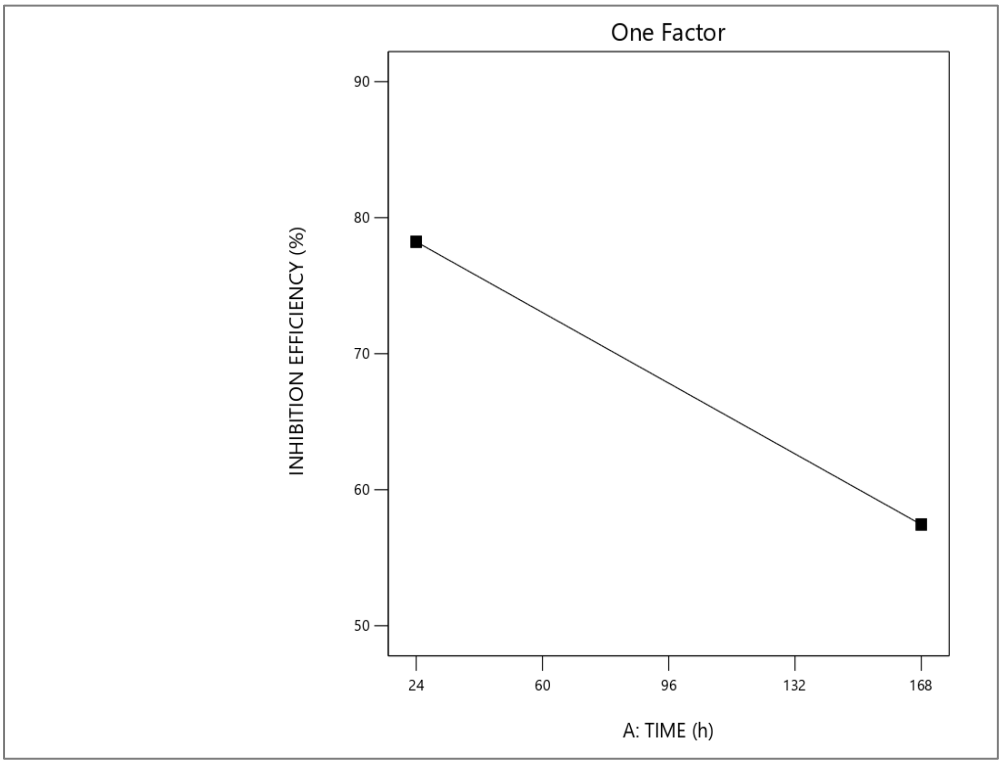

Figure 1: Effect of Time on the Inhibition Efficiency by *Sida acuta* Leaf Extract

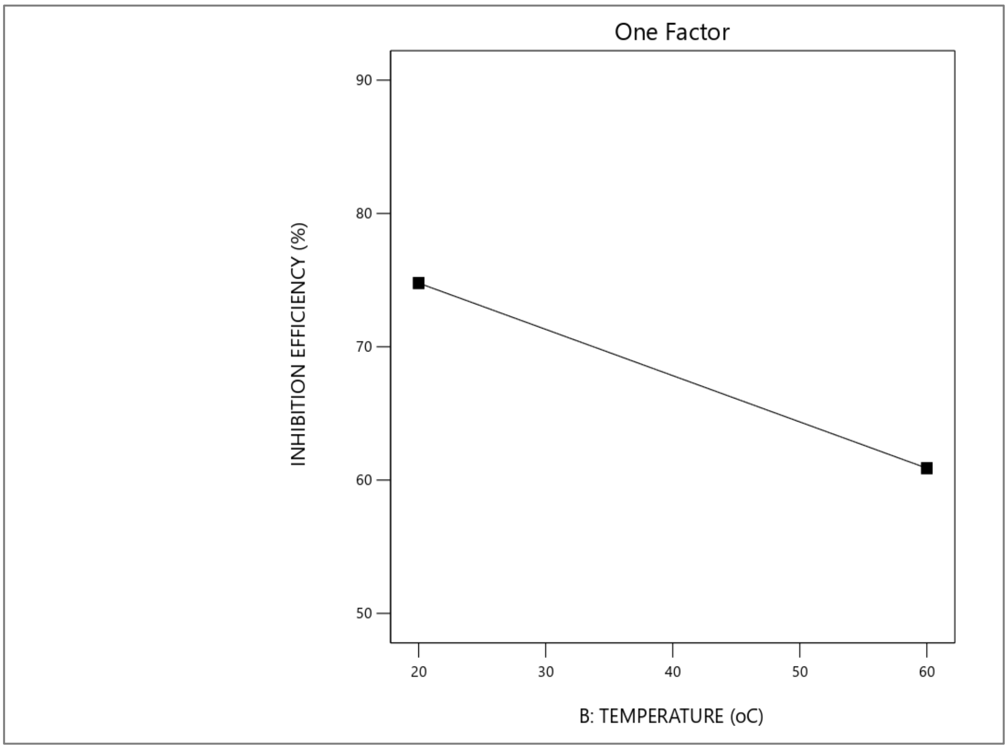

Figure 2: Effect of Temperature on the Inhibition Efficiency by *Sida acuta* Leaf Extract

Chemical transformation of phytochemicals under acidic conditions may further contribute to the decline in efficiency. Compounds such as tannins, flavonoids, and phenols are susceptible to hydrolysis and oxidative degradation during long exposure, reducing their effective concentration and ability to sustain surface protection (Tang *et al*., 2024). Overall, the observed trend reflects an adsorption-controlled inhibition mechanism in which adsorption dominates at short times, while desorption and film breakdown become significant at longer immersion durations.

3.2.2 Effect of Temperature

Figure 2 illustrates the effect of temperature on the inhibition efficiency of *Sida acuta* leaf extract on aluminium. A consistent decrease in inhibition efficiency with increasing temperature was observed, indicating that the inhibition process is temperature-sensitive. Higher efficiencies at lower temperatures suggest strong adsorption of phytochemicals onto the aluminium surface, while elevated temperatures weaken this protective interaction (Perumal *et al.*, 2023).

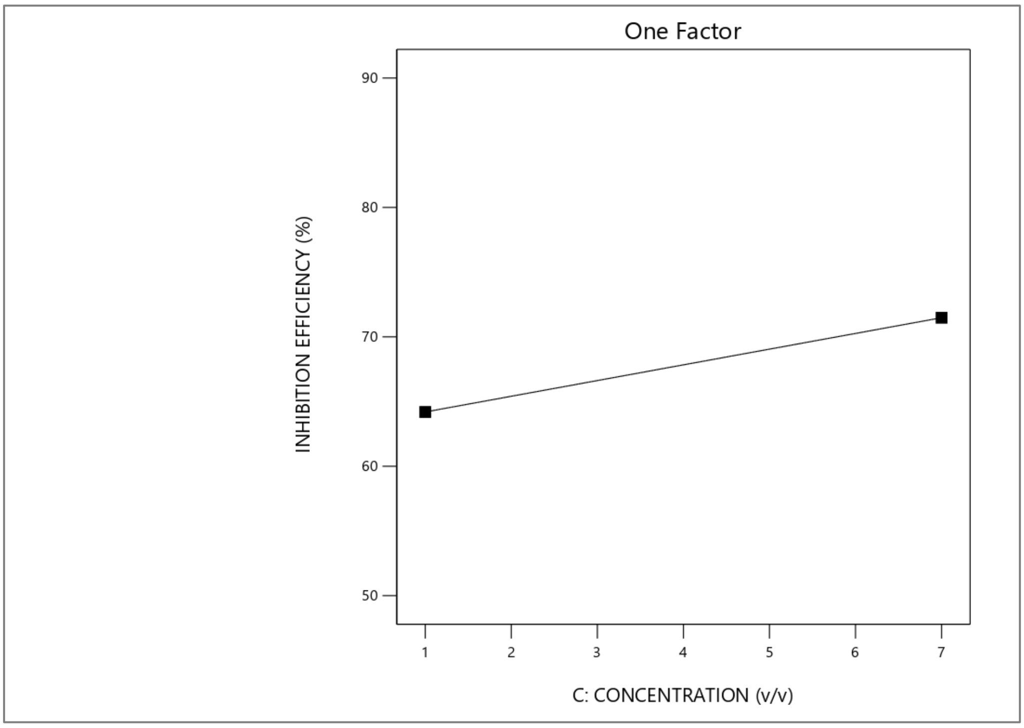

Figure 3: Effect of Inhibitor on the Inhibition Efficiency by *Sida acuta* Leaf Extract

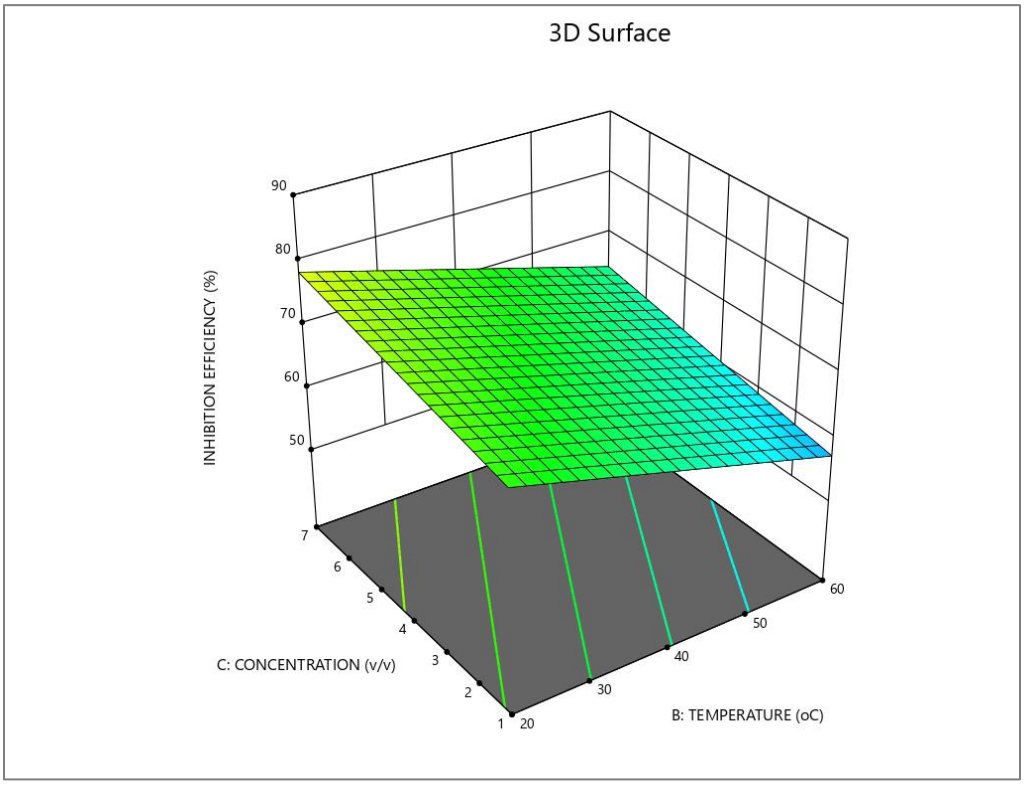

Figure 4: 3D surface plot of the Interaction of Concentration and Temperature on the Inhibition Efficiency by *Sida acuta* Leaf Extract

The decline in efficiency with temperature is associated with accelerated corrosion kinetics, including increased anodic dissolution, cathodic hydrogen evolution, and enhanced transport of aggressive ions to the metal surface (Gómez-Sánchez *et al.*, 2023). The inhibition mechanism appears to be predominantly physisorption-driven, involving weak interactions such as hydrogen bonding, π–electron interactions, and van der Waals forces (Holla *et al.*, 2024). Since physisorption is exothermic, increasing temperature promotes desorption of inhibitor molecules, resulting in reduced surface coverage and film instability.

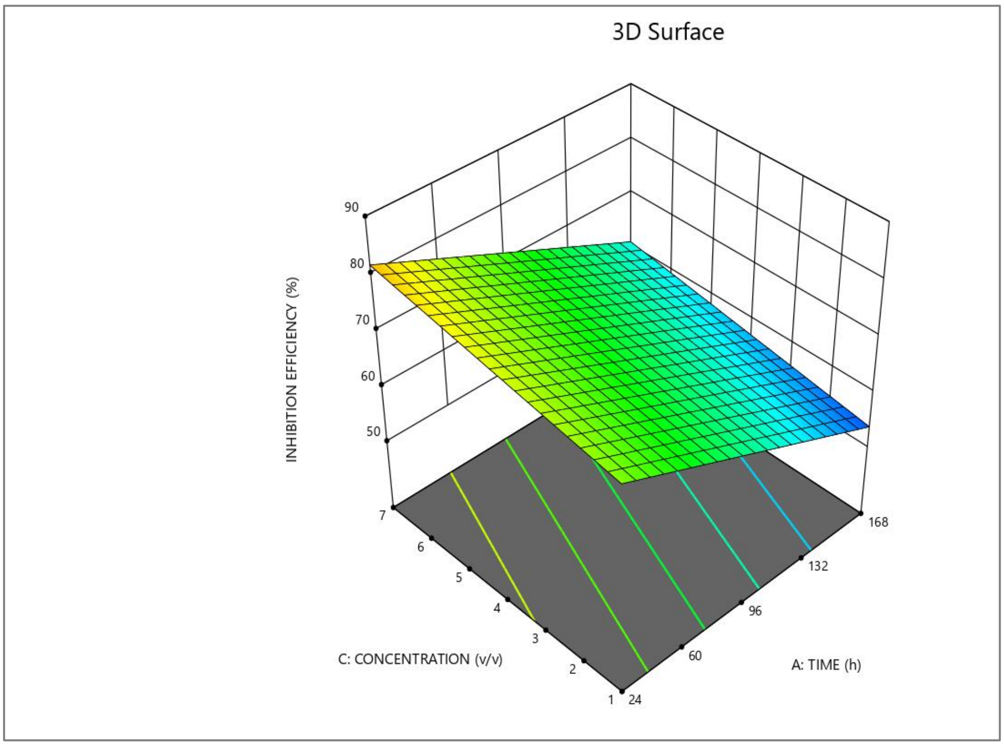

Figure 5: 3D surface plot of the Interaction of Concentration and Time on the Inhibition Efficiency by *Sida acuta* Leaf Extract

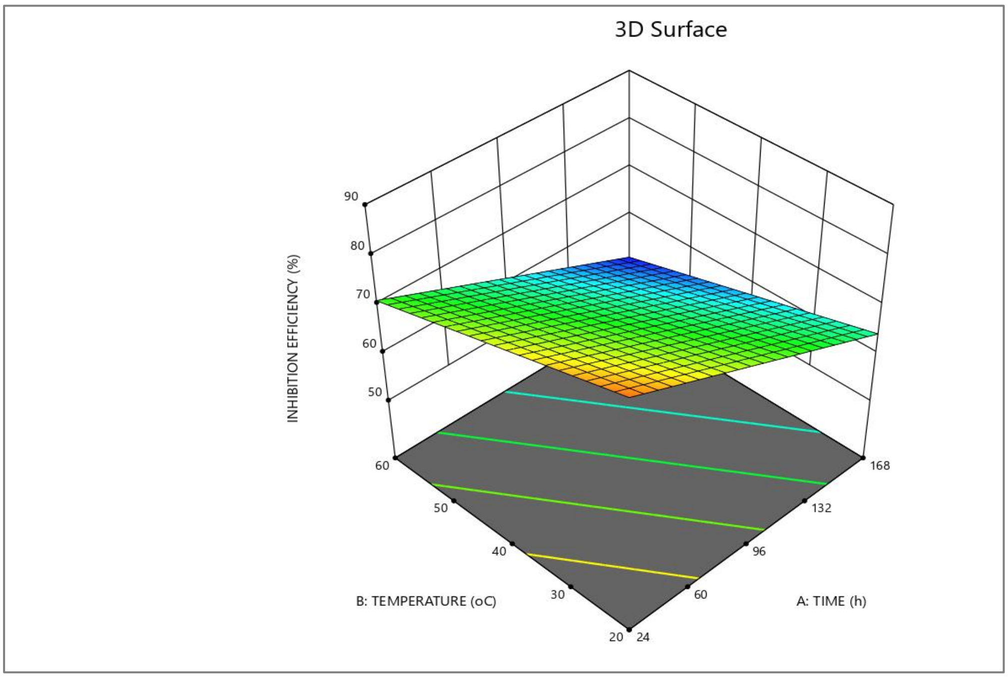

Figure 6: 3D surface plot of the Interaction of Temperature and Time on the Inhibition Efficiency by *Sida acuta* Leaf Extract

Furthermore, elevated temperatures may induce chemical degradation of phytochemicals, such as hydrolysis of tannins and oxidative modification of flavonoids, thereby diminishing the availability of active adsorption sites. Increased ionic mobility at higher temperatures also enhances the penetration of corrosive species, which compete with inhibitor molecules for adsorption (Sabiha *et al*., 2025). Consequently, the inhibition efficiency decreases with increasing temperature, consistent with adsorption–desorption equilibrium behavior reported for plant-based corrosion inhibitors.

3.2.3 Effect of Inhibitor Concentration

Figure 3 shows the effect of *Sida acuta* leaf extract concentration on the inhibition efficiency of aluminium in acidic medium. A clear and progressive increase in inhibition efficiency was observed with increasing extract concentration. At lower concentrations, inhibition efficiency was moderate, while higher concentrations produced a marked improvement, indicating that corrosion protection is strongly dependent on the availability of active inhibitor species in solution (Abd El-Baset *et al*., 2025).

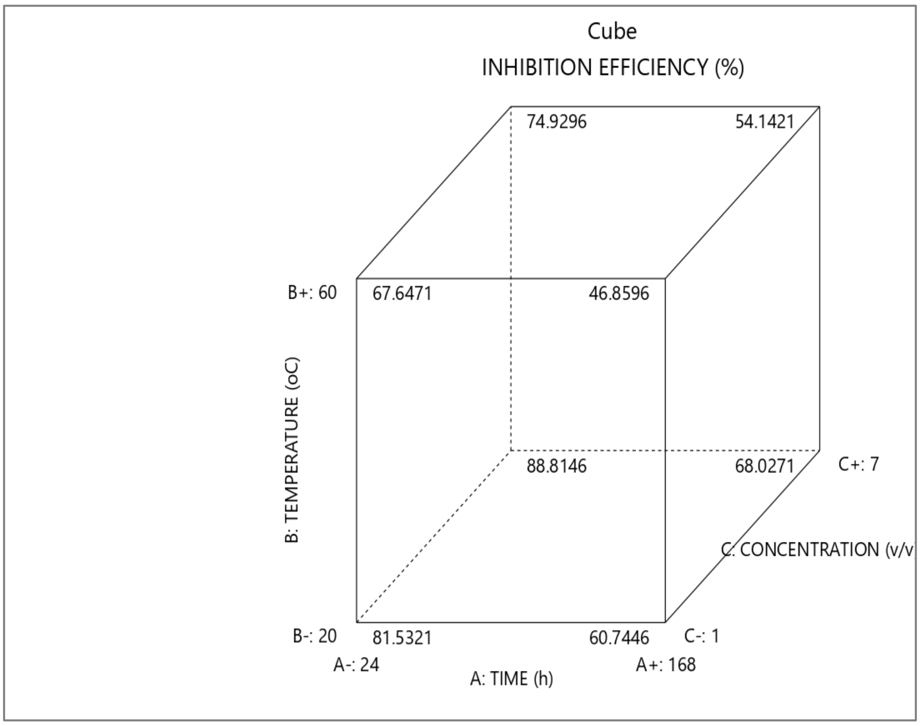

Figure 7: Cube plot of the effect of Concentration, Time, and Temperature on the Inhibitor Efficiency by *Sida acuta* Leaf Extract

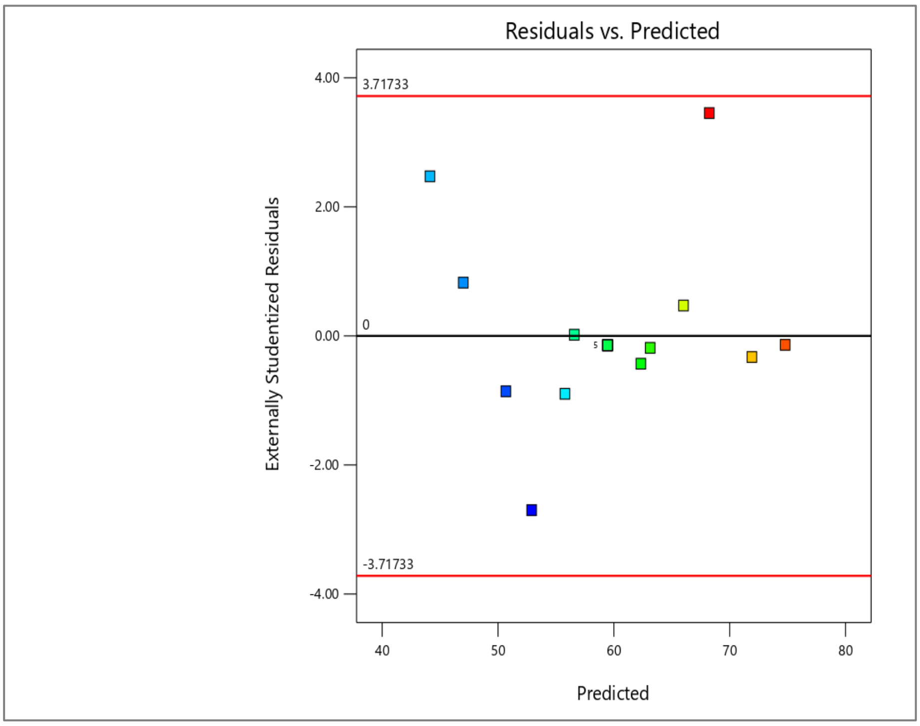

Figure 8: Residual vs Predicted Values Plot on the Inhibition Efficiency by *Sida acuta* Leaf Extract

Table 3: ANOVA Table for the Inhibition Efficiency by *Sida Acuta* Leaf Extract

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1355.90	3	451.97	17.76	< 0.0001	significant
A-time	864.24	1	864.24	33.96	< 0.0001	
B-temperature	385.59	1	385.59	15.15	0.0019	
C-concentration	106.07	1	106.07	4.17	0.0620	
Residual	330.84	13	25.45			
Lack of Fit	330.83	9	36.76	3.063E+05	< 0.0001	significant
Pure error	0.0005	4	0.0001			
Cor total	1686.73	16				

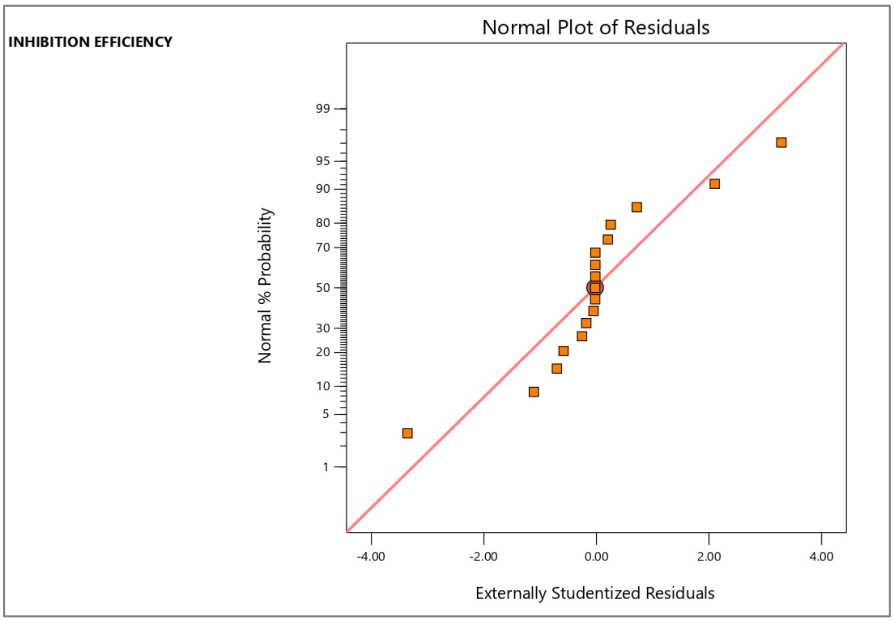

Figure 9: Normal Probability Plot on the Inhibition Efficiency by *Sida acuta* Leaf Extract

Table 4: Fit Summary Table for the Inhibition Efficiency by *Sida Acuta* Leaf Extract

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	**< 0.0001**	**< 0.0001**	**0.7586**	**0.5895**	**Suggested**
2FI	0.5930	< 0.0001	0.7383	0.1598	
Quadratic	0.8819	< 0.0001	0.6579	-1.3948	
Cubic	< 0.0001		1.0000		**Aliased**

Table 5: Sequential Sum of Squares Table for the Inhibition Efficiency by *Sida Acuta* Leaf Extract

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	78231.73	1	78231.73			
Linear vs Mean	**1355.90**	**3**	**451.97**	**17.76**	**< 0.0001**	**Suggested**
2FI vs Linear	54.94	3	18.31	0.6638	0.5930	
Quadratic vs 2FI	23.43	3	7.81	0.2166	0.8819	
Cubic vs Quadratic	252.47	3	84.16	7.013E+05	< 0.0001	Aliased
Residual	0.0005	4	0.0001			
Total	79918.46	17	4701.09			

Table 6: Coefficients in Terms of Coded Factors for the Inhibition Efficiency By *Sida Acuta* Leaf Extract

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	67.84	1	1.22	65.19	70.48	
A-time	-10.39	1	1.78	-14.25	-6.54	1.0000
B-temperature	-6.94	1	1.78	-10.80	-3.09	1.0000
C-concentration	3.64	1	1.78	-0.2119	7.49	1.0000

This behaviour is consistent with adsorption-controlled inhibition mechanisms. Increasing the extract concentration enhances the availability of phytochemicals, such as tannins, phenols, flavonoids, and alkaloids, thereby promoting greater adsorption onto the aluminium surface. The resulting increase in surface coverage effectively blocks active corrosion sites, suppressing both anodic aluminium dissolution and cathodic hydrogen evolution reactions (Rashvand *et al.*, 2024**).** The adsorbed phytochemicals form a protective film at the metal–solution interface, acting as a barrier against aggressive ions in the acidic environment.

The concentration-dependent trend further reflects the synergistic action of the extract components. Tannins and phenols contribute through metal–ligand complexation, while flavonoids and alkaloids enhance adsorption via π–electron interactions and electron donation from heteroatoms (Eddy *et al.*, 2023). At higher concentrations, these interactions produce a more compact and adherent protective layer. Although present in lower amounts, saponins may also aid inhibition by improving molecular dispersion and surface wetting, thereby minimizing unprotected regions susceptible to localized corrosion.

The observed increase in efficiency with concentration is consistent with adsorption isotherm behavior, particularly the Langmuir model, in which surface coverage increases with inhibitor concentration until near-saturation is reached. At low concentrations, competitive adsorption by aggressive ions such as chloride limits protection; however, higher inhibitor concentrations enable phytochemicals to dominate available adsorption sites (Rajendran *et al.,* 2025**)**. Overall, the results confirm that *Sida acuta* extract exhibits concentration-dependent inhibition, with increased dosage leading to enhanced surface coverage and improved corrosion resistance.

3.3 Two-Way Interaction Effects

3.3.1 Interaction Effect of Concentration and Temperature

The three-dimensional response surface illustrating the combined influence of *Sida acuta* extract concentration and temperature on the inhibition efficiency of aluminum in an acidic medium is shown in Figure 4. The inhibition efficiency showed a strong dependence on both variables: it increased with higher extract concentration and decreased with increasing temperature. At low inhibitor concentration (1% v/v) and elevated temperature (60 °C), the inhibition efficiency was minimal (≈45%), reflecting thermal desorption and instability of the adsorbed phytochemical film. In contrast, increasing the extract concentration to 7% v/v significantly enhanced inhibition efficiency, reaching values above 75% at 20 °C. This improvement is attributed to the increased availability of adsorption-active phytochemicals, including tannins, flavonoids, and polyphenols, which promote greater surface coverage and improved film integrity (Odadayerewhre, 2024).

The response surface reveals a clear interaction between concentration and temperature. While increasing concentration enhanced inhibition efficiency across the entire temperature range, the effect was more pronounced at lower temperatures, as indicated by the steeper slope of the surface. This behaviour suggests that adsorption of *Sida acuta* extract constituents is favoured at lower temperatures and weakens with increasing temperature, consistent with predominantly physisorption-controlled inhibition mechanisms (Tang, 2024). The relatively smooth and continuous surface profile indicates a near-linear response within the studied range, suggesting predictable inhibition behaviour through concentration adjustment (Meena *et al.*, 2024). The maximum inhibition efficiency (~78%) observed at 7% v/v and 20 °C highlights the optimal performance of *Sida acuta* extract under mild thermal conditions.

3.3.2 Interactive Effect of Inhibitor Concentration and Immersion Time

Figure 5 illustrates the combined effect of *Sida acuta* leaf extract concentration and immersion time on the inhibition efficiency of aluminium in acidic medium. The response surface reveals that inhibition efficiency is strongly influenced by both variables, with inhibitor concentration exerting the more dominant effect across the studied range.

At the shortest immersion time (24 h) and lowest extract concentration (1% v/v), inhibition efficiency was below 50%, indicating limited surface coverage by the extract constituents. Increasing the concentration led to a substantial improvement in inhibition efficiency, reaching approximately 78% at 7% v/v. This enhancement is attributed to the increased availability of adsorption-active phytochemicals, such as alkaloids, phenolics, and flavonoids, which promote the formation of a protective film on the aluminium surface (Ezugha and Aralu, 2023).

A general decline in inhibition efficiency with increasing immersion time (24–168 h) was observed at all concentrations, with the effect being more pronounced at lower extract dosages. This time-dependent reduction is indicative of gradual desorption or degradation of the adsorbed inhibitor film during prolonged exposure in acidic media, a behaviour commonly associated with physisorption-controlled plant-based inhibitors (Okore *et al.*, 2025). Notably, at 168 h, inhibition efficiency decreased to approximately 43% at 1% v/v, whereas at 7% v/v it remained relatively higher (~70%), suggesting improved film durability at elevated concentrations.

The non-linear response surface indicates a significant interaction between concentration and immersion time, in which increasing inhibitor concentration partially offsets the adverse effect of prolonged exposure (Abakedi and Anweting, 2024).

3.3.3 Interactive Effect of Temperature and Immersion Time

Figure 6 presents the combined influence of temperature and immersion time on the inhibition efficiency of aluminium in acidic medium in the presence of *Sida acuta* leaf extract. The response surface clearly shows that inhibition efficiency decreases progressively with increasing temperature and prolonged exposure time, highlighting the extract's thermal and temporal sensitivities.

At shorter immersion periods (24 h) and lower temperatures (20–30 °C), the inhibition efficiency remains relatively high, approaching 70%. This enhanced performance under ambient conditions can be attributed to the stable adsorption of phytochemical constituents onto the aluminum surface, forming an effective protective film that restricts electrolyte access to the metal substrate (Zhao *et al.*, 2024). However, as temperature increases towards 60 °C, a pronounced decline in inhibition efficiency is observed across all immersion times. Under the most severe conditions examined (168 h and 60 °C), the efficiency drops below 50%, suggesting substantial weakening, desorption, or degradation of the inhibitor film.

The observed temperature-dependent decrease in inhibition efficiency is characteristic of a predominantly physisorption-controlled adsorption mechanism, which is generally exothermic and becomes less stable at elevated temperatures (Ahmed and El-Haddad, 2024). In addition, prolonged immersion may accelerate inhibitor film breakdown and facilitate competitive adsorption of aggressive species, such as chloride ions present in the acidic environment, leading to gradual deterioration of surface protection over time (Saigaa *et al.*, 2023).

Notably, the surface plot shows nearly parallel contour lines along the immersion time axis, indicating that temperature exerts a stronger influence on inhibition efficiency than exposure duration within the studied range (Desai and Desai, 2023).

3.4 Cube Plot Analysis of Factor Interactions

The cube plot shown in Figure 7 illustrates the combined effects of immersion time (A), temperature (B), and inhibitor concentration (C) on the predicted inhibition efficiency (IE) of Sida acuta leaf extract for aluminum corrosion in an acidic medium. The results reveal a strong dependence of inhibition efficiency on all three variables, with pronounced interaction effects. The maximum inhibition efficiency of 88.81% was achieved at the highest inhibitor concentration (C^+ = 7% v/v), lowest immersion time (A^- = 24 h), and lowest temperature (B^- = 20 °C). This optimal condition reflects the enhanced availability of adsorption-active phytochemicals, including tannins, flavonoids, alkaloids, and saponins, which promote extensive surface coverage and formation of a stable protective film. The high efficiency at low temperatures further supports a predominantly physisorption-controlled mechanism, as elevated temperatures tend to weaken adsorptive interactions by increasing molecular desorption (Tshimangadzo *et al.*, 2023**).**

In contrast, the lowest inhibition efficiency (46.86%) was observed at the lowest inhibitor concentration (C^- = 1% v/v), the highest immersion time (A^+ = 168 h), and the highest temperature (B^+ = 60 °C). These conditions favor desorption and degradation of the inhibitor film, while prolonged exposure enhances competitive adsorption by aggressive ions in the acidic medium. The limited availability of phytochemicals at low concentrations further limits effective surface protection over time (Oyewole *et al.*, 2024).

Intermediate factor combinations resulted in moderate inhibition efficiencies, such as 74.93% at high concentration, high temperature, and short immersion time, and 60.74% at low concentration, low temperature, and long immersion time. These outcomes indicate that although inhibitor concentration is the dominant parameter governing inhibition performance, temperature and immersion time play critical roles in modulating the stability and persistence of the adsorbed film (Thakur *et al.*, 2023).

3.5 Residual vs Predicted Values Plot

The externally studentized residuals versus predicted plot (Figure 8) confirms the adequacy of the Response Surface Methodology (RSM) model for aluminium corrosion inhibition by *Sida acuta* leaf extract. The critical bounds (±3.71733) indicate that only one experimental run, at a predicted inhibition efficiency of ~75%, exceeded the upper limit, suggesting slight model underestimation for that condition. No residuals fell below the lower bound, indicating the absence of extreme negative deviations. The observed outlier is likely due to variations in phytochemical composition, particularly flavonoids and polyphenols, influenced by factors such as leaf maturity, extraction conditions, or minor environmental inconsistencies. Such variability has been widely reported to affect adsorption behaviour and inhibition performance (Mert *et al.*, 2025). Importantly, the remaining residuals were randomly distributed around zero, confirming homoscedasticity and demonstrating that the model adequately captures the interactions among concentration, temperature, and immersion time. Similar trends have been reported in related studies (Ahmadi and Khormali, 2023). Overall, the model is statistically reliable, with only one influential point requiring further experimental validation.

3.6 Normal Probability Plot

The normal probability plot (Figure 9) demonstrates that the residuals closely follow the reference straight line, confirming that the model errors are approximately normally distributed. Minor deviations observed at the tails are negligible and likely arise from experimental variability at extreme conditions. The linear alignment of the residuals indicates that the Response Surface Methodology (RSM) model adequately represents the relationship between inhibitor concentration, temperature, and exposure time, with no significant systematic bias. This confirms that variations in inhibition efficiency are primarily due to random experimental error rather than model inadequacy (Khaled, 2021). Overall, the normality assumption is satisfied, validating the regression model's reliability and supporting the robustness of the predicted corrosion-inhibition efficiency of *Sida acuta* leaf extract.

3.7 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) was performed to assess the statistical significance and reliability of the regression model describing the inhibition efficiency (IE) of aluminum corrosion by *Sida acuta* leaf extract (Table 3). The model exhibited high significance, with an F-value of 17.76 and $p < 0.0001$, indicating that the selected factors adequately explain the observed variation in inhibition efficiency.

Among the individual factors, **immersion time (A)** emerged as the most influential parameter, contributing the highest sum of squares (864.24) and F-value (33.96) with a p-value < 0.0001. This confirms that immersion time strongly controls IE, reflecting the dynamic adsorption–desorption processes and progressive degradation of the inhibitor film under prolonged exposure (Verma et al., 2018).

Temperature (B) was also statistically significant (F = 15.15, p = 0.0019), demonstrating that thermal conditions substantially affect IE by promoting desorption of active phytochemicals and accelerating corrosion reactions. In contrast, **inhibitor concentration (C)** had a comparatively weaker effect, with an F-value of 4.17 and p = 0.0620. Although increased concentration enhances surface coverage and IE, the effect was marginally above the 95% confidence level, suggesting a less dominant role than immersion time and temperature (Obi-Egbedi *et al.*, 2012).

The residual sum of squares (330.84) was low relative to the model sum of squares, indicating reasonable agreement between predicted and experimental values. However, the **significant lack-of-fit ($p < 0.0001$)** suggests that some systematic variation remains unexplained by the linear model, which is consistent with the complex, non-linear interactions inherent in plant extract-based inhibition. The very small pure error (0.0005) confirms excellent experimental repeatability, indicating that the lack of fit arises from the model structure rather than measurement error.

Overall, the ANOVA results demonstrate that the model is statistically robust for trend analysis. Immersion time and temperature were identified as the primary factors controlling inhibition efficiency, while inhibitor concentration played a supportive, yet less influential, role within the experimental domain. These findings provide a sound statistical basis for understanding factor significance and guiding future optimization studies.

3.8 Fit Summary

The model summary statistics (Table 4) indicate that the **linear model** is the most suitable for describing aluminium corrosion inhibition by *Sida acuta* leaf extract. Its highly significant sequential p-value (< 0.0001) confirms that key factors such as concentration, temperature, and exposure time strongly influence inhibition efficiency. Despite a significant lack-of-fit (< 0.0001), the model was selected due to its relatively high adjusted R^2 (0.7586) and reasonable predicted R^2 (0.5895), indicating acceptable predictive performance. The **2FI model** is not significant ($p = 0.5930$), suggesting minimal interaction effects, as further supported by its low predicted R^2 (0.1598). Likewise, the **quadratic model** is insignificant ($p = 0.8819$) and shows a negative predicted R^2 (–1.3948), indicating poor predictive ability. Although the **cubic model** is significant, it is aliased and therefore unreliable. Overall, the results confirm that the inhibition behaviour is adequately described by a linear model, with negligible contributions from interaction and higher-order effects.

3.9 Sequential Sum of Squares

The sequential sum-of-squares analysis (Table 5) further supports the suitability of the linear model for describing aluminium corrosion inhibition by *Sida acuta* leaf extract. The linear term shows a significant contribution ($F = 17.76$, $p < 0.0001$), indicating that the primary factors exert a strong influence on inhibition efficiency and justifying its selection. In contrast, the addition of interaction terms (2FI) does not significantly improve the model ($F = 0.6638$, $p = 0.5930$), confirming that interactions between variables are negligible. Similarly, the quadratic model contributes insignificantly ($F = 0.2166$, $p = 0.8819$), indicating that higher-order effects do not enhance model performance. Although the cubic model appears statistically significant ($p < 0.0001$), it is aliased, indicating overfitting and unreliable results due to insufficient degrees of freedom. The very small residual error further indicates that most of the variation is already captured by the linear model.

3.10 Coefficients in Terms of Coded Factors

The estimated regression coefficients for the developed model describing the inhibition efficiency of aluminum corrosion using *Sida acuta* leaf extract, together with their associated statistical parameters, are presented in Table 6. The intercept value (67.84) represents the predicted inhibition efficiency when all coded independent variables, immersion time (A), temperature (B), and inhibitor concentration (C) are at their reference (central) levels. The narrow 95% confidence interval (65.19 –70.48) and low standard error (1.22) indicate a stable and well-defined baseline response (Toghan *et al.*, 2023).

The coefficient for immersion time (A) is negative (–10.39) and statistically meaningful, with a 95% confidence interval ranging from –14.25 to –6.54. This clearly indicates that increasing immersion time leads to a substantial reduction in inhibition efficiency. The magnitude of this coefficient confirms that time is the most influential factor among the studied variables, consistent with film degradation, the desorption of phytochemical constituents, and the progressive exposure of the aluminum surface to the corrosive medium during prolonged immersion (Okore *et al.*, 2025).

Similarly, temperature (B) exhibits a negative coefficient (–6.94), with its 95% confidence interval (–10.80 to –3.09) entirely below zero, confirming a statistically significant adverse effect on inhibition efficiency. This behavior reflects the thermally induced weakening of adsorption interactions between *Sida acuta* phytochemicals and the aluminium surface, supporting a predominantly physisorption-controlled inhibition mechanism. Elevated temperatures promote desorption and accelerate corrosion kinetics, thereby reducing protective performance.

In contrast, inhibitor concentration (C) shows a positive coefficient (3.64), indicating that increasing extract concentration enhances inhibition efficiency. However, its 95% confidence interval (–0.21 to 7.49) slightly overlaps zero, suggesting that the effect of concentration is weaker and marginally significant within the investigated range. This implies that while higher concentrations improve surface coverage and protective film formation, their influence is less dominant compared to immersion time and temperature, particularly when evaluated independently (Kusuma *et al.*, 2024).

The Variance Inflation Factor (VIF) values for all model terms are exactly 1.000, indicating the complete absence of multicollinearity among the independent variables. This confirms that each factor contributes independently to the model and that the estimated coefficients are reliable and not distorted by intercorrelations.

3.11 Regression Model Interpretation for Inhibition Efficiency

The derived regression equation for the inhibition efficiency (IE%) of aluminium in acidic medium using *Sida acuta* leaf extract is expressed as:

IE (%) = 90.73 − 0.144 TIME − 0.347 TEMPERATURE + 1.214 CONCENTRATION

The intercept (90.73%) represents the predicted inhibition efficiency under the model's reference conditions (the central values of all factors). This high baseline value highlights the inherent corrosion-inhibiting potential of *Sida acuta* extract under mild operating conditions.

The negative coefficient for TIME (–0.144) indicates a gradual decrease in inhibition efficiency with prolonged immersion. This aligns with the expected desorption or degradation of adsorbed phytochemicals over extended exposure, resulting in a weaker protective film on the aluminum surface. Similarly, the negative coefficient for TEMPERATURE (–0.347) reflects the adverse effect of elevated temperatures on inhibitor performance. Higher temperatures accelerate the desorption of phytochemicals and the corrosion kinetics, reducing the efficacy of the protective barrier, consistent with physisorption-dominated inhibition mechanisms (Iheaturu *et al*., 2024). Also, the positive coefficient for concentration (+1.214) demonstrates that increasing the extract dosage enhances inhibition efficiency. This effect arises from greater surface coverage and the formation of a more compact protective layer, enabled by increased availability of active phytochemicals such as tannins, flavonoids, and alkaloids.

CONCLUSION

The corrosion-inhibition performance of *Sida acuta* leaf extract on aluminum in an acidic medium was evaluated using gravimetric analysis combined with Response Surface Methodology (RSM). The Box–Behnken design modeled the effects of immersion time (24–168 h), temperature (20–60 °C), and inhibitor concentration (1–7 v/v) on inhibition efficiency (IE), which ranged from 46.86% to 88.83%. The model was statistically significant ($F = 17.76$, $p < 0.0001$) and accurately predicted experimental responses, with a maximum predicted IE of 88.81%, which closely matched the experimental value of 88.83%. Fit summary statistics indicated that the linear model was most suitable, with a sequential p-value < 0.0001, an adjusted R^2 of 0.7586, and a predicted R^2 of 0.5895. Sequential sum-of-squares analysis confirmed the significance of the linear model ($F = 17.76$, $p < 0.0001$), while the interaction ($F = 0.6638$, $p = 0.5930$) and quadratic terms ($F = 0.2166$, $p = 0.8819$) were insignificant; the cubic model was significant but aliased.

Inhibition efficiency was highly sensitive to operational conditions; high efficiencies at shorter immersion times and lower temperatures suggest rapid adsorption and effective protective film formation, whereas prolonged exposure and higher temperatures led to reduced IE, indicating partial desorption. Immersion time ($F = 33.96$) and temperature ($F = 15.15$) were the most influential factors, while concentration contributed positively but less strongly. Negative regression coefficients for time (–0.144) and temperature (–0.347), along with a positive coefficient for concentration (+1.214), indicate an adsorption-controlled mechanism. Overall, *Sida acuta* extract shows strong potential as an eco-friendly corrosion inhibitor under mild thermal conditions and short exposure durations.

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