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Eco-Friendly Corrosion Inhibition of Mild Steel in Marine Environments Using Musanga cecropioides Leaf Extract: Gravimetric, Adsorption Isotherm, and RSM Optimization Studies

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Abstract

Marine environments accelerate the corrosion of mild steel, posing significant operational challenges across global industries. This study investigates the corrosion inhibition potential of Musanga cecropioides leaf extract (MCLE) as a green, eco-friendly alternative to synthetic inhibitors. Phytochemical analysis revealed the presence of bioactive compounds such as alkaloids, flavonoids, tannins, Seriods , and terpenoids, which facilitate corrosion protection by forming adherent protective films on steel surfaces. Gravimetric weight loss measurements conducted over a period of 85 hrs assessed the inhibitor's performance across varying concentrations (0.2–0.8 g/L) in seawater. Maximum inhibition efficiency of 95.1% was achieved at 0.8 g/L after 68 hours of immersion. Adsorption behavior followed the Langmuir isotherm model with a correlation coefficient (R^2) of 0.99087, confirming monolayer adsorption and suggesting physisorption as the dominant mechanism ($\Delta G\_ads = -13.8$ kJ/mol). Optimization using Response Surface Methodology (RSM) and Central Composite Design (CCD) yielded a statistically robust quadratic model ($R^2 = 0.8492$, adjusted $R^2 = 0.7953$, Adeq Precision = 11.1362). Validation experiments confirmed model accuracy, showing a low uncertainty error of 1.66% between predicted and experimental inhibition efficiency. These findings demonstrate that Musanga cecropioides leaf extract offers a highly effective, sustainable, and economically viable solution for mitigating mild steel corrosion in marine environments.

Paper type: Research Paper

Keywords: Corrosion nhibition, Musanga cecropioides, Mild Steel, Marine Environment, Green Inhibitor

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1. Introduction

Global industries face serious difficulties because mild steel metals degrade rapidly in marine environments (Wang *et al*.,2021;Okuma et al.,2023). Chloride ions found in seawater accelerate the corrosion of steel surfaces. Industries such as oil, gas, shipping, and construction face considerable economic losses along with critical safety hazards because of the destructive process (Verma *et al*.,2021;Aslam *et al*.,2022;Răuță *et al*.,2025). Traditional corrosion inhibitors show effectiveness but their toxic chemical composition creates environmental and health threats (Aslam *et al*.,2022;Verma, *et al*.,2023;Al-Amiery *et al*.,2023). The push for sustainable corrosion inhibitors has become stronger over recent years (Royani, *et al*.,2022;Veedu *et al*.,2022;Medupin *et*

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al.,2023;Emmanuel,2024). These natural inhibitors break down easily in the environment while being safe and widely obtainable. *Musanga cecropioides* also known as the umbrella tree stands out among plant sources because of its potent phytochemical profile. The leaves of this plant contain flavonoids, tannins, saponins and other organic compounds that can form protective films on metal surfaces (Adeneye et al.,2006;Nwidu et al.2018;Ziale *et al*.,2021;Ogbue *et al*., 2023;Okugbo *et al*.,2024).

The study investigated *Musanga cecropioides* leaf extract potentiality for protecting mild steel against corrosion in marine simulation conditions. The study optimized extraction and application parameters to increase the effectiveness of the process. Researchers evaluated how the inhibitor adhered to steel surfaces to determine its protective function's underlying mechanism. The extract qualifies as an industrial option because of its environmentally friendly characteristics. *Musanga cecropioides* use advances sustainable development goals compared to synthetic inhibitors. Using plant-based inhibitors supports worldwide environmental protection goals (Medupin *et al.*, 2023). Its practical value increases due to both the minimal extraction expenses and ease of extraction process (Zhang, *et al*., 2025).

1. Materials and Methods

1.1 Material preparation

This study's mild steel specimen contained 0.20 wt% carbon along with 0.46 wt% manganese, 0.23 wt% chromium, 0.29 wt% nickel, 0.19 wt% silicon and 0.23 wt% copper while iron made up the balance of the composition. For the weight loss test the dimensions of each steel specimen were 40 mm by 20 mm by 5 mm. The working specimens underwent immersion in seawater through an area measuring 1 cm^2. Prior to use the samples underwent washing with distilled water, polishing using emery paper at 600 and 800 grit levels, degreasing with acetone, drying and subsequent storage in desiccators. All chemicals and reagents were of analytical grade.

1.2 Plant Extract Preparation

The leaves of *Musanga cecropioides* were found around the Kurutie campus of Nigeria Maritime University located in Okerenkoko Delta State. Researchers placed the leaves into sterile plastic bags during collection then washed them before air-drying and grinding them into a fine powder. The extraction was conducted at a ratio of 1:10 (plant particles: solvent volume) and left to percolate for 72 hours before filtering it through Whatman filter paper. The necessary volumes of crude extract (filtrate) were dissolved in 1000 cm^3 of seawater to achieve concentrations of 0.2, 0.4, 0.6 and 0.8 g/L. Before conducting each experiment, the test solution was prepared freshly from the stock solution.

1.3. Phytochemical analysis

Phytochemical study of the Musanga cecropioides leaf (MCL) extract was performed to check for bioactive substances such as alkaloids, flavonoids, terpenoids and tannin.

1.3 Weight loss

The weight loss technique was carried out over a period of 85hrs at a temperature of 27°C. Pre-weighed mild steel samples, after being cleaned, were submerged in beakers containing seawater, both with and without different concentrations of the aqueous extract from *Musanga cecropioides* leaf (MCL) extract at room temperature. Every 17 hrs, the corroded steel specimens were removed. Once retrieved, the specimens were thoroughly washed with distilled water, rinsed with acetone, dried with a stream of warm air, and then reweighed to determine the weight loss. These experiments were performed in triplicate, and only the average values of the weight losses were reported. The collected weight loss(w) data were used to calculate the corrosion rate (CR) and inhibition efficiency (IE%) using equations 1–4, following established methodologies outlined in the literature (Anadebe *et al*., 2019; Aziz *et al*., 2022; Okuma *et al*., 2022).

$$\Delta w = w_i - w_a \tag{1}$$

$$C_R = \frac{W_{bl} - W_{inh}}{A(m^2)x\ t(day)} \tag{2}$$

$$IE\% = \frac{W_{bl} - W_{inh}}{W_{bl}} x\ 100 \tag{3}$$

$$\theta = \frac{w_{bl} - w_{inh}}{w_{bl}} \quad (4)$$

Where w_i and w_a are initial and after weight of the specimens. w_{bl} and w_{inh} are the weight loss values obtained in the uninhibited and inhibited environments, A is the total surface area of the specimen and t denotes period of exposure.

1.4 Adsorption isotherm studies

Investigations of the plant extract adsorption isotherm shed light on its interaction with the metal surface. The best adsorption isotherm model for explaining the behavior of the plant extract on mild steel in seawater was found by examining the relationship between inhibitor concentration (C) and surface coverage (θ) at 325K for immersion times of 17, 34,51,68 and 85 h. The linearized isotherm equations were used to fit the experimental data into various models such as Langmuir (Eq. 5), and Freundlich (Eq. 6) adsorption isotherm to determine the best-fitting model (Okuma *et al.*, 2024)

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \quad (5)$$

$$\text{Log}\,\theta = \text{Log}K_{ads} + \frac{1}{n} Log\, C_{inc} \quad (6)$$

The correlation between the standard adsorption equilibrium constant and inhibitor free adsorption energy can be express by Eq. (7).

$$\Delta G_{ads} = -\,\text{RTIn}(55.5K_{ads}) \quad (7)$$

Where R stands for gas constant (8.314kJ/mol), T represents temperature (K) and 55.5 stand for the molar concentration of water in the solution.

1.5 Optimization process

Response Surface Methodology (RSM) combined with central composite design (CCD) from Design Expert (DOE) software version 11 made modelling processes easier and enhanced inhibitory efficiency (IE). The study employed a quadratic layout model. This study's independent factors consisted of inhibitor concentrations at 0.2, 0.4, 0.6 and 0.8 g/L along with immersion duration of 17, 34, 51, 68 and 85 hours. The dependent variables assessed the inhibition efficiency (IE). A total of 20 independent experimental trials were done to collect data in respect to the dependent variable (Nwaeju et al., 2022; Okuma et al.,2024).). Table 1 displays the levels of each factor.

Table 1 Variable level of Independent parameters for central composite design(CCD)

Independent Parameters	Low(-)	High(+)
Immersion Time(hrs)	17	85
Inhibitor Concentration(g/l)	0.2	0.8

2. Results and Discussion

2.1 Phytochemical analysis

The experiment aimed to identify the Phytochemicals present in the extract. The analytical method detects Phytochemicals through alterations in the extract solution's physical properties which include color changes, foam generation and precipitate development. Table 2 displays the organic compounds known as Phytochemical in MCLE. The Table 2 analysis reveals that the inhibitor has alkaloids and tannins together with flavonoids,steroidss and terpenoids (Ogbue et al.,2022). The study confirms prior research on *musanga Cecropoides* leaf extract extraction which revealed the presence of tannins, flavonoids, steroids, and terpenoids when using a highly polar solvent such as ethanol. A solvent selection is crucial during extraction since polar solvents boost phytochemical dissolution and extract yield while enabling the solubilization of organic and inorganic substances and enhancing leaf cell wall penetration alongside permeability

Table. 2 Phytochemical analysis chart

Phytochemicals	Occurrences
Alkaloids	+
Tannins	+++
Flavonoids	+++
Steroids	+
Terpenoids	+

Key: +++ = Present in abundance**,** + = Present in small concentration

2.2 Gravimetric analysis

The gravimetric analysis method was employed to evaluate corrosion rate, weight loss, inhibition efficiency, and surface coverage of mild steel in marine environments. The test involved immersing pre-treated mild steel specimens in seawater containing varying concentrations (0.2–0.8 g/L) of *Musanga cecropioides* leaf extract (MCLE) under controlled conditions From Fig. 1 and 2 , the results indicated that higher concentrations of MCLE led to increased adsorption of phytochemical constituents onto the metal surface, forming a coherent and protective barrier layer that significantly reduced corrosion. This barrier restricted the access of aggressive chloride ions to the metal surface, thus enhancing corrosion resistance (Yadav et al.,2024).As surface coverage (θ) increased with higher inhibitor concentrations, a corresponding rise in inhibition efficiency (IE%) was observed. However, extended immersion time beyond 68 hours led to a gradual decline in IE% and a rise in corrosion rates. This reduction in efficiency is attributed to the desorption or degradation of the adsorbed phytochemicals over time, especially in the moderately acidic and chloride-rich marine environment (Hossain et al.,2023; Mustapha et al.,2024). Notably, MCLE exhibited nearly complete surface coverage and maximum inhibition efficiency after 17 hours of immersion, suggesting rapid and effective initial adsorption.

Compared to synthetic inhibitors commonly used in marine corrosion control such as chromates, phosphates, and amine-based compounds MCLE demonstrated comparable performance, achieving up to 95.1% inhibition efficiency under optimized conditions. While some industrial inhibitors may reach similar or slightly higher efficiencies, their toxicity, cost, and environmental persistence present significant drawbacks. In contrast, MCLE offers a biodegradable and non-toxic alternative that aligns with environmental sustainability goals, making it a promising candidate for industrial-scale applications in marine settings.

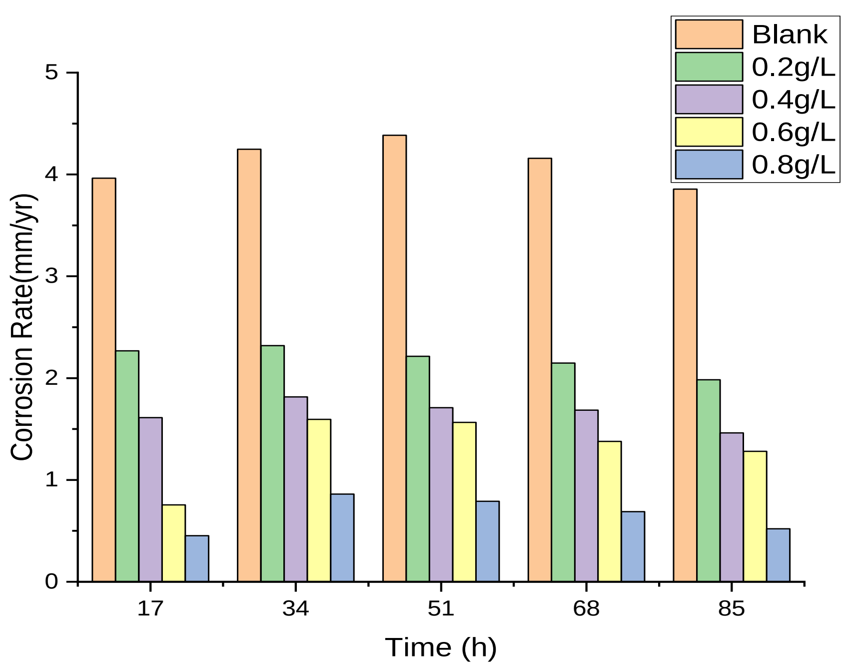

Fig. 1. Plot of Corrosion rate against time

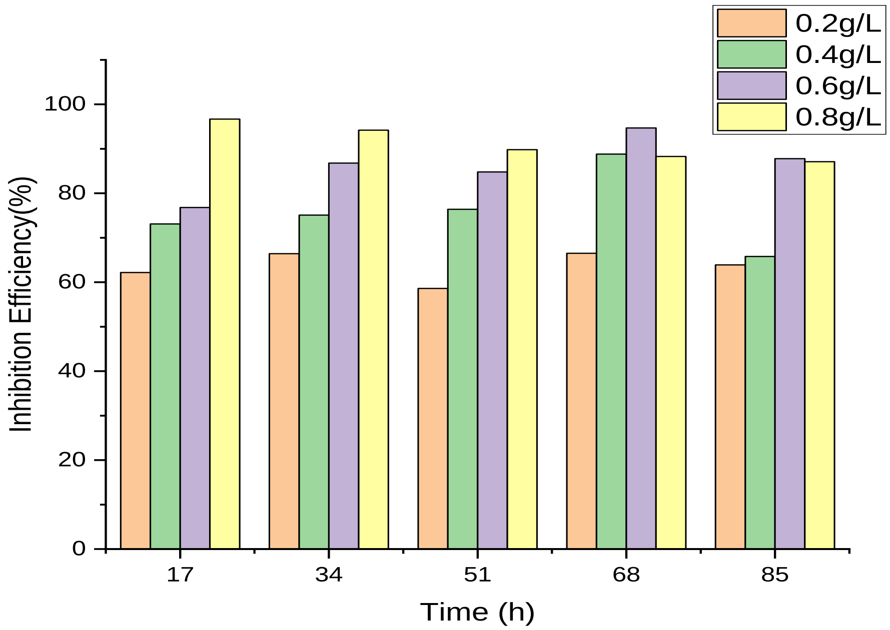

Fig. 2. Inhibition efficiency against time

2.3. Adsorption isotherm analysis

The researchers analyzed the experimental data through the application of Langmuir and Freundlich adsorption isotherm models. Table 3 displays the calculated parameters for the adsorption isotherms and Fig. 3 and 4 show the fitting outcomes for these models. The adsorption data exhibited a better fit with the Langmuir model which had a higher correlation coefficient (R^2) of 0.9883 compared to the Freundlich model that showed an R^2 of 0.877. The straight-line plot and its R^2 value near unity demonstrate that the inhibition process adheres to the Langmuir adsorption model. Each adsorbate molecule attaches to a specific spot on the metal surface without interacting with other adsorbate molecules as per Langmuir's adsorption theory (Darweesh *et al.*, 2022).

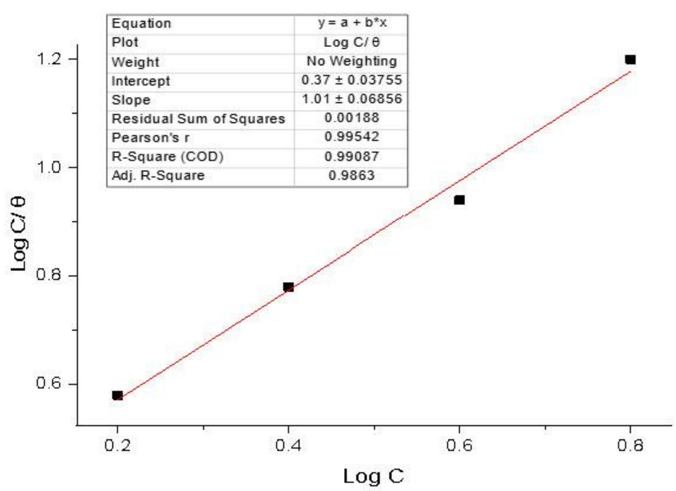

Fig. 3. Isotherm fitting curves of Langmuir

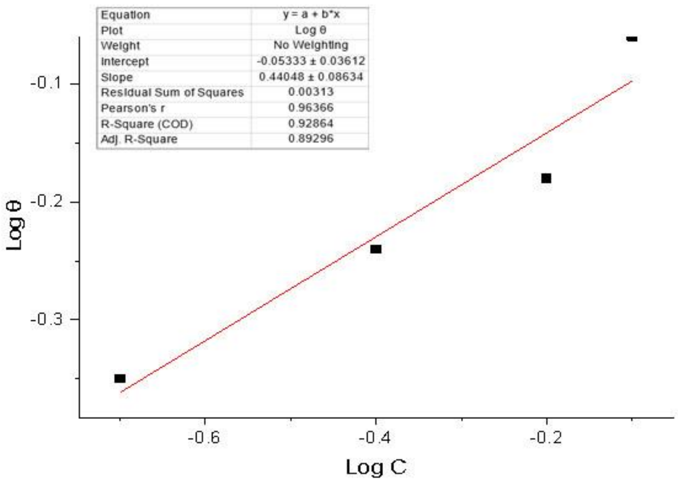

Fig. 4. Isotherm fitting curves of freundlich

Table 3. Musanga cecropioides leaf adsorption parameters for mild steel in seawater

Isotherm	Parameter	Musanga cecropioides leaf
Langmuir		
	Slope	0.94144
	Intercept	0.33245
	R^2	0.99087
	Kads (mL/L)	3
	ΔGads (kJ/mol)	-13.8
Freundlich		
	Slope	0.52682
	Intercept	-0.01721
	R^2	0.92864
	Kads (mL/L)	0.96115
	ΔGads (kJ/mol)	-10.75

2.4 Response Surface Analysis

The Response surface analysis of mild steel in the induced acid corrosion is presented in Table 4. A total of 20 experimental runs were analyzed from the design tool.

Table 4. Factors and response design layout

		Factor 1	Factor 2	Response 3
Std	Run	A:Immersion Time	B:Inhibitor Conc	Inhibition Efficiency
		hr	ppm	%
2	1	17	0.2	62.18

5	2	17	0.4	73.1
15	3	17	0.6	76.8
9	4	17	0.8	84.3
8	5	34	0.2	66.4
1	6	34	0.4	75.7
18	7	34	0.6	86.8
20	8	34	0.8	87.2
16	9	51	0.2	58.6
14	10	51	0.4	76.4
7	11	51	0.6	84.8
6	12	51	0.8	86.2
4	13	68	0.2	66.5
19	14	68	0.4	88.8
12	15	68	0.6	94.7
10	16	68	0.8	95.1
3	17	85	0.2	63.9
11	18	85	0.4	65.8
17	19	85	0.6	87.8
13	20	85	0.8	92.1

2.5 Statistical Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) results presented in Table 5 confirm that the quadratic model effectively analyzes experimental data. The model demonstrates statistical significance with an F-value of 17.77 as the model F-value shows a 0.01% chance of occurrence. A model term achieves statistical significance when its "Prob > F" value falls below the threshold of 0.0500. The letters A, B, AB, A^2, B^2 stand as significant model terms in this analysis. The significance of a model term depends on its value exceeding 0. 1000.This implies that according to the reported model analysis the signal strength permits variation throughout the design space (Nwaeju et al., 2022). The established model forecasts the inhibition efficiency of corrosion prevention for mild steel exposed to seawater after applying M*usanga cecropoides* leaf extract. The results demonstrate statistical reliability. The model equation is expressed in Eq. (8) which expresses the coded values of the process variables.

$$IE(\%) = 83.8599 + 2.772A + 12.9918B + 2.7384AB - 4.37429A^2 - 5.42475B^2 \quad (8)$$

Table 5. ANOVA results for inhibition efficiency on mild steel in seawater with M*usanga cecropoides* leaf extract

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	2177.14	5	435.43	15.77	0.0001 significant
A-Immersion Time	76.84	1	76.84	2.78	0.1175
B-Inhibitor Conc	1875.41	1	1875.41	67.91	0.0001
AB	41.66	1	41.66	1.51	0.2396
A^2	66.97	1	66.97	2.43	0.1417
B^2	116.26	1	116.26	4.21	0.0594
Residual	386.61	14	27.61		
Cor Total	2563.75	19			

The R^2 values shown in Tables 5 match the corresponding adjusted R^2 values. The process uses an ideal model because its variances fall below 0.2 and the R^2 approaches 1. Adeq Precision performs measurements of the signal-to-noise ratio. A ratio exceeding 4 represents an acceptable and desirable value. Tables 5 show sufficient signal levels as indicated by 11.1362 ratios. These models enable successful navigation of the design space.

2.6 Diagnostic fitness plots

The diagnostic fitness plot in Fig 5(a) illustrates the normal distribution pattern for inhibition efficiency. The data points from the depicted Figure show clustering near the line of best fit. Analysis shows fitted models provide an accurate data representation for the response (Okuma *et al.*,2024). Fig 5(b) demonstrates the interaction between actual and predicted inhibition efficiency values of mild steel in seawater when *Musanga cecropoides* leaf extract serves as a corrosion inhibitor. The fitness model demonstrated how well the model's predicted values matched the experimental results. The figures demonstrated a good fit result by showing data points randomly clustered around intersection points for all responses (Emembolu *et al.*,2022). The design model proves sufficient for predicting how well *Musanga cecropoides* leaf extract protects mild steel from corrosion in seawater environments.

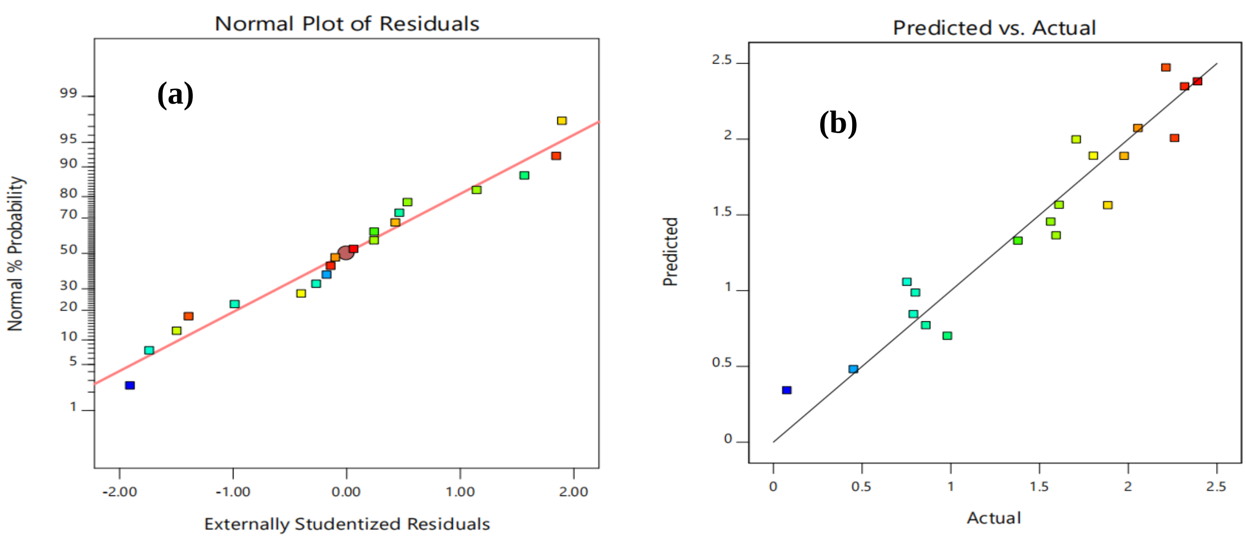

Fig.5. (a) Normal distribution plots for responses and **(b)** Model graph of predicted *versus* actual

Figure 6 illustrates a three-dimensional (3D) surface plot that shows how the inhibition efficiency response interacts with independent factors like immersion time and inhibition concentration. The figures demonstrate that the responses show dependency on the independent variables. The surface plots demonstrate that the inhibition efficiency improves with higher concentrations of *Musanga cecropoides* leaf extract and longer immersion times while also showing substantial effects on anticipated responses from elevated environmental conditions. The average atmospheric temperature increases to 45 degrees Celsius would trigger electrochemical reactions. The surface 3D model results demonstrated agreement with experimental findings which indicates *Musanga cecropoides* leaf extract's suitability as a plant extract for mild steel surface treatment in aggressive conditions.

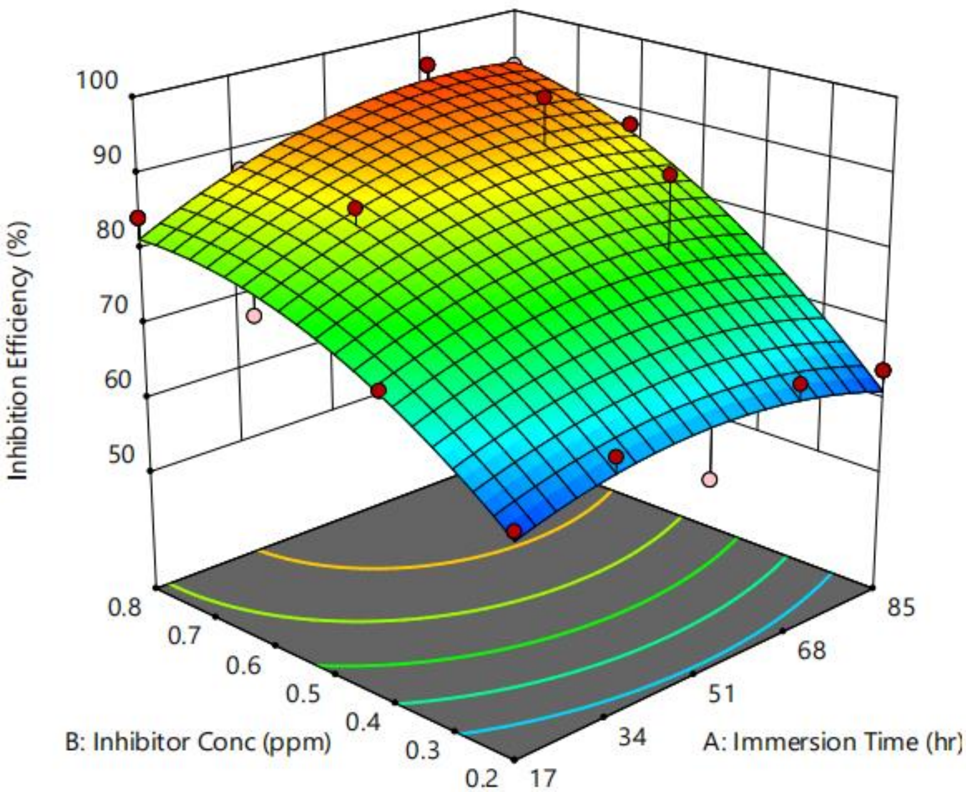

Fig.6. Three-dimensional surface interaction plot for Inhibition efficiency

2.7 Optimization of the Corrosion Inhibition process

The study aimed to identify the best parameter conditions needed to achieve maximum corrosion control for mild carbon steel in the tested environment. The process underwent optimization through the use of Design-Expert-Software which relied on the established inhibition efficiency model (Okuma *et al*., 2024). The present work's optimization criteria (main objectives) aim to maximize inhibition efficiency. The characteristics and pre-set optimization.The independent factor optimal solutions according to Table 6 show 85 hours for immersion time and 0.8g/l for inhibition concentration. The maximum inhibition efficiency response reached 95.1%. Optimum conditions provide dependable results for determining response significance. The selected optimization solution met all given conditions and was displayed in the overlay plot as shown in Fig. 7.

Table 6 Pre-set optimization goals for desirability

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Immersion Time	is in range	17	85	1	1	3
B:Inhibitor Conc	is in range	0.2	0.8	1	1	3
Inhibition Efficiency	maximize	58.6	95.1	1	1	3

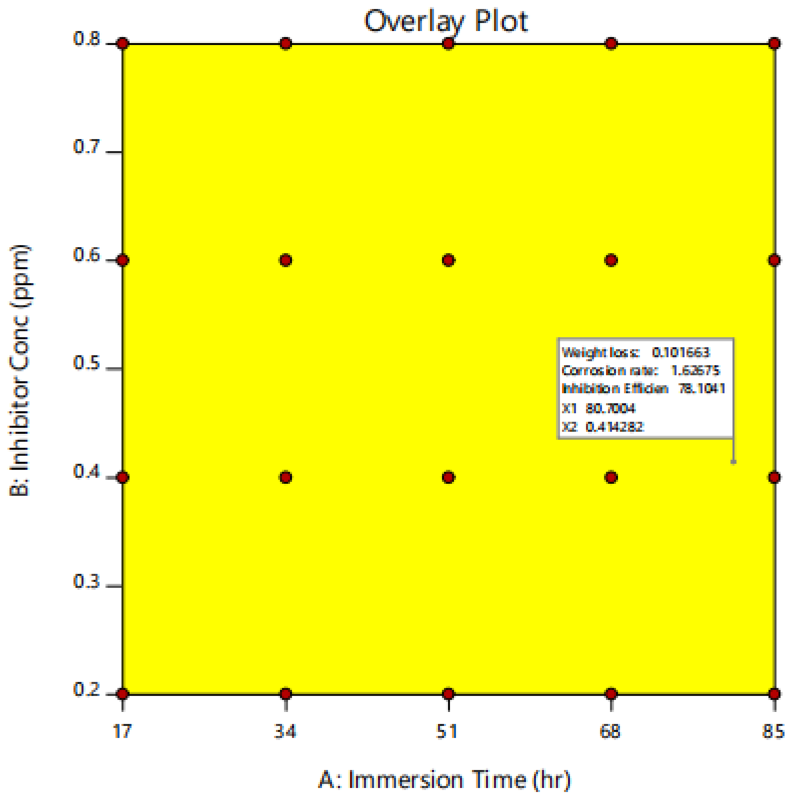

Fig. 7. Optimization Overlay

2.7 Validation of Predicted Model

An additional experiment to validate the model's prediction was done with the predicted optimum conditions. For each test duplicate samples of mild steel underwent machining, and their average outcome was documented. The results are shown in Table 7. The table shows that predicted values match experimental results closely with uncertainty errors of 1.66% since the error is below 5%, This tend to confirm the model to have statistical accuracy for inhibition efficiency prediction.

Table 7 Comparative validation of predicted and experimental values of *Musanga cecropoides* leaf extract as corrosion inhibitor

Parameter	Inhibitor Conc. g/L	Time h	Predicted value	Experimental value	Uncertainty error %
Inhibition Efficiency (IE)	0.4	80.7	65	66.1	1.66

2.8 Comparative, Mechanistic, and Practical Considerations

Gravimetric weight-loss experiments using mild steel in seawater demonstrated that increasing the concentration of Musanga cecropioides leaf extract (MCLE) from 0.2 to 0.8 g/L significantly reduced corrosion rates and enhanced inhibition efficiency, reaching a maximum of 95.1% after 68 hours. Surface coverage (θ) and inhibition efficiency were directly correlated, with nearly complete adsorption observed at 17 hours, though efficiency declined slightly over time due to desorption in the moderately acidic, chloride-rich environment. These findings align with recent literature on plant-derived inhibitors like Pomegranate peel and Punica granatum , which also show efficiencies of 90–95% and obey Langmuir adsorption behavior in saline or acidic media(Karamnia and Yousefpour, 2024; Magni et al.,2020). Mechanistically, phytochemical screening confirmed the presence of flavonoids, tannins, alkaloids, steroids, and terpenoidscompounds known for coordinating with iron via –OH, –COOH, and π-electron donor–acceptor interactions. Adsorption isotherm analysis yielded a Langmuir model fit ($R^2 = 0.9909$) and $\Delta G\_ads = -13.8$ kJ/mol, indicating spontaneous, monolayer physisorption that effectively forms a barrier to aggressive ions. These observations are consistent with studies highlighting flavonoids' ability to adsorb onto surfaces, forming dense, protective films .

Environmentally and economically, MCLE presents considerable advantages. It delivers inhibition performance comparable to high-performing synthetic inhibitors such as chromates or amine-based compounds used in industry without associated toxicity or regulatory burdens. With *Musanga cecropioides* widely available in West Africa and extraction relying on low-cost solvents like water or ethanol, MCLE aligns with global sustainability mandates for biodegradable and non-toxic corrosion control .However, for industrial integration, several considerations must be addressed. The slight decline in efficiency over time suggests exploring strategies to enhance film durability, perhaps by combining MCLE with other green inhibitors, coatings, or stabilizers. Additionally, rigorous testing under dynamic marine conditions, variable pH, and elevated temperatures is essential. Preliminary scale-up should consider extract shelf-life, production consistency, and regulatory compliance within environmental frameworks. Overall, MCLE offers a promising, eco-friendly alternative to synthetic corrosion inhibitors, meriting further study and development for marine industrial applications.

3. Conclusion

This study demonstrates that Musanga cecropioides leaf extract (MCLE) is an effective, eco-friendly, and sustainable corrosion inhibitor for mild steel in marine environments. Phytochemical analysis confirmed the presence of key organic compounds, including alkaloids, flavonoids, tannins, steroids, and terpenoids, which contribute to corrosion inhibition by forming protective films on the steel surface.Gravimetric analyses revealed that inhibition efficiency increases with higher extract concentrations, reaching a maximum of 95.1% at 0.8 g/L after 68 hours of immersion. However, prolonged exposure leads to a gradual decline in efficiency due to phytochemical desorption. The adsorption mechanism follows the Langmuir isotherm model ($R^2 = 0.99087$), indicating monolayer coverage and suggesting a physisorption-dominated process, supported by a Gibbs free energy value (ΔG_ads) of -13.8 kJ/mol.Optimization via Response Surface Methodology (RSM) and Central Composite Design (CCD) produced a statistically robust quadratic model ($R^2 = 0.8492$, adjusted $R^2 = 0.7953$, Adeq Precision = 11.1362). Experimental validation confirmed the model's reliability, with only a 1.66% deviation between predicted and actual inhibition efficiency.Despite these promising results, this study has some limitations. First, the research focused only on short-term immersion tests (up to 85 hours), and the long-term stability of the inhibitor remains to be investigated. Second, the experiments were conducted under controlled laboratory conditions, which may not fully replicate real-world marine environments with fluctuating temperatures, salinity, and microbial activity. Third, the study did not explore the synergistic effects of combining MCLE with other green inhibitors to enhance performance. Finally, the scalability and economic feasibility of large-scale extraction and application require further assessment.These findings highlight Musanga cecropioides leaf extract as a cost-effective, sustainable, and industrially viable alternative to synthetic corrosion inhibitors, particularly in harsh marine conditions. Future research should address these limitations by conducting long-term durability tests, field studies, and investigations into optimized inhibitor formulations for industrial applications.

CRediT Author Contribution Statement

T.J. Tuaweri : Conceptualization , Supervision and Project Administration ,
S.O.Okuma and C.C. Nwaeju : Experiments, Data Curation and Writing,
T.J. Tuaweri, S.O.Okuma and C.C. Nwaeju : Review & Editing

Declaration Statements

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Conflicts of Interest
The authors declare no conflict of interest.

Nomenclature

Symbol	Description	Unit
A	Surface area	m²
C	Concentration	mol/L
t	Time of exposure	hr
CR	Corrosion rate	Pa
w	Weight loss	g
IE	Inhibition efficiency	%
R	Gas constant	Kj/mol
K_{ads}	Equilibrium constant	mL/L
ΔG_{ads}	Gibbs free energy	KJ/mol
T	Temperature	K

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