Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2025, Volume 16, Issue 8, Page 1438-1456

http://www.jmaterenvironsci.com

Eco-Friendly Corrosion Control of Mild Steel in Sulfuric Acid Using Syzygium guineense: A Response Surface Optimization Study

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Received *24 May 2025,*
Revised *06 July 2025,*
Accepted *08 July 2025*

Keywords:
- ✓ *Solar irradiation;*
- ✓ *Temperature-based model;*
- ✓ *Residual analysis;*
- ✓ *Empirical model;*
- ✓ *Energy assessment*

Citation*: Jimoh I., Musa L.A., & Asipita P.O. (2025) Eco-Friendly Corrosion Control of Mild Steel in Sulfuric Acid Using Syzygium guineense: A Response Surface Optimization Study, J. Mater. Environ. Sci., 16(8), 1438-1456*

Abstract: This study investigated the physicochemical profiling of Syzygium *guineense* leaf (SGL) extract and the fine-tuning of critical operational factors that affect its ability to suppress corrosion of mild steel immersed in a 0.1 M H_2SO_4 solution. To assess the influence of various parameters, including acid molarity (0.02–0.1 M), inhibitor concentration (0.1–0.5 g/L), immersion duration (1–6 hours), and system temperature (303–343 K), Response Surface Methodology (RSM) was employed. Phytochemical analysis revealed the presence of organic compounds within the extract that contribute significantly to its corrosion-inhibiting capability. Surface morphology analysis via Scanning Electron Microscopy (SEM) revealed that the extract provided substantial protection to the mild steel, while Fourier Transform Infrared Spectroscopy (FTIR) validated the attachment of organic moieties to the steel surface, indicating that this interaction was the main pathway for corrosion inhibition. The experimental data were analyzed statistically, leading to the formulation of predictive equations describing the corrosion behavior and the protective performance of the inhibitor. The highest protective efficiency was observed at an acid concentration of 0.033 M, with 0.028 g/L of inhibitor, a system temperature of 318 K, and an exposure duration of 1.375 hours. Under these optimized conditions, the leaf extract demonstrated an inhibition performance reaching 83.368%. These findings indicate that *Syzygium guineense* leaf extract is highly effective in reducing both pitting and general corrosion of mild steel in acidic media, highlighting its potential as an environmentally friendly anticorrosive agent.

Keywords**:** *Corrosion inhibition; Mild steel protection; Syzygium guineense extract; Response Surface Methodology; Photochemical screening; Green inhibitor optimization.*

1. Introduction

Low-carbon steel is widely utilized in a broad range of industrial and engineering fields due to its durability and economical nature. However, its vulnerability to corrosion, particularly in highly reactive chemical settings, creates major concerns, such as compromised structural integrity and increased maintenance costs (Jimoh *et al.*, 2025). To mitigate this issue, corrosion inhibitors are often utilized to decelerate the deterioration of metals by disrupting the underlying electrochemical processes (Emembolu *et al.*, 2020; Merimi *et al.*, 2022; Jimoh & Musa, 2024). Traditionally, most studies have centered around synthetic inhibitors; however, contemporary research is increasingly focused on environmentally sustainable alternatives, particularly those derived from plant sources. Studies have highlighted the effectiveness of synthetic inhibitors in both acidic and alkaline conditions (Al Hamzi *et al.* (2013); Merimi *et al.*, (2021); Liu *et al.* (2022); Blessing (2023); and Hussaini (2025). Concurrently, natural inhibitors obtained from plant extracts—known to contain bioactive compounds such as alkaloids, phenolics, lipids, and carbohydrates—have demonstrated considerable promise in corrosion prevention (Hmamou *et al.*, 2012; Aourabi *et al.*, 2021; Dawodu *et al.*, 2024; Ibrahim & Zakaria, 2025; Jimoh *et al.*, 2025). This shift indicates a broader commitment to green and sustainable corrosion control practices. To achieve this goal, the present research explores the corrosion-preventing potential of *Syzygium guineense* leaf extract applied to mild steel exposed to a 0.1 M sulfuric acid solution. Furthermore, it utilizes Response Surface Methodology (RSM) for statistical modeling and refinement of the protective performance across a range of experimental parameters.

2. Experimental procedure

Preparation of Mild Steel Specimens

Low-carbon steel served as the base material for this study and was procured from Kofan Ruwa Aluminium Limited in Kano State, Nigeria. The metal sheet underwent mechanical preparation and was cut into rectangular samples with dimensions of 3 cm × 2 cm × 0.1 cm, which were then used in gravimetric (weight loss) evaluations. Before commencing the experiments, the metal specimens were polished with silicon carbide papers of different grit sizes to remove surface impurities, including oils and residual organic matter. After polishing, the specimens were cleaned by rinsing with ethanol, followed by immersion in acetone. The cleaned samples were then air-dried and stored in a desiccator until needed (Sanusi *et al.*, 2022; Jimoh *et al.*, 2025).

Collection and Pre-treatment of Plant Material

Fresh *Syzygium guineense* leaves were collected from Tudun Yola in Gwale Local Government Area, Kano State, Nigeria. Taxonomic verification was conducted at the Herbarium Unit of the Department of Plant Science, Bayero University Kano, where the plant was catalogued under accession number BUKHAN 0406. The harvested leaves were thoroughly washed with distilled water to eliminate soil and surface impurities, and subsequently left to air-dry at ambient temperature for seven days. After complete drying, the leaves were pulverized into a fine powder using a traditional wooden mortar and pestle. The powdered material was sieved through a 2 mm mesh to ensure uniform particle size and stored in airtight glass containers placed in a cool, dry environment until extraction was performed.

Preparation of Plant Extract

An amount of 300 grams of finely ground, air-dried *Syzygium guineense* leaves was soaked in *1.2 liters of ethanol with a concentration of 95%*, and the container was occasionally stirred over a *72-hour period* to enhance the extraction of bioactive constituents. Following this process, the mixture was *passed through Whatman filter paper to effectively remove solid plant matter*, yielding a clear liquid extract. This resulting filtrate, representing the crude plant extract, was left exposed to air under ambient conditions for about ten days, allowing it to gradually evaporate and produce a thick, dark brown residue. The residue was then *transferred into a clean and tightly closed sample container* and preserved *for later use in corrosion inhibition studies* (Sanusi et al., 2022; Ayuba & Abdullateef, 2020).

Characterization of *Syzygium guineense* Leaf (SGL) Extract:

❖ **Phytochemical Evaluation of the SGL Extract**

Both qualitative and quantitative phytochemical assessments were conducted on the *Syzygium guineense* leaf extract to identify and measure the levels of key bioactive compounds, including alkaloids, flavonoids, saponins, and tannins. The primary objective of these analytical procedures was to identify and quantify the specific phytochemicals *that contribute to the extract's effectiveness as a corrosion inhibitor*. The *approaches adopted for conducting these assessments* were derived from the experimental protocols established by Ebele et al. (2021) and Zaïri et al. (2020).

❖ **Fourier Transform Infrared (FTIR) Spectroscopic Analysis**

An Agilent Technologies Cary 630 instrument was used to perform *Fourier Transform Infrared (FTIR) spectroscopy* for the purpose of identifying *the key functional groups contained within the Syzygium guineense leaf extract*, as well as those present on the surfaces of mild steel samples exposed to corrosion and in the *corrosion by-products* that developed as a result of interaction with *the* inhibitor. To facilitate this, mild steel specimens were submerged in 100 mL of 0.1 M H_2SO_4 solution enriched with the plant extract for a duration of four hours, allowing a protective film to form through adsorption onto the metal surface. Following the immersion, *the layers formed on the metal surface* were gently detached, air-dried, and finely scraped to prepare them for FTIR analysis. Spectral measurements were recorded within a wavenumber range of 650 to 4000 cm^{-1} to detect distinct absorption peaks indicative of functional groups that play a role in mitigating corrosion (Jimoh & Musa, 2024; Jimoh & Asipita, 2025).

❖ **Scanning Electron Microscopy (SEM) Analysis**

An investigation into the *surface features* of mild steel specimens was carried out by employing **scanning electron microscopy (SEM)** to analyze how corrosion and its suppression affect the metal's morphology. Each mild steel sample, with dimensions of 3.0 cm × 2.0 cm × 0.1 cm, underwent surface preparation through sequential polishing with emery paper, followed by thorough cleaning with distilled water, ethanol, and acetone. The cleaned samples were then left to dry in ambient air. The prepared steel coupons were subsequently immersed in 0.1 M H_2SO_4, both in the absence and presence of various concentrations of *Syzygium guineense* leaf (SGL) extract, ranging from 0.00 to 0.50 g/L. This treatment was carried out at a constant temperature of 333 K for a duration of 4 hours. Post-immersion, the specimens were washed with distilled water, dried, and subjected to SEM analysis using a PW–100–012 model microscope (Serial No. MVE015707775), operating at an accelerating voltage of 10.00 kV and a magnification of 500×. SEM micrographs were recorded to visually compare the surface conditions of: (i) unexposed (as-prepared) steel, (ii) steel exposed to acid without inhibitor, and (iii) steel exposed to acid containing different concentrations of SGL extract. This comparative study enabled a clear evaluation of the effectiveness of the SGL extract in mitigating corrosion and preserving the steel's surface integrity. The methodology was adapted in line with previous works by Jimoh & Bishir (2021), Jimoh & Musa (2024), and Husaini et al. (2025).

Weight Loss Analysis Using Response Surface Methodology (RSM)

A corrosion study based on material weight reduction was formulated and evaluated using a statistical optimization technique known as Response Surface Methodology (RSM), which was executed through Design Expert software, version 10.0.0. The investigation considered several critical experimental parameters—namely, the concentration of the acidic medium, the quantity of inhibitor applied, the operating temperature, and the duration of sample immersion. These parameters functioned as independent variables, while dependent variables or response metrics included the amount of material lost due to corrosion, the rate of corrosion progression, and the effectiveness of the inhibitor in minimizing degradation (Lawal *et al.*, 2025).

To understand the extent to which each independent variable affected the responses, RSM was utilized to model and analyze these relationships. Evaluation of the inhibitor's performance was supported through statistical means, particularly Analysis of Variance (ANOVA), and complemented by visual data representations. Predictive equations were formulated using standardized or coded factor levels, where each variable's minimum and maximum values were denoted as -1 and +1, respectively, in alignment with the methodology outlined by Emembolu (2020); Sumaila *et al.* (2024). These regression models enabled the projection of system responses across a range of experimental settings. Additionally, the models facilitated the identification of optimal conditions under which the inhibitor demonstrated the highest efficiency, with the corresponding results detailed in **Table 1.**

Table 1. Experimental factors and their corresponding levels utilized in the response surface design framework.

Predictor variables	**Symbol**	**Ranges and levels**				
		-α	**-1**	**0**	**+1**	**+α**
Acid concentration (M)	A	0.02	0.04	0.06	0.08	0.10
Inhibitor conc. (g/L)	B	0.10	0.20	0.30	0.40	0.50
Reaction time (hr)	C	1.00	2.00	3.00	4.00	5.00
Temperature (K)	D	303	313	323	333	343

- **Experimental Design**

To thoroughly evaluate how temperature, sulfuric acid concentration, inhibitor dosage, and immersion time collectively influence the corrosion resistance of mild steel in a 0.1 M H_2SO_4 environment, this study employed Response Surface Methodology (RSM) as a robust statistical modeling and optimization technique. A Central Composite Design (CCD) was specifically adopted to explore the effects of four independent variables across a defined experimental range, enabling efficient model development with a reduced number of experimental trials.

The CCD layout was constructed based on four variables, denoted as X_1 through X_4, each tested at five coded levels: –α, –1, 0, +1, and +α. The complete design consisted of 38 experimental runs, structured as follows:

24 factorial points, representing all possible combinations of high (+1) and low (–1) levels of the four factors,

8 axial (or star) points, positioned symmetrically at a distance of ±α along each variable axis to capture potential curvature in the response surface,

6 center points, conducted at the median level (0) of all variables to assess experimental repeatability and determine the intrinsic variance (pure error).

The axial distance, denoted by α, plays a vital role in ensuring rotatability — a desirable characteristic of RSM designs that guarantees uniform prediction accuracy across all directions from the center of the design space. The value of α is computed as:

$$\alpha = (2^k)^{1/4}$$

For a design involving four variables (k = 4), α was calculated to be approximately 2.0. This value ensured the inclusion of design points beyond the factorial boundary, allowing the model to accurately capture both linear and quadratic behaviors of the system.
The actual and coded ranges for each factor were carefully chosen based on preliminary experiments and practical constraints, and are listed in **Table 1.** The complete experimental matrix used for model construction is provided in **Table 2.** Response measurements included mass loss, corrosion rate, and inhibition efficiency, which were statistically analyzed using RSM to determine optimal conditions and explore interaction effects between variables.
To describe the relationship between the response and the process parameters, a second-order polynomial regression model was developed. This approach was adapted in accordance with methodologies previously reported by Emembolu *et al.* (2020), Asipita *et al.* (2024), Jimoh & Asipita (2024), and Jimoh *et al.* (2025). The general form of the equation is expressed as:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \beta_{ij} X_i X_j + e \quad (1)$$

Where: ***Y*** represents the estimated response (e.g., inhibition efficiency), B_o is the intercept of the model, β_i denotes the coefficients for the linear terms, β_{ii} are the coefficients for the quadratic (squared) terms, β_{ij} accounts for interactions between variable pairs, and X_j are the coded values of the input variables, ***k*** is the number of variables (equal to 4 in this case), and ***e*** represents the random error associated with the experimental data.
An expanded version of this polynomial model, tailored to this investigation, is given below:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{14}X_1X_4 + \beta_{23}X_2X_3 + \beta_{24}X_2X_4 + \beta_{11}X_1^{\,2} + \beta_{22}X_2^{\,2} + \beta_{33}X_3^{\,2} + \beta_{44}X_4^{\,2} \quad (2)$$

This model structure allowed for the simultaneous assessment of individual variable effects, two-way interactions, and non-linear (curvature) responses. Overall, the application of CCD within the RSM framework provided a systematic and statistically validated method to optimize corrosion inhibition performance and gain insight into the complex interdependencies between the experimental parameters.

Table 2. The corrosion inhibition performance of mild steel in 0.1 M sulfuric acid solution was evaluated using Response Surface Methodology (RSM) with Syzygium guineense leaf extract as the inhibitor.

Std	Run	Factor 1 Acid conc. (M)	Factor 2 Inhibitor conc. (g/L)	Factor 3 Time (hrs)	Factor 4 Temp. (K)	Response 1 Weight loss (g)	Response 2 Corrosion rate (g/cm^2hr)	Response 3 Inhibition efficiency (%)
11	1	0.033	0.028	3.125	333.00	0.448	5.168	61.628
1	2	0.050	0.020	2.250	318.00	0.408	6.828	69.628
9	3	0.050	0.020	2.250	339.21	0.278	6.828	68.558
5	4	0.033	0.028	3.125	318.00	0.978	6.998	68.558
7	5	0.050	0.020	1.000	333.00	0.528	5.498	49.628
12	6	0.033	0.028	1.375	318.00	0.448	6.828	83.368
2	7	0.050	0.035	2.250	296.79	0.408	6.828	67.628
8	8	0.050	0.005	2.250	318.00	0.278	13.998	55.878
10	9	0.033	0.013	1.375	303.00	0.978	9.798	43.998
6	10	0.067	0.013	1.375	343.00	0.528	8.828	72.408
3	11	0.050	0.028	2.250	303.00	0.588	5.898	68.288
13	12	0.050	0.028	2.250	318.00	0.861	8.628	46.398
4	13	0.050	0.028	2.250	318.00	0.408	6.828	69.628

❖ Evaluation of Corrosion Inhibition Efficiency and Statistical Modeling

The experimental results obtained for mass loss, corrosion rate, and inhibition efficiency were subjected to statistical analysis using Design Expert software, version 10.0.3. To understand how different experimental variables and their interdependencies affected the corrosion inhibition characteristics, the study employed Analysis of Variance (ANOVA), regression analysis, and response surface visualizations. Through ANOVA, the impacts of the linear, interaction, and quadratic components of the independent variables on the response metrics were thoroughly assessed to determine the extent of each factor's influence.

The statistical importance of the model's regression terms was evaluated by analyzing their p-values, with a significance level set at 0.05 or below. This criterion was used to confirm the reliability and relevance of the regression coefficients. In order to assess the accuracy and predictive capability of the regression models, the predicted values generated by the model were compared against the actual experimental data, with emphasis placed on evaluating the coefficient of determination (R^2) and the adjusted R^2 values.

Additionally, graphical tools were utilized to illustrate the relationship between the observed and predicted outcomes for all three response parameters—weight loss, corrosion rate, and inhibition efficiency. This comprehensive evaluation strategy was conducted following the procedural framework established by Jimoh *et al.* (2025).

3. Results and discussion

❖ Evaluation of Weight Reduction Data Using Response Surface Modeling Techniques

Response Surface Methodology (RSM) was employed to systematically investigate how critical operational variables—specifically acid concentration, concentration of the inhibitor, temperature, and immersion duration—affect the corrosion performance of mild steel when exposed to a 0.1 M sulfuric acid (H_2SO_4) solution, with Syzygium guineense leaf (SGL) extract serving as the corrosion inhibitor. The main performance indicators analyzed in this work included mass loss, corrosion rate, and the efficiency of inhibition. A detailed summary of the findings is presented in **Table 2.**

As presented in **Table 2,** the maximum observed inhibition efficiency was 83.368%, achieved under particular experimental conditions: a temperature of 318 K, an acid concentration of 0.033 M, an inhibitor dosage of 0.028 g/L, and an immersion duration of 1.375 hours.This suggests that the SGL extract exhibited optimal inhibitory performance at elevated temperatures and relatively low inhibitor concentrations and time durations. The observed efficiency under these conditions indicates effective surface adsorption and protective film formation by the plant extract, particularly in less aggressive environments. These findings are consistent with previous reports by Odejobi & Akinbulumo (2019), Emembolu *et al.* (2020), and Jimoh et al. (2025).

❖ Corrosion Inhibition Efficiency and Statistical Evaluation

An in-depth statistical evaluation was performed to determine the validity and significance of the inhibition efficiency data related to the corrosion resistance of mild steel in a 0.1 M sulfuric acid (H_2SO_4) environment, where Syzygium guineense leaf (SGL) extract served as the inhibiting agent. Five of the six interaction terms were statistically significant, as evidenced by p-values less than or equal to 0.05, confirming their influence on the process under investigation.Among these, inhibitor concentration and temperature emerged as the most influential variables, underscoring their dominant roles in enhancing corrosion inhibition efficiency—findings that align with the reports of Emembolu *et al.* (2020).

According to the ANOVA data presented in **Table 3,** the model yielded an F-value of 34.77, indicating that the regression model is highly statistically significant. This suggests that there is only a 0.01% likelihood that the observed outcomes are attributable to random variation or background noise. Such variability may arise from fluctuations in the flow behavior of heterocyclic constituents within the inhibitor extract. In addition, model terms associated with p-values below 0.05 were deemed statistically significant, suggesting strong confidence in their measurable impact on the system's response. Among these, interaction effects such as AB—which represents the interplay between acid concentration and temperature—emerged as particularly influential. The statistical relevance of this interaction indicates that the effect of one factor is not uniform but is modified by changes in the other. For example, the corrosion inhibition efficiency of the plant-based inhibitor at a fixed acid concentration may vary considerably when the system temperature shifts. This points to either a synergistic or antagonistic relationship between the two variables, reinforcing the need for simultaneous optimization rather than isolated parameter tuning (Lin *et al.*, 2024; Hussaini *et al.*, 2025). In the same vein, the statistical significance of quadratic terms like A^2 (the squared effect of acid concentration) and B² (the squared effect of temperature) highlights the presence of non-linear trends in the inhibition behavior. Practically, this suggests that corrosion inhibition does not respond in a strictly proportional manner to increasing or decreasing values of these variables. Instead, there is likely an optimal range for each parameter, beyond which performance begins to decline. For instance, while a moderate acid concentration may facilitate effective inhibitor adsorption, excessively high acidity could promote aggressive corrosion, overwhelming the protective barrier. Similarly, a mild increase in temperature might enhance molecular mobility and adsorption kinetics, but excessive heating could compromise the integrity of the adsorbed inhibitor film through desorption or thermal degradation (Nik *et al.*, 2023; Hussaini *et al.*, 2025).

Table 3. Statistical Evaluation (ANOVA) of Mild Steel Corrosion Inhibition in 0.1 M H_2SO_4 using Syzygium guineense Leaf extract

ANOVA for Response Surface Reduced Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	**Sum of squares**	**d.f**	**Mean square**	**F-value**	**p-value Prob > F**	
Model	2957.15	5	591.43	34.77	< 0.0001	Significance
A: Temp	1520.87	1	1520.87	89.40	< 0.0001	
B: Conc.	1306.15	1	1306.15	76.78	< 0.0001	
AB9.24	1	9.24	0.54	0.4851	< 0.0001	
$A^2$26.01	1	26.01	1.53	0.2561	< 0.0001	
$B^2$106.56	1	106.56	6.26	0.0408	0.0103	
Residual	119.08	7	17.01			
Lack of Fit	119.08	3	39.69			
Pure Error	0.000	4	0.000			
Cor Total	3076.23	12				
R-Squared	0.9613					
Adj R-Squared	0.9336					
Pre R-Squared	0.9068					
Adeq Precision	18.961					
Std. Dev.	4.12					
Mean	31.42					
C.V. %	13.13					
PRESS	846.81					

These statistically significant terms do more than refine the predictive strength of the regression model—they offer important mechanistic insights into how system variables interact. They emphasize the delicate balance required to maintain effective inhibition and reveal the complex dependencies among key factors. Understanding these interactions is essential not only for accurately predicting optimal conditions but also for designing corrosion inhibitors that maintain consistent performance across diverse operational environments. Ultimately, this knowledge supports the development of more sustainable and efficient corrosion prevention strategies, especially when using green, plant-based formulations (Bouiti et al., 2022; Hussaini et al., 2025)

Among all the variables studied, temperature emerged as the most influential factor, exhibiting the highest F-value of 89.40, with inhibitor concentration ranking second at 76.78. The model demonstrated a strong predictive capability, as reflected by a coefficient of determination (R^2) of 0.9613, signifying a robust correlation between experimental observations and model predictions. Moreover, the predicted R^2 value of 0.9068 was closely aligned with the adjusted R^2 of 0.9336, with a difference of less than 0.2, thereby affirming the consistency and reliability of the model (Jimoh & Asipita, 2025).

The Adequate Precision (Adeq Precision) value was determined to be 18.961, significantly surpassing the recommended minimum value of 4. This high value indicates a strong signal-to-noise ratio, confirming the model's effectiveness in exploring and optimizing the design space. These outcomes align well with earlier findings reported by Anadebe et al. (2018), Emembolu et al. (2020), and Ibrahim et al. (2024). Based on this analysis, the established model demonstrates reliable predictive capability for estimating the corrosion inhibition efficiency of Syzygium guineense leaf (SGL) extract in a 0.1 M sulfuric acid environment. As a result, the second-order polynomial regression equation—formulated using the coded values of the experimental factors—is provided in Equation (3), offering a statistically sound basis for interpreting and forecasting the system's behavior.

$$I.E = +35.02 - 13.79A + 12.78B - 1.52AB - 1.93A^2 - 3.91B^2 \quad (3)$$

Following the elimination of regression terms with p-values greater than 0.05—indicating statistical insignificance—the refined form of Equation (3) is expressed as follows:

$$I.E = -618.08774 + 4.69887A + 283.71448B - 0.50667AB - 8.59444E\text{-}003A^2 - 97.84375B^2 \quad (4)$$

❖ **Graphical Interpretation of Inhibition Performance via Response Surface Methodology**

This study employed three-dimensional surface plots to visually examine how critical process variables—particularly temperature and inhibitor concentration—interact and influence the corrosion inhibition efficiency of Syzygium guineense leaf (SGL) extract in a 0.1 M sulfuric acid solution. The graphical analysis was performed using Design Expert software, version 10.0, and the corresponding 3-D representations are displayed in **Figure 1.** To further validate the predictive accuracy of the developed model, a plot comparing predicted values to actual experimental results was generated, as shown in **Figure 2.** The near-linear trend observed in this plot indicates strong agreement between the predicted and observed data, confirming the model's reliability. The investigation into corrosion inhibition demonstrated that elevating the amount of inhibitor used typically resulted in a notable improvement in its ability to prevent corrosion. In contrast, an increase in temperature was observed to reduce this protective effectiveness, implying that elevated thermal conditions may hinder the adsorption process of the plant extract onto the metallic substrate. These observations are consistent with the trends documented in previous research conducted by Emembolu *et al.* (2020) and Ibrahim *et al.* (2024). The plots illustrating inhibition efficiency (I.E) against both inhibitor concentration and temperature followed a characteristic quadratic trend. To gain deeper insight into the inhibition performance, a combination of Analysis of Variance (ANOVA), mathematical modeling, and optimization techniques was employed. The ANOVA results were instrumental in identifying which model terms significantly influenced the response. Furthermore, the presence of squared terms in the regression equation confirmed the suitability of a quadratic model structure. Three-dimensional surface plots were constructed to illustrate how inhibition efficiency is influenced by key operational parameters, specifically the concentration of the inhibitor and the temperature. These graphical representations provided clear insight into the variation in the extract's anticorrosive performance as these conditions changed. Moreover, the plots distinctly showcased the interplay between temperature and inhibitor dosage, emphasizing their combined impact on the overall effectiveness of the corrosion protection mechanism.

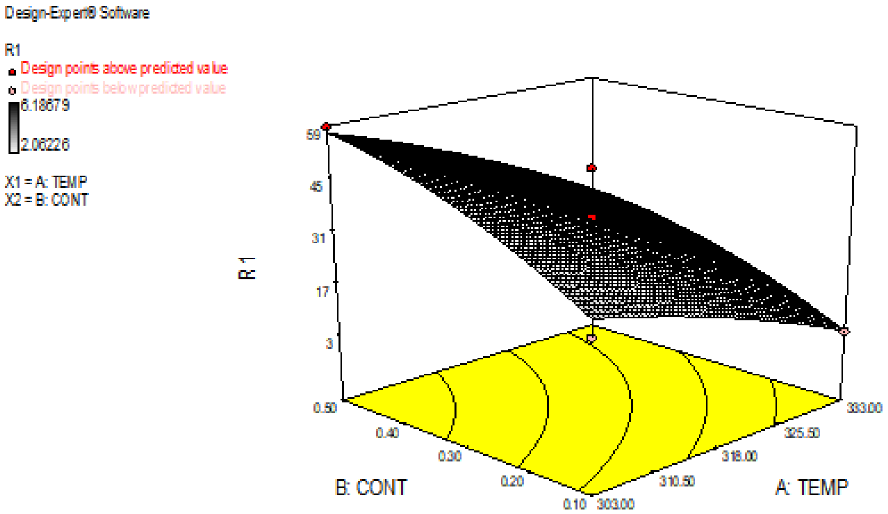

Figure 1. Variation in Inhibition Efficiency (%)(R1) of *Syzygium guineense* Leaf Extract as a Corrosion Inhibitor for Mild Steel in Sulfuric Acid(0.033 M) with Respect to Temperature(318 K) and Inhibitor Dosage (0.028 g/L)(CONT)

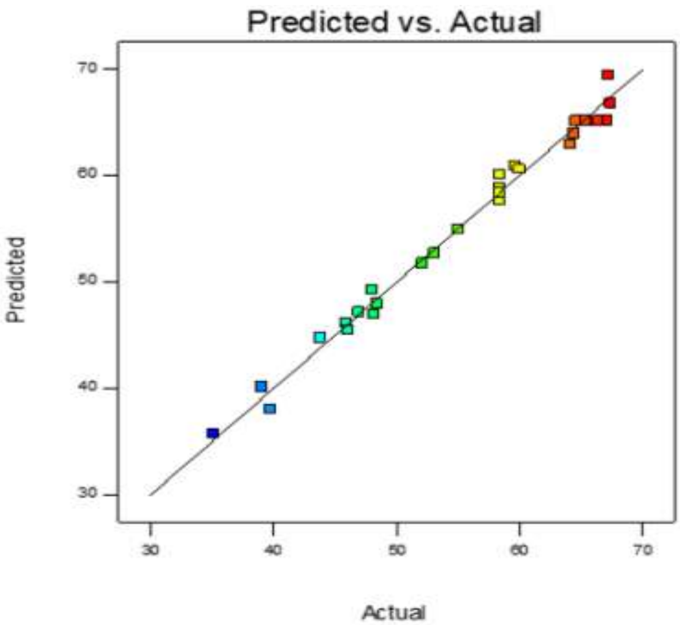

Figure 2. Comparison of Predicted and Experimental Inhibition Efficiency (%) Values for *Syzygium guineense* Leaf Extract as a Corrosion Inhibitor of Mild Steel in Sulfuric Acid Medium

❖ Optimal Conditions for Corrosion Inhibition

The high values of inhibition efficiency, as shown in **Table 4**, indicate that the leaf extract of *Syzygium guineense* possesses significant capability to function as a protective surface treatment for metals exposed to corrosive conditions. This underscores its potential usefulness in the development of corrosion prevention techniques and strategies.

Table 4. Optimal Conditions for Achieving Efficient Corrosion Protection of Mild Steel in Acidic Environments Through the Use of *Syzygium guineense* Leaf Extract

Acid conc. (M)	Inhibitor conc. (g/L)	Temperature (K)	Time (hrs)	Inhibition efficiency (%)
0.033	0.028	318	1.375	83.368

❖ Confirmation and Verification of Findings

Additional experimental investigations were performed to verify the dependability of the optimal parameters presented in **Table 4. Table 5** displays both the anticipated and experimentally measured inhibition efficiencies under these optimized conditions. The strong correlation between the predicted and actual values demonstrates the effectiveness of the Response Surface Methodology (RSM) as a reliable tool for optimizing the corrosion inhibition process. These results align well with earlier findings reported by Emembolu *et al.* (2020) and Jimoh *et al.* (2025).

Table 5. Confirmed Data Demonstrating the Corrosion Inhibition Performance of Mild Steel in Acidic Solution Using *Syzygium guineense* (SGL) Extract

Acid conc. (M)	Inhibitor conc. (g/L)	Temp. (K)	Time (hrs)	Predicted I.E (%)	Measured I.E (%)
0.033	0.028	318	1.375	83.368	85.143

Phytochemical Profile of Syzygium guineense Leaf (SGL) Extract

The phytochemical screening results, as presented in **Table 6,** reveal a significant presence of flavonoids within the SGL extract. Compounds such as tannins, phenolics, anthocyanins, triterpenes, and steroids were found in moderate concentrations. In contrast, coumarins and terpenoids appeared only in trace amounts, while saponins, phlobatannins, glycosides, and amino acids were either absent or present at undetectable levels. Based on these findings, it can be deduced that the high inhibition efficiency observed is largely due to the abundant flavonoid content in the extract. This conclusion is supported by earlier reports from Olawale *et al.* (2019) and Enembolu *et al.* (2020). Additionally, the molecular structure of flavonoids—which features two aromatic rings and a heterocyclic ring containing oxygen—further substantiates the potential of *Syzygium guineense* leaves as an effective corrosion inhibitor.

Fourier Transform Infrared (FTIR) Spectroscopic Investigation Confirming the Binding Interaction of *Syzygium guineense* Leaf Extract with the Mild Steel Surface.

To gain deeper insight into the adsorption characteristics of *Syzygium guineense* leaf (SGL) extract on mild steel, Fourier Transform Infrared (FTIR) spectroscopy was employed. The infrared spectrum of the unaltered ethanol-based extract (illustrated in **Fig. 3a**) was analyzed alongside the spectrum obtained from the corrosion layer formed in the extract's presence (**Fig. 3b**). A detailed comparison of the observed vibrational peak positions and their corresponding intensities is provided in **Table 7.**

Table 6. Analysis of the Biologically Active Constituents Found in the Leaf Extract of *Syzygium guineense*

Parameters	Qualitative screening of SGL extract	Quantitative screening of SGL extract (mg/100g)
Tannins	++	14.6
Phenolics	++	23.0
Saponin	-	-
Flavonoids	+++	144.8
Coumarin	+	3.8
Phlobatinin	-	-
Terpenoid	+	1.7
Anthrocyanin	++	12.4
Alkaloids	-	
Triterpenes	+	13.3517
Steroids	+	10.7433
Glycosides	-	-
Amino acid	-	-

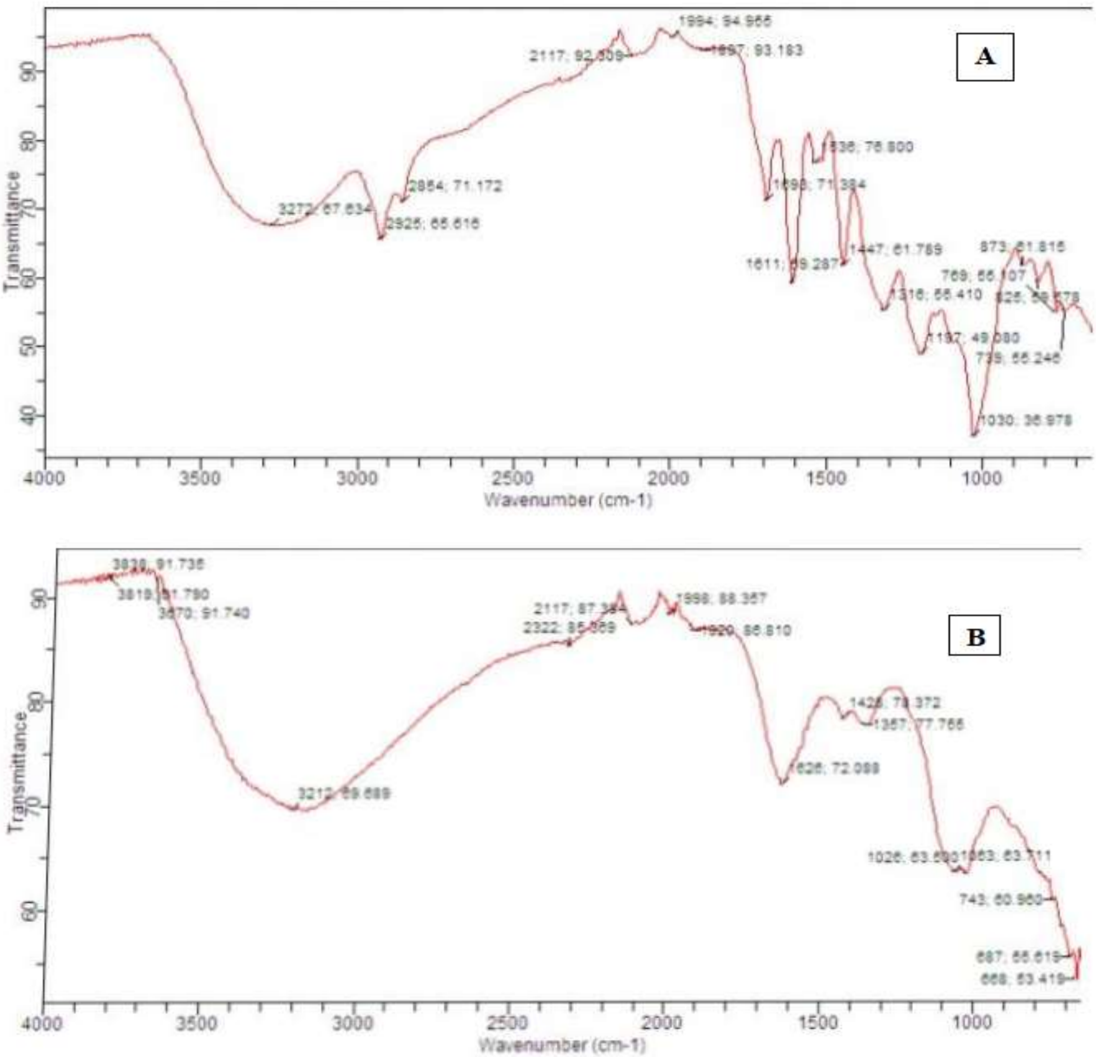

Figure 3. FT–IR Spectra Showing (a) the Ethanolic Extract of *Syzygium guineense* Leaves and (b) the Corrosion Product Formed on Mild Steel in the Presence of the Inhibitor

Table 7. Identification of Functional Groups in the Ethanol Extract of *Syzygium guineense* Leaves Involved in Surface Adsorption and in the Formation of Corrosion Products During Inhibition.

SGL pure extract			Protective oxide film		
Peaks. cm^{-1}	**Height**	**Band assignments**	**Peaks. cm^{-1}**	**Height**	**Band assignments**
3272	67.634	O-H or N-H Stretching in Phenol or alcohol	3838	91.735	Free O–H stretching in alcohols or phenols
2925	65.618	C-H Stretch in alkene	3819	91.790	Free O–H stretching in alcohols, phenols, or carboxylic acids
2854	71.172	C-H Stretch (aliphatic)	3670	91.740	Free O–H stretching in alcohols, phenols, or carboxylic acids:
2117	92.309	C≡C stretching vibrations in alkynes.	2117	87.384	C≡C stretching in alkynes C≡N stretching in nitriles Isocyanate stretching group (–N=C=O)
1994	94.935	C=O Stretch in conjugated or bridge system C=C Stretch in highly conjugated system	-	-	-
1897	93.183	C=O Stetch in metal carbonyl/complex	2322	85.369	C≡N stretching in nitriles C≡C stretching in alkynes
1693	71.384	C=O (carbonyl)Stretching (ketone or aldehyde or carboxylic acid or amides)	1998	88.357	C=C stretching in alkenes C≡C stretching in alkynes C=O stretching
1536	76.800	C=C stretching in aromatic rings:	1520	86.810	C=C stretching in aromatic compounds N–O asymmetric stretching in nitro compounds N–H bending in amines or amides
1611	59.287	N-H bending in amides C=C in aromatic ring	-	-	-
1447	61.789	C-H bending in methylene group C=C stretch in aromatic ring N-O bending in nitro group	1428	78.372	C–H bending in alkanes C=C stretching in aromatic compounds N–O asymmetric stretching in nitro compounds
1316	53.410	C-N Stretching in amines O-H bending in phenol COOH	-	-	-
1197	49.080	C-N Stretch in aliphatic amine C-O Stretch in alcohol, ether or ester O-H bending if COOH is present	3212	69.689	N–H stretching vibrations in amines or amides O–H stretching in alcohols or carboxylic acids O–H stretching in water or hydrated systems
1030	36.978	C-O Stretch in alcohol C-N Stretch in amines	-	-	-
739	55.248	Aromatic C-H out of plane bending	743	60.960	C–H out-of-plane bending in aromatic compounds C–C bending in alkenes
825	59.598	C-H out-of-plane bending	687	55.619	C–H out-of-plane bending in aromatic compounds

769	55.017	C-H out-of-plane bending	668	53.419	C–H out-of-plane bending in aromatic compounds C–C bending in certain aliphatic compounds
873	61.815	C–H out-of-plane bending			

Distinct alterations in key absorption bands were detected between the two spectra, pointing to direct molecular interactions between the bioactive constituents of *Syzygium guineense* leaf extract and the surface of mild steel. Notably, the O–H stretching vibration, typically associated with alcohols and phenolic groups, exhibited a shift from 3272 cm^{-1} to 3838 cm^{-1}, while the C–H stretching vibration of alkenes shifted from 2925 cm^{-1} to 3819 cm^{-1}. These changes imply that hydroxyl and unsaturated functional groups may be engaging in hydrogen bonding or electrostatic attractions with the metallic substrate. Further spectral shifts were also recorded in regions corresponding to aliphatic C–H stretching, alkyne (C≡C) vibrations, carbonyl (C=O) groups, nitrile functionalities, aromatic C=C bonds, primary and secondary amines, as well as methylene C–H bending. These modifications are indicative of the formation of surface complexes or chemisorptive interactions, where electron-donating atoms—such as oxygen and nitrogen present in the extract's phytochemicals—coordinate with the empty d-orbitals of iron atoms on the steel surface. Such interactions corroborate the proposed corrosion inhibition mechanism, wherein the extract's active components adsorb onto the metal, generating a compact and stable barrier layer. This adsorbed film impedes both the oxidation of the metal (anodic reaction) and the reduction of hydrogen ions (cathodic reaction), thereby mitigating corrosion in the acidic environment. These spectral changes confirm the participation of active functional groups in adsorption, as supported by literature (Jimoh & Bishir, 2021; Riastuti *et al.*, 2022; Sumaila *et al.*, 2024).

In addition, the loss of certain characteristic vibrational bands—specifically the C–O stretch around 1260 cm^{-1}, the C–N stretch near 1380 cm^{-1}, the N–H bending vibration near 1600 cm^{-1}, and the O–H stretching vibration close to 3270 cm^{-1}—indicates that these functional groups were directly involved in the corrosion inhibition process. Their absence following the adsorption of the extract onto the steel surface suggests that these groups underwent interaction with the metal, likely through coordination. This occurs when electron-rich atoms such as oxygen and nitrogen donate lone electron pairs to the vacant d-orbitals of iron atoms on the mild steel surface. Such bonding behavior is consistent with a chemisorption mechanism, in which the active compounds from the extract firmly adhere to the metal surface and form a protective layer that shields it from corrosive attack (Jimoh & Bishir, 2021). Therefore, the FTIR analysis provides strong evidence that the corrosion-inhibiting action is primarily due to the attachment of bioactive constituents from the SGL extract onto the metallic surface through reactive functional groups, thereby confirming its potential as an environmentally friendly corrosion inhibitor.

Surface Morphological Analysis Using Scanning Electron Microscopy (SEM)

The surface structures of mild steel specimens subjected to varying conditions were examined using Scanning Electron Microscopy (SEM). These included a freshly polished sample (**Fig. 4a**), a specimen immersed in 0.1 M H_2SO_4 without any corrosion inhibitor (**Fig. 4b**), and another treated with 0.5 g/L of Syzygium guineense leaf extract serving as a corrosion inhibitor (**Fig. 4c**).

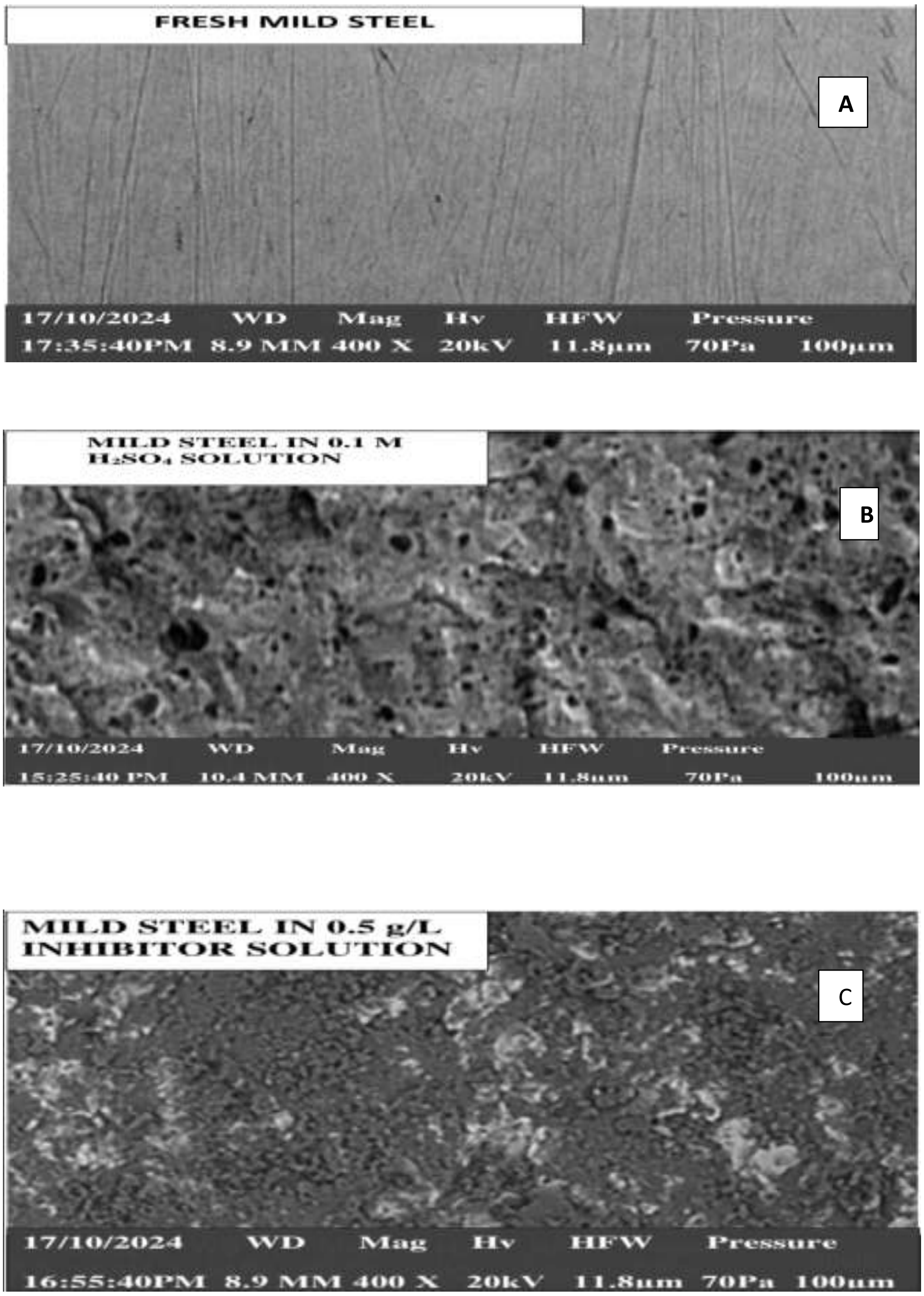

Figure 4: Scanning Electron Micrographs illustrate the structural appearance of mild steel surfaces when subjected to three conditions: (a) the untreated, freshly polished metal; (b) the corroded surface after exposure to 0.1 M sulfuric acid without any inhibitor; and (c) the protected surface following treatment with 0.5 g/L of *Syzygium guineense* plant-based leaf extract utilized for mitigating corrosion.

The SEM image in **Fig. 4b** reveals significant surface degradation caused by the corrosive action of sulfuric acid, indicating severe material loss and surface roughness. In contrast, **Fig. 4c** shows a visibly smoother and more uniform surface for the inhibited sample, suggesting that the extract formed a protective coating layer formed on the steel substrate. This layer serves as a protective shield that physically impedes corrosive agents, minimizing direct acid interaction and effectively reducing corrosion. The improvement in surface condition confirms the protective role of the inhibitor through surface adsorption, leading to a more controlled and uniform corrosion product layer. These observations align with findings reported by Jimoh & Bishir (2021) and Emmanuel (2024), further supporting the inhibitor's effectiveness in mitigating acid-induced corrosion.

❖ Proposed Inhibition Mechanism

Findings from FTIR and SEM analyses suggest that the corrosion inhibition mechanism involves the adsorption of active molecules from the *Syzygium guineense* leaf extract onto the mild steel surface, effectively blocking it from corrosive attack. This surface coverage forms a protective barrier, limiting metal interaction with the aggressive acidic environment. The effectiveness of the adsorption mechanism is governed by a variety of parameters, notably the molecular structure and functional groups present in the inhibitor, the physicochemical characteristics and surface charge of the metal substrate, as well as the specific properties of the corrosive environment. Analytical evaluations, including phytochemical profiling and Fourier-transform infrared (FTIR) spectroscopy, verified that the extract contains several biologically active constituents, such as flavonoids, tannins, phenolic compounds, anthocyanins, triterpenes, and steroids. Among these, flavonoids play a key role, likely interacting electrostatically with the negatively charged metal surface due to their positively charged functional groups. This interaction promotes the development of a durable barrier on the metal surface, which significantly improves the ability of mild steel to withstand corrosive attack, and then, to introduce the intermolecular synergistic effect of the various components at the metal surface as discussed in literature (Elmsellem *et al.*, 2019; Lrhoul *et al.*, 2023; Haddou *et al.*, 2025; Okonji, 2025)

Conclusion

Comprehensive analyses using phytochemical screening and Fourier-transform infrared (FTIR) spectroscopy revealed that the *Syzygium guineense* leaf extract contains a diverse array of bioactive molecules, such as flavonoids, tannins, phenolic acids, anthocyanins, triterpenoids, and steroids. These naturally occurring compounds are believed to contribute significantly to the extract's effectiveness in mitigating the corrosion of mild steel. Complementary surface examination through scanning electron microscopy (SEM) confirmed the presence of an adsorbed protective layer on the metal, indicating that the primary inhibition mechanism involves the formation of a physical barrier that prevents interaction between the steel and the corrosive medium.

Employing Central Composite Design (CCD) within the Response Surface Methodology (RSM) framework, the study demonstrated that inhibitor dosage and system temperature play crucial roles in determining the overall corrosion inhibition efficiency. Optimal conditions were established at 0.033 M sulfuric acid concentration, 0.028 g/L of the plant extract, an immersion duration of 1.375 hours, and a temperature of 318 K. Under these parameters, the model predicted an inhibition efficiency of 83.368%, which was closely matched by the experimental result of 85.143%, thus validating the model's predictive capability and the robustness of the optimization process.

Recommendations for Future Research

To further advance this research, future investigations should assess the long-term performance and environmental resilience of the protective layer formed by the extract under varying operational conditions. A deeper understanding of the inhibition mechanism could be achieved through theoretical studies involving quantum chemical modeling and advanced surface characterization methods such as X-ray photoelectron spectroscopy (XPS) or atomic force microscopy (AFM). Additionally, it would be valuable to evaluate the extract's anticorrosive effectiveness across a range of aggressive environments—including saline, alkaline, and marine systems—as well as on different metal substrates like copper, aluminum, or galvanized steel, to establish its broader potential as a green and versatile corrosion inhibitor.

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