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Modelling the Inhibitory Effect of Moringa oleifera on Mild Steel Corrosion Using Nonlinear Adsorption, Dose–Response, and Multivariate Statistical Approaches

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KEYWORDS

Corrosion Inhibition, Moringa oleifera, Langmuir Adsorption, Dose–Response Modelling, Principal Component Analysis (PCA), Corrosion Rate

ABSTRACT

Mild steel corrosion is one of the key problems of the industry as it has an economic effect and can easily be deteriorated in acidic conditions, which requires efficient and sustainable inhibitory measures. The application of synthetic inhibitors is, however, restricted by toxicity, environmental issues and cost, and available research on plant-based inhibitors is largely experimental and has not extensively incorporated the use of sophisticated statistical modelling. This knowledge gap explains why a full modelling framework is necessary to integrate experimental evidence and sound analytical methods to enhance predictions and mechanistic insights. The study purposes were to determine the inhibitory activity of the Moringa oleifera extract on mild steel corrosion by establishing the rate of corrosion, weight loss, the efficiency of the inhibitor, and surface coverage; modeling the adsorption behaviour by employing the Langmuir isotherm; examining the relationships between concentration and response; and selecting the most appropriate modelling framework. Primary experimental data collection was performed by gravimetric and gasometric methods, under controlled laboratory conditions. R version 4.4.3 was used to perform data analysis with linear regression, nonlinear least squares (NLS), log-logistic dose response modelling, Principal Component Analysis (PCA), and Akaike Information Criterion (AIC) to evaluate the model. Results indicate strong inhibition performance, with a significant adsorption constant ($K = 1.1916$, $p = 0.0011$) and excellent regression fit ($R^2 = 0.98$; $F = 366.70$; $p = 1.31 \times 10^{-6}$). In comparison to the linear model, the Langmuir model was better (AIC = -13.9402 vs 46.9929) and PCA showed that 99.40 percent of the variance is described by a single dominant factor. The study concludes that Moringa oleifera is a promising green corrosion inhibitor and the combined modelling method has a strong potential of offering an effective framework of optimising corrosion control measures.

1. Introduction

Corrosion continues to be a thorny and expensive problem in engineering and industrial systems, especially mild steel since it is widely used, and it is prone to electrochemical corrosion in harsh environments such as acidic and alkaline conditions. Metallic corrosion is causing major economic losses, loss of structural integrity and higher costs of maintenance and the world estimates have been in trillions of dollars per year (Didouh et al., 2025). Consequently, this has made the pursuit of viable methods of controlling corrosion to gain a lot of focus, particularly in areas like petroleum, construction and chemical processing.

Synthetic corrosion inhibitors have traditionally been used to reduce the corrosion that occurs in metals, but due to their toxicity, environmental risks, and high-cost factors, there has been a shift to the sustainable alternatives. In this regard, the use of plant-based inhibitors has proven to be a promising eco-friendly solution because of its biodegradability, availability, and low toxicity. One of them, Moringa oleifera, has become eminent due to its high phytochemical

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content, which contains polyphenols, tannins, and other bioactive components that enable adsorption onto metal surfaces, creating protective coatings that prevent corrosion processes (Odusote et al., 2016; Arockiaselvi et al., 2018).

The studies reviewed also all deal with corrosion as an electrochemical degradation process of mild steel and aluminum in acidic and alkaline environments with a high level of economic and industrial consequences. The growing environmental concerns regarding synthetic inhibitors have seen the need to research on environmentally friendly substitutes especially plant extracts like Moringa oleifera. In the studies, the main aim has been to assess the efficiency of inhibition (IE%), rate of corrosion (CR), and adsorption processes through gravimetric, electrochemical (Electrochemical Impedance Spectroscopy (EIS), Potentiodynamic Polarization (PDP)) and surface characterization (Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray Analysis (EDAX). There is strong and consistent inhibition performance which is proven by empirical findings. As an example, the efficiency of inhibition was 96% in sulphuric acid systems (Arockiaselvi et al., 2018), more than 80% in alkaline systems (Idu et al., 2016) and more than 92% in hydrochloric acid systems (Odusote et al., 2016). High-tech research also states that efficiencies are more than 93 percent under optimized conditions (Didouh et al., 2025), whereas approaches to synergize plant extracts with polymers or oils increased durability and adhesion (Sadiq et al., 2024; Bam et al., 2018). Response Surface Methodology (RSM) was statistically optimized and demonstrated a high coefficient of determination (R^2) of more than 0.96 (Jimoh et al., 2025). Comparative studies also indicate that some extracts (e.g., Lawsonia inermis and neem (Azadirachta indica)) can reach inhibition efficiencies of over 95% (Okore et al., 2025; Ndukwe et al., 2023).

Mechanistically, the majority of the research proves that inhibition of corrosion takes place as a result of adsorption of phytochemical compounds (tannins, flavonoids, alkaloids) creating protective layers on metal surfaces. The adsorption behavior mainly conforms to Langmuir, Temkin or Frumkin isotherms, which depict monolayer or interaction-controlled adsorption mechanisms. The degree of inhibition, however, is extremely concentration-dependent, exposure-time dependent, and environment-dependent, where certain researchers have found lower effectiveness at extremely high concentrations (Omojogberun and Olakolegan, 2025). To conclude, vegetable-derived inhibitors, specifically Moringa oleifera, have great potential as eco-friendly and economical corrosion inhibitors in various settings. Although this has been achieved, predictive modelling, long-term stability evaluation, and incorporation of sophisticated statistical and machine learning strategies to optimize inhibitor performance still have gaps (Ndukwe et al., 2023).

Moringa oleifera has always proven effective as a corrosion inhibitor in different environments as demonstrated in empirical studies. As an example, sulphuric acid systems have been reported to achieve inhibition efficiencies up to 96% (Arockiaselvi et al., 2018), hydrochloric acid-based media have been reported to reach up to 92% (Odusote et al., 2016), and even 93% under optimized conditions (Didouh et al., 2025 Equally, the extent of corrosion has been reduced significantly in alkaline environments, with an inhibition efficiency of more than 80 percent being achieved based on concentration and length of exposure (Idu et al., 2016). These results affirm that most of the performance of the Moringa oleifera inhibition is concentration-specific and determined by the environmental factors, as the best results were obtained under certain ranges of concentrations (Omojogberun, 2025). Mechanically, the mechanism through which plant extracts inhibit corrosion is mainly determined by the adsorption processes in which phytochemical substances are attached to the metal surface, creating a layer that limits the dissolution and electrochemical interactions of the metal. Past experiments demonstrated that these adsorption processes tend to be described by classical isotherm frameworks, such as Langmuir, Temkin, and Frumkin, suggesting that the adsorption process is monolayer-based or interaction-based (Bam et al., 2018; Adagashi et al., 2023b).

Although these models give valuable insights in the mechanisms of inhibition, the majority of the current studies are mostly based on experimental and empirical studies, and few have applied more sophisticated statistical modelling methods to improve the predictive power and explain complex connections.

The recent developments have emphasized the need to integrate experimental data with statistical and computational modelling frameworks. Response Surface Methodology (RSM) and other techniques have proven to be highly predictive with coefficients of determination of over 0.96 (Jimoh et al., 2025), whereas multivariate techniques have enhanced knowledge about the interaction of variables and system dynamics. Nevertheless, there is still a significant lack in the use of integrated modelling strategies that can simultaneously model nonlinear adsorption behaviour, dose response relationships and multivariate data structures in corrosion research.

It is against this background that the current research attempts to fill this gap by formulating a holistic framework of modelling the nonlinear adsorption models, dose response model, and multivariate statistical method to assess the inhibitory effect of Moringa oleifera on mild steel corrosion. Through the combination of experimental measurements and sophisticated statistical modelling, the study offers a better understanding of the corrosion kinetics, adsorption processes, and inhibitor efficacy, thus helping to create robust, sustainable, and data-driven corrosion control measures. Hence, the specific objectives of the study are to determine the corrosion rate, weight loss, inhibition efficiency, and surface coverage of mild steel at varying concentrations of Moringa oleifera extract; to model the adsorption behavior of the inhibitor using the Langmuir adsorption isotherm and estimate the adsorption constant; to examine the relationship between inhibitor concentration and corrosion rate using linear regression modelling; to analyse the dose–response relationship between inhibitor concentration and inhibition efficiency using a four-parameter log-logistic model; to evaluate and compare model performance using statistical criteria such as residual standard error, coefficient of determination (R^2), and Akaike Information Criterion (AIC); to assess the rate of change in corrosion response with respect to inhibitor concentration through gradient evaluation; to explore the underlying structure and interrelationships among corrosion variables using Principal Component Analysis (PCA); and to identify the most suitable modelling framework for accurately describing corrosion inhibition behaviour and optimizing inhibitor performance.

1.1 Conceptual Framework of the Study

The interaction between the concentration of inhibitors, adsorption behaviour and corrosion performance is the conceptual framework of this study and statistical modelling is the analytical bridge that explains these relationships. The model presumes that corrosion inhibition is a phytochemical adsorption dependent variable which depends mainly on the concentration of the Moringa oleifera extract. This relationship is explicated in three intertwined elements:

(i) Independent Variable

Inhibitor Concentration (C)

Indicates the different concentrations of the Moringa oleifera extract added to the corrosive medium.

Is the main corrosion inhibitor.

(ii) Mediating Mechanism

Adsorption Behavior

Adsorbed with the Langmuir isotherm of adsorption.

Explains the binding of phytochemical constituents (e.g., polyphenols, saponins) to the mild steel surface.

Causes the development of a protective film, lessening the contact between metal and acid.

Surface Coverage (θ)

Determines the amount of metal covered by the inhibitor.

Acts as an immediate connection between the inhibition efficiency and concentration.

(iii) Dependent Variables (Corrosion Performance Indicators)
Corrosion Rate (CR)
Weight Loss (WL)
Inhibition Efficiency (%IE)
These are measured variables that determine the performance of the inhibitor in terms of limiting metal corrosion.

1.2. Analytical Layer and Modelling.

The research combines various modelling choices to explain and authenticate the relations in the system:
Linear Regression Model
Investigates how the concentration of the inhibitors influences the rate of corrosion.
Langmuir Nonlinear Adsorption Model.
Takes on adsorption equilibrium and strength.
Dose–Response Model (Log-Logistic)
Describes the nonlinear correlation between the concentration and inhibition efficiency.
Multivariate Analysis (PCA)
Determines latent structure and interrelationships between variables.
Model Evaluation Metrics
AIC, R^2, Residual Standard Error to decide on the best fitting model.

1.3. Conceptual Relationships

The framework is as follows:
Changing concentration upwards (C)
⟶ increases adsorption to metal surface.
⟶ increases surface coverage (θ)
⟶ decreases weight loss (WL) and corrosion rate (CR)
⟶ enhances inhibition efficiency (%IE)
At the same time:
The efficiency of the rate of conversion of concentration into protection is dictated by the nature of adsorption (nonlinear behavior).
These relationships are validated, quantified and compared using statistical models.
The framework is based on:

- Adsorption theory (surface chemistry viewpoint),
- and EECT, and
- Statistical modelling theory (to be empirically validated).

It represents a cause mechanism effect structure, where:

- Cause → Inhibitor concentration
- Mechanism → Adsorption behavior
- Effect → Corrosion reduction

2. Material and Methods

2.1 Research Design

This study uses experimental laboratory design to assess the corrosion inhibition activity of Moringa oleifera leaf extract on mild steel in an acidic environment. The design is a combination of gravimetric (weight loss) and gasometric (hydrogen evolution) methods to give complementary information on corrosion kinetics and inhibition efficiency. The experimental design enables the inhibitor concentration and temperature to be controlled, so reliable evaluation of the corrosion rate, surface coverage, and inhibitor efficiency as time progresses is ensured. The several methods of analyses used strengthens the findings and internal validity..

2.2 Source of Data Collection

The information used in this research is primary experimental data, which was obtained using controlled laboratory procedures. *Moringa oleifera* leaves were fresh and were gathered locally and authenticated at the Department of Botany, University of Calabar, Nigeria. Mild steel sheets were obtained commercially in Calabar, Nigeria. Systematic laboratory measurements were made to measure weight loss and hydrogen gas evolution at given intervals with different concentration of inhibitors and temperatures. The basis of these observations was used to estimate the corrosion rate, inhibition effectiveness, and adsorption behavior..

2.3 Material Preparation and Sample Processing

Mild steel sheets with thickness of 0.08 mm were cut into coupons using a mechanical cutter to sizes of 2 cm 4 cm (gasometric analysis) and 5 cm 4 cm (gravimetric analysis). The samples were polished until a smooth surface with a uniform finish was achieved, on the paper of graded emery to a maximum of 600 grit. Then, samples were cleaned with ethanol, dried with acetone and stored in desiccators to avoid moisture content before experimentation.

The *Moringa oleifera* fresh leaves were washed followed by drying in the oven at 40 o C over a period of 48 hours and blended into a fine powder. Soxhlet extraction was performed on the powdered sample by using ethanol to extract the crude extract which was later concentrated and kept in refrigerated conditions to be used further.

2.4 Preparation of Corrosion Medium and Inhibitor Solutions

The medium of corrosion was made up of 5 M hydrochloric acid (HCl) with analytical grade reagents and distilled water. The stoichiometric quantities of molarity, density (1.18 g/cm 3) and purity (36) were utilized to calculate the volume of required concentrated acid. The solution of a stock inhibitor was prepared by dissolving 10 g of the plant extract in 1 litre of 5 M HCl. Serial dilution was done with the blank acid solution to obtain subsequent working concentrations (0.5-10.0 g/L).

2.5 Phytochemical Characterization

The ethanol extract was screened by phytochemical analysis to determine active constituents that caused corrosion inhibition. The analysis showed the existence of saponins and polyphenols, and the absence of alkaloids, flavonoids, tannins and other substances. These bioactive compounds are reported to strengthen adsorption on metal surfaces, thus playing a role in corrosion prevention processes.

2.6 Experimental Procedures

2.6.1 Gravimetric (Weight Loss) Method

Mild steel coupons with a pre-determined weight were immersed in 250 ml of 5 M HCl solutions of the presence and absence of an inhibitor at different concentrations. The experiment has been carried out during 168 hours (7 days), measurements were made after every 24 hours. The specimens were after every interval retrieved, cleaned, dried, and reweighed. Weight loss. The calculation of the weight loss (WL) was made as the difference between initial and final weights:

$$WL = W0 - W1 \qquad (1)$$

The corrosion rate (CR) was evaluated as:

$$CR = WL \times A \times t \qquad (2)$$

where A is the surface area and t is the exposure time. Inhibition efficiency (%IE) and surface coverage (θ) were determined using standard relationships based on corrosion rates in the presence and absence of inhibitor.

2.6.2 Gasometric (Hydrogen Evolution) Method

Hydrogen gas evolution was monitored using the gasometric technique as the corrosion process was taking place. The experimental apparatus was made up of a reaction vessel in contact with a burette. When the mild steel sample was immersed in the acid medium the volume of hydrogen gas evolved was measured at 1-minute intervals over 45 minutes. Temperature was varied to 30C and 60C to determine the influence of temperature on the corrosion kinetics and inhibitor effectiveness.

2.7 Analytical Techniques and Performance Metrics

Corrosion performance was evaluated using the following indicators:

- Weight loss (WL)
- Corrosion rate (CR)
- Inhibition efficiency (%IE)
- Surface coverage (θ)

These measurements give a quantitative understanding of the performance of plant extract as a corrosion inhibitor and its adsorption characteristics on the metal surface.

2.8 Statistical and Model Evaluation

A combination of linear regression, nonlinear adsorption modelling, and multivariate statistical techniques were used to analyze the experimental data and investigate corrosion kinetics and inhibitor performance. In particular, nonlinear least squares (NLS) was used to estimate the Langmuir adsorption isotherm in order to determine the behavior of adsorption, and a log-linear regression model was used to determine the relationship between corrosion rate and the concentration of the inhibitor. Moreover, a four parameter log-logistic dose-response model was also fitted to describe the nonlinear relationship between the inhibitor concentration and the inhibition efficiency.

The standard diagnostic statistics, such as residual standard error, coefficient of determination (R^2 and adjusted R^2), F-statistics, and Akaike Information Criterion (AIC) were used to assess model adequacy and comparative performance. Nonlinear models were also evaluated in convergence diagnostics, including the number of iterations and tolerance. Moreover, gradient assessment was done to test the local rate change of corrosion response in relation to the concentration of the inhibitor. Principal Component Analysis (PCA) was used to research multivariate structure and the relationships between the variables to gain understanding of the variance decomposition and correlation patterns between the corrosion-related variables. The combination of these methods provided strong model validation and sound inference about the mechanisms of corrosion inhibition

2.9 Method of Data Analysis

Data analyses were conducted in R statistical software version 4.4.3 and thus reproducible and computationally efficient. The first calculations were done using descriptive statistics to summarise the corrosion parameters measured as weight loss, corrosion rate, inhibition efficiency, and surface coverage at various levels of inhibitor concentration and exposure conditions.

To perform inferential analysis, the linear regression modelling was used to assess the influence of the concentration of the inhibitor on the logarithm of the corrosion rate that allowed the interpretation of the kinetic relationships. NLS estimation was used to estimate adsorption models, especially the Langmuir isotherm, to determine the adsorption constants and the intensity of the interaction between the molecules of the inhibitor and the metal surface. A four-parameter log-logistic model was estimated to further model the nonlinear dose-response dynamics, the slope, asymptotic limits, and effective dose (ED 50) could be determined. To measure predictive accuracy and model reliability, model diagnostics such as residual standard error and goodness-of-fit statistics were examined.

Akaike Information Criterion (AIC) was used to select the model, the smaller the AIC, the better the model is performing. Also, Principal Component Analysis (PCA) was performed to decrease the dimensions and analyze the latent structure of the data, showing the leading components of variance and inter-variable correlations. All statistical tests were done at a significance level of 5 percent and results were tabulated, fitted curves and graphical representations were used to represent the results and to make it easy to interpret the corrosion inhibition behavior.

3. Result and Discussion

Table 1: Langmuir Adsorption Model Estimation Results for Corrosion Inhibition Efficiency

Parameter	Estimate	Std. Error	t-value	p-value	Significance
K (Adsorption constant)	1.1916	0.2223	5.3620	0.0011	**

Table 1 shows that the Langmuir adsorption model fits the corrosion inhibition data well and statistically significantly. The calculated adsorption constant K=1.1916 indicates a rather high affinity between the molecules of the inhibitors and the metal surface indicating that the surface is effectively covered. This parameter has a moderately accurately estimated value of 0.2223, and a high t-value of 5.3620, which confirms that this estimate is not close to zero according to statistics. The corresponding p-value of 0.0011 suggests a significance of 1% level, which is a strong indication that adsorption is a crucial process in the inhibition process. Generally, the scale and statistical significance of K denote that the inhibitor establishes a steady protective coating on the metallic surface which is in line with the suppositions of Langmuir isotherm.

Table 2: Model Diagnostics of the Langmuir Isotherm Model

Statistic	Value
Residual Standard Error	0.08429
Degrees of Freedom	7
Iterations to Convergence	4
Convergence Tolerance	6.435×10^{-6}

Table 2 demonstrates that the Langmuir isotherm model fits the data effectively and converges effectively. The standard error of the residual is low (0.08429) which means that the predictions of the model are very similar to the observed values and the variation which is not explained by the model is small. The model has 7 degrees of freedom which means that it is not under-informed and therefore can be inferred with a relatively small sample. The convergence was reached in 4 iteration only which is a sign that it is computationally efficient, and the extremely low convergence tolerance (6.435×10^{-6}) indicates that it is numerically stable and the parameters are estimated with high accuracy. In general, the diagnostics indicate that the Langmuir model is statistically sound and computationally efficient in modeling the adsorption process in this experiment.

Table 3: Parameter Estimates of the Four-Parameter Log-Logistic Dose–Response Model (ED_{50} Parameterization)

Parameter	Interpretation	Estimate	Std. Error	t-value	p-value	Significance
b (Slope)	Curve steepness	-0.8254	0.2630	-3.1384	0.0349	*
c (Lower limit)	Minimum response	19.4114	3.8335	5.0635	0.0072	**
d (Upper limit)	Maximum response	120.896	25.9102	4.6660	0.0095	**
e (ED_{50})	Effective dose (50% response)	2.4043	1.7451	1.3778	0.2403	ns

As shown in Table 3, the general trend of inhibition is only reflected in the log-logistic dose-response model with unevenly significant parameters. The slope parameter is negative and statistically significant (b= -0.8254, *p*=0.0349), which proves the declining response with concentration increase, which is in line with effective inhibition. Both of the asymptotic parameters are also quite important with the lower limit (c=19.4114, *p*=0.0072) and upper limit (d=120.896, *p*=0.0095) being precise, which indicates that the model is a reliable estimate of the minimum and maximum levels of responses. Nonetheless, the ED 50 parameter is not statistically significant (e=2.4043, *p*=0.2403), which implies that there is a great deal of uncertainty regarding the concentration that is necessary to obtain the 50% effect. In general, the model can sufficiently explain the range of responses and direction, but due to the imprecision of ED50, it is not interpretable to estimate midpoint dose.

Table 4: Model Diagnostics of the Four-Parameter Log-Logistic Dose–Response Model

Statistic	Value
Residual Standard Error	3.9109
Degrees of Freedom	4

Table 4 indicates that log-logistic dose response model is a moderate but less accurate model to fit compared to the simple adsorption models. The standard error of the residual is quite high (3.9109) which shows that there is a significant difference between the observed and predicted values and therefore the actual variation of the data is not explained by the model. The estimation has merely 4 degrees of freedom meaning that it is estimated using a small sample and therefore lowers the reliability and stability of the parameter estimates. Such a combination of increased residual error and low degrees of freedom suggests that there could be over-parameterization of the four-parameter model in comparison to the available data. All in all, the model is structurally suitable to dose response analysis, but its diagnostic statistics imply that its predictive performance is limited, and it should be interpreted with caution.

The curve in figure 1 indicated that there is a nonlinear, increasing relationship between the inhibitor concentration (C) and the inhibition efficiency (IE), such that the greater the concentration, the better the corrosion inhibition. The log-logistic curve fitted is close to the observed values, at least in the middle and higher ranges, which confirms the appropriateness of the model in the description of the dose-response trend. This visual pattern is in line with the Table 3 statistical results that have a significant slope parameter (b=−0.8254, *p*=0.0349), which signifies a systematic change in response with concentration, and lower and upper asymptotes are also significant (c=19.4114, *p*=0.0072; d=120.896, p=0.0095). Nevertheless, the dispersion of the points along the curve at diluted concentrations along with the fairly large standard error of the residual (3.9109) in Table 4 indicate that there is some variability, which is not fully explained by the model. Also, the non-significant ED 50 parameter (e=2.4043, *p*=0.2403) suggests that it is not clear what the actual midpoint concentration is. In general, the number indicates the presence of a powerful concentration-dependent effect of inhibition, and the model is a reasonable but not ideal fit.

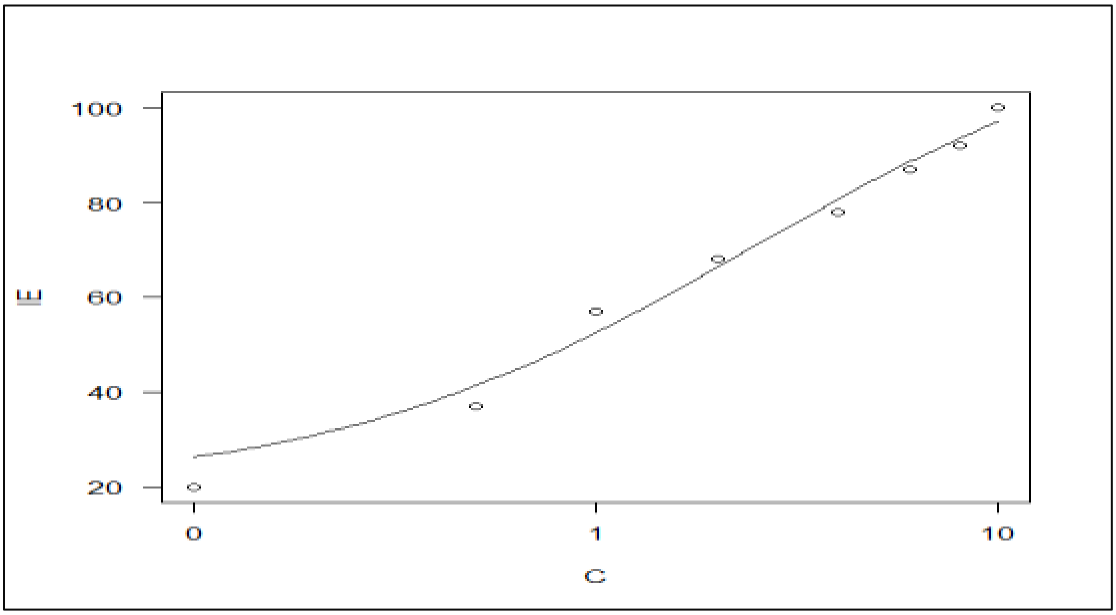

Figure 1: Dose–Response Relationship between Inhibitor Concentration (C) and Inhibition Efficiency (IE) Using Log-Logistic Model Fit

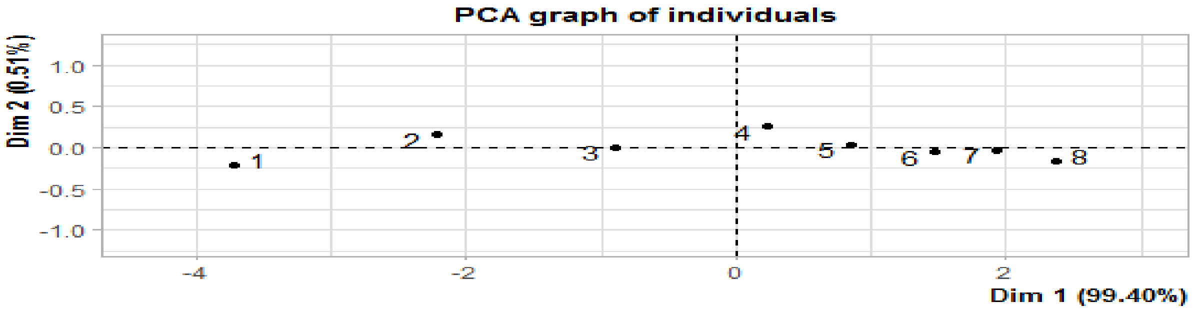

Figure 2: Principal Component Analysis (PCA) Plot of Observations Showing Variance Structure and Clustering Pattern

The PCA projection of the observations as in Figure 2 illustrates that the first principal component (Dim 1) has a huge influence on the data structure, representing 99.40% of the total variance, with the second component (Dim 2) representing only 0.51%. It means that almost all the variability in the data is explained by a single dimension, which implies that variables have a strong linear relationship. The data points are mostly distributed along Dim 1, with obvious differentiation between lower-valued (e.g., 1, 2, 3 on the negative axis) and higher-valued (e.g., 6, 7, 8 on the positive axis) data, not discrete clusters, but an effect of gradient or ordering. The fact that the dispersion along Dim 2 is minimal supports that it does not contribute significantly to discrimination. Point 4 is near the origin which represents an average profile whereas point 1 and 8 seem to be the extremes on the principal axis which could be possible outliers or extreme observations. In general, the PCA outcome indicates a very structured data set with one underlying variable with minimal multidimensionality.

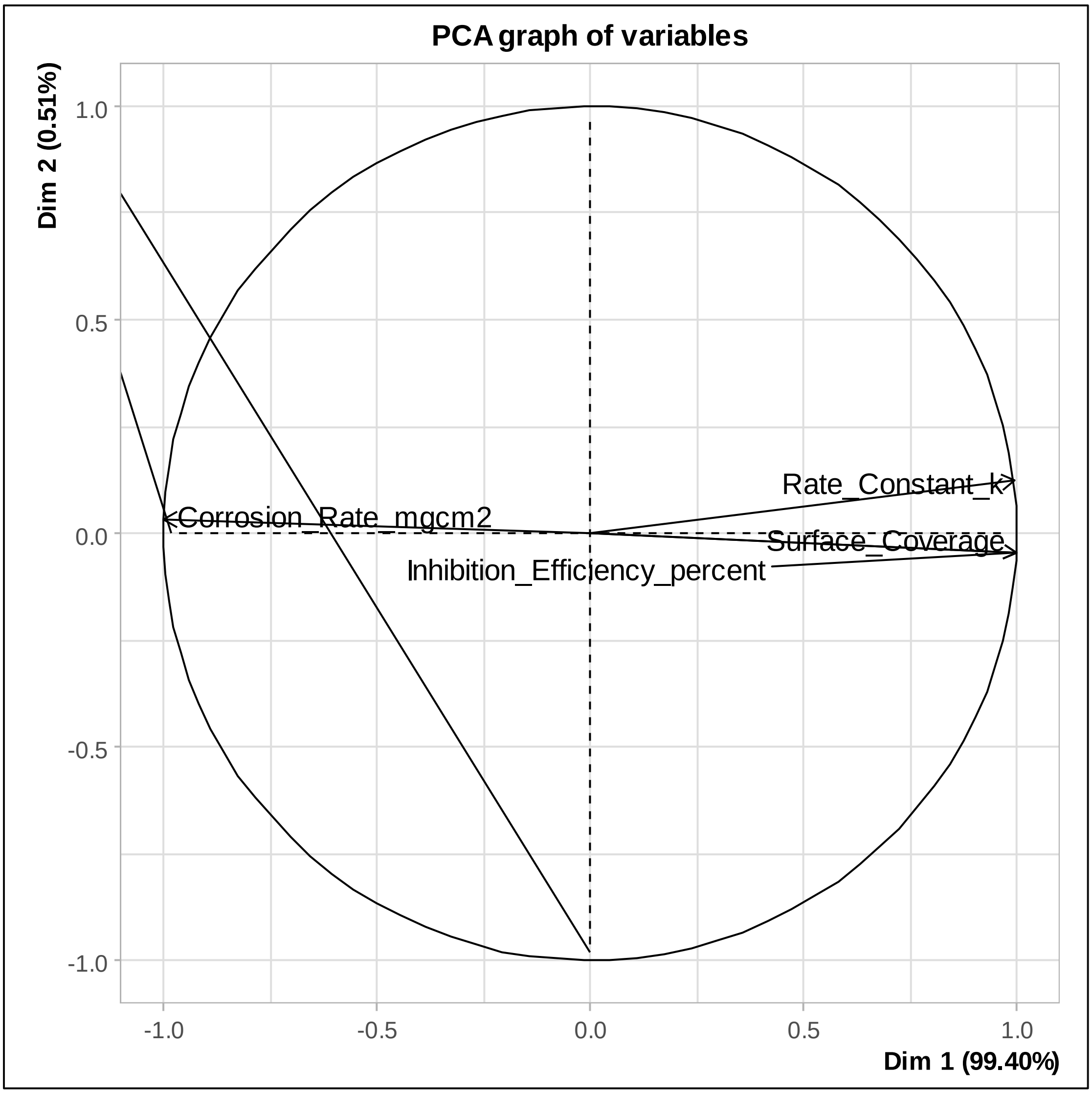

Figure 3: Principal Component Analysis (PCA) Loading Plot Showing Relationships among Corrosion Variables

The loading plot of the PCA is shown in figure 3 and it indicates the relationship among the variables. The first principal component (Dim 1) describes 99.40 percent of total variance, with the second component (Dim 2) describing only 0.51 percent, meaning that overall the dataset is almost one-dimensional. Surface Coverage, Rate Constant (k), and Inhibition Efficiency (%) have strong positive correlation with each other, as indicated by their vectors that point in the same direction in Dim 1. Corrosion Rate (mg/cm 2) on the other hand, is on the other end of the scale implying a negative relationship with these variables. This means that the better the performance of the inhibitor (increased surface coverage and efficacy), the lower the rate of corrosion. The fact that all the vectors are almost horizontal is an assurance that Dim 2 does not contribute much explanatory power. Also, the long lengths of the vectors (near to the unit circle) indicate that every variable is well represented by the PCA. In general, the plot proves a great inverse dependence between the corrosion rate and the variables that relate to inhibition, the main cause of which is a single underlying factor to run the system.

Table 5: Linear Regression Results for Corrosion Rate Kinetics Model (logCR∼C)

Parameter	Interpretation	Estimate	Std. Error	t-value	p-value	Significance
Intercept	Baseline log corrosion rate	3.05	0.06	46.95	6.26×10^{-9}	***
C	Effect of inhibitor concentration	-0.24	0.01	-19.15	1.31×10^{-6}	***

Table 5 indicates a strong relationship and statistically significant between the concentration of inhibitors and the rate of corrosion. The intercept value is very large (3.05, p=6.26×10^{-9}), which is the initial log corrosion rate at zero concentration. More so the coefficient of concentration is negative and significant (β=−0.24, t=−19.15, p=1.31×10^{-6}) meaning that the increase in the concentration of the inhibitor causes a significant decrease in logarithm of the corrosion rate. The high size of the t-value supports the power of this effect and the very small p-value supports the null hypothesis of no effect with high confidence. In general, this model shows that the inhibitor concentration is a prime factor to corrosion inhibition, and the inverse relationship is nearly linear with statistical significance.

Table 6: Model Diagnostics for Corrosion Rate Kinetics Model

Statistic	Value
Residual Standard Error	0.12
Degrees of Freedom	6.00
Multiple R^2	0.98
Adjusted R^2	0.98
F-statistic	366.70
Model p-value	1.31×10^{-6}

Table 6 shows that the corrosion rate kinetics model fits the observed data very well with a very low standard error of the residue of 0.12, which implies that there is not much variation between the predicted and actual values. The model elucidates a high percentage of variance in the rate of corrosion with a Multiple R^2 of 0.98 and an Adjusted R^2 of 0.98 indicating that the explanatory variables are still very relevant even when taking into consideration the complexity of the model. A high F-statistic of 366.70 and a highly significant model p-value of 1.31×10^{-6}, however, strongly supports the overall importance of the model as a whole, as they show that the predictors (as a group) have a statistically significant effect on the corrosion rate. The model has 6 degrees of freedom, which is enough to ensure reliability and does not over-fit, which strengthens it and makes it a good predictor.

The performance of the models are compared against each other and information criteria and gradient evaluation are used to give insight into the behavior of the corrosion process in Table 7. The gradient of $f(x = 5) = -2.0042$, means that it is negative, which implies that the rate of corrosion is negative at that point, which means that the greater the concentration of the inhibitor, the slower the rate of corrosion. The Langmuir nonlinear model (the theta=KC/(1+KC)) is clearly superior to the linear model in terms of model fit as the AIC of the former is much less than that of the latter, AIC =-13.9402 vs. 46.9929 respectively. Such a significant difference in AIC suggests that the Langmuir model gives a far superior trade-off between goodness-of-fit and model complexity, even though it has fewer degrees of freedom (df = 2) compared to the linear model (df = 3). In general, the findings indicate that the corrosion mechanism is more effectively described by a nonlinear adsorption mechanism, and the Langmuir model is more effective and efficient to explain the process.

Table 7: Gradient Evaluation and Model Comparison Using Akaike Information Criterion (AIC)

Analysis Component	**Model / Function**	**Degrees of Freedom (df)**	**Estimate / Value**	**AIC**
Gradient Evaluation	$\nabla f(x=5)$	–	-2.0042	–
Linear Model	Corrosion Rate∼C	3	–	46.9929
Langmuir Model (NLS)	$\theta = \frac{KC}{1+KC}$	2	–	-13.9402

3.2 Discussion of Findings

The results of the study present good empirical and statistical evidence that *Moringa oleifera* extract is a good corrosion inhibitor of mild steel in acidic environments and its performance is dictated by the adsorption processes and concentration-dependent tendencies. The Langmuir adsorption constant (K = 1.1916, p = 0.0011) is estimated as a strong affinity of the molecules of the inhibitor to the metal surface, which validates the formation of a protective monolayer film. This is consistent with previous literature which has described the adsorption-based inhibition of plant-based inhibitors, specifically those with Langmuir-like behavior (Bam et al., 2018; Adagashi et al., 2023b). The insignificant residual standard error (0.08429) and the quick convergence of the framework also support the strength of the adsorption framework, which is in line with the previous results suggesting the high inhibition efficiency to be due to stable surface film formation (Odusote et al., 2016).

The dose response analysis shows that there is a nonlinear relationship between the concentration of the inhibitor and the efficiency of inhibition with the slope and asymptotic parameters being significant to represent definite response limits. Nevertheless, the insignificance of the ED_{50} parameter indicates that it is not clear which middle concentration is the best to inhibit. This finding indicates how complicated the interactions between inhibitors and metals are, where the efficiency is not always proportional to the concentration. Omojogberun and Olakolegan (2025) have reported similar nonlinear behavior and threshold-dependent behavior, reporting that the efficiency of inhibition increases to an optimal concentration and decreases at higher concentrations because of potential desorption effects or saturation of the surface. The standard error of the residuals of the log-logistic model (3.9109) is relatively larger than that of the Langmuir model (1.0275), which indicates that the dose-response framework shows the overall tendencies of the corrosion process, whereas the adsorption-based models can depict the corrosion process in a more detailed manner.

This regression analysis also reveals that the relationship between the inhibitor concentration and the rate of corrosion is very strong and the coefficient ($\beta = -0.24$, $p = 1.31 \times 10^{-6}$) is very significant. It implies that the corrosion rate decreases dramatically with the rise in inhibitor concentration, which is also aligned with the results of many studies that found an inhibitor concentration-dependent efficiency (Arockiaselvi et al., 2018; Idu et al., 2016). The model diagnostics give a very good fit (R^2 = 0.98; F = 366.70) indicating that concentration is a dominant variable affecting the corrosion rates. This confirms previous findings that the rate of corrosion slows down considerably with a higher dosage of the inhibitor because of higher coverage of the surface and a reduction in the rate of dissolution of the metal (Didouh et al., 2025).

The comparison of the models based on the Akaike Information Criterion (AIC) gives additional information on the underlying corrosion mechanism. The AIC of the Langmuir model (-13.9402) is significantly lower than that of the linear model (46.9929), which means that the model is better and supports the fact that nonlinear adsorption processes are predominant. This result is aligned with previous research that highlights the significance of adsorption isotherms in a precise understanding of the mechanisms of corrosion inhibition (Ndukwe et al., 2023). The value of the negative gradient ($\nabla f(x = 5) = -2.0042$) also proves the existence of negative gradient meaning that the higher the concentration of the inhibitor, the lower the rate of corrosion, which is also a sign of good inhibition behavior.

The Principal Component Analysis (PCA) of the data indicates that there is a dominant factor that controls most of the data in the dataset, with the first principal component accounting to 99.40 percent of the total variance. The good positive correlation of the inhibition efficiency with the surface coverage and the rate constant, and the negative correlation of the inhibition efficiency with the corrosion rate demonstrate the interdependence of the variables of corrosion. This compliments the mechanistic interpretation that the enhanced adsorption and surface protection is directly proportional to reduced corrosion rates. The same inter-variable association is observed with other corrosion studies that consider integrated analysis methods, with the efficiency of adsorption and the reduction of corrosion being inextricably connected (Sadiq et al., 2024).

Thus, the findings of the current research are in line with the literature and prove that the use of the Moringa oleifera plant as a potential environmentally-friendly corrosion inhibitor due to adsorption processes is possible. Along with confirming the previous results, the study contributes to the field of knowledge by combining nonlinear adsorption modelling, dose-response analysis, regression analysis, and multivariate statistics into one analytical model, thus filling the gap in terms of the use of advanced statistical methods to study corrosion (Ndukwe et al., 2023). This capacity-driven and innovative strategy is associated with the focus on the efficiency and productivity of institutions introduced by Chukwurah et al. (2020), where better methods promoted the results of an organization. In the same way, the research indicates the developmental orientation emphasized by Ume and Chukwu (2019) that shows how sustainable local resources can be used to facilitate industrial growth. Obi et al. (2026) also find the framework of predictive and evidence-based appealing, as they stressed the importance of effective resource management by means of strategic partnerships. Similarly, the paper reinforces the inclusivity, innovation and national development advocated by Iwuno (2025), by advocating the creation of indigenous scientific solutions to industrial corrosion issues.

4. Conclusion

This study presents an analysis of the corrosive inhibitory effect of *Moringa oleifera* extract on mild steel corrosion in acidic solutions based on a combined statistical modelling system. These findings corroborate that the extract is a good green corrosion inhibitor and the performance is highly dependent on adsorption processes and concentration dependence. The Langmuir adsorption model proved to be more reliable and fit better showing that the inhibition process is mainly via monolayer adsorption of phytochemical constituents on the metal surface. The regression analysis also found that there was a strong and statistically significant inverse correlations between the inhibitor concentration and the corrosion rate and the dose-response model described the nonlinear result of the inhibition efficiency with respect to the concentration. AIC-based model comparison always preferred nonlinear adsorption modelling to linear specifications, which supported adsorption-controlled kinetics dominating the corrosion process.

The multivariate analysis showed that there is one dominant factor that controls corrosion behaviour and an interdependence of a strong level among the inhibition efficiency, surface coverage, and the corrosion rate. This observation highlights the consistency of the corrosion system, and proves the effectiveness of integrated modelling techniques in reflecting the underlying relationships. In general, the nonlinear adsorption, regression, and multivariate methods are combined to offer a powerful and predictive model of corrosion inhibition processes.

As a practical implication, the research shows that *Moringa oleifera* extract provides a cheaper, greener substitute of synthetic corrosion inhibitors, and may have a lot of potential in industry regarding its application in acidic conditions. Its high adsorption capacity and high inhibition efficiency indicates that it is suitable in the protection of mild steel structures in oil and gas, chemical processing, and infrastructure development sectors. The study methodologically builds on the current body of literature, by going beyond the purely experimental methods and integrating rigorous statistical modelling, enhancing the predictive accuracy and interpretation. Combination of adsorption modelling, dose response and multivariate techniques gives a more holistic view of the corrosion processes and bridges gaps associated with the use of few states of art analytical tools in previous studies.

To policy and practice, the results justify the use of plant-based inhibitors as one of the steps of sustainable corrosion management systems, in line with the global trends of minimizing environmental footprint and encouraging green chemistry. This framework should be further developed in future studies by adding long-term stability analysis, thermodynamic modeling and advanced machine learning methods to add additional predictive power and maximize inhibitor performance under various environmental conditions.

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