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EVALUATION OF SELECTED PLANT EXTRACTS AS GREEN CORROSION INHIBITORS FOR MILD STEEL IN HYDROCHLORIC ACID MEDIUM

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ABSTRACT

This study assesses the corrosion inhibition performance of neem leaves, moringa leaves, and ginger rhizomes as eco-friendly alternatives to traditional corrosion inhibitors for mild steel in hydrochloric acid. It explores the impacts of extract type, concentration, temperature, and immersion time on corrosion rates and inhibition efficiency. The study utilizes descriptive statistics, ANOVA, and Tukey's post-hoc test to evaluate corrosion performance and determine the significance of factors at a 5% level.The study found that neem extract was the most effective corrosion inhibitor, showing a mean corrosion rate of 0.730 mm/year and an inhibition efficiency of 52.04%. As the concentration of the extract increased to 500 mg/L, the inhibition efficiency rose to 56.32%. However, higher temperatures negatively impacted the extracts' performance. Factorial ANOVA indicated that the type of extract, concentration, temperature, and immersion time significantly affected corrosion rates ($p < 0.05$). The optimal results were achieved with neem extract at 500 mg/L, 25°C, and 48 hours, yielding an inhibition efficiency of 71.97%. These results highlight neem leaf extract's potential as a green corrosion inhibitor for mild steel in acidic conditions.

KEYWORDS: Corrosion inhibition; Green inhibitors; Mild steel; Neem extract; Moringa extract; Ginger extract; Hydrochloric acid; Inhibition efficiency.

1. INTRODUCTION

Mild steel is widely used in industrial applications, including construction, manufacturing, oil and gas production, chemical processing and storage facilities, owing to its availability, mechanical strength and relatively low cost. However, its susceptibility to corrosion,

particularly in acidic environments, presents a significant challenge to the durability, safety and economic performance of industrial equipment. Hydrochloric acid (HCl) is commonly employed in industrial operations such as acid cleaning, pickling, descaling and oil-well acidizing. Despite its industrial importance, exposure of mild steel to hydrochloric acid accelerates metal dissolution, resulting in material degradation, reduced service life and increased maintenance costs (Raja & Sethuraman, 2008; Umoren &Ebenso, 2008). Corrosion inhibition is an important approach to controlling metal deterioration in aggressive environments. Conventional corrosion inhibitors, particularly synthetic organic and inorganic compounds, have been widely applied to reduce the corrosion rate of metals. However, concerns regarding their toxicity, environmental persistence, high cost and potential hazards to human health have encouraged the development of environmentally friendly alternatives. Consequently, green corrosion inhibitors derived from natural products have attracted considerable research attention because of their biodegradability, renewability, availability and relatively low environmental impact (Raja & Sethuraman, 2008; Verma et al., 2018).

Plant extracts offer considerable potential as green corrosion inhibitors because they contain naturally occurring organic compounds, including alkaloids, flavonoids, tannins, saponins, phenolic compounds and other phytochemicals. These compounds possess functional groups containing oxygen, nitrogen and aromatic structures that can interact with metal surfaces through adsorption. The formation of an adsorbed protective layer reduces the contact between the metal surface and the corrosive medium, thereby limiting anodic metal dissolution and cathodic reactions. The effectiveness of plant extracts depends on their chemical composition, concentration, extraction method, temperature and the nature of the corrosive environment (Eddy et al., 2010; Verma et al., 2018). Several experimental investigations have demonstrated the effectiveness of plant-derived materials in protecting mild steel against acidic corrosion. For instance, Okafor et al. (2008) evaluated *Phyllanthus amarus* leaf and seed extracts as corrosion inhibitors for mild steel in hydrochloric and sulphuric acid solutions, reporting that inhibition efficiency increased with extract concentration. Similarly, Medupin et al. (2023) reviewed the application of plant-based inhibitors for sustainable corrosion control in mild steel, highlighting their potential as alternatives to conventional chemical inhibitors. More recently, Holla et al. (2024) reviewed the corrosion inhibition performance of different plant extracts on steel materials and emphasized the importance of extract composition, concentration and experimental conditions in determining inhibition efficiency. Sharma et al. (2024) also discussed the protective potential of different plant parts and their phytochemical constituents in acidic

corrosion environments. These studies demonstrate the growing relevance of plant extracts in developing sustainable corrosion protection strategies (Okafor et al., 2008; Medupin et al., 2023; Holla et al., 2024; Sharma et al., 2024).

1.1 Objectives

The aim of the research is to evaluate some selected plant extracts as green corrosion inhibitors for mild steel in hydrochloric acid medium. Through the following objectives:

1. Evaluate the corrosion rate of mild steel in hydrochloric acid without an inhibitor.
2. Compare the corrosion inhibition performance of neem, moringa and ginger extracts.
3. Determine the effect of extract concentration on inhibition efficiency.
4. Investigate the influence of temperature and immersion time on corrosion.
5. Identify the most effective plant extract and experimental conditions.

1.2 Research hypotheses

Hypothesis	Null hypothesis
H01	Plant extract type has no significant effect on corrosion rate.
H02	Extract concentration has no significant effect on corrosion rate.
H03	Temperature has no significant effect on corrosion rate.
H04	Immersion time has no significant effect on corrosion rate.

Significance level: (α=0.05).

2.0 Literature Review

2.1 Corrosion of Mild Steel in Acidic Environments

Mild steel is one of the most widely utilized engineering materials because of its relatively low production cost, good mechanical strength, ductility, weldability and versatility in industrial applications. It is extensively employed in construction, manufacturing, petroleum refining, transportation, pipelines, storage tanks and chemical processing industries. Lebrini et al., (2005). Despite these desirable properties, mild steel is highly susceptible to corrosion, particularly when exposed to aggressive acidic environments. Hydrochloric acid (HCl), for instance, is frequently used in industrial operations such as acid pickling, descaling, chemical cleaning and oil-well acidizing. Although these processes are essential for removing unwanted deposits and improving industrial efficiency, they can accelerate the dissolution of metallic materials, resulting in significant material loss and deterioration of equipment. Ghaderi et al. (2022). Corrosion is an electrochemical process involving the oxidation of metal atoms and the corresponding reduction reactions occurring at different sites on the metal surface. In hydrochloric acid solutions, mild steel undergoes anodic dissolution, while

hydrogen ions are reduced at cathodic sites, resulting in hydrogen gas evolution. Chigondo&Chigondo (2016) investigate the continuous occurrence of these reactions results in the gradual dissolution of iron and the degradation of the steel surface. The severity of corrosion depends on several factors, including acid concentration, temperature, exposure duration, solution composition and the physicochemical characteristics of the metal. Consequently, effective corrosion-control strategies are necessary to minimize material degradation, extend equipment service life and reduce the economic losses associated with industrial corrosion. Ghaderi et al., (2022).

2.2 Corrosion Inhibitors and Their Mechanisms of Action

The application of corrosion inhibitors is widely recognized as an economical and practical method of protecting metals against deterioration in aggressive environments. Corrosion inhibitors are substances introduced into corrosive media in relatively small quantities to reduce the corrosion rate without significantly altering the essential properties of the metal. Their protective action generally involves adsorption onto the metal surface, formation of a protective film, modification of electrochemical reactions or a combination of these mechanisms. Conventional corrosion inhibitors are broadly classified into inorganic and organic compounds. Organic inhibitors are particularly effective because their molecular structures often contain heteroatoms such as nitrogen, oxygen and sulphur, as well as aromatic rings and conjugated electron systems. These structural features facilitate interaction with metallic surfaces through electron donation, electrostatic attraction and other adsorption processes (Singh et al., 2016). However, the application of some conventional inhibitors has raised environmental and health concerns because of their toxicity, relatively high production costs, limited biodegradability and potential environmental persistence. Chigondo&Chigondo (2016). The growing emphasis on environmental sustainability has therefore encouraged the development of alternative corrosion inhibitors derived from renewable natural resources. Plant extracts have emerged as promising alternatives because they contain several naturally occurring compounds capable of interacting with metal surfaces and reducing corrosion reactions. Their protective effectiveness is generally associated with the formation of an adsorbed organic layer that limits direct contact between the corrosive solution and the steel surface Fazal et al. (2022).

2.3 Plant Extracts as Green Corrosion Inhibitors

Plant-derived corrosion inhibitors have received considerable attention because of their potential to provide effective metal protection while minimizing the environmental and health problems associated with conventional synthetic inhibitors. Different parts of plants,

including leaves, roots, flowers, fruits, seeds, bark and natural exudates, contain bioactive compounds that can function as corrosion-retarding agents. These natural materials are particularly attractive because they are renewable, readily available in many geographical locations and generally biodegradable. According to Zakeri et al. (2022), plant extracts have demonstrated considerable potential for protecting ferrous metals against corrosion in different corrosive environments, with their performance commonly assessed using gravimetric, electrochemical and surface-characterization techniques. The corrosion-inhibiting properties of plant extracts are largely attributed to their phytochemical constituents. Important compounds include flavonoids, tannins, alkaloids, phenolic acids, saponins, terpenoids and other organic molecules containing heteroatoms and aromatic structures. These constituents may interact with the steel surface through physical or chemical adsorption, depending on the molecular structure, solution conditions and nature of the metal. The adsorption process produces a protective film that reduces the availability of active corrosion sites and restricts the movement of corrosive species towards the metal surface. Furthermore, the presence of electron-rich functional groups, particularly hydroxyl, carbonyl and aromatic groups, can facilitate interactions between phytochemical molecules and the metal surface (Verma et al., 2018; Fazal et al., 2022).

2.4 Review of Previous Studies on Plant-Based Corrosion Inhibitors

Several researchers have investigated the application of natural plant extracts for protecting mild steel and other ferrous materials against corrosion in acidic environments. Their findings have demonstrated that different plant species possess varying degrees of inhibition effectiveness depending on their phytochemical composition and experimental conditions.

For instance, Berrissoul et al. (2020) investigated the ethanolic extract of *Lavandula mairei* as an environmentally friendly corrosion inhibitor for mild steel in 1 M hydrochloric acid. The study employed weight-loss measurements, electrochemical techniques and surface-characterization methods to evaluate the protective performance of the extract. Their results demonstrated that the inhibition efficiency increased with increasing extract concentration, reaching approximately 92% at 0.4 g/L and 303 K. The adsorption behaviour was consistent with the Langmuir adsorption isotherm, indicating the formation of an adsorbed protective layer on the steel surface. Their findings established the potential of *Lavandula mairei* as an effective natural corrosion inhibitor (Berrissoul et al., 2020). Similarly, Thomas et al. (2020) examined the corrosion-inhibiting properties of aqueous fruit-rind extract of *Garcinia indica* (Binda) on mild steel exposed to hydrochloric acid. Their investigation involved gravimetric and electrochemical measurements, together with spectroscopic characterization of the

extract. The results indicated that the extract achieved inhibition efficiencies of approximately 93% in 0.5 M HCl and 87% in 1 M HCl at 303 K. The presence of anthocyanin compounds, particularly cyanidin-related constituents, was associated with the protective action of the extract. Electrochemical investigations further suggested that the extract acted as a mixed-type inhibitor by influencing both anodic and cathodic corrosion reactions.

In another investigation, Dehghani et al. (2020) evaluated the protective potential of *Laurus nobilis* leaf extract against carbon-steel corrosion in 1 M hydrochloric acid. The researchers combined experimental electrochemical measurements with microscopic and computational investigations to understand the inhibition mechanism. Their results showed that the extract provided a maximum inhibition efficiency of approximately 92% at an optimum concentration of 400 ppm. Potentiodynamic polarization measurements indicated mixed-type inhibition, while electrochemical impedance spectroscopy demonstrated improved corrosion resistance in the presence of the extract. Abdelaziz et al. (2021) investigated the use of *Arbutus unedo* L. leaf extract as a green corrosion inhibitor for mild steel in hydrochloric acid. The research combined experimental and computational approaches, including electrochemical measurements and theoretical analysis, to investigate the adsorption behaviour and inhibition mechanism. Their results revealed that the addition of the leaf extract significantly reduced corrosion current density, with inhibition efficiency increasing from approximately 65.76% to 88.09% as the extract concentration increased from 0.1 to 0.5 g/L.

Furthermore, Mamudu et al. (2023) investigated the adsorption behaviour and molecular modelling of phytochemical constituents obtained from *Dillenia suffruticosa* leaves for corrosion protection of mild steel in 1 M hydrochloric acid. Their study focused on understanding the interaction between the plant-derived compounds and the steel surface using adsorption analysis and molecular modelling. The investigation provided additional theoretical evidence of the potential of *Dillenia suffruticosa* phytoconstituents to interact with metallic surfaces and contribute to corrosion protection. This work provided a theoretical foundation for subsequent experimental investigations of the same plant material. More recently, Mamudu et al. (2024) experimentally evaluated the ethanolic extract of *Dillenia suffruticosa* leaves as a green corrosion inhibitor for mild steel in 1 M hydrochloric acid. The researchers extracted the phytochemical constituents using ethanol and a Soxhlet extraction apparatus. The corrosion-inhibiting performance was investigated using gravimetric and electrochemical techniques, while scanning electron microscopy (SEM) and Fourier-

transform infrared spectroscopy (FTIR) were employed to examine the surface characteristics and functional groups associated with inhibition. Their findings revealed that the inhibition efficiency increased with extract concentration, attaining a maximum value of 81.4% at 1,000 mg/L. Potentiodynamic polarization results further established that the extract behaved as a mixed-type corrosion inhibitor, while surface examination supported the adsorption of phytochemical constituents onto the mild-steel surface.

Other studies have also demonstrated the potential of natural materials and plant-derived compounds in corrosion control. Qiang et al. (2018) investigated *Ginkgo biloba* leaf extract as an environmentally friendly inhibitor for X70 steel in hydrochloric acid, demonstrating the relevance of naturally occurring organic compounds in protecting steel surfaces. Li et al. (2021) examined *Brassica oleracea* L. extract for corrosion protection of Q235 steel in acidic environments, while Yao et al. (2022) explored the use of *Brassica rapa* extract as a renewable and low-cost corrosion inhibitor. Similarly, Wang et al. (2023) investigated the combined effects of maple leaf extract and iodide ions on corrosion inhibition of Q235 steel in sulphuric acid. These investigations further demonstrate the growing interest in plant-derived inhibitors and the possibility of improving their performance through suitable formulation and synergistic combinations.

2.5 Phytochemical Composition and Corrosion-Inhibition Mechanisms of Plant Extracts

The phytochemical composition of plant extracts significantly influences their corrosion-inhibiting properties due to various organic compounds like flavonoids, tannins, and alkaloids. These compounds interact with metallic surfaces, particularly via oxygen-, nitrogen-, and sulfur-containing functional groups, facilitating adsorption through their hydroxyl and carbonyl groups. The mechanisms of inhibition include physical adsorption, driven by electrostatic attraction, and chemical adsorption, involving electron transfer. Both mechanisms may operate depending on the extract's composition and the corrosive environment (Verma et al., 2018).The mechanisms' effectiveness can be explored through adsorption isotherms, notably the Langmuir, Temkin, and Freundlich models. The Langmuir isotherm effectively describes the correlation between inhibitor concentration and surface coverage, assuming identical adsorption sites and monolayer adsorption. Computational techniques such as density functional theory (DFT), Monte Carlo simulation, and molecular dynamics (MD) can reveal the electronic properties of inhibitor molecules and their interactions with metallic surfaces, as highlighted by Verma et al. (2018), who emphasized the significance of these computational methods in understanding corrosion inhibitors' adsorption behavior at the metal–solution interface.In addition to adsorption studies,

experimental characterization techniques are important for establishing the effectiveness and mechanism of plant-based inhibitors. Weight-loss measurements provide information about the corrosion rate and inhibition efficiency, while potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) are used to examine the influence of inhibitors on anodic and cathodic reactions and charge-transfer resistance. Furthermore, SEM, FTIR and other surface-analysis techniques provide information about surface morphology, functional groups and the formation of protective films. The combination of these methods offers a more comprehensive understanding of the corrosion-inhibiting performance of natural plant extracts (Mamudu et al., 2024; Zakeri et al., 2022).

Despite variations in effectiveness based on plant species and extraction methods, evaluating different plant extracts under consistent conditions is crucial. This study assesses selected plant extracts as green corrosion inhibitors for mild steel in hydrochloric acid, focusing on their inhibition efficiencies and protective capabilities. The results aim to support the creation of cost-effective, environmentally friendly corrosion-control materials for industrial use.

3. METHODOLOGY

This study adopts an experimental research design to investigate the corrosion inhibition performance of selected plant extracts, namely neem (*Azadirachta indica*) leaves, moringa (*Moringa oleifera*) leaves and ginger (*Zingiber officinale*) rhizomes, on mild steel exposed to hydrochloric acid medium. The investigation considers four principal experimental factors: plant extract type, inhibitor concentration, temperature and immersion time. An uninhibited mild steel specimen serves as the control for evaluating the effectiveness of the selected plant extracts. Quantitative measurements of corrosion rate and inhibition efficiency are used as the principal response variables.

3.1 Statistical Analysis

The experimental data used both descriptive and inferential statistical analyses. Descriptive statistics, such as means and standard deviations, to summarize the corrosion rates and inhibition efficiencies of selected plant extracts. A four-factor ANOVA used to assess the effects of plant extract type, inhibitor concentration, temperature, and immersion time on corrosion rates, with significance evaluated at $\alpha = 0.05$. Tukey's HSD test to identify significant differences among extracts. The proportion of variation in corrosion rates explained by the model was assessed using the coefficient of determination (R^2). Statistical software like SPSS, is utilized.



Figure 1: Schematic representation of plant extract preparation and experimental setup for corrosion inhibition studies of mild steel in hydrochloric acid medium.

4. RESULTS AND DISCUSSION

4.1 Descriptive statistical analysis

The first analysis examines the average corrosion rate and inhibition efficiency of each plant extract.

Table 1: Corrosion performance by plant extract.

Plant extract	Observations	Mean corrosion rate (mm/year)	Mean inhibition efficiency (%)
Neem leaf	81	0.730	52.04
Moringa leaf	81	0.823	45.56
Ginger rhizome	81	0.892	40.67
Uninhibited control	27	1.479	0.00

The uninhibited mild steel recorded the highest average corrosion rate of 1.479 mm/year.

Neem leaf extract recorded the lowest average corrosion rate of 0.730 mm/year and the highest average inhibition efficiency of 52.04%.Moringa leaf achieved 45.56% inhibition efficiency, while ginger achieved 40.67%.These results suggest that all three plant extracts reduced corrosion under the experimental conditions, with neem showing the strongest overall performance.

4.2 Effect of extract concentration

Table 2: Influence of extract concentration on corrosion.

Extract concentration (mg/L)	Mean corrosion rate (mm/year)	Mean inhibition efficiency (%)
100	0.989	34.03
250	0.788	47.92
500	0.668	56.32

The results show an inverse relationship between extract concentration and corrosion rate.

At 100 mg/L, the mean inhibition efficiency was 34.03%. Increasing the concentration to 250 mg/L improved inhibition efficiency to 47.92%.At 500 mg/L, inhibition efficiency increased

further to 56.32%.This suggests that higher extract concentrations provide more corrosion protection, potentially through increased adsorption of protective phytochemical compounds on the steel surface.

4.3 Effect of temperature and immersion time

Table 3: Effect of temperature.

Temperature (°C)	Mean corrosion rate (mm/year)	Mean inhibition efficiency (%)
25	0.486	51.39
35	0.763	46.23
45	1.196	40.65

The corrosion rate increased as temperature increased. The average inhibition efficiency also declined.This indicates that higher temperatures may accelerate the corrosion process and reduce the protective performance of the plant extracts.

Table 4: Effect of immersion time.

Immersion time (hours)	Mean corrosion rate (mm/year)	Mean inhibition efficiency (%)
24	0.788	45.66
48	0.815	47.40
72	0.842	45.20

The average inhibition efficiency varied only slightly across immersion periods. This suggests that the inhibition performance was relatively stable over the tested periods, although the corrosion rate increased slightly.

4.4 Inferential statistical analysis: Factorial ANOVA

A four-factor ANOVA was performed using the inhibitor-treated observations.

The factors were:

- Plant extract.
- Extract concentration.
- Temperature.
- Immersion time.

Table 5: Factorial ANOVA results.

Source of variation	F-statistic	p-value	Decision
Plant extract	164.84	0.00	Significant
Concentration	650.39	0.00	Significant
Temperature	3169.86	0.001	Significant
Immersion time	17.81	0.001	Significant

The very small p-values are shown in simplified form where appropriate; all four factors are statistically significant at the 5% level.

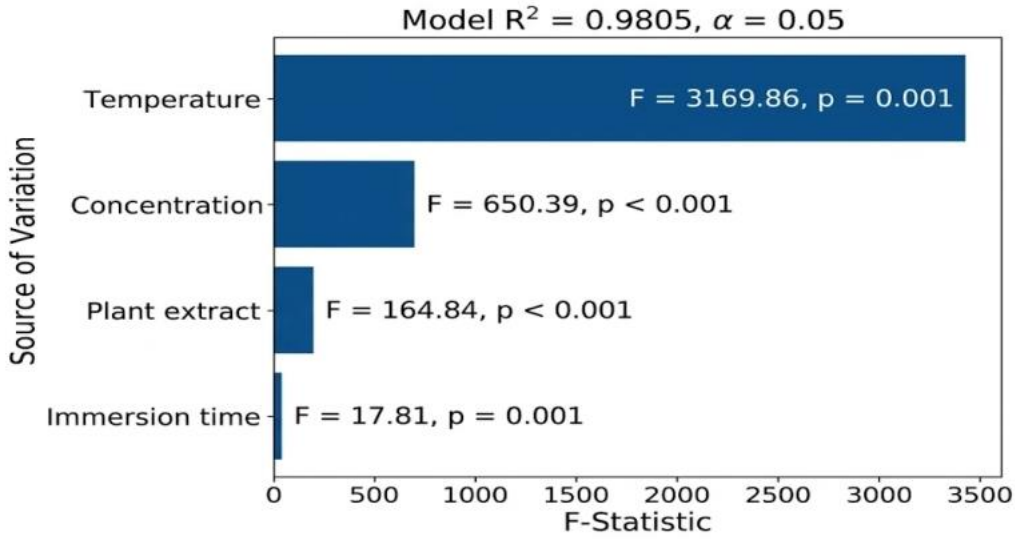

Figure 2: Comparative influence of plant extract type, inhibitor concentration, temperature and immersion time on the corrosion rate of mild steel based on factorial ANOVA.

$$\boldsymbol{Model\ R^2 = 0.9805}$$

The four experimental factors significantly influenced corrosion rate in the dataset.
Temperature had the largest F-statistic, suggesting that it was an especially important factor in explaining differences in corrosion rates.Extract concentration also had a strong influence.
The model explains approximately 98.05% of the observed variation in corrosion rate within this experimental design. This is not a guarantee of predictive performance on real laboratory data.

4.5Post-hoc comparison of plant extracts

Tukey's HSD test was used to identify which plant extracts differed significantly.

Comparison	Mean rate difference (mm/year)	Adjusted p-value	Decision
Ginger vs Moringa	-0.0696	0.3730	Not significant
Ginger vs Neem	-0.1628	0.0054	Significant
Moringa vs Neem	-0.0932	0.1723	Not significant

Neem performed significantly better than ginger in this comparison. The difference between neem and moringa, however, was not statistically significant at 5%.

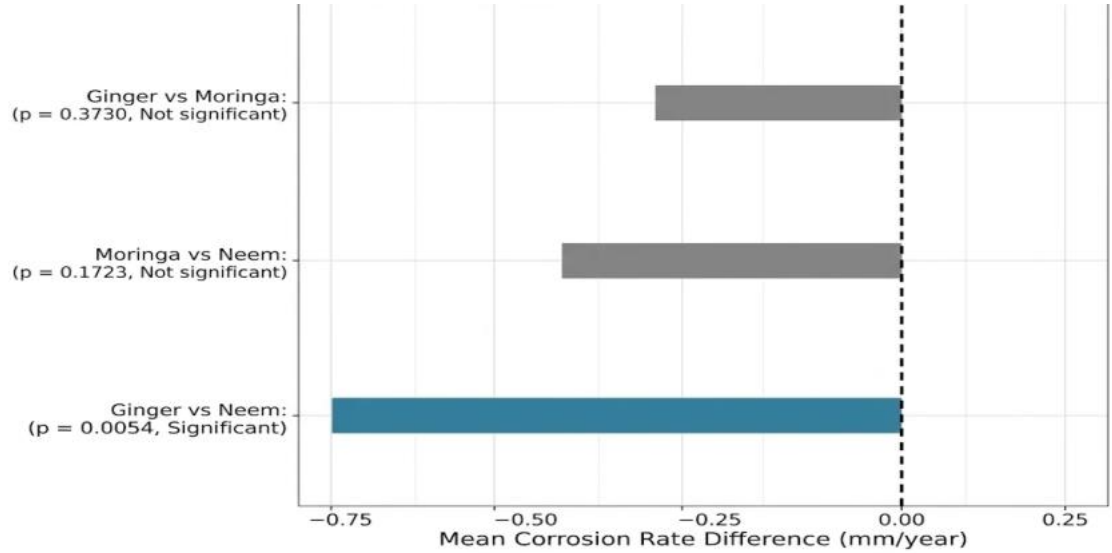

Figure 3: Pairwise comparison of the mean corrosion rates of neem, moringa and ginger extracts using Tukey's Honestly Significant Difference (HSD) test.

4.6 Best-performing experimental condition

The best-performing combination based on average replicate performance was:

Parameter	Best condition
Plant extract	Neem leaf
Concentration	500 mg/L
Temperature	25°C
Immersion time	48 hours
Mean inhibition efficiency	71.97%

5. CONCLUSION

This study evaluated the corrosion inhibition effectiveness of neem leaf, moringa leaf, and ginger rhizome extracts on mild steel in hydrochloric acid. Results showed all extracts offered corrosion protection, with neem leaf extract performing best, achieving a mean corrosion rate of 0.730 mm/year and an inhibition efficiency of 52.04%. Moringa and ginger extracts had efficiencies of 45.56% and 40.67%, respectively. Increasing the concentration of extracts from 100 to 500 mg/L improved inhibition efficiency, while rising temperature decreased it. Statistical analysis confirmed significant effects of extract type, concentration, temperature, and immersion time on corrosion rates. The optimal conditions were neem extract at 500 mg/L, 25°C, and 48 hours immersion, achieving 71.97% efficiency. These findings position neem leaf extract as a leading candidate for sustainable corrosion inhibition solutions, warranting further investigation into its practical applications.

6. Recommendations

Based on the study's findings, the recommendations include: further investigation of neem leaf extract as a green corrosion inhibitor; optimization of inhibition concentration beyond 500 mg/L; electrochemical characterization using potentiodynamic polarization and EIS; surface morphology evaluation with SEM and EDS; phytochemical and FTIR analysis for active constituents identification; examination of adsorption behavior using various isotherm models; assessment of temperature and long-term stability; economic and environmental evaluation of extracts; improving statistical reliability through independent laboratory replicates and appropriate designs; and exploring industrial applications of neem-based corrosion inhibitors in various acidic environments.

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