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Research Article

COMPARATIVE STUDY OF PLANTAIN PEEL AND STEM EXTRACTS AS ECO-FRIENDLY CORROSION INHIBITORS FOR MILD STEEL AND ALUMINIUM IN 0.5M H_2SO_4

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Abstract

Corrosion is a widespread problem that affects metallic materials, resulting from the thermodynamic instability of metals when exposed to moisture, water, or oxidizing agents. This slow and irreversible degradation occurs through chemical reactions between metals and their environment, presenting significant challenges across various industries. This research investigates the potential of unripe plantain peel and stem extracts as alternatives to conventional chemical inhibitors for mild steel and aluminium in sulphuric acid. The method of weight loss measurements were employed to evaluate the corrosion inhibition performance on metal coupons. The study also characterized the bioactive chemicals in the extracts using Gas Chromatography-Mass Spectrometry (GC-MS), identifying thirty significant compounds, including stigmasterol, carpaine, cedrene, benzoic acid, pyrogallol, epicatechin, gallocatechin, and p-coumaric acid ethyl ester, which demonstrated protective properties against sulfuric acid-induced corrosion. The extraction yields were found to be satisfactory, with plantain peel yielding 38.46%, significantly higher than the 19.14% yield for the plantain stem. This difference highlights the varying richness in their bio-active chemicals between the two plant extracts. Corrosion inhibition efficiencies of 98.43% for aluminium and 93.76% for mild steel were observed with plantain peel extract, while the stem extract showed efficiencies of 94.27% for aluminium and 86.63% for mild steel. These efficiencies, attributed to surface adsorption, were higher for aluminium across both extracts. The Gibbs free energy of adsorption (ΔG_{ads}) values, ranging from -19 to -20 kJ/mol, indicate spontaneous physio-adsorption, demonstrating the ease of desorption under suitable condition.

Keywords: Corrosion, Inhibitor, Mild Steel, Aluminium, plantain peel, plantain stem, extracts, sulphuric acid, H_2SO_4.

INTRODUCTION

Corrosion is widely recognized as a process that affects metallic materials, resulting from the thermodynamic instability of metals when exposed to moisture, water, or oxidizing agents (Pumps, 2010). This process entails the gradual, irreversible degradation of metals due to chemical reactions with their surroundings, which frequently include moisture, oxygen, and other elements to form a more stable compounds such as oxides, hydroxides, or sulphides are usually formed as a result of these reactions (Balangao, 2024).Corrosive environments can take different forms, including solids, liquids, and gases. These environments are commonly referred to as electrolytes because they allow ion mobility (both cations and anions), which causes the two main reactions: anodic and cathodic processes (Harsimran *et al.,* 2021). When two distinct types of metals coexist in an electrolyte, the less noble metal operates as the anode and corrodes, whereas the more noble metal serves as the cathode and is protected. Electrons go from the anodic to the cathodic metal. When comparing two metals in a given environment, the metal with a larger reduction potential (positioned higher in the electrochemical series) or the less noble metal is more susceptible to corrosion (Harsimran *et al.,* 2021; Pedeferri and Pedeferri, 2018). Corrosion continues to be one of the biggest challenges in industries where there is heavy dependence on metals like mild steel and aluminium including oil and gas, petrochemical, automotive, power sector and other sectors where these metals are extensively used (Zamani *et al.,* 2021). From bridge collapses and vehicle breakdowns to chemical spills and fires, the costs associated with corrosion-related failures are substantial (Tamalmani and Husin, 2020; Bender, 2022). Sectors like manufacturing, chemical processing, oil and gas, and food production are particularly vulnerable (Al-Moubaraki and Obot, 2021; Gould, 1996). The global economic loss due to corrosion is estimated to be USD 2.5 trillion a year, about 3-4% of global gross domestic product, in the form of maintenance costs, premature component replacement, unplanned downtimeand even operational failures which impact the efficiency, safety of workers and environmental damage (Sonwani *et al.,* 2019; Zehra, 2022; Ibrahimi *et al.* 2021). Toaddress the challenges associated with corrosion, the industries are investing in new fields such as research and development of new materials, new coating technology, and innovative mitigation strategies. Traditional methods for mitigating the effect associated with metal corrosion have been implemented by several industries, these measures include coatings, regular inspections, and the use ofsynthetic inhibitors. Despite their widespread use, synthetic inhibitors are often toxic to the environment, expensive and not biodegradable, making their sustainability an issue (Zhang *et al.,* 2019). Recently, extracts from plant sources are known to contain bio-active chemicals like Tannins, flavonoid, alkaloids, phenols, and saponins are bioactive chemicals that have long been prized for the protective coating they impart to metal surfaces (Badaw and Fahim, 2021). Moreover, have emerged as highly sustainable, biodegradable, easily renewable and eco-friendly raw material with great potential for cost-effective production (Tolumoye *et al.,* 2015; Mandal *et al.,* 2020; Deepa and Sivakumar, 2020). Loto*et al*. (2016) used weight-loss measurements to investigate the corrosion inhibition of mild steel in acidic solution by Allium sativum extract and inhibition efficiency was enhanced by concentration with a peak of near 100 % using pure extract. Khadom *et al*. (2018) also immersed low-carbon steel in 0.5 M

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HCl treated with Xanthium strumarium leaf extract and gravimetric results showed corrosion rate reduction equivalent to around 95 % inhibition. However, limited knowledge exists on a comparative basis for their efficacy under acidic conditions. This study focusses on addressing this gap by investigating the corrosion inhibition properties of unripe plantain peel and stem extracts on mild steel and aluminium in sulphuric acid (H_2SO_4), with the potential to contribute to more sustainable and environmentally friendly corrosion prevention strategies.

METHODOLOGY

Materials

The materials for this research consist of 0.5M of H_2SO_4 (sulphuric acid), distilled water, acetone, plant-based corrosion inhibitors such as unripe plantain peel and stem, metal specimens such as mild steel and aluminium metals cut into dimensions of 2.4 cm x 4 cm with a thickness of 2 mm, auxiliary materials such as masking tape, aluminium foil, thread, filter paper, and wire mesh, along with equipment such as 100 ml beakers, an analytical balance, water bath, an industrial oven, and emery papers.

Material Preparation

Mild steel and aluminium coupons, each initially weighing between 9.2 g for mild steel and 4.2 g for aluminium, were cut into rectangular shapes measuring 2.5cm by 4cm with thickness of 2mm. These coupons were degreased with acetone to eliminate residual grease, oil, and dust. Following multiple rinses with distilled water, the coupons were dried afterwards. They were then mechanically polished using emery papers before being cleaned and dried once more. To facilitate handling, the 25 mild steel and 25 aluminium coupons were affixed in sets of five using threads threaded through pre-drilled holes. After this preparation, the specimens (mild steel and aluminium) were each separately weighed using a digital weighing balance. Subsequently, the specimens were immersed in five separate sets of beakers. Each beaker contained 100 ml of 0.5M H_2SO_4 solution. One additional set of beakers served as the control experiment and contained no extract. The immersion period lasted for four days. During this time, the concentration of the extract varied in the beakers (except for the control with no extract) for both the mild stell and aluminium specimen. Steel.

Figure 1. Threaded mild steel and aluminium coupons

Specimen Preparation

Samples of unripe plantain peels and stems were sourced for and washed thoroughly with distilled water to with distilled water to remove any dirt that might contaminate them. The cleaned peels and stem were then air-dried to retain their bioactive chemicals until they reached a constant weight, ensuring complete dehydration (Sheydaei, 2024). The dried plantain peels and stem were grounded using an industrial scale grinder to powdered form and was then run through a fine mesh sieve to get a smooth consistency and remove any remaining large pieces. The extracts from the unripe plantain peels and stem were concentrated using a water bath set at 78.37°C, which is the boiling point of ethanol (Rouaiguia *et al.,* 2024). This removed the ethanol, leaving behind the isolated inhibitors in their pure form within the respective conical flasks containing the peels and stem extracts. Finally, we prepared stock solutions of the extracts from both the peels and stem at different concentrations. We did this by dissolving 0.2 grams per litre (g/L), 0.4 g/L, 0.8 g/L and 1.0 g/L of each extract in a solution of 0.5M sulfuric acid.

Figure 2. Unripe plantain peel

Figure 3. Unripe plantain stem

Figure 4. Flasks containing plantain peel and stem powder in ethanol

Figure 5. Mild steel and aluminium coupons immersed in 0.5M H_2SO_4 with unripe plantain peel and stem extract

Yield Estimation

The yield of the extracts is determined by weighing the samples (the unripe plantain peel and stem powder) before extraction and after separating the extracts from the solvent by an analytical balance. The extract efficiency is determined by the following equation;

$$\text{Yield (\%)} = \frac{\text{weight of extract (g)}}{\text{weight of sample before etraction}} \times 100 \quad (1)$$

Characterization of Bio active compounds

After extraction, the concentrated extracts of unripe plantain peels and stem will be analysed using gas chromatography mass-spectrometry to identify any corrosion inhibitory components (Ananaba and Okonkwo, 2023; Okore *et al.,* 2021). The GC-MS system will transport the samples to the chromatograph, where their molecular characteristics will determine the separation of their constituent parts. The mass spectrometerthen identifies each of the ionised components, which contribute to the distinct mass spectra of the compounds (Harborne, 1998).

Weight Loss Measurement

The weight loss is calculated using the formula below (Jerome *et al.,* 2015; Elazabawy *et al.,* 2023);

$$\Delta W = W_i - W_f \quad (2)$$

Where;
ΔW = weight loss (g)
W_i = the initial weight of the specimen before immersion (g)
W_f = final weight of specimen after immersion, rinsing, and drying (g)

Corrosion Rate

Corrosion rate is the mass lost a material per unit area (A) over time (t). The unit of measurement for corrosive environments is gram per square meter per hour, day, or year(Ekeke *et al.,* 2025). So, the rate of corrosion indicates the amount of material loss in gram per unit time from a surface area of that material. From a mathematical perspective, it is calculated using the formula below:

Where; $CR = \frac{\Delta W}{A \times t}$ (3)

Where:
CR= Corrosion rate (g/cm²/h)
ΔW = weight loss in metal (g)
A = surface area of the metal (cm^2)

Inhibitor Efficiency

The inhibition efficiency evaluates the effectiveness of inhibitors that are used in corrosion protection. This parameter reflects the effectiveness or efficiency of the inhibitor in percentage due to the fact that inhibitors are added to the solution which in turn decreases the corrosion rates (Ekeke *et al.,* 2025). The higher the value of the inhibitor efficiency for extracts, the more efficient they are in preventing corrosion on a metal surface. Mathematically, it can be expressed as:

$$IE\% = \frac{CR_o - CR_i}{CR_o} \times 100 \quad (4)$$

Where;
IE: Inhibitor Efficiency (%)
CR_o: Corrosion Rate without inhibitor ($gcm^{-2}\ h^{-1}$)
CR_i: Corrosion Rate of the Inhibited ($gcm^{-2}\ h^{-1}$)

Langmuir Adsorption Isotherm

To study the effects of plantain stem and peel extracts on metal surface adsorption, adsorption isotherms were utilised. Because it adequately describes monolayer adsorption on a homogenous surface, the Langmuir adsorption isotherm was used for this investigation.

The Langmuir adsorption isotherm is given by this equation:

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

where:
C_{inh}= inhibitor concentration in g/L.
K_{ads} = adsorption equilibrium constant (in units of L/g),
θ =surface coverage.

The expression for the adsorption equilibrium constant K_{ads} is found by plotting C/θ against C. The Langmuir isotherm's validity is reflected in the linearity of this graphic. In order to determine K_{ads}, the slope and intercept is retrieved from this graph. The greater the K_{ads} value, the stronger the adsorption onto the metal surface, since it gives an insight about the strength of adsorption (Rathod *et al.,* 2021).

Thermodynamic Parameters

The thermodynamic parameters give a better understanding about the adsorption process and evaluate how the plantain peel and stem extracts interacts with the mild steel and aluminium metals(Najim and Yassin, 2009). Additionally, the thermodynamic parameters will be calculated using the equation for the Gibbs free energy of adsorption, $\Delta G°_{ads}$ as shown below:

$$\Delta G°_{ads} = -RT \ln (C_w \times K_{ads}) \quad (6)$$

where:
R = universal gas constant (8.314 J/mol•K)
T = temperature (K)
K_{ads}= adsorption equilibrium constant (mL^{-3})

C_w= concentration of water containing1000 g/L in aqueous solution.

RESULTS AND DISCUSSION

Analysis of the Yield of extracts

The yields obtained in Tables 1 and 2 are relatively high and considered satisfactory. Since the yield of unripe plantain peel extract is 38.46%, which is quite high, it shows that ethanol is a good solvent to use for extracting essential components from plantain peels. Its efficacy in this extraction is supported by the fact that it is comparable to the conventional result obtained for identical plant materials (Deepa and Sivakumar, 2020).Consequently, the yield from the plantain stem was 19.14%, which was significantly lower compare to the peel. There is a yield disparity of about 19.32% between the plantain stem and peel. This massive discrepancy suggests that the two plant components were extracted with different degrees of effectiveness.

Table 1. Yield of plantain peel extract

Solvent type	Weight of Sample Before Extraction (g)	Weight of Sample after extraction (g)	Weight of Extract (g)	Percentage Yield (%)
Ethanol	212.92	131.03	81.89	38.46

Table 2. Yield of plantain peel extract

Solvent type	Weight of Sample Before Extraction (g)	Weight of Sample after extraction (g)	Weight of Extract (g)	Percentage Yield (%)
Ethanol	92.64	75.91	17.73	19.14

Characterisation of Unripe Plantain Peel and Stem Extract

Figure 6 shows the GC-MS results for the unripe plantain peel extract, while Figure 7 shows the results for the stem extract. A total ion chromatogram is a time-dependent graph showing the relative abundance of ions (molecule fragments) detected by the mass spectrometer (Harborne, 1998; DeRuiter, 2005).Time is shown on the x-axis in minutes also known as retention time, the peak area (%) is shown on the y-axis in arbitrary units as well as deviation.

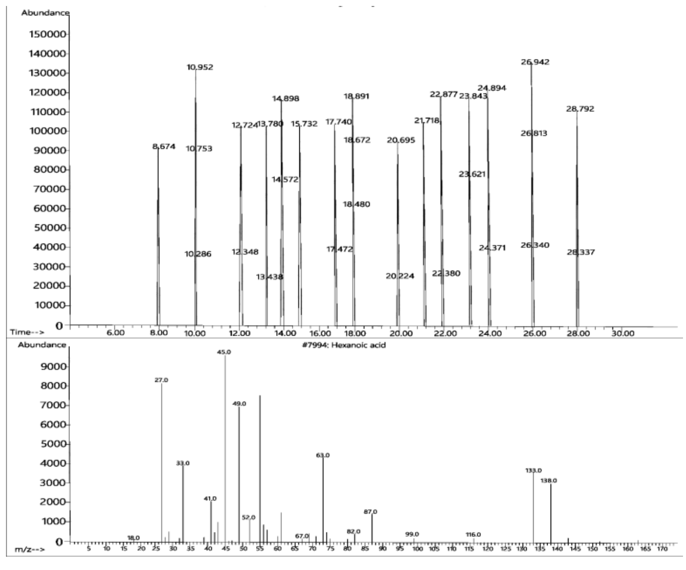

Figure 6. Chemical compound analysis for plantain peel extract by GC-MS

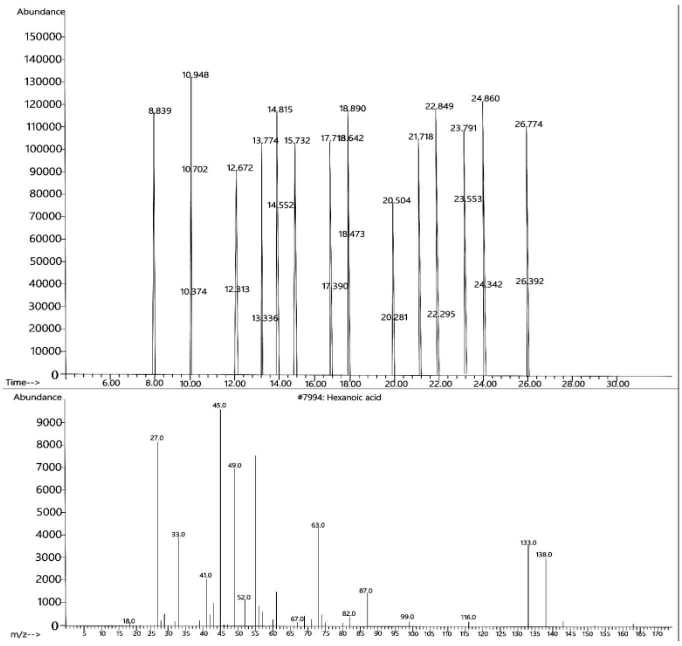

Figure 7. Chemical compound analysis for plantain stem extract by GC-MS

The study also characterized the bioactive compounds in the extracts using Gas Chromatography-Mass Spectrometry identifying thirty significant compounds, including stigmasterol, carpaine, cedrene, benzoic acid, pyrogallol, epicatechin, gallocatechin, and p-coumaric acid ethyl ester, which demonstrated protective properties against sulfuric acid-induced corrosion (Taylorand Schwartz, 2003; de la Rosa *et al.,* 2019; Supanivatin *et al.,* 2023; Supanivatin *et al.,* 2023).

Analysis of Weight Loss Measurement

Corrosion inhibition on mild steel and aluminium was consistently better with the plantain peel extract compared to the stem extract which can be seen from the figures below. The significantly reduced weight loss seen for the peel extract under various settings clearly demonstrated its superiority. Take mild steel as an example, the weight loss was much lower when treated with plantain peel extract as opposed to the stem extract; hence, it showed that the peel extract, had better protection. Also, aluminium treated with peel extract resulted in reduced weight loss compared to the mild steel treated with stem extract. The peels superior performance is due to its higher concentration of corrosion-inhibiting compounds.

Table 3. Langmuir Adsorption Isotherm for Mild Steel in 0.5M H_2SO_4 with and without Plantain Peel Extract

T (K)	K_{ads} *(L/g)*	ΔG_{ads} *(kJ mol^{-1})*	R^2
298.15	2.7746	-19.6528	0.998
298.15	3.2258	-20.0262	0.996
298.15	3.8008	-20.4328	0.997
298.15	4.2499	-20.7097	0.997

Table 4. Langmuir Adsorption Isotherm for Mild Steel in 0.5M H_2SO_4 with and without Plantain stem Extract

T (K)	K_{ads} *(L/g)*	ΔG_{ads}*(kJ mol^{-1})*	R^2
298.15	1.5246	-18.1685	0.951
298.15	2.1204	-18.9862	0.986
298.15	2.6911	-19.5769	0.98
298.15	3.3738	-20.1374	0.981

Table 5. Langmuir adsorption isotherm for aluminium in 0.5M H_2SO_4 with and without plantain peel extract

T(K)	K_{ads}*(L/g)*	ΔG_{ads} *(kJ mol^{-1})*	R^2
298.15	3.3546	-20.1233	0.994
298.15	3.8506	-20.4651	0.998
298.15	4.4444	-20.8206	0.998
298.15	4.6463	-20.9310	0.998

Table 6. Langmuir adsorption isotherm for aluminium in 0.5M H_2SO_4 with and without plantain stem extract

T (K)	K_{ads} *(L/g)*	ΔG_{ads} *(kJ mol^{-1})*	R^2
298.15	3.4662	-20.204	0.996
298.15	3.9841	-20.5496	0.997
298.15	4.6904	-20.9542	0.999
298.15	4.0080	-20.5644	0.999

Analysis of Corrosion Rate

Figure 8 - 11 show the relationship between plantain peel extract concentration and the corrosion rate of mild steel and aluminium respectively in a 0.5M H_2SO_4 solution over time intervals of 24, 48, 72, and 96 hours. A clear trend emerges: as the extract concentration increases, the corrosion rate decreases, indicating the extract's effectiveness as a corrosion inhibitor. Aluminium has intrinsic advantages over mild steel in a 0.5 M H_2SO_4 solution. Even without inhibitors, aluminium has a lower corrosion rate than mild steel. But in both cases, adding plantain extracts helps; as the concentration of the extracts increases, the corrosion rate decreases in a similar fashion. Plantain peel extract outperforms the control group (Pure 0.5 M solution) and reduces corrosion rate by a greater percentage overall, with the greatest benefit for mild steel, which is more vulnerable to acidic conditions.

Although the stem extract did exert some inhibition, it was not as strong as the peel extract. This therefore, means that on the protection of mild steel and aluminium from corrosion in 0.5 M H_2SO_4, the plantain peel extract is better as compared to its stem extract. This is because extracts are usually known to lower the corrosion rate of the material due to the ease with whichacids attackmild steel. Extracts have lesser effects on metals like aluminium since it is normally resistant to corrosion (Badawi and Fahim, 2021, Deyab *et al.,* 2017).

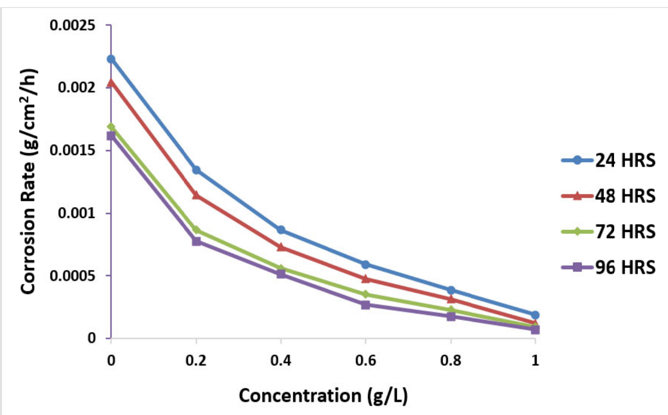

Figure 8. Graph of corrosion rate of mild steel against concentration of plantain peel extract

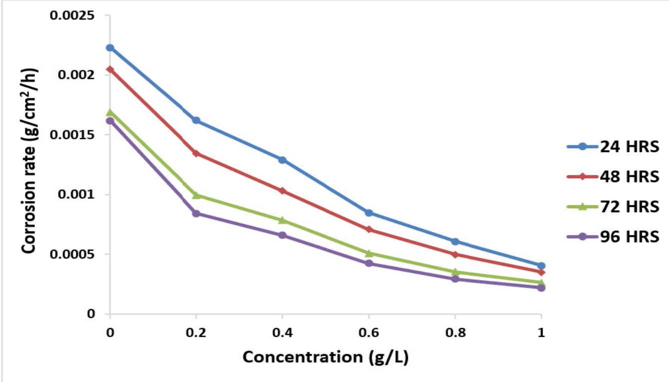

Figure 9. Graph of corrosion rate of mild steel against concentration of plantain stem extract

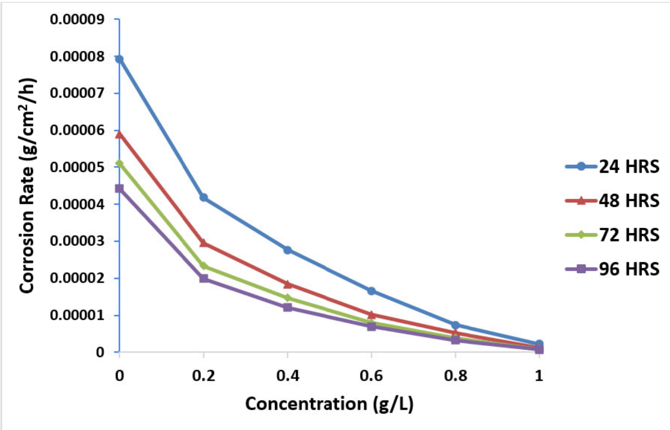

Figure 10. Graph of corrosion rate of aluminium against concentration of plantain peel extract

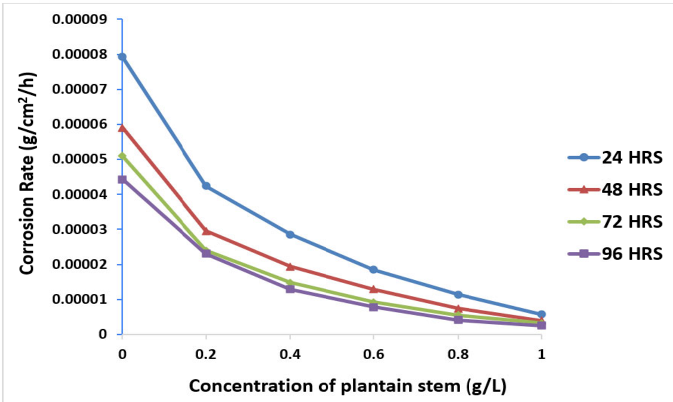

Figure 11. Graph of corrosion rate of aluminium against concentration of plantain stem extract

Analysis of Inhibitor Efficiency (%)

The relationship between inhibitor efficiency and concentration of the extracts is visualized in Figure 16-19, showing the inhibitor efficiency of mild steel and aluminium in 0.5M of $H_2SO_4$with varying concentrations of unripe plantain peel and stem extracts over a period of 24, 48, 72, and 96 hours. The data demonstrate a clear trend: inhibitor efficiency increases with the concentration of unripe plantain extract. There was a significant performance gap between the extractsat a period of 96 hours exposure, with plantain peel extract inhibiting corrosion more effectively than both aluminium (98.43%) and mild steel (93.76%). Compared to mild steel's 86.63% efficiency and aluminium's 94.27%, the plantain stem extract's\ results were noticeably lower. The extraction yields reveal that the bioactive chemicals found in plantain peel are higher, at 38.46%, compared to 19.14% in the stem both. The plantain peel and stem extracts aluminium performed better than the mild steel.

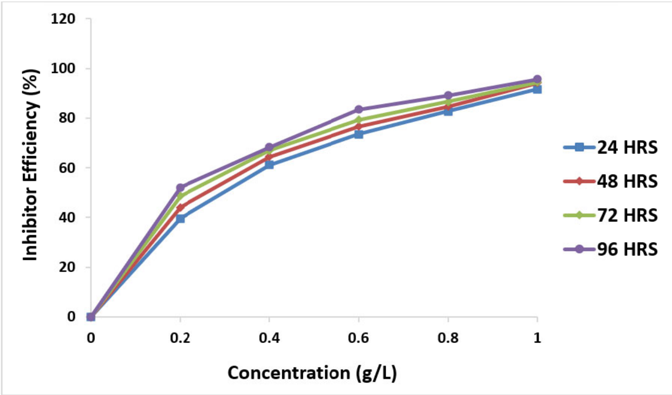

Figure 12. Graph of Inhibitor efficiency on mild Steel against plantain peel extract

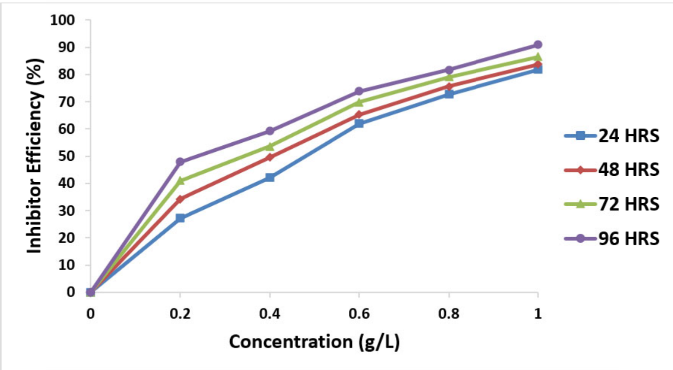

Figure 13. Graph of Inhibitor Efficiency on mild Steel against plantain stem extract

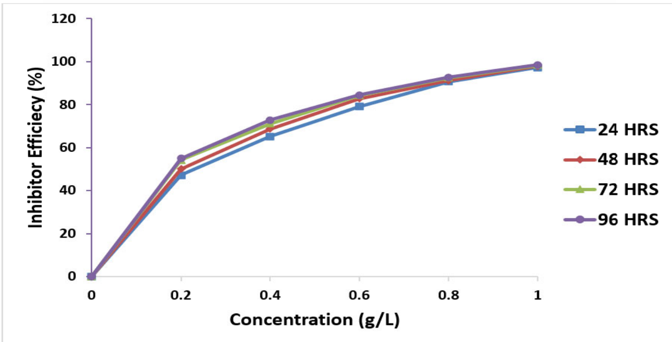

Figure 14. Graph of Inhibitor efficiency on aluminium against plantain peel extract

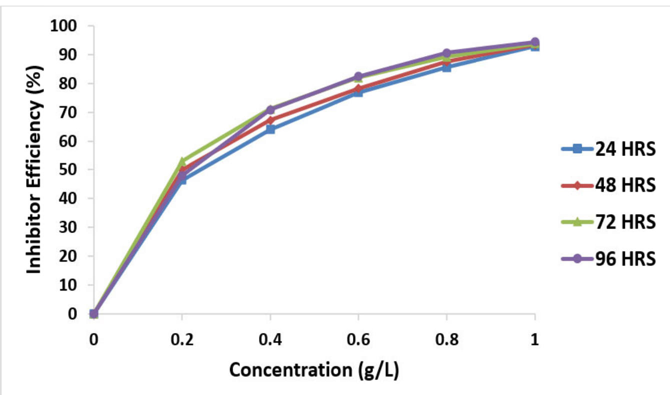

Figure 15. Graph of Inhibitor efficiency on aluminium against plantain peel extract

Analysis of adsorption isotherms and thermodynamic parameters

The Langmuir adsorption isotherm gives a clear idea about the functionality of inhibitors. The good fit of the isotherm to experimental data for the two metals would imply therefore that monolayer adsorption of inhibitors takes place onto the metal surface (Kokalj, 2023; Langmuir and Schaefer, 1937). The higher performance exhibited by the unripe plantain peel extract than the stem extract at both metals' points to its richer composition of bioactive compounds. High values of K_{ads} for the peel suggest better molecular interaction with the metal surfaces forming a more stable protective layer. The enhanced performance of the peel extract, particularly on aluminium, indicates that it may serve as a more effective corrosion inhibitor, at room temperature. The thermodynamic parameter ΔG_{ads} in the expression represents the Gibbs free energy of adsorption, developed to assess the spontaneity and nature of the adsorption process. From the calculated values between -19 to -20 kJ/mol, it can be inferred that the process is spontaneous due to the negative value of the thermodynamic parameter ΔG_{ads}, which infers that physisorption of plantain extracts on the metal surface takes place. The negative sign indicates that this process is energetically favourable and will take place naturally without external influence.

Table 7. Langmuir Adsorption Isotherm for Mild Steel in 0.5M H_2SO_4 with and without Plantain Peel Extract

T (K)	*K_{ads} (L/g)*	*ΔG_{ads} (kJ mol^{-1})*	*R^2*
298.15	2.7746	-19.6528	0.998
298.15	3.2258	-20.0262	0.996
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298.15	2.6911	-19.5769	0.98
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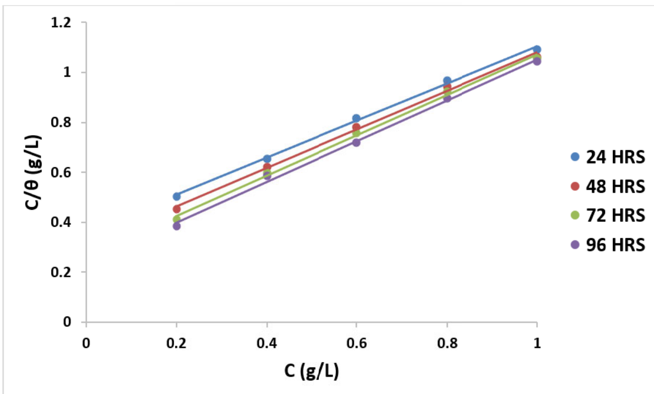

Figure 16. Langmuir adsorption plot for mild steel with and without plantain peel extract in 0.5M H_2SO_4

Table 10. Langmuir adsorption isotherm for aluminium in 0.5M H_2SO_4 with and without plantain stem extract

T (K)	K_{ads} *(L/g)*	ΔG_{ads} *(kJ mol^{-1})*	R^2
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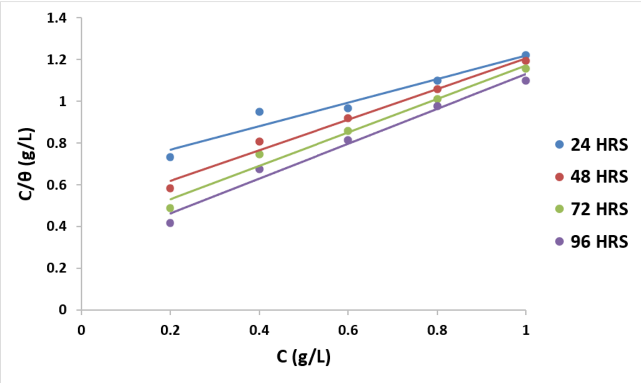

Figure 17. Langmuir adsorption plot for mild steel with and without plantain stem extract in 0.5M H_2SO_4

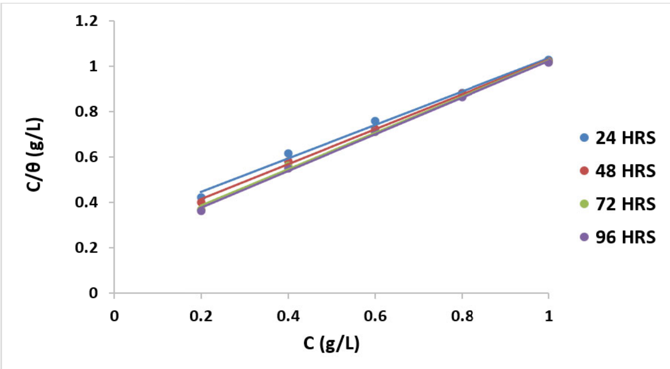

Figure 18. Langmuir adsorption plot for aluminium with and without plantain peel extract in 0.5M H_2SO_4

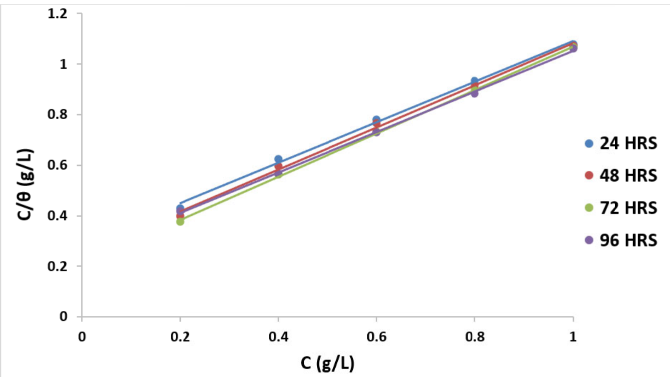

Figure 19. Langmuir adsorption plot for aluminium with and without plantain extract in 0.5M H_2SO_4

Conclusion

Unripe Plantain peel extract significantly outperformed the stem extract in protecting both mild steel and aluminium coupons in a highly corrosive 0.5M sulfuric acid solution.

1. Plantain peel extract achieved near-complete inhibition for aluminium (close to 100%) and exceptional efficiency (around 98%) for mild steel.
2. Plantain stem extract offered a lower degree of protection compared to the peel extract, with efficiencies of approximately 88% and 79% for aluminium and mild steel, respectively.
3. Plantain peels are a readily available and low-cost by-product, making the extract a potentially economical alternative to synthetic corrosion inhibitors as effective corrosion inhibitors in industrial settings.
4. Utilizing a renewable resource like plantain peels minimizes dependence on non-renewable resources and reduces waste generation, promoting environmental sustainability.

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