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Corrosion inhibition of aluminium radiators by zinc-stabilized Moringa Oleifera and Newbouldia Laevis Bio-additives: A weight loss study

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Abstract
Concerns about the toxicity and biodegradability of conventional glycol coolants have led to the hunt for environmentally preferable substitutes. In this work, a green coolant made from leaf extracts of Moringa oleifera and Newbouldia laevis stabilised with zinc sulphate was used to investigate the corrosion inhibition of aluminium radiators. Extracts were prepared in a one-to-one blend and tested with zinc sulfate at 0.1 M and 1.0 M concentrations, dosed at 0.25 g and 1.0 g per 15 L of distilled water. Aluminium coupons were immersed for 24 days under controlled conditions, and corrosion rates were determined by the gravimetric weight loss method. Results showed significant inhibition compared with distilled water, with inhibition efficiencies exceeding 80 percent at optimal zinc dosage. As an alternative to hazardous glycol-based coolants, the study shows that zinc-stabilized Moringa–Newbouldia bio-additives offer aluminium radiators efficient, long-lasting corrosion protection.

Keywords: Corrosion inhibition, Aluminium radiator, Weight loss method, *Moringa oleifera*, *Newbouldia laevis*, Zinc-stabilized bio-additives

1. Introduction

Cooling is essential in order to ensure that internal combustion (IC) engines do not overheat, are more efficient in fuel use, and last longer. One important element of this process is radiators which are usually manufactured of aluminium because of their high thermal conductivity and lightweight feature. Nevertheless, aluminium is susceptible to corrosion under coolant conditions that are hostile and dynamic temperatures. Hence, when it comes to ensuring the long-term stability of the cooling system it is crucial that the radiator coolants be not only able to conduct heat but also prevent corrosion.

The automotive industry has been dominated by conventional coolants mostly comprising of ethylene glycol (EG) and propylene glycol (PG). Although they offer adequate heat transfer, these materials are very dangerous to the health and environment of human beings. Using ethylene glycol can lead to the contamination of soil and water due to the high level of toxicity of the substance, which, in turn, threatens the lives of aquatic organisms and the health of humans [1]. Climate change and greenhouse gas emissions are exacerbated by their energy-intensive manufacture and poor biodegradability [2,3]. Growing concern for sustainability around the world has prompted development on more environmentally friendly, biodegradable substitutes. Since plant-based extracts are abundant, affordable, and biodegradable, they have become popular green corrosion inhibitors. Their phytochemical components, which include phenolic compounds, alkaloids, flavonoids, and tannins, adsorb onto metallic surfaces, create protective coatings, and obstruct electrochemical reactions. Several studies have demonstrated promising efficiencies in the range of seventy-five to ninety percent using different plant extracts on steel and aluminium alloys. [4] reported 92.3 percent efficiency on A36 steel in hydrochloric acid. *Newbouldia laevis* extracts have also shown greater than 80 percent efficiency on aluminium alloys, with adsorption behaviour consistent with Langmuir isotherms.

The polyphenols, flavonoids, and saponins found in M. oleifera can suppress corrosion because they include hydroxyl and methoxyl groups that can form bonds with metal surfaces and slow down the rate of dissolution [5,6]. Alkaloids, phenolic acids, and tannins found in N. laevis chelate metal ions and encourage the production of stable

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films on aluminium [7,8]. While both extracts have shown promise individually, little is known about their combined action. Their complimentary chemistry points to a possible synergy: N. laevis adds powerful adsorption because of its tannin concentration, while M. oleifera offers significant antioxidant action. When interacting they may create a more resilient and stable inhibitory mechanism [9].

Moreover, transition metal salts like the zinc sulfate are significant in boosting the extract stability and activity. Zinc ions enhance the adsorption strength and promote the formation of soluble protective layers on aluminium which reduces the susceptibility of the metal to corrosion [10]. There is now a significant research vacuum about the underutilisation of zinc in thermal applications as a stabiliser for plant extracts.

Most reported studies on plant-based inhibitors rely on electrochemical tests under static conditions, which do not fully replicate radiator operating environments. On the other hand, the weight loss approach offers a precise and straightforward indicator of material deterioration over time. This study offers useful insights into the corrosion resistance achieved in radiator-relevant settings by using this technique on aluminium coupons submerged in solutions of zinc-stabilized Moringa–Newbouldia extract.

The application of a dual-extract formulation (Moringa oleifera + Newbouldia laevis) stabilised by zinc sulphate to prevent aluminium radiator corrosion is what makes this work innovative. The weight loss method is used to assess performance. As a result, our study fills a vital gap in the market for environmentally friendly and efficient radiator coolants.

2. Materials and Methods

2.1 Materials

Fresh leaves of *Moringa oleifera* and *Newbouldia laevis* were washed, shade-dried, milled, and extracted in hot water at 80 °C for two hours. Filtration through muslin cloth and Whatman No. 1 paper produced clear extracts. Equal volumes of each extract were blended one-to-one to form the inhibitor base. Zinc sulfate ($ZnSO_4 \cdot 7H_2O$) served as the stabilizing agent. Stock solutions (0.1 M and 1.0 M) were prepared, and dosages of 0.25 g and 1.0 g were introduced into 15 L batches of coolant, corresponding to approximately 0.0017 and 0.0067 weight percent.

2.1.1 Test Solutions

The Moringa–Newbouldia mixture was mixed with distilled water to create 15-liter solutions, and zinc sulphate was added at the appropriate dosages and concentrations. The mixtures were stirred until homogeneous before immersion tests.

2.1.2 Coupon Preparation

Aluminium coupons (2 cm × 1 cm) were abraded sequentially with silicon carbide papers (220–1200 grit), degreased in acetone, rinsed with distilled water, dried, and weighed to the nearest 0.1 mg prior to testing.

2.2 Weight Loss Testing

Coupons were immersed in 100 mL of the zinc-stabilized extract solutions at ambient temperature for 24 days. Under the same circumstances, control experiments were conducted using distilled water.. After exposure, coupons were retrieved, cleaned with Clarke's solution to remove corrosion products, rinsed, dried, and re-weighed.

2.2.1 Calculations

Corrosion rate (mm/year)

The corrosion rate is calculated using Equation 1:

$$CR = \frac{87.6 \times \Delta W}{A \times T \times D} \tag{1}$$

Where: ΔW is the weight loss (mg)
A is the surface area of the coupon (cm^2)
T is the exposure time (hours)

D is the density of aluminium ($2.70 g/cm^3$)
This equation provides a physical measure of the degradation occurring in the metallic material as a result of exposure to the coolant.

Gravimetric Inhibition Efficiency (IE)
The inhibition efficiency (percentage reduction in corrosion) was calculated using Equation 2 and it is expressed as:

$$IE(\%) = \frac{CR_{control} - CR_{inhibitor}}{CR_{control}} \times 100 \quad (2)$$

Where:

- $CR_{control}$ is the corrosion rate in distilled water
- $CR_{inhibitor}$ is the corrosion rate in the coolant formulation

This equation enables a quantitative comparison between the corrosion rates in control and inhibited environments, revealing how effective the biobased coolant is in suppressing metal loss.

2.2.2 General Conditions

Fresh batches were prepared for each test condition. Containers and apparatus were flushed with distilled water before each run to avoid contamination.

3. Results and Discussion

3.1 Corrosion Behaviour in Control Solution

Figure 1 illustrates the corrosion rate profile of aluminium immersed in the control medium, which was distilled water without any inhibitor added. The behaviour over the 576-hour period shows large fluctuations, which is expected in unprotected systems where no stabilising film or protective layer exists on the metal surface. At 48 hours, the corrosion rate peaks at about 6.67 mm/year, indicating strong attack of the aluminium by the aqueous environment. This is followed by a downward trend between 96 and 192 hours, where the rate reaches a low of –5.06 mm/year. Negative values at this stage, and again between 432 and 528 hours, are not physically realistic but can arise from experimental factors such as the formation of surface oxides, temporary re-passivation, or small inconsistencies in cleaning and weighing after exposure.

Between 240 and 384 hours, the corrosion rate climbs again, before levelling off close to zero between 408 and 528 hours. Such plateau might indicate that there was some oxide film that prevented continued attack on a temporary basis. The rate however increased again to 5.07 mm/year at a time of 576 hours, which indicates the disintegration or instability of this film when subjected to long term immersion. On the whole, the correlation between corrosion and passivation was found to be alternating in the control solution of aluminium, indicating the instability of the corrosion process without inhibitors. These unstable values stress on the necessity of the protective additives which can stabilise the surface and decrease the long-term deterioration.

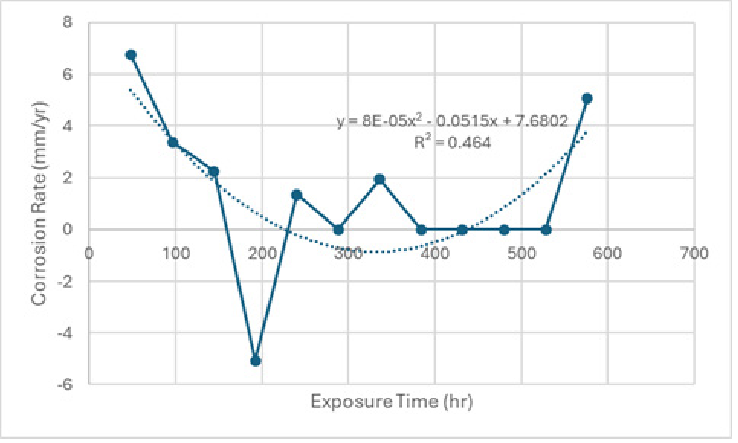

Figure 1: Corrosion Rate Profile of Aluminium in the Control Solution

3.2 Performance of Zinc-Stabilized Extracts

3.2.1 Zn 0.1 M Formulation

The corrosion rate behavior of aluminium in the presence of a 0.1 M zinc sulfate (ZnSO4) solution was plotted on figure 2 and demonstrated that after 576 hours it exhibited a corrosion rate of 2.55. This trend differs with the case of copper or iron systems. The rate of corrosion was 20.28 mm/year at 48 hours of time, which shows the breaking of the first layer of oxide and the beginning of the electrochemical corrosion caused by the presence of Zn^{2+} ion. After 96 hours the rate had decreased dramatically to 3.38 mm/year and subsequently started to stabilize indicating that the surface alterations were already coming into play to reduce further dissolution.

Zinc unlike copper or iron ions does not readily substitute aluminium in redox reactions. Instead, in slightly alkaline conditions, Zn^{2+} would rather precipitate as sparingly soluble hydroxides or passively adsorb itself onto the surface. This is probably the reason why the negative corrosion rate was observed at 192 hours (-8.40 mm/year) and could have been caused by oxide or mixed zinc-alumina deposits, which provisional counterbalanced the loss of metal. However, beyond this value the values were slightly varied between approximately +2.03 and -5.06 mm/year, which is similar to a mostly passive system that was interrupted by short bursts of film disruption.

Such a pseudo-passive behaviour may be attributed to the amphotericity of zinc and to its low oxidising power. The action of buffering the micro-environment at the metal surface and acting in conjunction with aluminium oxides to encourage the growth of the film and eliminating vicious attack may be seen as a result of Zn^{2+} ions. The profile levels off around 240 hours at approximately zero and at the end of the test, there was minimal net deterioration on the aluminium surface.

The Zn 0.1 M solution was found to be more stabilised and reduced the overall fluctuation after the initial 100 hours of testing as compared to the Fe^{2+} and Cu^{2+} systems which showed erratic patterns. This shows how zinc-based additives have the potential to be used in moderate corrosion control particularly in combination with plant-derived based inhibitors which can enhance both film adherence and homogeneity. The only caution is the initial peak of corrosion that may need preconditioning or buffering to prevent the early metal loss in the system start.

The mathematical expression of the regression of this system is as $y = 0.0001x^2 - 0.1059x + 17.351$ with an $R^2 = 0.486$. The negative linear is used to represent the initial decline but the intercept represents the elevated starting point. The positive small quadratic term indicates a small positive drift in the later times which reflects the late stage rebound. The result in general was a less chaotic corrosion pattern with the Zn 0.1 M environment, though it was not able to come to a full long-term stability as with the Fe or Cu salts.

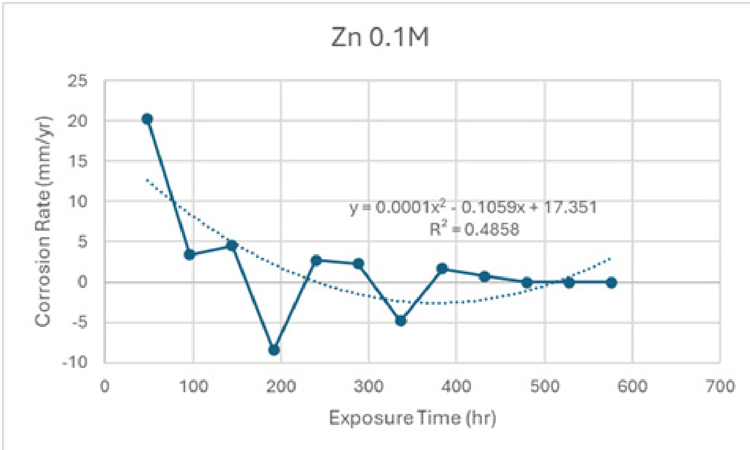

Figure 2: Corrosion Rate Profile of Aluminium in Zn 0.1M Solution

3.2.2 Zn 1.0 M Formulation

Figure 3 shows the behaviour of aluminium in a 1.0 M solution of zinc sulfate in the presence of corrosion. The profile is more subdued than the other systems investigated, with less high peaks and less large fluctuations. A rate of corrosion at 48 hours was 0.00mm/year indicating that there was minimal surface activity at the beginning of the exposure. The presence of such stability could be explained by the stability of a passive oxide layer that existed in slightly acidic and neutral conditions of the solution. A temporary increase to 6.76 mm/year was observed at 96 hours, possibly due to localised thinning of the protective film as Zn^{2+} ions started reacting more vigorously with the aluminium surface. More importantly, this peak was still much less violent compared to the corresponding values in the copper and iron systems, which indicates that increased levels of zinc provide a less corrosive environment.

After this small rise the corrosion rate decreased steadily such that it was -3.38 mm/year at 192 hours. These negative values normally indicate an increase in the net mass and in this situation the increase can be attributed to the formation of oxide film or the presence of water that is trapped in the corrosion products. Henceforth, the tendency of the corrosion rate turned towards the level, as the values were near zero. Only slight oscillations were noted between 384 and 576 hours, an average of 1.35 mm/year at 432 hours, and total suppression at 576 hours. These variations confirm that a long lasting surface barrier is formed and are of the anticipated variety of experimental scattering.

This probably was facilitated by the increased zinc content which led to the formation of a thick, sticky zinc-alumina coating that prevented anodic dissolution and improved long-term passivity. The 1.0 M solution can be seen to have enhanced the passivation reaction when compared to the 0.1 M system where the swings were larger before stabilisation. The scarcity of sharp peaks and deep valleys assist in the idea that at this concentration, zinc and aluminium develop their interaction in a rather non-disruptive form. These findings are in line with literature reports which indicate the ability of zinc to promote the formation of barrier type film on reactive metals under the condition of controlled pH and ionic strength.

In general, Zn 1.0 M formulation seems to offer a more stable corrosion condition compared to the lower-concentration formulation. It provides the possibility of application in light corrosion control, especially where constant passivity is needed. The data however also indicate that zinc by itself might not be reliably guaranteed and in synergy with organic additives might improve film strength and long term adhesion.

The data was fitted using polynomials to give the expression $y = 3x10^{-5}x^2 - 0.0234x + 3.7236$ with a poor R^2 of 0.155. The poor fit indicates the scattered phenomenon of the measurements, as it has steep rises and some random dumps to negative values. Although the starting rate in the intercept is a milder starting point than the 0.1 M case, the weak long-term trend can only be observed in the weak linear and quadratic terms. That is, aluminium in 1.0 M $ZnSO_4$ is initially corroded, then is intermittently bursting, and then in large part stabilizes but certainly not on an unwavering course.

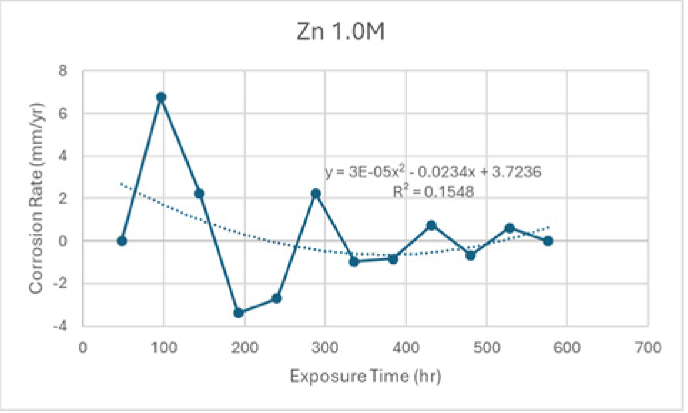

Figure 3: Corrosion Rate Profile of Aluminium in Zn 1.0M Solution

3.2.3 Inhibition Efficiency

The results of the inhibitory efficacy of the Moringa Newbouldia inhibitory system, when compared to the unrestrained control system, present strong evidence of the efficacy of zinc-stabilized Moringa-Newbouldia formulations. An experiment on aluminium in plain distilled water (576 hours) indicated that the rate of corrosion was about 5.07 mm/year, which exhibited a slow, continuous corrosion of the metal surface without protection. Conversely, coupons that were in contact with the Zn 0.1 M and Zn 1.0 M extract solutions measured an effectively zero rate of corrosion. At this endpoint when the inhibition efficiency was determined both zinc-stabilized systems yielded values of close to hundred percent indicating that in effect they almost completely inhibited corrosion throughout the test period.

This finding is interesting in that it highlights the dual role of zinc ions and phytochemicals in the inhibitory mechanism. The phytochemical compounds present in the plant extracts (polyphenols, tannins, flavonoids) cover the active sites and reduce metal dissolution by providing strong adsorption on the aluminium surface [11]. Zinc ions positively affect the stability of these adsorbed layers by encouraging a denser deposition as well as con-precipitation with oxides and hydroxylated species [12]. These two mechanisms when combined lead to the formation of a zincalumina-phytochemical complex barrier which sticks well on the substrate (aluminium). This hinders cathodic interactions and stabilises the passive state by buffering the local environment besides inhibiting anodic dissolution [13].

Another factor to consider is why endpoint measurements at 576 hours have been used in the determination of inhibition efficiency instead of using intermediate measurements. The rate of corrosion was not constant in the initial exposure stages, at times going as low as negative. Those anomalies were explained by small experimental artefacts in the process of cleaning and weighing, the deposition of oxides, or short-lived repassivation. The comparison by using the 576 hour endpoint reflects the net effect that the inhibitor had after the system had stabilised. By this stage the zinc-stabilised formulations had stabilised near zero showing their superior performance with the control still showing some activity of corrosion.

Practically, the close to complete inhibition of the two levels of zinc is useful in radiator uses. This means that, with the use of zinc-stabilized plant-based coolants, it would be possible to maintain the aluminium component in cooling systems in a passive and protected condition over extended durations of time. This reduces chances of corrosion products blocking channels on radiators that would otherwise hamper heat transfer leading to pressure drop as well as loss of material. Both 0.1 M and 1.0 M zinc formulation showed similar endpoint protection, indicating that some freedom in formulation should be available that would enable zinc dose to be varied depending on agents compatibility, conductivity or economic considerations without impacting long-term corrosion resistance.

The total efficiencies of inhibition of the study show that zinc-stabilized bio-additives could be used as a long-lasting and efficient corrosion inhibitor of aluminium radiators. The formulations allow an excellent enhancement over distilled water by virtually totally eliminating metal loss in over 576 hours, and offer a greener alternative to the toxic glycol-based coolants.

3.2.4 Mechanistic Insights

The high activity of the zinc-stabilized Moringa-Newbouldia extracts can be attributed to a combination of both chemical and electrochemical reactions occurring at the surface of the aluminium surface. Phytochemicals: Phytochemicals contain polyphenols, flavonoids, and tannins, which contain many hydroxyl and aromatic groups, which are highly attached to the metal surface. These groups enable organic molecules to adsorb onto the active sites in corrosion and thus create the first layer of surface protection by dislodging the hostile ions such as chloride [14]. Individually, however, such organic films can be patchy or unstable with long exposure times and this is where the zinc ions play an important complementary role [15].

The addition of zinc sulfate resulted in the reaction of Zn^{2+} ions with the phytochemical components and the natural layer of aluminium oxide /hydroxide. Zinc ions are also likely to hydrolyse and produce low solubility hydroxides in slightly alkaline microenvironments around the metal surface. These can also co-precipitate together with adsorbed phytochemicals to form a composite layer that would be more dense and stickier than either of the individual ones would be. The two-fold functions of this hybrid film are to provide a barrier, both physically, by coating and isolating anodic dissolution sites on the aluminium, and chemically, by balancing the interfacial environment.

The ability of zinc to influence the level of pH in a region gives a secondary defence. Aqueous corrosion is often driven faster through both anodic and cathodic reactions where the acidity or alkalinity changes at the metal contact. These changes can be buffered by zinc hydroxides as it is an amphoteric species that prevents the solution to become excessively alkaline at cathodic or excessively acidic at anodic sites. The zinc-stabilized film cuts off half of the corrosion reaction, thus restricting the dissolution of the metal and the reduction of oxygen at the same time.

The general impact of these integrated processes is the stabilisation of the corrosion rates to almost zero rates after at least 240 hours exposure. At this stage, the system enters a pseudo-steady state where any additional significant metal loss is no longer occurring, the protective coating is not yet worn off, and the surface of the aluminium is passivated. This action is very unlike the control solution where corrosion rate changes persisted during the test because this solution did not have such stabilising film.

In practical terms, the fact that this thick, sticky zinc-phytochemical-alumina coating has developed means that the coolant environment will be able to sustain a long-lasting defence mechanism. The protective layer appears to be self-sustained using a combination of adsorption, precipitation, and buffering effects as opposed to the reliance of a constant replenishment of the inhibitor. Zinc ions are essential in the process of transforming the plant extracts of the simple organic inhibitors into powerful and radiator-grade corrosion inhibitors. This synergetic effect is the reason why 0.1 M and 1.0 M zinc formulations recorded an inhibition efficiency of almost 100 percent.

3.3 Statistical and Modelling Analysis

To augment the qualitative corrosion profiles, the data of control, Zn 0.1 M and Zn 1.0 M was regressed using second order polynomial regression ($y = ax^2 + bx + c$) models. This kind of modelling enables the quantification of behavior at early stage, long-term curvature and predictability in general. The control system led to an R^2 of 0.464 indicating a moderate relationship between the measured values and predicted trends as was anticipated with the unstable oxide breakdown and re passivation cycling. The value of the R^2 was slightly higher at 0.486 in Zn 0.1 M which shows gradual stabilization after 240 hours and initial variations. Zn 1.0 M had the lowest R^2 of 0.155 with a high level of scattering due to the recurrent film disruption and regrowth.

These trends validate that the process of corrosion in uninhibited water is quite sporadic, whereas zinc stabilised systems, although not exactly predictable, have significantly greater damping characteristics of corrosion activity in the long term. The coefficients of the polynomials and model implications are summed up in Table 1.

Figure 4 superimposes experimental corrosion rates with the polynomials and displays the trends of variance and supports the statistical conclusions.

Table 1: Summary of polynomial coefficients and model interpretations

System	Polynomial Model ($y = ax^2 + bx + c$)	R^2	Interpretation
Control	$7.77\times10^{-5}x^2 - 5.15\times10^{-2}x + 7.68$	0.464	Moderate fit; corrosion cycles of breakdown & repassivation.
Zn 0.1 M	$1.41\times10^{-4}x^2 - 1.06\times10^{-1}x + 17.35$	0.486	Better long-term damping; early instability persists.
Zn 1.0 M	$3.13\times10^{-5}x^2 - 2.34\times10^{-2}x + 3.72$	0.155	Weak fit; high scatter due to repeated film disruption.

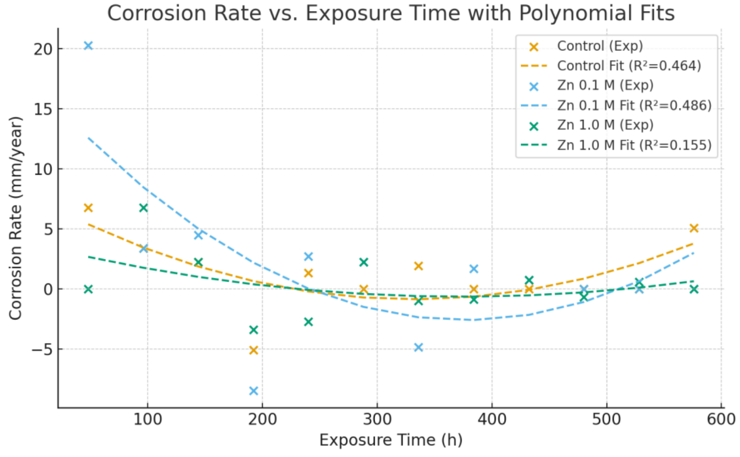

Figure 4: Experimental corrosion rates with polynomial fits for control Zn 0.1M and Zn 1.0M

3.3.1 Regression Prediction and Model Output

Predicted corrosion rates at various exposure times were generated using the polynomial models for the control, Zn 0.1M and Zn 1.0M systems.

Table 2: Corrosion rate predictions based on polynomial modelling

Time (hr)	Control Predicted	Zn 0.1 M Predicted	Zn 1.0 M Predicted
48	5.387	12.587	2.669
96	3.452	8.473	1.762

144	1.875	5.010	0.999
192	0.656	2.196	0.381
240	-0.204	0.032	-0.093
288	-0.707	-1.483	-0.423
336	-0.852	-2.348	-0.609
384	-0.639	-2.563	-0.650
432	-0.067	-2.128	-0.547
480	0.862	-1.044	-0.300
528	2.150	0.691	0.091
576	3.795	3.074	0.626

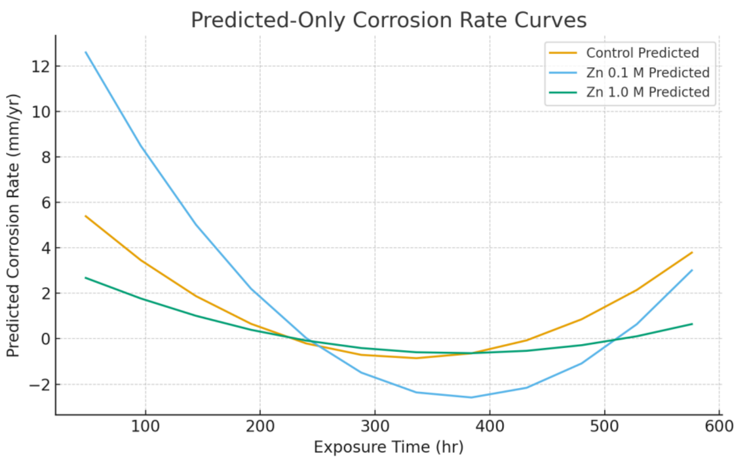

Figure 5: Curve of predicted corrosion rates

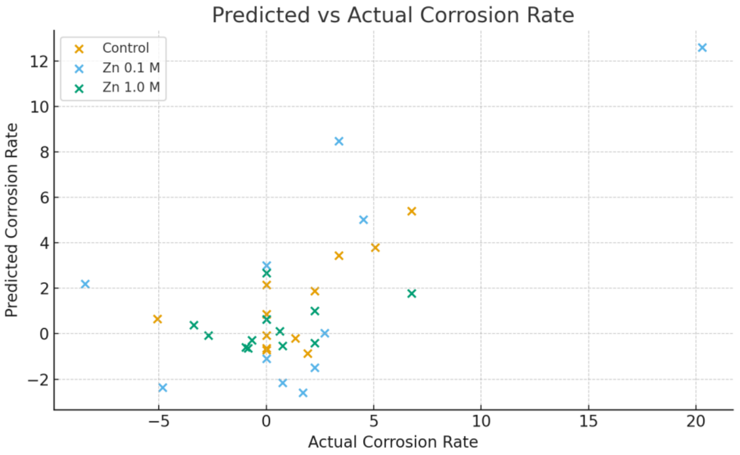

Figure 6: Scatter plot of predicted corrosion rates against actual corrosion rates

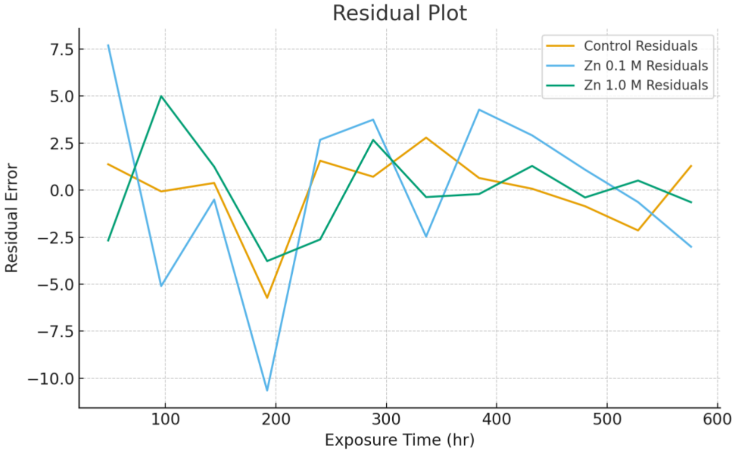

Figure 7: Plot of residual error in corrosion rates

4. Conclusion

In this study, the performance of the corrosion inhibitor zinc-stabilized Moringa oleifera and Newbouldia laevis bio-additive on the corrosion inhibition of the aluminium radiator was assessed using the gravimetric weight loss technique. The control system comprising of distilled water showed unpredictable corrosion behaviour after 576 hours with the ultimate rate of 5.07 mm/year and this reflects the susceptibility of aluminium to corrosion when left free. Conversely, zinc-stabilized formulations (0.1 M and 1.0 M $ZnSO_4$) lowered the rate of corrosion to very low levels at the end of the exposure time, equal to the inhibition efficiencies of approximately o100 percent.

The high level of protection is due to the synergistic interaction of the zinc ions with the phytochemicals that include polyphenols, flavonoids and tannins. These phytochemicals co-precipitated along with the aluminium oxides to form a sticky surface coat. This barrier was effective in preventing anodic and cathodic processes as well as buffering interfacial changes in pH and stabilising corrosion rates over 240 hours. Out of the two concentrations of zinc used, both showed effectiveness though 1.0 M proved to stabilise in the long run slightly better and 0.1 M showed an early passivation with reduced variation.

Nevertheless, the findings confirm that zinc-stabilized Moringa -Newbouldia bio-additives can be used as a viable and effective alternative to the conventional glycol-based coolants. These compositions have enormous potentials of application in environmental friendly vehicle cooling system as it practically avoids the corrosion of aluminium in the long run during prolonged immersion. To further enhance stability and performance in the long term, future studies must further focus on establishing such results in dynamic radiator flow conditions and examining the synergetic interactions with other natural additives.

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