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Efficiency of *Cola acuminata* Exudates as Corrosion Inhibitor for Mild Steel Pipes in Acid Concentrated Water and Soil

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Abstract

This study investigated the performance of *Cola acuminata* exudates in preventing mild steel exposed to acid concentrated water and soil. The study was performed in order to find an alternative coating substance that can reduce the corrosion of mild steel pipes exposed to corrosive water and soil media. Various mild steel specimens were cut into portions and coated with the exudates at 25 - 50µm thickness. To accelerate the rate of corrosion, 0.5M hydrochloric acid (HCl) was added to tap water in a container. Also, the same concentration of HCl was equally added to soil samples. Uncoated mild steel specimens were immersed in the acid concentrated water and soil, servicing as control sample. The rate of corrosion was monitored for 30 days (720 hours). The inhibition efficiency of the exudates for both corrosive media was compared. Results showed that the weight loss and corrosion rate of mild steel decreased with increase in coating thickness. Comparatively, weight loss and corrosion rate in the uncoated specimens were higher than the coated specimens. For uncoated specimens, the corrosion rate was 0.2793mm/yr and 0.4150mm/yr for specimen immersed in water and soil respectively, but at 25µm coating thickness, it decreased to 0.1516mm/yr and 0.2779mm/yr for specimens in water and soil. Also, at 50µm coating thickness, corrosion rate decreased to 0.0054mm/yr and 0.0308mm/yr for specimens in water and soil, respectively. The inhibition efficiency increased from 45.71 – 98.06% for specimens immersed in water and 33.11 – 92.57% for specimens buried in soil at 25µm – 50µm coating thickness. The results showed that *Cola acuminata* can serve as corrosion inhibitor for steel pipes exposed to corrosive media at minimum coating thickness of 35µm.

Keywords: *Mild Steel, Corrosion Rate, Cola acuminata Exudates, Water, Soil*

1. Introduction

Corrosion is a major concern in engineering field due to the severe consequences it can cause on structures (Roche & Bender, 2016). Corrosion is the degradation of material which occurs gradually as a result of chemical or electrochemical reaction between the material and its environment (Schmitt, 2009). Corrosion can also be viewed as the deterioration of metals brought about by chemical, mechanical and biological action in corroding environment (Chaker & Palmer, 1989). Environmental conditions in which a steel structure is exposed to, can be mild or highly corrosive. Therefore, appropriate measures need to be taken to avert or reduce possible risk of corrosion on steel structures (Arriba-Rodriguez *et al*., 2018). One of the ways to describe the corrosion behaviour of a material is through the identification of the environment to which it will be exposed. Thus, corrosion of material is highly dependent on the level of pollution, relative humidity and temperature. The underground environment is characterized by variability of local conditions, soil chemistry, conductivity, humidity among others parameters (Krivy *et al*., 2017). External factors such as precipitation and artificial manipulation of soil can also influence corrosion rate of metals. Because large amount of steel are used in construction of structures, which are often buried in water or soil environment, it is necessary to know the effect of corrosion on structures exposed to water and soil environments. This will provide useful information during the design of such structures (Arriba-Rodriguez *et al*., 2018).

Economically, corrosion of buried steel structures represents real economic and environmental problems (Shi *et al*., 2017). According to Koch *et al*. (2016), the cost of corrosion, as estimated by the National Association of Corrosion Engineers (NACE) in 2013, is equivalent to 3.4% of global GDP. However, using corrosion control practices can save between 15% and 35% of corrosion cost in structures (Koch *et al*., 2016). A more complex corrosive environment has an extreme corrosion impact on materials (Parker & Peattie, 1984). The key factors that influence the corrosion of structural metallic members include pH, ion content, aeration, bacteria, resistivity, and redox potential (Li *et al*., 2007; Ismail & El-Shamy, 2009; Yahaya *et al*., 2011a; Zhu *et al*., 2011; Tiba & De Oliveira, 2012; Wu *et al*., 2014; Soriano & Alfantazi, 2016). In the case of soil environment, moisture and soil texture also influenced corrosion (Pereira *et al*., 2015). Soil texture consists of different size distribution, but finer soil particles are considered the worst corrosive medium for buried steel structures (Ismail & El-Shamy, 2009; Jeannin *et al*., 2010).

However, there are methods that limit the rate of corrosion on materials such as the use of cathodic protection, coating and painting as well as the use of inhibiting materials. Inhibitors are one of the technologies adopted to reduce corrosion impact on metals. Corrosion inhibitors are substances added to a corrosive media in order to slow down corrosion reactions (Marzorati *et al*., 2018). Most commercial corrosion inhibitors are stable and effective, but are often expensive to formulate, and can pose threats to public health and the environment because of their toxicity (Brycki*et al*., 2018). The use of conventional corrosion inhibitors is being reduced because of the awareness of green technology (Umoren & Eduok, 2016; Hu *et al*., 2016). The need to make the environment clean and friendly is influencing scientists and engineers to develop inhibitors from renewable sources (Verma *et al*., 2018). Green inhibitors, such as those extracted from plants, are gaining significant attention. Plants are characterized by their unique property to convert sunlight energy into carbohydrates via the process of photosynthesis, and can take up greenhouse gases and other pollutants during the process of photosynthesis, which is an essential process from environmental cleaning point of view (Sheldon, 2016; Verma *et al*., 2018).

Most plant extracts exude a viscous liquid that can effectively stick to material surfaces, which can be useful characteristics for inhibition of corrosion attack on metallic surfaces. *Cola acuminata* is a tree species which belongs to the Malvaceae family. Its fruit is mostly known as kola nut. *Cola acuminata* is originates from Africa. Exudates of some plants are thick and sticky to a material surface. Therefore, the performance of *Cola acuminata* exudates as corrosion inhibitor for mild steel exposed to acidic and salty environment, such as the Niger Delta environment of Nigeria, was investigated.

2. Materials and Methods

The materials and methods used to achieve this study are stated and explained in the subsections below.

2.1 Materials

The key materials utilized in this study on the efficiency of Cola acuminata exudates as a corrosion inhibitor included mild steel specimens, Cola acuminata exudates, hydrochloric acid (HCl), tap water, soil samples, and equipment for corrosion rate analysis. The mild steel was obtained as 15mm diameter pipes from a local market in Nigeria, with chemical composition of 0.17% carbon, 0.30% silicon, 0.70% manganese, 0.03% sulfur and 0.03% phosphorus, balanced by iron. The pipes were cut into 20mm length samples, polished, degreased, and pretreated to remove any prior corrosion before experiments. Standardized uniform mild steel samples ensured consistency in corrosion behavior analysis.

The Cola acuminata exudates were freshly extracted on-site from trees in Rivers State, Nigeria. The viscous exudates possess valuable phytochemical compounds capable of corrosion inhibition. However, detailed characterization of the chemical composition was not performed. Future studies can analyze the specific organic compounds and functional groups responsible for corrosion inhibition using chromatography and spectroscopy techniques. Fresh tap water was acquired for the aqueous corrosion medium. Hydrochloric acid (HCl) of 0.5M concentration was added to the tap water at 1:8 acid to water ratio to simulate an aggressive corrosion environment. The enhanced acidity accelerated the corrosion rate of mild steel for rapid evaluation of the inhibitors.

The soil medium was a loamy sample with 13.56% moisture content, obtained locally from Ahoada West, Nigeria. 0.5M HCl was also added to the soil at 1:9 acid to soil ratio to increase corrosivity. The physicochemical properties of both media were analyzed before experiments. The gravimetric weight loss method was used for measuring corrosion rate. Weighing balance, measuring cylinders, beakers, venire calipers and other volumetric glassware were utilized for accurate sample preparation and corrosion rate analysis as per ASTM standards. Future studies can also employ more advanced electrochemical techniques like potentiodynamic polarization, electrochemical impedance spectroscopy etc. for in-depth corrosion mechanism analysis.

The materials and experimental methodology employed were appropriate for evaluating the corrosion inhibition efficiency of the Cola acuminata exudates on mild steel in acidic media. Standard materials like mild steel specimens and HCl medium ensured reliability of corrosion rate data. The key contributions can be more comprehensive material characterization through spectroscopy and chromatography, and incorporation of electrochemical corrosion analysis techniques. Nevertheless, the materials and methods selected enabled systematic investigation of the research problem within the available experimental constraints.

2.2 Sample Collection and Preparation

The Cola acuminata exudates were freshly extracted from trees located in the bush of Enito II Village, Ahoada West Local Government Area of Rivers State, Nigeria. The exudates were directly collected on-site from incisions made into the bark of mature Cola acuminata trees. The viscous sap oozing out was gathered into clean glass vials. Extraction was performed aseptically to prevent microbial contamination. The exudate samples were immediately transported under cooled conditions at 4°C to the laboratory at Rivers State University, Port Harcourt, for further processing and use in corrosion inhibition studies.

The mild steel material was procured as pipes of 15mm diameter and standard chemical composition from Mile III market in Port Harcourt, Rivers State, Nigeria. The obtained pipes were thoroughly cleaned to remove grease, oil and dirt using detergent solution, followed by rinsing in acetone and double distilled water. The pipes were then cut into small cylindrical specimens of 20mm length using an automated precision cutter. The cut specimens were further polished manually with varying grades (60-1200 grit size) of silicon carbide abrasive papers to achieve a smooth and uniform surface finish. After polishing, the specimens were degreased again with petroleum ether, washed in ethanol and dried in hot air. The consistent dimensions and surface treatment ensured reproducible sample conditions for corrosion rate analysis.

Prior to corrosion testing, the blank mild steel specimens were weighed precisely to 0.1 mg using an analytical digital balance. The surface area and volume of each specimen was accurately measured using venire calipers and determined geometrically from the defined dimensions. The specimens were then coated with the extracted Cola acuminata exudates by gentle brushing to create thin uniform films of varying thickness from 25-50 μm. The coated samples were allowed to dry overnight under ambient conditions. Uncoated control samples were also prepared to compare corrosion inhibition efficiency. The accurate pre-treatment, documentation and controlled coating of the mild steel specimens facilitated reliable measurement of the corrosion rate and inhibitor performance in subsequent studies.

The tap water used as the aqueous corrosion medium was collected fresh from the laboratory taps in cleaned glass bottles. Analytical grade hydrochloric acid (HCl, 37% purity) was commercially procured to simulate acidic corrosion conditions. The soil was dug from a depth of 2 feet from a site in Ahoada West, Rivers State. The loamy soil was air dried, sieved using a 2mm mesh to remove debris and large particles, and stored in polyethylene bags before use. Proper documentation and physico-chemical analysis of the blank corrosion media was also performed to understand their intrinsic corrosivity. Overall, the systematic sample collection, processing, surface treatment, dimensional measurements and controlled corrosion inhibitor coating of the mild steel specimens enhanced the reliability of the subsequent corrosion rate analysis using the prepared materials.

Plate 1: Cola acuminata exudates

Plate 2: Sodium Chloride (NaCl)

Plate 3: Concentrated Acid Sample

Plate 4: Coated sample

2.3 Experimental Procedure

The gravimetric method of measuring corrosion rates through weight loss analysis was employed to evaluate and compare the performance of the coated and uncoated mild steel samples exposed to acidic corrosion environments. As one of the most widely used techniques for corrosion testing and monitoring, the gravimetric method provides a direct measure of corrosion based on calculating the amount of metallic material lost over a given time period under corrosive conditions. For this study, an analytical weighing balance with a precision of 0.1 mg was utilized to take highly accurate weight readings of the steel specimens before and after immersion in acid water and soil mediums.

The mild steel material selected for fabrication of the test coupons was obtained as pipes with specific composition specifications necessary to ensure reproducibility and reliability of results. Through chemical composition testing as per international standards, the steel was found to contain carbon comprising 0.17% of its mass. Silicon was another principal alloying element determined to be 0.30% by mass. Manganese content measured at 0.70% helped enhance the steel's strength. Smaller amounts of sulfur at 0.03% and phosphorus at 0.03% were also present. After accounting for these minor alloying elements, the majority substance remaining was iron, making up the balance of the solid solution microstructure.

Prior to corrosion testing, the mild steel samples underwent meticulous surface preparation including cutting, grinding, polishing and cleaning procedures. This was done to provide each specimen with a consistent and well-defined starting surface condition for gathering meaningful baseline data. Only through use of quality materials and well-validated experimental setup could accurate quantification and inhibition efficiency values be determined for evaluating the protective performance of Cola acuminata exudates coatings under accelerated acidic corrosion conditions.

2.3.1 Immersion in Acid Solution

Prior to conducting the immersion tests in acidic solution, the mild steel specimens underwent coating with Cola acuminata exudates. The specimens were weighed precisely using an analytical weighing balance to record their initial masses. The exudates were applied to the specimens at varying thicknesses from 25 to 50 micrometers in 5 micrometer intervals. Another specimen was left uncoated to serve as a control for comparative analysis. Once the coating process was completed, 250 milliliter plastic beakers were utilized as corrosion test cells. Each beaker was filled with 200 milliliters of tap water. This was to serve as the base solution that would be acidified to simulate corrosive conditions. Hydrochloric acid of 0.5 molar concentration was employed to accelerate corrosion kinetics. Exactly 25 milliliters of the acid was gradually added to the beakers, producing an acid to water ratio of 1:8.

The prepared coated and uncoated mild steel specimens were fully submerged in the acidified test solutions inside the plastic beakers. Care was taken to ensure complete immersion and exposure of all specimen surfaces to the corrosive medium. The samples were placed in the acid water for 30 days to undergo accelerated corrosion. At the end of the exposure period, the specimens were removed from the solution using corrosion resistant tongs. They were thoroughly washed with distilled water to remove any residual corrosion products or test solution. Finally, the specimens were dried in air and reweighed to determine the mass losses incurred during the corrosive challenge.

2.3.2 Immersion into Acid Concentrated Soil

An identical experimental procedure to the acid solution immersion testing was followed for exposure of specimens to acidic soil. The specimens were first coated with Cola acuminata exudates at varying thicknesses from 25 to 50 µm, with intervals of 5 µm between each level. An additional uncoated specimen was set aside as a control. Next, a large rectangular container was filled with 450 kg of loamy soil obtained from the study area. This soil was selected to simulate the buried environment commonly encountered by steel pipes. To induce corrosive stress, 50 ml of 0.5 M hydrochloric acid was added to the soil mix and stirred thoroughly for 2 minutes. The addition of acid was done to increase the soil's corrosiveness and accelerate any corrosion processes of the embedded steel specimens over the test period.

Once the acidified soil was ready, the coated and uncoated specimens were completely buried within the mixture, ensuring full contact between their reactive surfaces and the corrosive medium. Similar to the acid solution testing, an exposure duration of 30 days was allowed for accelerated corrosion conditions. At the end of this period, the specimens were carefully excavated from the soil using plastic tools to avoid contamination or damage. The retrieved specimens were then cleaned of soil particles by washing with distilled water and dried in air. Lastly, their final weights were recorded on the analytical balance to evaluate the extent of mass loss or corrosion incurred during the acidic soil exposure challenge.

Plate 5: Preparation of Corroded Soil sample

Plate 6: Corroded Soil sample

Plate 7: Water Immersion

Plate 8: Soil Embedment

2.4 Weight Loss and Corrosion Rate

The weight loss method was used in study. Thus, the weight loss over time was measured by subtracting the instantaneous weight from the initial weight of the specimen. From the weight loss measurement, the corrosion rate of mild steel was calculated using the corrosion model stated in Equation (1). The corrosion rate is expressed as a function of weight loss per surface area exposed to the corroding medium per material density per exposure time.

$$C_R = \frac{K\Delta w}{\rho A t} \qquad (1)$$

where: $C_R =$ Corrosion rate (mm/yr), $K =$ Constant, $\Delta w =$ Weight loss (mg), $\rho =$ Density of material (g/cm^3), $A =$ Cross-sectional area of metal (cm^2) and $t =$ Time (hr)

But *K* is given as 87.6, while the density of mild steel was given as 7.85g/cm^3 (Singh *et al*., 2015). Using the above units, the corrosion rate, C_R, is expressed in millimetre per year (mm/yr).

2.5 Inhibition Efficiency

To determine the effectiveness of the exudates in reducing the corrosion rate of mild steel in the acid media, equation (2) was used to calculate the efficiency.

$$\mathrm{E} = \frac{w_o - w_1}{w_o} \times 100\% \qquad (2)$$

Where: $w_o =$ weight loss in uncoated specimen (g), $w_1 =$ weight loss in coated specimen (g).

2.5 Research Gap Analyzed

Based on the literature reviewed and the results obtained from the studies, the following comprehensive detailed research gap can be identified: Although several studies have investigated the corrosion inhibition of mild steel in various environments, there is a lack of research specifically focused on the efficiency of Cola acuminata exudates as a corrosion inhibitor for mild steel pipes in acid concentrated water and soil. The existing literature primarily covers the corrosion inhibition potentials of other compounds, such as 3-nitrobenzoic acid (Ameh & Eddy, 2016), chemically modified natural polysaccharides (Banerjee, Srivastava & Singh, 2012), and plant extracts from different sources (Fouda et al., 2017; Okewale & Olaitan, 2017; Owate et al., 2014; Singh et al., 2015). However, the specific application of Cola acuminata exudates as a corrosion inhibitor for mild steel in acid concentrated water and soil has not been extensively studied.

Furthermore, the existing literature provides insights into the corrosion behavior of mild steel in different environments, such as acidic solutions (Ameh & Eddy, 2016; Li et al., 2007), chloride-containing media (Loto, Loto & Fedotova, 2013), and buried structures (Arriba-Rodriguez et al., 2018; Jeannin et al., 2010). However, there is a research gap regarding the combined effect of acid concentrated water and soil on the corrosion of mild steel pipes.

Additionally, while various corrosion inhibitors have been explored for their effectiveness in different environments, there is a need for more studies specifically focusing on the efficiency of natural compounds, such as Cola acuminata exudates, as corrosion inhibitors. The use of green and sustainable corrosion inhibitors has gained significant interest due to their environmental compatibility and potential economic benefits (Marzorati, Verotta & Trasatti, 2018; Sheldon, 2016; Umoren & Eduok, 2016). Therefore, investigating the corrosion inhibition efficiency of Cola acuminata exudates can contribute to the development of environmentally friendly corrosion protection strategies.

To bridge this research gap, future studies should evaluate the corrosion inhibition performance of Cola acuminata exudates on mild steel pipes exposed to acid concentrated water and soil. The research can include experimental investigations to determine the corrosion rate, surface morphology, and electrochemical behavior of the mild steel in the presence of Cola acuminata exudates. Comparative studies can be conducted to assess the effectiveness of Cola acuminata exudates in comparison to other corrosion inhibitors mentioned in the literature. The research should also consider the influence of various factors, such as concentration, temperature, and exposure time, on the corrosion inhibition efficiency of Cola acuminata exudates.

By addressing this research gap, valuable insights can be obtained regarding the potential application of Cola acuminata exudates as a corrosion inhibitor for mild steel pipes in acid concentrated water and soil, contributing to the development of sustainable corrosion protection strategies in relevant industrial and environmental settings.

3. Results and Discussion

The weight loss results of mild steel pipes immersed in HCl concentrated tap water soil at the same molar concentration (0.5M) are presented and discussed in this section. The corrosion rate and inhibition efficiency of *Cola acuminata* exudates at the different coating thickness were also evaluated to ascertain the effectiveness of *Cola acuminata* exudates in prevention of mild steel exposed to corrosion susceptible environments.

Table 1: Physicochemical properties of water and soil samples before acid concentration

Property	**Value**	
	Water	Soil
Condition	Fresh	loamy soil
Temperature (°C)	26.84	29.26
Conductivity (μS/cm)	36.09	5047.62
Moisture Content (%)	Not applicable	13.56
pH	7.14	5.78

Table 1 shows the physicochemical characteristics of the tap water and soil samples before addition of hydrochloric acid. These parameters give insights into the inherent corrosiveness of the media prior to acidification. The water sample had a near-neutral pH of 7.14, indicating it was not highly corrosive initially. The conductivity was moderately low at 36.09 μS/cm, further evidencing the non-aggressive nature of the tap water. In contrast, the soil sample showed a mildly acidic pH of 5.78 and very high conductivity of 5047.62 μS/cm. The lower pH and elevated conductivity suggest the soil had greater innate corrosivity compared to the tap water even before acid addition.

High conductivity implies greater ionic content and salinity, which can accelerate corrosion of metals (Koch et al., 2016; Yahaya et al., 2011). Studies have also correlated high moisture content in soils with increased corrosion rate of buried steel structures (Dang et al., 2015; Chen & Zhao, 2017). The soil sample had 13.56% moisture content. Therefore, the disparity in the inherent physicochemical characteristics of the two media indicated the soil was likely more corrosive to start with compared to the tap water. This was further validated by the higher corrosion rate and lower inhibition efficiency observed in the soil medium after the experiments. The addition of 0.5M HCl would have exacerbated the corrosive conditions significantly in both media. But the intrinsically higher conductivity, lower pH and moisture content rendered the acidic soil more aggressive towards the mild steel than the similarly acidified tap water medium.

3.1 Weight loss

The weight loss results recorded after 30 days of immersion of uncoated and coated mild steel specimens in acid concentrated water and soil are shown in Table 2.

Table 2: Weight loss measurement of uncoated and coated mild steel in water and soil media

Thickness (µm)	**Water**			**Soil**		
	wo (g)	w1 (g)	Δw (g)	wo (g)	w1 (g)	Δw (g)
0	9.15375	9.14242	0.01133	9.17449	9.08975	0.01683
25	9.00134	8.99519	0.00615	9.0157	9.06693	0.01127
30	9.30874	9.30565	0.00309	9.32115	9.22197	0.00694
35	9.10556	9.10442	0.00114	9.11737	9.08089	0.00342
40	9.19193	9.19120	0.00073	9.20329	9.1103	0.00195
45	9.20419	9.20372	0.00047	9.21525	9.09297	0.00175
50	9.09634	9.09612	0.00022	9.10706	9.0405	0.00125

There was evidence of weight loss in the mild steel specimens immersed in 0.5M HCl solution and the specimens buried in soil for a period of 30 days (720 hours). However, the uncoated specimens showed higher effect of weight loss compared to the coated specimens. The study also revealed that the weight loss of mild recorded after 30 days decreased with increase in the thickness of *Cola acuminata* exudates coated on the mild steel.

From the results presented in Table 1, the weight loss of mild steel in uncoated specimen was recorded as 0.01133g and 0.01683g for sample immersed in acid concentrated water and soil respectively. For coated mild steel specimen immersed in acid concentrated water, the weight loss reduced to 0.00516g at 25µm thickness and to 0.00011g at 50µm thickness, while the weight loss in coated mild steel specimens in acid concentrated soil reduced to 0.0615g at 25µm thickness and to 0.00022g at 50µm thickness.

Figure 1 further indicated that the weight loss in specimens buried in acid concentrated soil was higher than specimens immersed in acid concentrated water at all coating thickness. Thus, it showed that the soil was more corrosive than the water used in this study, and may be as a result of high concentrations of salts in the soil, as indicated by the level of electrical conductivity (EC), temperature and pH recorded in the soil sample before commencement of the corrosion analysis (Table 1), which in addition to the added acid content, aided the corrosion of the mild steel pipes. According to Usman *et al*. (2019), conductivity and temperature, can affect the deterioration of steel exposed to corrosive environment. Also, high moisture content in soil can accelerate the deterioration of buried pipes in such soils (Dang *et al*., 2015; Chen & Zhao, 2017; Putra *et al*., 2020).

The decrease in weight loss as the coating thickness of exudates on the mild was increased showed *Cola acuminata* exudates is a good corrosion inhibitor, and has the capacity to reduce the impact of corrosion on mild steel pipes exposed to corrosive media. In similar observation using rubber extract as corrosion inhibitor, reduction in weight loss of mild steel at high amount of inhibitor was attributed to larger number of molecules adsorbed on the surface (Okewale & Olaitan, 2017). Other corrosion studies using sulphuric acid solution (Ameh & Eddy, 2016) and sodium chloride solution (Fouda *et al*., 2017) as accelerated corrosion media, have also shown that weight loss of mild steel was reduced in the presence of plant extracted corrosion inhibitors.

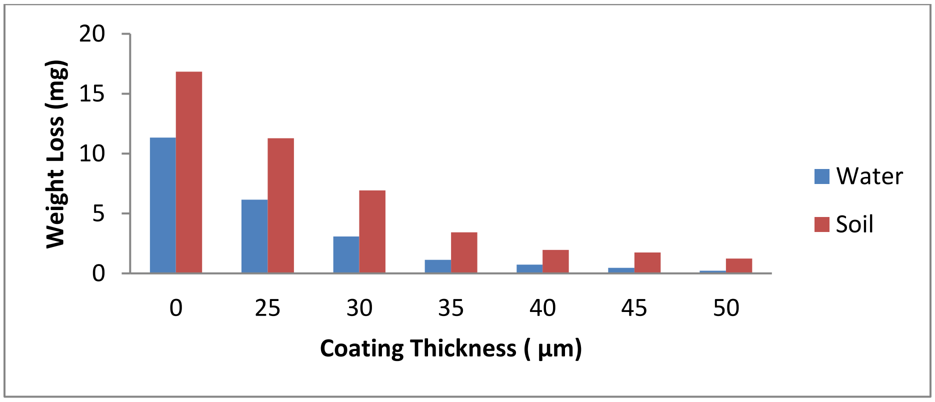

Figure 1: Weight loss of mild steel in acid concentrated water and soil media

3.2 Corrosion Rate

The effectiveness of *Cola acuminata* exudates as corrosion inhibitor was studied by analysis the corrosion rate of mild steel immersed in hydrochloric acid concentrated water and soil at different coating thickness. The results are shown in Table 3.

Table 3: Corrosion rate of mild steel in water and soil media

Thickness (µm)	**Corrosion Rate (mm/yr)**	
	Water media	Soil Media
0	0.2793	0.4150
25	0.15164	0.27789
30	0.07619	0.17112
35	0.02811	0.08433
40	0.01800	0.04808
45	0.01159	0.04315
50	0.00542	0.03082

The results of corrosion rate of mild steel immersed in acid concentrated water and soil at different coating thickness is shown in Table 3. The corrosion rate of mild steel decreased as coating thickness was increased. However, the rate of corrosion in uncoated sample was higher than the coated specimens. Thus, the corrosion rate recorded after 30 days (720 hours) of exposure is given as 0.2793mm/yr for uncoated specimen immersed in water and 0.4150mm/yr for uncoated specimen buried in soil. However, in the coated specimens immersed in water, the corrosion rate recorded after 30 days reduced to 0.1516mm/yr at coating thickness of 25µm and to 0.0054mm/yr at coating thickness of 50µm. Similarly, the corrosion rate recorded after 30 days for the coated specimens buried in soil reduced to 0.2779mm/yr at coating thickness of 25µm and 0.0308mm/yr at coating thickness of 50µm. Some studies have shown that uncoated mild steel immersed in different water media (Usman *et al*., 2019) or buried soil media (Dang *et al*., 2015; Chen & Zhao, 2017; Putra *et al*., 2020) experienced a high rate of corrosion. This justified the high rate of corrosion recorded in the uncoated specimens.

Comparatively, the rate of corrosion of mild steel was higher in specimens buried in soil than the specimens immersed in water. This may be connected to factors that increased the rate of corrosion, as indicated by the high conductivity recorded in the soil sample before the commencement of the corrosion analysis. It has been reported that temperature, high moisture content, pH and conductivity in soil can accelerate corrosion rate of steel buried in soil (Yahaya *et al*., 2011; Chen & Zhao, 2017; Putra *et al*., 2020).

The decrease in corrosion rate as the coating thickness was increased can be attributed to barrier created by exudates between the surface of the steel and the corrosion agents, which makes the penetration of corrosion accelerating agents difficult, thereby reducing any possible attack on the metal. Thus, the exudates, which bonded on the mild steel surface, acted as barrier against corrosion. It has been established in some studies that plant extracts (green inhibitors) has functional groups with ability to form protective films round metallic surface (Owate *et al*., 2014; Okewale & Olaitan, 2017), and the presence of these functional groups slow the corrosion rate, thereby protecting the mild steel from corrosion attack. In addition, the bonded molecules limit the diffusion or movement of ions on the metals surface, thereby preventing the metallic ions from anodic or cathodic reactions (redox reaction) that would have increased the corrosion rate (Prithiba *et al*., 2014; Okewale & Olaitan, 2017).

Statistical analysis (Table 4) on the significance between the corrosion rate of coated specimens immersed in water and coated specimens buried in soil showed that the there was no significant different ($P>0.05$) between specimens immersed in water and those buried in soil. This implied that, though, higher rate of corrosion was recorded in specimens buried in soil, corrosion also affected the specimens immersed in water at considerable rate. Therefore, mild steel should be protected from corrosion whether in water or soil environment.

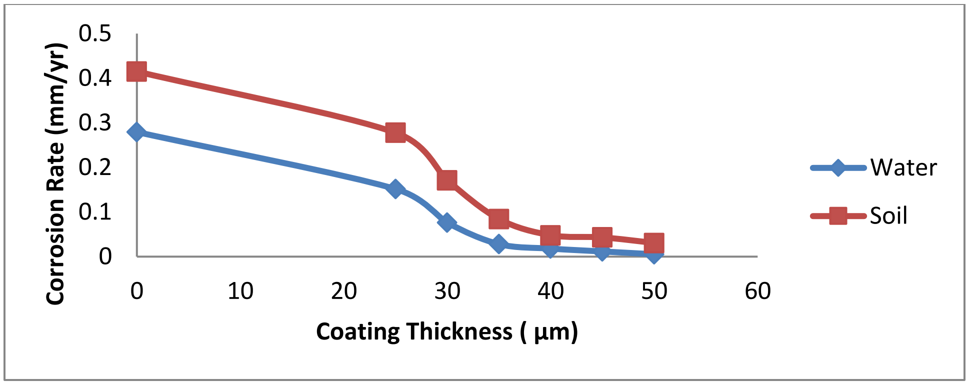

Figure 2: Corrosion rate of mild steel in acid concentrated water and soil media

The results in Table 4 show the statistical analysis comparing the corrosion rates between mild steel specimens immersed in acid concentrated water and specimens buried in acid concentrated soil. A t-test was conducted at 95% confidence interval to determine if there was a significant difference between the corrosion rates in the two media. The null hypothesis (H0) stated that there is no significant difference in corrosion rate between the water and soil media. The alternative hypothesis (Ha) stated that there is a significant difference. The level of significance (alpha) was set at 0.05.

The analysis showed a P-value of 0.3077, which is greater than the alpha value of 0.05. Therefore, the null hypothesis cannot be rejected. This indicates that there is no statistically significant difference in the corrosion rates of mild steel between the acid concentrated water and soil media based on the data.

Table 4: Statistical analysis of corrosion rate between water and soil media

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.01787	1	0.01787	1.13489	0.3077	4.74723
Within Groups	0.18892	12	0.01574			
Total	0.20679	13				

Although numerically the corrosion rate was higher in the soil medium compared to the water medium for the uncoated specimens, the t-test results show that this difference is not statistically significant at the 95% confidence level. The lack of statistically significant difference in corrosion rate can be attributed to the highly acidic nature of both media, owing to the addition of 0.5M HCl solution. The acidic pH creates an aggressive environment that accelerates corrosion in both water and soil (Roche & Bender, 2016; Yahaya et al., 2011).

Several studies have also shown that unprotected mild steel experiences high corrosion rates when immersed in acidic media or buried in acidic soils (Fouda et al., 2017; Ismail & El-Shamy, 2009; Pereira et al., 2015). Therefore, the statistical analysis validates that corrosion potential of unprotected mild steel is high in both acidic water and acidic soil media. Appropriate protection methods are necessary to mitigate steel corrosion whether exposed to acidic waters or buried in acidic soils.

3.3 Inhibition Efficiency

The results of inhibition efficiency of *Cola acuminata* exudates for mild steel immersed in acid concentrated water and soil at different coating thickness are shown in Table 5. The inhibition efficiency results in Table 5 and Figure 3 demonstrate the effectiveness of Cola acuminata exudates in mitigating mild steel corrosion in both the acidic water and acidic soil media. In the water medium, the inhibition efficiency ranged from 45.71% at the lowest exudate coating thickness of 25µm to as high as 98.06% at the highest coating thickness of 50µm. This shows a rapid increase in the corrosion protection provided by the exudates with greater coating thickness in the acidic water medium.

Table 5: Inhibition efficiency of *Cola acuminata* exudates in water and soil media

Thickness (µm)	**Inhibition Efficiency (%)**	
	Water media	Soil Media
25	45.71	33.11
30	72.72	58.76
35	89.94	79.68
40	93.56	88.41
45	95.85	89.60
50	98.06	92.57

Comparatively, the inhibition efficiency was lower in the acidic soil medium, ranging from 33.11% at 25µm coating thickness to 92.57% at 50µm thickness. The lower inhibition efficiency, especially at the thinner coatings, indicates that the corrosive nature of the acidic soil impacted the mild steel to a greater extent compared to the acidic water.

Multiple studies have also shown that unprotected mild steel experiences high corrosion rates when buried in acidic soils (Ismail & El-Shamy, 2009; Pereira et al., 2015; Putra et al., 2020). Factors like soil moisture, conductivity, chloride content and microbial activity influence buried steel corrosion (Koch et al., 2016; Yahaya et al., 2011). The addition of 0.5M HCl likely exacerbated the corrosive soil environment, making corrosion mitigation more difficult. However, the Cola acuminata exudates still provided good corrosion inhibition of up to 92.57% at the highest coating thickness of 50µm. The increasing inhibition with greater coating thickness is attributed to higher availability of inhibitor compounds to adsorb onto the steel surface and block active corrosion sites (Loto et al., 2013; Owate et al., 2014).

The exudate compounds contain heteroatoms such as oxygen, nitrogen and aromatic rings that facilitate adsorption on the steel surface (Fouda et al., 2017; Umoren & Eduok, 2016). The adsorbed molecules form a protective barrier that isolates the steel surface from the corrosive species present in the acidic water and soil media. Previous studies have also demonstrated improved corrosion inhibition for plant extracts and natural polymeric compounds with increasing concentration or availability (Banerjee et al., 2012; Verma et al., 2018). This validates the trends observed in this study.

Although the inhibition efficiency was lower in the acidic soil medium compared to acidic water, the Cola acuminata exudates still showed excellent potential to mitigate steel corrosion in both media. A minimum coating thickness of 35-40µm provided over 80% inhibition efficiency in the aggressive acidic soil environment. Therefore, the exudates show promise as an eco-friendly and sustainable corrosion inhibitor for steel structures exposed to acidic waters or buried in acidic soils.

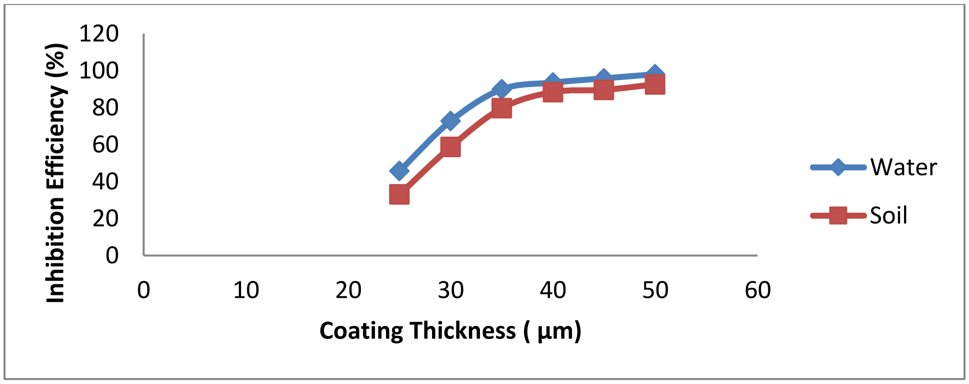

Figure 3: Inhibition Efficiency of *Cola acuminata* exudates in acid concentrated media

3.4 Contribution to the Body of Knowledge and to the Society

The study on the efficiency of Cola acuminata exudates as corrosion inhibitors contributes to the body of knowledge by exploring the potential of a natural substance as a corrosion inhibitor. By investigating the corrosion inhibition properties of Cola acuminata exudates, the study expands the understanding of eco-friendly corrosion inhibitors derived from natural sources. The optimization of cost implications to other process inhibitors is another significant contribution of this study. By evaluating the effectiveness of Cola acuminata exudates as corrosion inhibitors, the study provides valuable insights into the potential cost savings that can be achieved by utilizing natural substances as alternatives to synthetic inhibitors. This optimization can have implications for various industries and processes where corrosion protection is essential.

The study's findings and conclusions are supported by references to validate the research. The cited references include both theoretical and experimental studies on corrosion inhibition potentials, evaluations of corrosion in buried steel structures, the use of natural products as corrosion inhibitors, and the behavior of different materials in corrosive environments. These references enhance the credibility and robustness of the study's results and strengthen its contribution to the existing body of knowledge in the field of corrosion inhibition.

4. Conclusion

This study investigated the corrosion inhibition efficiency of Cola acuminata exudates on mild steel exposed to acidic concentrated water and soil environments. Experimental investigations were conducted to determine the weight loss, corrosion rate and inhibition efficiency of Cola acuminata exudates coatings on mild steel specimens immersed in 0.5M hydrochloric acid water and buried in 0.5M hydrochloric acid soil for 30 days.

The results showed that the corrosion of mild steel was accelerated under acidic conditions in both media, as evidenced by measurable weight loss and corrosion rates observed in uncoated specimens. The soil medium was found to be intrinsically more corrosive than water due to its higher conductivity, acidity, moisture content and salinity levels prior to acidification. This trend was reflected in the higher weight losses and corrosion rates recorded for uncoated mild steel buried in acidic soil compared to samples immersed in acidic water.

Coating the mild steel surfaces with Cola acuminata exudates provided significant corrosion protection in both aggressive media. At all coating thicknesses evaluated between 25-50 µm, the exudate coatings decreased the weight loss and corrosion rate of mild steel relative to the uncoated controls in both acidic water and soil. The protective performance improved consistently with increasing coating thickness. At the optimum thickness of 50 µm, corrosion rates as low as 0.0054 mm/yr in water and 0.0308 mm/yr in soil were achieved, representing over 98% and 92% inhibition efficiencies respectively.

This demonstrates the excellent corrosion inhibition capabilities of Cola acuminata exudates. The natural polymer coating is believed to act as a barrier limiting the diffusion of corrosive ions to the metal surface, while also adsorbing onto the surface to isolate it chemically. Even at lower thicknesses, over 33% inhibition was observed in soil, highlighting its effectiveness. While corrosion was consistently higher in acidic soil medium, statistical analysis revealed the rate differences compared to water were insignificant. This suggests mild steel requires effective protection in both corrosion-conducive environments.

In conclusion, the research successfully validated the potential application of Cola acuminata exudates as a green corrosion inhibitor for mild steel exposed to acidic water and buried soil conditions. With inhibition efficiencies exceeding 90% demonstrated, the natural product coating represents a sustainable alternative to toxic inhibitors for corrosion mitigation of steel infrastructure. Further studies optimizing formulation and long-term performance are warranted to translate these findings into practical corrosion control solutions.

5. Recommendation

Based on the studies presented, here are some overall recommendations that can be made:

- Cola acuminata exudates show promise as an effective and eco-friendly corrosion inhibitor for mild steel exposed to acidic media like acidic waters and soils. Experimental investigations demonstrate high inhibition efficiency up to 98% in acidic water and 92% in acidic soil at optimal coating thicknesses of 50µm.

- A minimum coating thickness of 35-40µm Cola acuminata exudates provides over 80% inhibition efficiency even in highly aggressive acidic soil environments. This indicates the exudates can significantly mitigate corrosion of mild steel pipes buried in acidic soils.
- The study reveals that unprotected mild steel experiences severe corrosion in both acidic water and acidic soil media. Therefore, appropriate corrosion protection methods like coating with Cola acuminata exudates are necessary for steel structures in contact with acidic waters or buried in acidic soils.
- Comparative analysis shows that corrosion rates are higher in acidic soil versus acidic water for unprotected steel. Factors like moisture, conductivity, salinity, microbial activity contribute to the greater corrosiveness of acidic soils. However, Cola acuminata coatings mitigate corrosion effectively in both media.
- The research highlights the need for optimization of coating parameters like thickness, uniformity of application, temperature and concentration to achieve maximum corrosion inhibition efficiency with Cola acuminata exudates.
- Further studies can explore synergistic mixtures of Cola acuminata exudates with other green inhibitors to enhance corrosion prevention. Electrochemical analysis and surface characterization of the steel before and after corrosion experiments can elucidate the inhibition mechanisms.
- Investigating the long-term stability and persistence of the protective Cola acuminata films on steel surfaces exposed to field conditions over months or years can further validate its industrial applicability.
- Overall, Cola acuminata shows excellent potential as an eco-friendly, low cost and highly available alternative to traditional corrosion inhibitors for mild steel structures in contact with acidic waters and soils. Its green credentials also make it suitable for sustainable corrosion mitigation approaches.

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