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Effect of Bitter Leaf Extract on Corrosion Resistance Properties of Welded Stainless-Steel Joints in Aquatic Medium

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Abstract: Stainless steels are widely used in engineering applications owing to their unique combination of mechanical strength, formability, and corrosion resistance (Roy & Mandal, 2020; Sheng, 2023). Their corrosion resistance derives primarily from the formation of a stable, self-repairing passive layer of chromium oxide (Cr_2O_3) on the surface (Sedriks, 1996; Revie, 2011), which protects the underlying metal from corrosive environments. However, this protective layer is not absolute; it is susceptible to localized breakdown in aggressive environments containing halide ions, particularly chlorides. When the passive film deteriorates, pitting corrosion and crevice corrosion often occur, leading to severe structural degradation, especially in marine and saline environments (Semin e*t al.*, 2025).

A critical challenge arises in welded joints, where the welding significantly compromises corrosion resistance. A welded joint typically contains three distinct microstructural zones: the fusion zone, where the base metal and filler material coalesce; the heat-affected zone, characterized by thermally induced metallurgical transformations; and the unaffected base metal. In the temperature range of approximately 425-850°C, chromium carbides ($Cr_{23}C_6$) precipitate along grain boundaries, depleting adjacent regions of chromium. This results in zones where the passive film can no longer be maintained, making those areas susceptible to intergranular corrosion, a process known as "sensitization". Unlike pitting or crevice corrosion, intergranular corrosion selectively attacks grain boundaries while leaving the grains themselves intact, thereby reducing grain cohesion and significantly undermining the mechanical integrity of welded structures. In chloride-rich environments, typical of marine and coastal regions, these sensitized grain boundaries become anodic compared to the surrounding metal, accelerating IGC and undermining structural integrity. (Raja & Shoji, 2011, Sedriks, 1996).

This vulnerability is particularly critical in-service conditions where welding is prevalent in marine and saline environments, such as those common in Nigeria's coastal regions and offshore installations, where chloride ions accelerate intergranular attack. In such conditions, welded stainless steel structures including pipelines, storage tanks, and marine platforms are prone to premature degradation, leading to high maintenance costs, structural failures, and safety risks. Considering the reliance of the oil and gas and construction industries on welded stainless-steel components, effective corrosion mitigation strategies are urgently required.

To mitigate corrosion, inhibitors are widely employed. Traditionally, inorganic inhibitors such as chromates, phosphates, and dichromates have been used to combat corrosion in steels because of their high efficiency. However, their severe toxicity, environmental, health risks, and carcinogenicity have led to restrictions on their application (Chigondo & Chigondo, 2016). This has shifted attention towards green corrosion inhibitors derived from plant extracts, which are biodegradable, eco-friendly, cost-effective, and readily available.

Plant extracts such as bitterleaf, and moringa, derived from renewable and biodegradable sources, are seen as possible sustainable alternatives, because;

i. they are rich in organic compounds such as alkaloids, flavonoids, tannins, saponins, and phenolic acids, which possess electron-donating groups capable of adsorbing onto metallic surfaces
ii. they form protective films that hinder electrochemical reactions (Umoren & Solomon, 2017; Singh, 2022).

According to Valdez-Salas *et al*. (2021) neem (Azadirachta indica), bitter leaf (Vernonia amygdalina), and moringa (Moringa oleifera) have demonstrated considerable potential as corrosion inhibitors in acidic and saline environments due to their abundance of bioactive phytochemicals. Although numerous studies have reported the effectiveness of plant extracts as corrosion inhibitors for mild steel and other alloys against general and pitting corrosion, there remains a paucity of research on their application to welded stainless steels particularly 304 and 316 austenitic grades when exposed to intergranular corrosion in marine environments.

Therefore, this study investigates the potential of bitter leaf extracts as eco-friendly inhibitors for mitigating intergranular corrosion in welded 304 and 316 stainless steels in marine environments.

2.0: Materials and Methods

2.1: Materials

The materials for this study are positive material identification spectrometer, metallurgical microscope, linear polarisation meter, desiccator, non-destructive tensile strength gauge, electric furnace, austenitic-304 steel and austenitic-316 steel, bitter leaf, blender, power hacksaw, vernier caliper, platinum crucible, hydrochloric acid, steel rule, welding machine and accessories, sea water, thermometer, distilled water, rotary vacuum evaporator, MH 1000 Rockwell type digital Micro Hardness testing machine, volumetric flask and Avery-Denison universal testing machine for tensile test.

2.2: Methods

2.2.1: Preparation of Specimen

To successfully carry out the cutting and preparation of test specimens, a number of basic tools and equipment were employed during the experimentation. These tools were selected to ensure accuracy, consistency, and safety throughout the sample preparation process.

The power saw was used to cut the stainless-steel plates into the required dimensions. Before cutting, the material was firmly clamped to prevent vibration or movement, ensuring straight and accurate cuts. The power saw enabled uniform sectioning of the samples, which is essential for achieving comparable results during subsequent welding, corrosion, and mechanical testing.

After cutting, each specimen was carefully measured using a vernier caliper. The vernier caliper is a precision measuring instrument designed for accurately determining external dimensions, internal diameters, and thicknesses of materials. This procedure ensured that all samples met the specified dimensional accuracies before further processing. A steel rule was also used for preliminary marking and alignment during cutting, serving as a quick reference tool for length measurements and straight-line marking, prior to the use of the power saw.

Welding operations were carried out using a DC MMA inverter welding machine (SMARTEC, Model ST-MMA200). The machine was set to the appropriate current and voltage based on the thickness and type of stainless steel being welded. Welding accessories such as electrodes, electrode holders, and protective equipment were properly prepared before commencement. The welding process was performed carefully to achieve consistent weld joints suitable for subsequent sensitization, corrosion testing, and mechanical evaluation.

2.2.2: Sea Water

Sea water was obtained from Abuloma Jetty area in Port Harcourt Local Government Area of Rivers State. It was used as the corrosive medium. It has a pH value of 8.1. The pH was determined in the laboratory using a calibrated digital pH meter, following APHA Standard Methods (2017). The meter was standardized with buffer solutions of pH 4.0, 7.0, and 10.0 prior to measurement. The seawater sample was brought to ambient temperature before analysis to minimize temperature-induced deviations. Given that coastal waters at Abuloma Jetty are influenced by tidal mixing, freshwater intrusion, and anthropogenic discharges, site-specific pH determination was essential to ensure that laboratory simulations and corrosion tests reflected in-situ field conditions, (Dickson *et al., 2007;* APHA, 2017).

2.2.3: Natural Inhibitors

Although, several natural inhibitors are available, bitter leaf was used in this study. The choice of bitter leaf extracts is premise on quercetin compounds they contain, which belong to the group of flavonoids. Flavonoids are naturally occurring substances known for their strong antioxidant, metal-chelating, and adsorption capabilities, which enable them to form protective films on metal surfaces and inhibit corrosion processes. The extracts also have functioned as antibacterial and antifungal substances. With these properties, these leaves are very promising resources to be used as natural inhibitors. The leaves are available in Port Harcourt, Rivers State.

2.3: Experimental Design

The research method employed in this study stems from design of experiments through sample preparations, Microstructural tests, welding operations, sensitization, corrosion tests, and test of mechanical properties.

2.3.1: Microstructural Examinations and Specimen Sensitization

Microstructural examination was carried out to understand the internal features of the materials and how these features influence their behaviour under corrosion and mechanical loading. Prior to microscopic analysis, the specimens were carefully prepared to obtain clean and representative surfaces suitable for observation. The prepared samples were then examined using a scanning electron microscope, which allows for high-resolution imaging and magnification of surface and near-surface features.

2.3.2: Corrosion Test

Several methods could be used, but in this study electrochemical polarization approach using linear polarization was adopted. The choice of this method emanates from the fact that corrosion rate will be obtained relatively fast (Alawadhl, 2009). During the process, the welded specimens was cleaned and given proper identity label.

2.3.3: Determination of Rate of Corrosion

The rate of corrosion was computed using the Equation (3.2) (Tuaweri *et al.,* 2015)

$$C_R = K \times W \times (A \times T \times D)^{-1} \quad (2.1)$$

where C_R is the rate of corrosion in mm/yr, K is a constant 8.7 $\times 10^4$, W is the mass loss(g), A represents area of the workpiece (cm^2), T stands for the time of exposure of workpiece in hours and D the density of austenitic stainless steel (g/cm^2) (Rahayuningsih *et al.*, 2019)

The concentration of the leaf extract and percentage of reduction due to corrosion was obtained using Equations (3.3 and 3.4) respectively (Tuaweri *et al.,* 2015)

$$\text{Concentration (g/Ml)} = \frac{Mass\ of_{\ leave\ extract}}{\text{Volume}_{\ \text{gravmetric}}} \qquad (2.2)$$

$$\text{The percentage of reduction (\%)} = \left|\frac{\acute{A} - A}{A}\right| \times 100 \qquad (2.3)$$

where Á represents the mechanical property of the as-received sample and A mechanical property of sample after corrosion.

3.0: Results and Discussions

The approach in obtaining started with determining the composition of each steel sample, after which the corrosion rates were determined.

3.1 Compositional Analysis of the Steel Samples and Leaf Extracts

3.1.1 Analysis of Steel Samples

The x-ray diffraction (XRD) analysis of the non-sensitized SS 304 and SS 316 samples are presented in Figures 3.1 and 3.2; composition is also shown in Table I. Both Figures 3.1 and 3.2 show predominant iron peaks, indicating huge iron content in austenitic stainless steels. The distinguishing elements between the two samples are molybdenum, titanium and arsenic. These elements are predominantly found in SS 316.

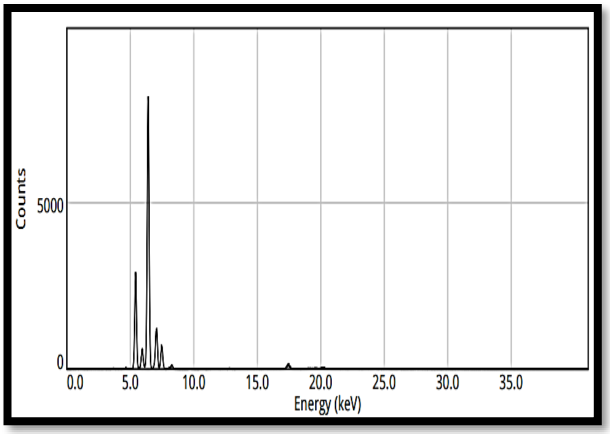
Table 1: Compositional Analysis of Samples

Table 1A: Chemical Composition of as Received Samples

	Element	Fe	Cr	Ni	Mn	Mo	Co	Cu	Ti	As
SS 304	**Weight %**	70.78	18.59	8.93	1.05	0.36	0.19	0.11	-	-
SS 316	**Weight %**	67.83	15.25	12.07	1.18	2.08	0.36	0.12	0.15	0.97

Table 1B: Chemical Composition of Corrosion Inhibitors

	Element	**Zn**	**Na**	**Mg**	**P**	**Ca**	**Fe**	**K**
Bitter Leaves	**Quantity (ppm)**	0.37	20.30	4.09	20.21	30.28	0.53	17.80



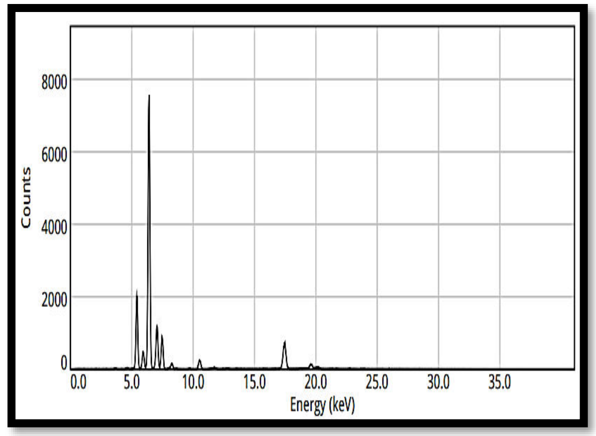


Figure 3.1: XRD Analysis of SS 304 Sample

Figure 3.2: XRD Analysis of SS 316 Sample

3.2: Corrosion Rate of SS 316 and SS 304 with Inhibitors

3.2.1: Corrosion Rate of SS 316 Samples

The experimental corrosion rate as a function of immersion period for the sensitized SS 316 using inhibitors are given in Figures 3.1 to 3.2.

Table 2A: LPR Corrosion Rate Measurement for Non-Sensitized Samples

Immersion Time(min)	***Corrosion rate(mpy) of SS 304 with Bitter Leave inhibitor***	
	oml inhibitor B_3	***2ml inhibitor B_4***
5	*1.98*	*1.84*
10	*2.11*	*1.97*
15	*2.21*	*1.82*
20	*2.41*	*2.17*
25	*2.50*	*2.15*
30	*2.69*	*2.12*
Average Corrosion rate	***2.32***	***2.01***

Table 2B: LPR Corrosion Rate Measurement for Non-Sensitized Samples

Immersion Time(min)	***Corrosion rate(mpy) of SS 316 with Bitter Leave inhibitor***	
	oml inhibitor A_3	***2ml inhibitor A_4***
5	*2.92*	*1.96*

10	*2.23*	*2.03*
15	*1.45*	*2.56*
20	*1.60*	*1.27*
25	*1.96*	*1.47*
30	*2.01*	*1.55*
Average Corrosion rate	***2.03***	***1.81***

Table 3A: LPR Corrosion Rate for Sensitized Samples

Immersion Time(min)	***Corrosion rate(mpy) of Sensitized SS 316 with Bitter Leave inhibitor***				
	0ml C6 inhibitor	***1ml C7 inhibitor***	***2ml C8 inhibitor***	***3ml C9 inhibitor***	***4ml C10 inhibitor***
5	*1.16*	*1.48*	*1.43*	*1.45*	*1.40*
10	*1.48*	*1.45*	*1.43*	*1.43*	*1.37*
15	*1.49*	*1.43*	*1.34*	*1.41*	*1.39*
20	*1.45*	*1.46*	*1.53*	*1.56*	*1.46*
25	*1.68*	*1.56*	*1.59*	*1.50*	*1.55*
30	*1.59*	*1.57*	*1.49*	*1.62*	*1.50*
Average Corrosion rate	***1.48***	***1.49***	***1.47***	***1.50***	***1.45***

Immersion Time(min)	***Corrosion rate(mpy) of Sensitized SS 304 with Bitter Leave inhibitor***				
	0ml D6 inhibitor	***1ml D7 inhibitor***	***2ml D8 inhibitor***	***3ml D9 inhibitor***	***4ml D10 inhibitor***
5	*2.03*	*2.01*	*1.73*	*1.98*	*1.96*
10	*2.05*	*2.06*	*1.87*	*1.86*	*1.88*
15	*2.40*	*1.99*	*1.96*	*1.94*	*1.54*
20	*2.07*	*2.13*	*1.98*	*2.05*	*1.96*
25	*2.18*	*2.17*	*2.03*	*1.97*	*2.02*
30	*2.09*	*1.98*	*2.10*	*1.81*	*2.27*
Average Corrosion rate	***2.14***	***2.06***	***1.95***	***1.94***	***1.94***

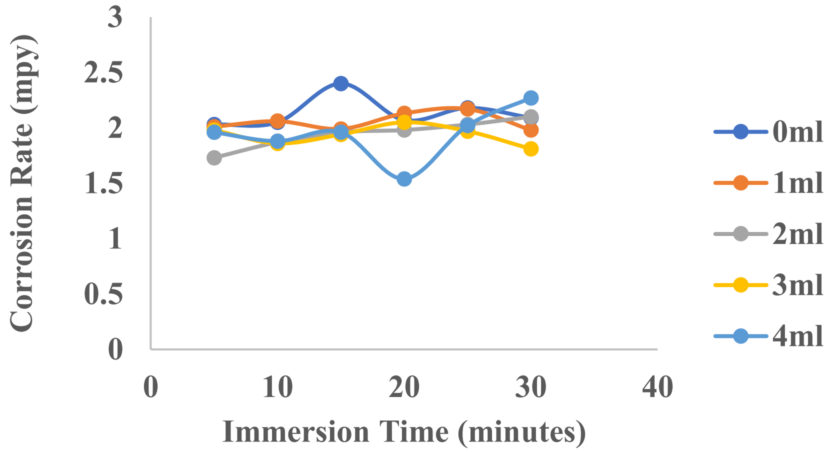


Fig. 3.2: Corrosion Rate of Sensitized SS 316 with Bitter Leaves Inhibitor

It was observed that corrosion rate decreased with increase in immersion period and increase in inhibitor concentration. This observation could be attributed to the formation of protective film formed by the inhibitor during the immersion period which covers the surface of the substrates. However, after 20 minutes of substate immersion, the corrosion rate of the substrate was increased significantly, which may be due to oxidation of the surface film. The phenomenon of gradually decreasing corrosion rate indicates the possible passivation of the substrate surface. Visual inspection of the specimens after the tests revealed the presence of a black film covering the surface which might have retarded the corrosion.

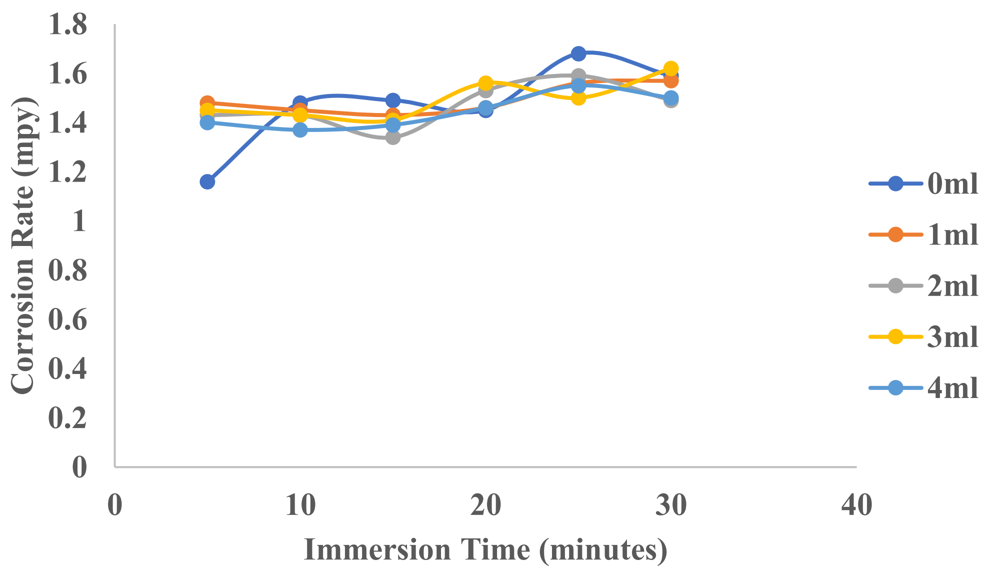


Fig. 3.3: Corrosion Rate of Sensitized SS 304 with Bitter Leaf Inhibitor

In contrast, an increase in corrosion rate of SS 304 with increasing immersion time and decreasing inhibitor concentration was observed following similar method when compared to the SS 316 as indicated in Figures 3.2. This was attributed to exposure of the sample in acid chloride solution which evoked pitting corrosion of all sensitized samples.
From tables 2A, 2B, 3A and 3B, it is observed that average corrosion rate is higher with non-sensitized steel than sensitized ones, the average corrosion rates SS 304 at 0ml is 2.32 and at 2ml is 2.01 whilst the sensitized values at 0ml is 2.14, 1ml is 2.06, 2ml is 1.95, 3ml is 1.94 and 4ml is 1.94. For SS 316, the non-sensitized values are 0ml = 2.01 and 2ml = 1.81, whilst sensitized values are 0ml = 1.48, 1ml = 1.49, 2ml = 1.47, 3ml = 1.50 and 4ml = 1.45.

4.0: Conclusion

From the results, it was clear that sensitization drastically increased the vulnerability of SS 304. Without any inhibitor, the tensile strength dropped by as much as 47%. However, when higher concentrations of the extracts (particularly 3–4 ml) were introduced, the steel showed remarkable recovery. Neem and bitter leaf produced the strongest improvements, reducing the loss to about 10.5% and 12.4% respectively, while moringa (14.6%), also offered good protection, though slightly less at the lower concentrations. For SS 316, the effect of sensitization was less severe, with tensile strength reducing by about 20% in the untreated condition. The inhibitors provided only modest improvement, which is expected given SS 316's naturally higher resistance to corrosion.

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