

Effects of *Bryophyllum pinnatum* Green Inhibitor on the corrosion of Marine Boilers in two mediums (Seawater and freshwater)

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ABSTRACT

In this study the effect of *Bryophyllum pinnatum* as a green inhibitor in the prevention of corrosion in marine boilers was studied. Four (4) Mild steel coupons and four (4) copper coupons was immersed in 200ml of freshwater and 200ml of sea water and extracts of 20ml of *Bryophyllum pinnatum* leaf was added to each media. The inhibitor exhibited some inhibitory properties with the addition of 20 ml extract. It was observed that the inhibitor took effect from after the first week of exposure to the corrosive media. After 1,176 hours of immersion, the green inhibitor was observed to be effective only in fresh water for both the Cu coupon and Mild Steel coupon reducing the corrosion rate for Cu from 0.0311 mm/yr to 0.0084 mm/yr and for mild steel from 0.0716 to 0.0362 mm/yr. Conversely, the corrosion rates in seawater increased with the addition of the green inhibitor from 0.0476 mm/yr to 0.0550 mm/yr for Cu and from 0.0816 to 0.0830 mm/yr for mild steel. It could therefore be concluded that the green inhibitor is only effective in fresh water.

Keywords: Corrosion; Boilers; Inhibitor; *Bryophyllum pinnatum*; Marine; Steel; Copper; Weight loss; Seawater; Freshwater; Exposure.

1.0. Introduction

The marine steam boiler is an important component of energy conversion in power plants (Feng et al. 2022). They are closed vessels that are typically used for the production of steam from water by the combustion of fuel (Ohijeagbon et al. 2013, Zhang et al. 2021, Adumene and Nitonye, 2018). Boilers are extensively used for steam generation in ships, electricity production and different other utilities (Nemitallah et al. 2023; Guan 2022), like fuel tank heating, separation cleaning, main engine jacket water heating and cargo pump operation (Ceylan and Celik, 2024). Boilers could be classified as biomass fired boilers, coal fired boilers and oil-fired boilers depending on their source (Nemitallah et al. 2023). The day to day running of a ship could be hindered when the production of hot steam is in short supply due to operational issues (Narto et al. 2023). The water in the marine boiler passes through three stages of preheating, evaporation and overheating (Feng et al. 2022).

Corrosion, an important and costly problem that scientist and engineers must find solutions to in order to avoid the collapse of structures and plants (Malaret, 2022), is defined as the process of the deterioration of a material due to its reaction with its environment, largely relating to the oxidation of metals through electrochemical process (Yang, 2008). Zaki (2006) described corrosion as a process of material decay by means of biological and chemical changes which is costly but could be prevented or controlled. Corrosion is a rampant phenomenon in marine environment. The world loses about \$2.2 trillion US, or 3% of global GDP to corrosion which could be avoidable and significantly reduced by the application of appropriate corrosion control methods (Zehra et al. 2022).

The marine boiler experiences oxidation and harsh thermal-mechanical fatigue on one hand and the quality of water on the other with corrosive gases on the fireside which causes damage to the boiler (Dev Choudhury et al. 2022). Further damages to the marine steam boiler may be caused by other factors such as uniform corrosion, pitting

corrosion, mechanical damage and electrochemical corrosion (Behrendt and Gawdzińska, 2016). Wheeldon and Shingledecker (2013) reported that one of the most advanced austenitic stainless steels at the time (SS 316) used in the manufacture of pipe sections suffered from fatigue cracking, which resulted in steam conditions reducing. They further reported that austenitic and ferritic stainless steels was used in the manufacture of supercritical marine boilers but operated below 590 °C.

1.1. Study Objectives

The objectives of this study are as follows:

- 1) Evaluation of corrosion on mild steel and copper in both freshwater and seawater media using the weight loss method.
- 2) Experimental analysis of the inhibition potentials of *Bryophyllum pinnatum* (never die leaf) on samples of mild steel and copper in both freshwater and seawater media.
- 3) Develop a model/mechanism of corrosion inhibition using the *Bryophyllum pinnatum* leaf extract from generated parameters.

2.0. Literature Review

2.1. Corrosion Inhibitors

Corrosion inhibitors are materials used in the prevention and reduction of metal surface corrosion in environments that are corrosive (Al-Amiery, 2023). De Damborenea (2014) described corrosion inhibitors as chemical substances when introduced in small amounts to the environment in which would corrode, would slow down, reduce or prevent the corrosion of metals. In a similar vein Shang and Zhu (2021) described corrosion inhibitors as chemical substances or a blend of substances when present in its proper forms and concentration in the environment, reduces or prevents corrosion. Corrosion inhibitors are divided into two, inorganic and organic based on their chemical composition (Shang and Zhu, 2021). Corrosion inhibitors should meet certain conditions in order to be used in industries (Shang and Zhu, 2021).

- It should provide protection that ensures the operation of downhole equipment, field pipelines, and other facilities in the presence of existing corrosion-hazard factors;
- The use of corrosion inhibitors need not have an adverse effect on the technical process of production, transportation, field operation, processing and storage of hydrocarbon and gas;
- Corrosion inhibitors need to be thermally stable at operating temperatures;
- The best corrosion inhibitors are those that are soluble in H₂O, while leaving a layer of corrosion inhibitor on the metal surface;
- Reduced quantity level of the inhibitor to provide anti-corrosion protection;
- The capacity to inhibit numerous corrosion types (Finšgar and Jackson, 2014), such as localized corrosion (Jiang et al., 2006), general corrosion (Papavinasam et al., 2003), bacteria corrosion (Polutrenko, 2018), crevice corrosion (Li et al., 2017), etc.

- The capacity to retain its corrosion inhibition efficacy in different climate zones, especially in deep sea environment (Shawabkeh et al., 2013), and polar environment (Panin et al., 2017).

2.2. *Bryophyllum pinnatum* (Never die leaf)

Bryophyllum pinnatum (*B. pinnatum*) is a perennial succulent plant (Zurfluh et al. 2025) that thrives in hot and wet regions, with leaves 10-20 cm long and decussate (Selyakumar, 2022), a fleshy shrub about 60-120 cm high and branched from the base (Igwe and Akunyili, 2005). *B. pinnatum* is a known medicinal plant that has been used in a good number of traditional system of medicines (Elufioye et al. 2022). Several researchers have studied the use of *B. pinnatum* in the treatment of humans such as preterm labour (Zurfluh et al. 2025), wound healing (Singh et al. 2024), inhibition of procrine detrusor contractility (Fürer et al. 2015), internal and external treatment of inflammation (Chibli et al. 2014). Ojewole (2005) studied the antinociceptive, anti-inflammatory and antidiabetic effects of *B. pinnatum*. Tatsimo (2012) determined the antimicrobial and the antioxidant properties of *B. pinnatum*.

While *B. pinnatum* has been proven to be a good medicinal plant, this study would help to determine if its extracts could be used as corrosion inhibitor. *B. pinnatum* was used as a green inhibitor in a few researches as detailed. Olawale et al. (2024) investigated the optimization and performance evaluation of *B. pinnatum* leaves extract for mild steel corrosion inhibition. Oyewole et al. (2024) in their research investigated the performance evaluation and optimization of *B. pinnatum*. Kolo et al. (2018) investigated the absorption and inhibitive properties of *B. pinnatum* leaves in ethanol extract using weight loss method. This paper presents a methodology and results of combating corrosion in marine boilers using *B. pinnatum* (Never Die Leaf) green inhibitor shown in Figure 1 in fresh water and sea water as mediums.



Figure 1. *Bryophyllum pinnatum* plant (SOURCE: Authors)

3.0. Materials and Methods

The study for the evaluation of *Bryophyllum pinnatum* (Never Die Leaf) green inhibitor as a corrosion inhibitor for marine steam boilers, the research made use of mild steel and copper in fresh water and sea water. The choice of copper and mild steel was because both metals are majorly used in the manufacture of boilers. According to Lazić et

al. (2016) and Wheeldon and Shingledecker, (2013) most boiler components are manufactured from alloyed steel and copper.

The fresh water with a pH of 7.06 was obtained from River Nun at the Wiberforce Island axis of Bayelsa State while the sea water with a pH of 6.87 was obtained from the Brass River, Brass Local Government Area of Bayelsa State. Several techniques were used to determine the behaviour of the green inhibitor on copper and mild steel in sea water and fresh water for a period of forty-nine (49) days. The weight loss on both metals at various concentrations of the inhibitor was determined. The weight loss analysis is the longest established technique for the measurement of corrosion in plants and equipment (El Ibrahim and Berdimurodov, 2023; Malaret, 2022).

Eight test specimens consisting of four (4) mild steel and four (4) copper coupons were purchased from Chidotex Global Company Port Harcourt, Rivers State, Nigeria. Seawater and freshwater, beakers, sand paper (rough and smooth), inhibitor (*B. pinnatum* leaf extract), jerry can, methylated spirit, distilled water, electronic digital scale, thread, measuring cylinder, acetone, and syringe.

The characterisation of the *B. pinnatum* leaf extract relied on Dauda and Garba (2017) whose work showed “the moisture content and the ash content of *B. pinnatum* leaf were found to be $83.91\% \pm 0.21$ and $13.30\% \pm 0.41$. The leave of the plant was found to contain Na, Ca, K, Mn, Mg, Fe, Cu, Cr and Zn. The level of these minerals in mg/100g sample were found to be $0.13\% \pm 0.3$, $599.97\% \pm 24.54$; $5.51\% \pm 0.08$; $4.71\% \pm 0.27$; $247.11\% \pm 33.11$; $6.62\% \pm 1.72$; $82.96\% \pm 6.96$; $60. \% \pm 8.01$ and $0.10\% \pm 0.01$ respectively. The elemental analysis using sodium fusion test shows that the leave contains nitrogen, chlorine, and bromine”.

3.1. XFT 7500 Analysis

The test coupons were subjected to positive material identification using the X-MET 7500 Positive material identification spectrometer as shown in Figure 2 with results shown in Figure 3



Figure 2. X-MET 7500 Positive Material Identification spectrometer (With the approval of Turret Engineering, where most of the experiments were undertaken).

1000g of *Bryophyllum pinnatum* was plucked, weighed and crushed. 500cl of distilled water was added to the crushed leaf, the mixture was put in a filter cloth and squeezed with hand to filter out the active ingredients. 50cl concentration of the extract was taken for the purpose of the experiment.

In preparation of the specimens all cut edges were ground out to prevent them from becoming sites for preferential attack. Abrasive paper with grit was used as finishing for the surface of the specimens with all rinsed with distilled

water. The specimens were further degreased with acetone and air dried. Upon drying, all specimens were weighed to obtain their initial weights.

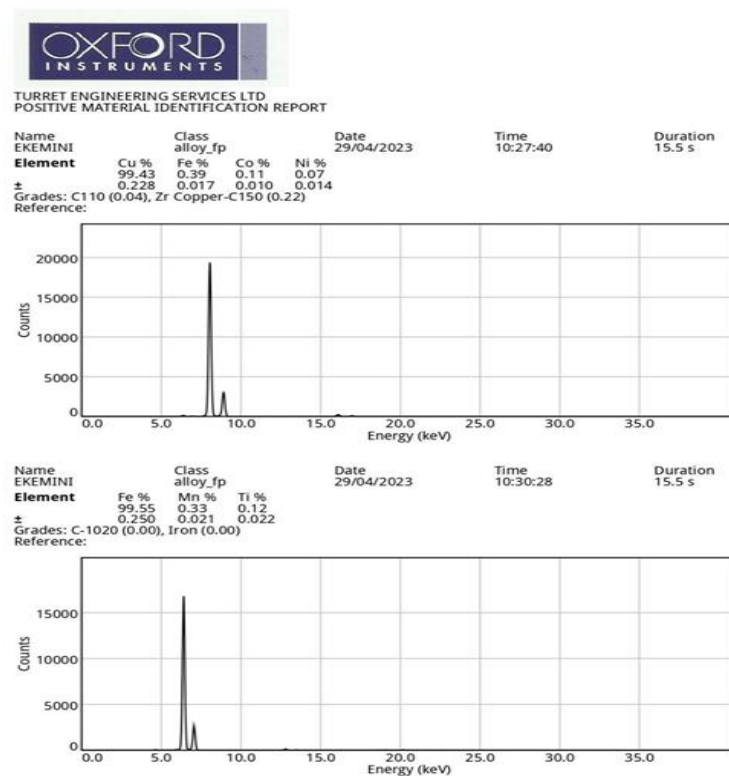


Figure 3. Positive material identification results for mild steel and copper specimens.

The specimens of mild steel and copper samples were immersed in different beakers containing 200ml of fresh water and sea water with no inhibitor present in both mediums, which were the control solutions. From the prepared *Bryophyllum pinnatum* (never die leaf) green inhibitor extract 20ml was measured using a syringe and added to each of the freshwater and seawater corrosive media containing both mild steel and copper coupons looped with threads tied to wooden stick hanging over each beaker. All eight (8) coupons were completely immersed in the test medias.

At the end of 168 hours (7 days) of immersion, all coupons were brought out of both medias, cleaned weighed and reintroduced into both media again. This process was repeated three times more but at an interval of two weeks (336 hours).

3.2. Determination of Corrosion Rate

The corrosion rate was determined in consonance with the requirements of ASTM D2688 and to ascertain the corrosion rate (CR) by the weight-loss method also known as immersion tests method, the calculated surface area and mass loss of the study specimen were determined by the difference in weight before and after immersion in the corrosive media for a specified period of time.

The formula applied in this study was adopted from Malaret, 2022 and it is detailed below in equation 1:

$$CR = \frac{k.m_{loss}}{A.t.\rho} \quad (1)$$

Where k is a constant 8.76×10^4 , m_{loss} is the mass loss of the metal (g) ($m_o - m_f$) in time t (hours), A is the surface area of the exposed specimen [cm^2], and ρ is the density of the test specimen [g/cm^3].

Density, (ρ) for mild steel = $7.87\text{g}/\text{cm}^3$ and ρ for copper = $8.96\text{g}/\text{cm}^3$

4.0. Results and Discussion

4.1. Results

Results obtained from the entire process for both mild steel and copper samples are detailed below from Tables 1 to 9 and Figures 4 to 10.

Table 1. Weight loss (g) and corrosion rate (mm/year) of mild steel sample with zero inhibitor in freshwater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	26.999	26.817	0.182	0.2158
MS3	504	26.999	26.812	0.187	0.0739
MS5	840	26.999	26.659	0.340	0.0806
MS7	1176	26.999	26.576	0.423	0.0716

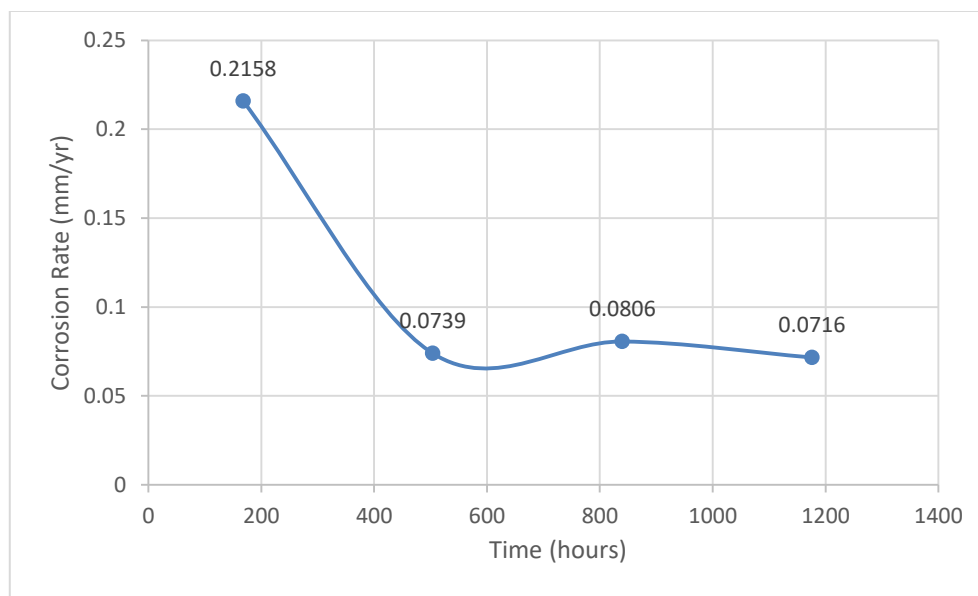


Figure 4. Corrosion rate (mm/year) against time for mild steel sample with zero inhibitor in freshwater

Table 2. Weight loss and corrosion rate of mild steel sample with 20ml inhibitor in freshwater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	31.921	31.792	0.129	0.1529
MS3	504	31.921	31.777	0.144	0.0569
MS5	840	31.921	31.805	0.116	0.0275
MS7	1176	31.921	31.707	0.214	0.0362

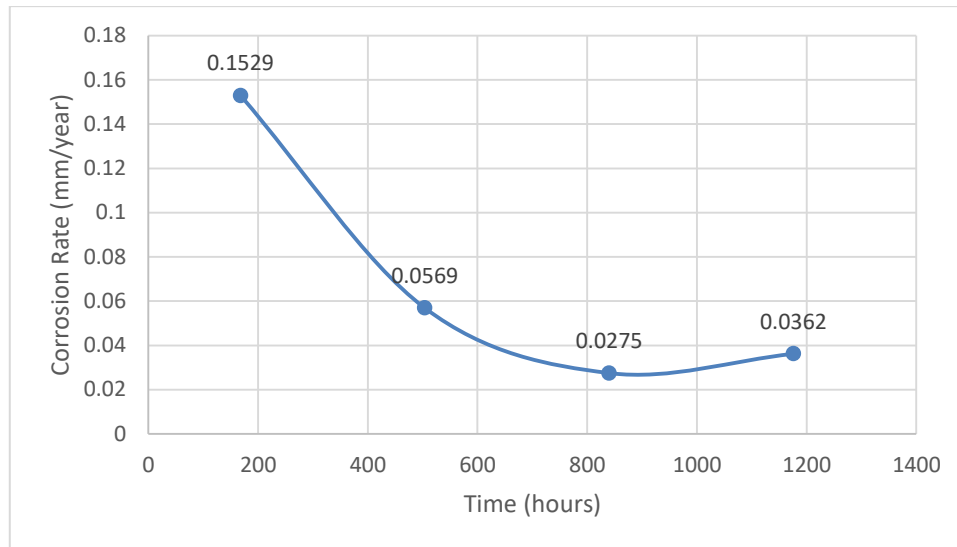


Figure 5. Corrosion rate (mm/year) against time for mild steel sample with 20 ml inhibitor in freshwater

Table 3. Weight loss and corrosion rate of mild steel sample with zero inhibitor in seawater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	19.878	19.592	0.286	0.3390
MS3	504	19.878	19.501	0.377	0.1490
MS5	840	19.878	19.460	0.418	0.0991
MS7	1176	19.878	19.396	0.482	0.0816

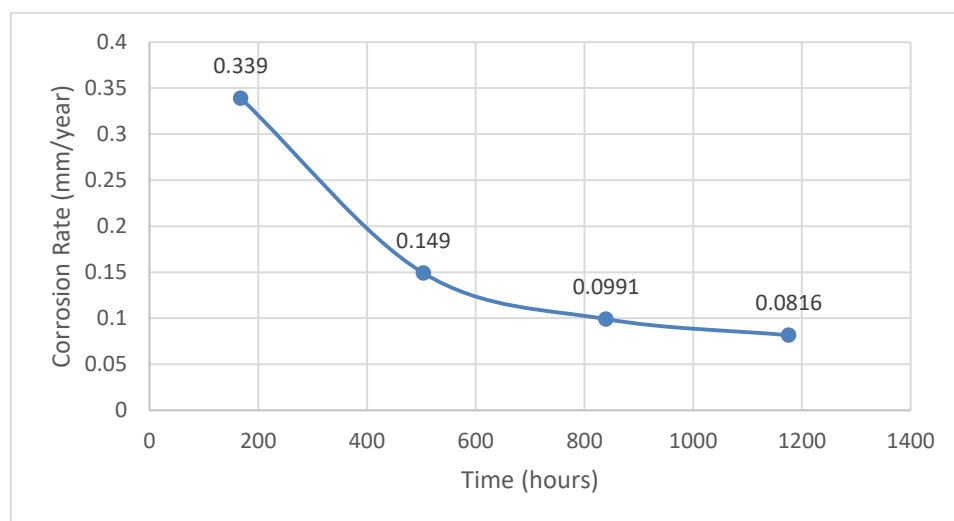


Figure 6. Corrosion rate (mm/year) against time for mild steel with zero inhibitor in seawater

Table 4. Weight loss and corrosion rate of mild steel sample with 20 ml inhibitor in seawater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	31.336	30.885	0.451	0.5347
MS3	504	31.336	30.998	0.333	0.1316
MS5	840	31.336	30.917	0.419	0.0993
MS7	1176	31.336	30.846	0.490	0.0830

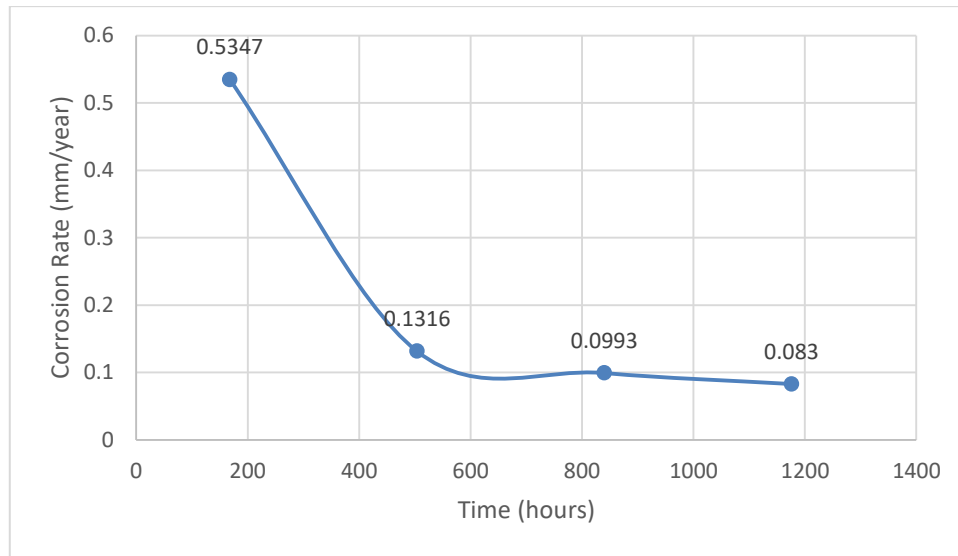


Figure 7. Corrosion rate (mm/year) against time (hours) for mild steel in 20ml inhibitor in seawater

Table 5. Weight loss and corrosion rate of copper sample with zero inhibitor in freshwater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	18.765	18.398	0.367	0.3873
MS3	504	18.765	18.694	0.071	0.0250
MS5	840	18.765	18.569	0.196	0.0414
MS7	1176	18.765	18.559	0.206	0.0311

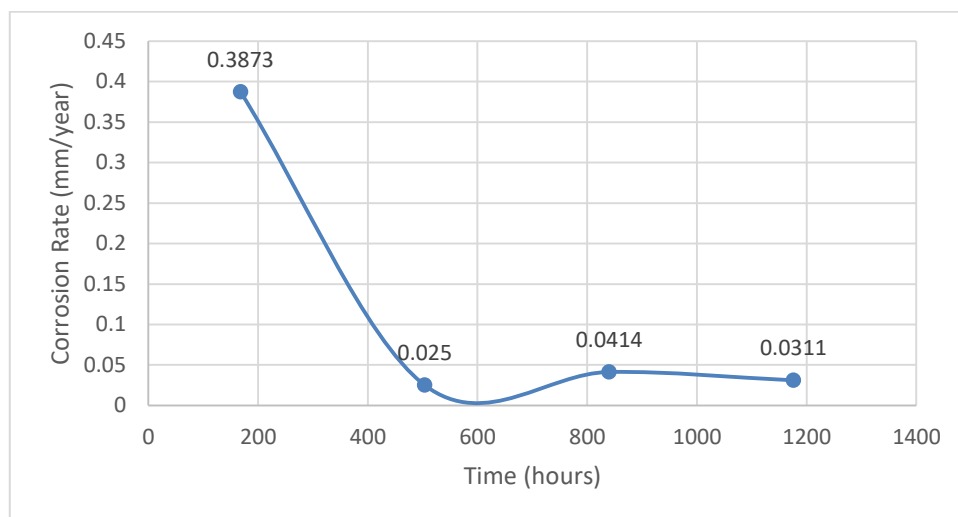


Figure 8. Corrosion rate (mm/year) against time (hours) for copper sample with zero inhibitor in freshwater

Table 6. Weight loss and corrosion rate of copper sample with 20ml inhibitor in freshwater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	26.537	26.525	0.012	0.0127
MS3	504	26.537	26.489	0.048	0.0169
MS5	840	26.537	26.487	0.050	0.0106
MS7	1176	26.537	26.481	0.056	0.0084

Table 7. Weight loss and corrosion rate of copper sample with zero inhibitor in seawater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	21.834	21.658	0.176	0.1858
MS3	504	21.834	21.618	0.216	0.0760
MS5	840	21.834	21.532	0.302	0.0637
MS7	1176	21.834	21.518	0.316	0.0476

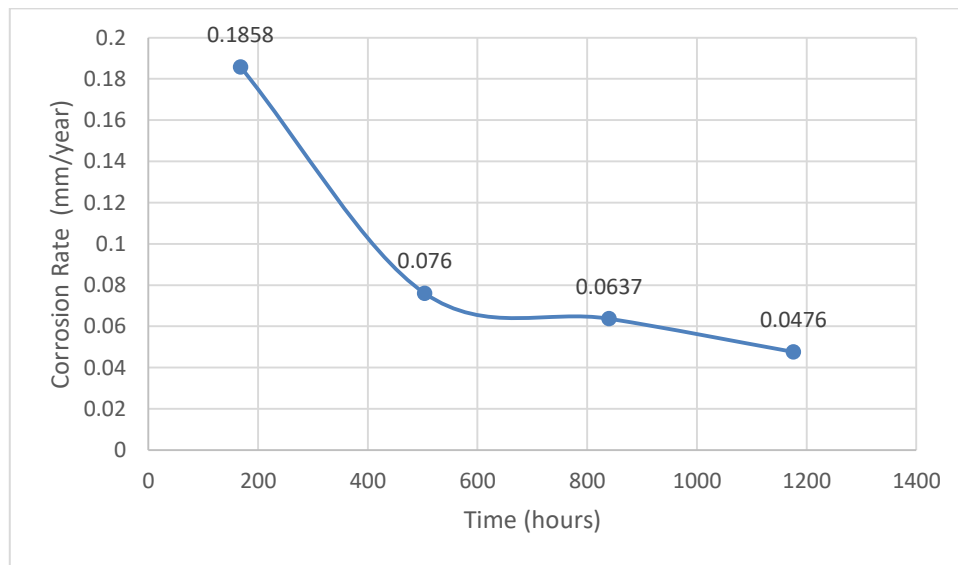


Figure 9. Corrosion rate (mm/year) against time (hours) for copper sample with zero inhibitor in seawater

Table 8. Weight loss and corrosion rate of copper sample with 20 ml inhibitor in seawater

Code	Time (Hour)	Initial Weight (g)	Final Weight (g)	Weight loss (g)	Corrosion Rate (mm/yr)
MS1	168	26.635	26.283	0.352	0.3715
MS3	504	26.635	26.281	0.354	0.1245
MS5	840	26.635	26.276	0.359	0.0758
MS7	1176	26.635	26.270	0.365	0.0550

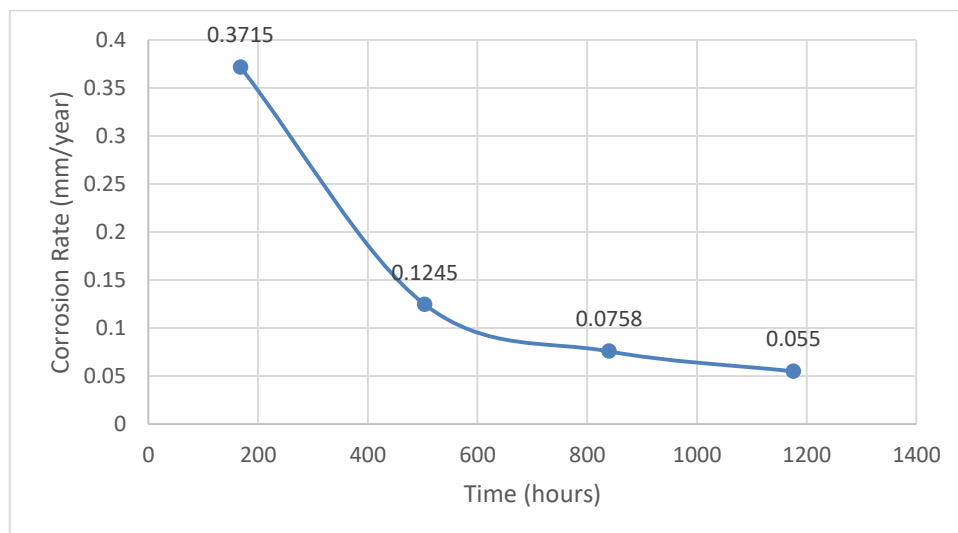


Figure 10. Corrosion rate (mm/year) against time (hours) for copper sample with 20ml inhibitor in seawater

Table 9. Corrosion rate after 1,176 hours of immersion in Seawater and fresh water

Coupons	Cu sea water with no inhibitor	Cu sea water with 20 ml inhibitor	Cu fresh water with no inhibitor	Cu fresh water with 20 ml inhibitor	Mild steel sea water with no inhibitor	Mild steel sea water with 20 ml inhibitor	Mild steel fresh water with no inhibitor	Mild steel fresh water with 20 ml inhibitor
Corrosion rate (mm/yr)	0.0476	0.0550	0.0311	0.0084	0.0816	0.0830	0.0716	0.0362

Surface scan of the copper and mild steel specimens was conducted before and after immersion in both media, as illustrated in Figures 11 through 16. These scans are critical because the microstructure of metals can undergo significant changes during high-temperature processing due to phase transformation or external factors, such as applied stress and electromagnetic fields (Chen, 2007). Analysis was performed using an Inverted Metallurgical Microscope (IMM). The resultant micrographs, which compare the specimens' surface morphology before and after exposure to the corrosive environments, are presented below.



Figure 11. Micrographs of C-1020 mild steel specimen before exposure

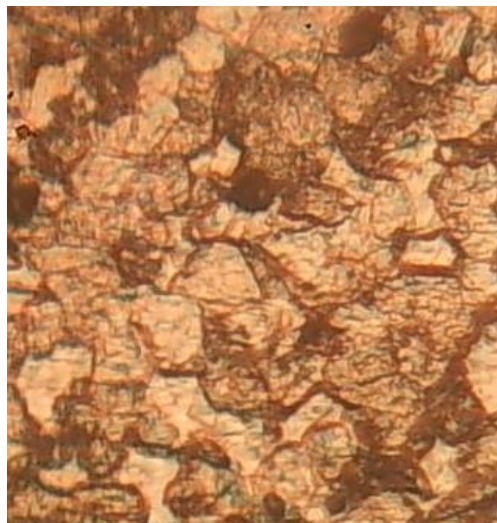


Figure 12. Micrograph of C-1020 mild steel specimen 20ml inhibitor in freshwater after exposure

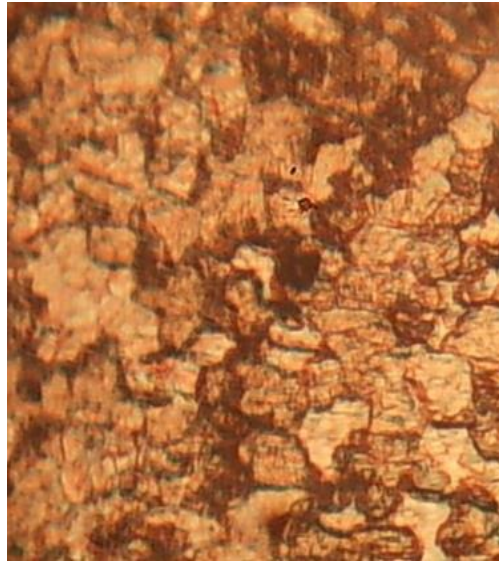


Figure 13. Micrograph of C-1020 mild steel specimen 20ml inhibitor in seawater after exposure



Figure 14. Micrograph of C-110 Copper specimens before exposure

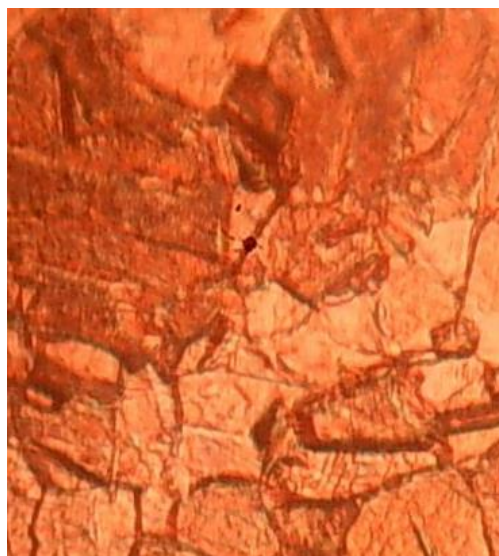


Figure 15. Micrograph of C-110 Copper specimen with 20ml inhibitor in freshwater after exposure

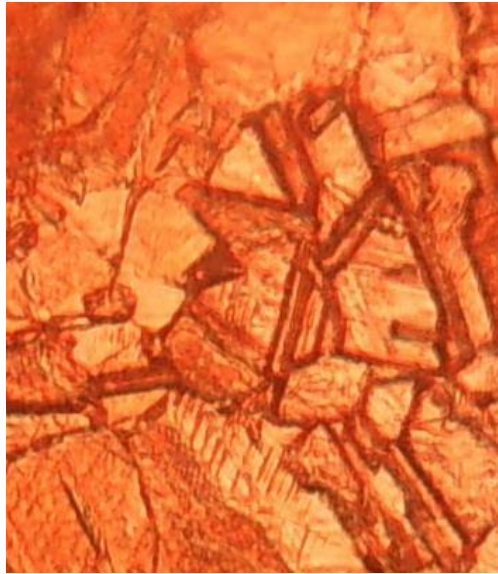


Figure 16. Micrograph of C-110 Copper specimen with 20ml inhibitor in seawater after exposure

4.2. Discussion of Results

Tables 1 to 8, were used in plotting the graphs of weight loss against time and corrosion rate against time for mild steel and copper. It was observed that from the zero inhibitor to the addition of 20ml inhibitor there was weight loss. With 20ml addition of inhibitor to the freshwater as represented in Table 2 and Figure 6 in could be observed that there was decline in weight of the sample in the first three weeks of exposure to the corrosive media while gradually slowing down in the in the fifth week. It was observed that the inhibitor does not kick in immediately. In the addition of 20ml inhibitor to seawater for mild steel in Table 4 and Figure 10 it was observed that there is a slight decrease in the weight of the specimen in the first week and negligible increase in the later weeks of exposure. Table 5 and Table 6 represents the weight loss and corrosion rate of copper sample with Zero ml and 20ml inhibitor in freshwater. It was observed that there is weight loss on the copper specimen. With the addition of the inhibitor the weight loss on the copper specimen is significantly reduced. Table 9 shows that after 1176 hours of immersion, the green inhibitor was observed to be effective only in fresh water for both the Copper coupon and Mild Steel coupon reducing the corrosion rate for Copper from 0.0311 mm/yr to 0.0084 mm/yr (73% reduction) and for mild steel from 0.0716 to 0.0362 mm/yr (49% reduction). Conversely, the corrosion rates in seawater increased with the addition of the green inhibitor from 0.0476 mm/yr to 0.0550 mm/yr (15.6% increase) for Cu and from 0.0816 to 0.0830 mm/yr (17.16% increase) for mild steel. It could therefore be concluded that the green inhibitor is only effective in fresh water.

The micrograph in Figure 11 is that of the mild steel specimen before exposure to the corrosive media while Figures 12 and 13 are the micrographs for mild steel specimen immersed in freshwater and seawater both with 20mls of inhibitor whereas Figures 14 is the micrograph of the copper specimen before immersion while Figures 15 and 16 are the micrographs for the copper specimens immersed in freshwater and seawater both with 20mls of inhibitor. For the mild steel specimen in freshwater and seawater there are slight distortions to the grain boundaries. The micrographs of the mild steels after immersion exposure show localized deep holes (pitting) with mild scales whereas the copper the corrosion followed the grain boundaries of the copper (intergranular corrosion). The

corrosion rates of the specimens immersed in fresh water with the inhibitors may have reduced over the 1,176 hours of immersion due to the formation of passivating oxide on the surface of the specimen whereas in the seawater immersion, the oxide films could not stabilize due to the presence of relatively small Chloride ion which are highly aggressive. They can penetrate the passivating oxide layer and locally destroy it and may have led to the increase in corrosion rates in the specimens immersed in seawater.

5.0. Conclusion

Corrosion is a multifaceted process that occurs in different forms and leads to loss of huge revenues for organizations. As was stated earlier in the introduction of this study corrosion inhibitors have been used to prevent metallic corrosion. This study investigated the evaluation of *Bryophyllum pinnatum* (Never Die Leaf) green inhibitor as a corrosion inhibitor for marine steam boilers manufactured from mild steel and copper. It was observed that the inhibitor did not take effect until the third week. Results revealed that the inhibitor took effect between the third week and the fifth week. Also, both mild steel and the copper specimens had low corrosion rate in freshwater compared to seawater. It could be concluded from the studies that the green inhibitor is only effective in fresh water. The study also revealed that to reduce the corrosion of both metals the inhibitor has to be added at regular intervals.

6.0. Future Suggestion

As a result of the findings from this research work on combating corrosion in marine boilers in both freshwater and saltwater using *Bryophyllum pinnatum* leaf extract, it is suggested as follows:

- 1) Further research on using *Bryophyllum pinnatum* leaf extract as a corrosion inhibitor should be carried out with an increased percentage of inhibitor in corrosive mediums.
- 2) *Bryophyllum pinnatum* leaf extracts should be used locally as corrosion inhibitors for marine boiler corrosion reduction, as they are very cheap and affordable.
- 3) The period of investigation of *Bryophyllum pinnatum leaf* extract should be extended further to determine its efficiency as an inhibitor over an extended period and to determine its suitability for mild steel and copper boilers that will be in use for a very long time in both seawater and freshwater environments.
- 4) An identification test should be carried out by industries manufacturing marine boilers as to ascertain the elements present in the material intended for use in boiler manufacturing are suitable.

Declarations

Source of Funding

This study did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors have not declared any conflict of interest.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Okpah Onyebuchi: Conceptualisation, formal analysis; Poku Robert: Investigation and Visualisation; Ernest Apresai: Writing and Review; Oyinkepreye Lucky Bebetidoh: Editing and writing; Alexandria N. Okpala: Supervision.

Informed Consent

Not applicable for this study.

Availability of data and material

Supplementary information is available from the authors upon request.

Institutional Review Board Statement

Not applicable for this study.

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