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Local Potential Eco-Friendly Corrosion Bio-inhibitors for Iron Material in Karang Jahe Marine

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ABSTRAK

Air laut Karang Jahe, Kabupaten Rembang, memiliki salinitas dan kandungan klorida yang tinggi sehingga mempercepat korosi pada material besi yang digunakan dalam kegiatan perikanan. Walaupun inhibitor korosi sintetis menunjukkan efektivitas yang tinggi, potensi toksisitas jangka panjangnya dapat mengganggu keseimbangan ekosistem setempat. Ekstrak tumbuhan berpotensi menjadi alternatif inhibitor korosi yang ramah lingkungan karena memiliki sifat biodegradabel dan tingkat toksisitas rendah. Namun, penelitian yang menyelidiki tumbuhan pesisir lokal dalam kondisi air laut alami masih terbatas. Kebaruan penelitian ini terletak pada pemanfaatan ekstrak daun jati (*Tectona grandis L.f.*) dan kulit kayu tengar (*Ceriops tagal*) dari kawasan pesisir Karang Jahe sebagai inhibitor korosi ramah lingkungan yang diuji dalam media air laut alami. Hasil pengujian perendaman mengindikasikan bahwa peningkatan konsentrasi inhibitor diikuti oleh penurunan laju korosi secara konsisten. Setelah 20 hari perendaman pada konsentrasi 20 ppm, efisiensi inhibisi tercapai sebesar 90,75% untuk ekstrak daun jati dan 93,49% untuk ekstrak kulit kayu tengar. Hasil tersebut menunjukkan perlindungan korosi yang kuat dan berkelanjutan dalam kondisi air laut yang realistis. Nilai efisiensi inhibisi mencapai maksimum pada hari ke-10, yang menunjukkan terbentuknya lapisan adsorpsi inhibitor yang efektif pada permukaan besi. Secara keseluruhan, ekstrak kulit kayu tengar memberikan perlindungan korosi yang lebih efektif. Temuan ini mengindikasikan bahwa ekstrak tersebut berpotensi dikembangkan sebagai inhibitor korosi ramah lingkungan berbasis sumber daya lokal untuk aplikasi kelautan.

Kata kunci: Inhibitor korosi ramah lingkungan, Korosi besi, Media air laut alami, Daun jati (*Tectona grandis L.f.*), Pohon tengar (*Ceriops tagal*), Laut Karang Jahe

ABSTRACT

The seawater of Karang Jahe, Rembang Regency, provides a highly saline, chloride-rich environment that accelerates the corrosion of iron materials widely used in local fishing activities. Although synthetic corrosion inhibitors are effective, their long-term application raises ecological concerns due to toxicity. Plant-based extracts offer a biodegradable and environmentally safer alternative. However, studies investigating locally sourced coastal plants under natural seawater conditions remain limited. This study is novel in that it evaluates locally sourced teak leaf (*Tectona grandis L.f.*) and tengar bark *(Ceriops tagal*) extracts from the Karang Jahe coastal area as eco-friendly corrosion inhibitors in natural seawater media. Immersion experiments showed a consistent decrease in corrosion rates with increasing inhibitor concentrations. After 20 days of immersion at 20 ppm, inhibition efficiencies of 90.75% for teak leaf extract and 93.49% for tengar bark extract were achieved, demonstrating strong and sustained corrosion protection under realistic marine conditions. Peak efficiencies were observed after 10 days, suggesting effective early-stage adsorption of the inhibitor molecules on the iron surface. Overall, tengar bark extract demonstrated stronger corrosion protection. This finding highlights its potential as a locally sourced and environmentally friendly inhibitor for marine applications.

Keywords: Green corrosion inhibitor, Iron corrosion, Natural seawater medium**,** Teak leaves (*Tectona grandis L.f*), Tengar tree (*Ceriops tagal*), Karangjahe Marine

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1. INTRODUCTION

Rembang Regency is located on the north coast of Central Java Province, covering an area of approximately 1,014 km. 35% of the area is coastal, which has a coastline of 51.5 km. Most of the population's livelihood is fishing (Statistik, 2014). Fishermen in Rembang Regency still use traditional boats to catch fish, with the engine positioned on the boat deck (Muna et al., 2023). These traditional ships still use wood and iron materials that lack protection, such as ship nails, engine frames, anchor chains, and anchors. Even though this ship always operates in seawater, which is a corrosive medium. This will cause problems, including the rapid corrosion of the iron material on the ship, thereby shortening the ship's helpful value.

Seawater is a corrosive medium that causes the degradation of metal materials, especially iron and steel, in ship construction. The corrosive nature of seawater is due to the high content of sulfate-reducing ions and bacteria. The ions in seawater form a salt bridge between the anodic and cathodic locations on the metal. These ions cause seawater to be more conductive than fresh water. Seawater causes corrosion five times faster than fresh water. The ions in seawater conduct electrons, resulting in a rust formation reaction. The fast movement of these electrons accelerates the reaction of metal rusting in seawater. In addition, seawater contains many sulfate-reducing bacteria. Sulfate-reducing bacteria carry out anaerobic respiration, which utilizes sulfate as an electron acceptor. Sulfate-reducing bacteria reduce sulfate using the enzyme ATP-sulfurilase to sulfite. Then, Sulfites are reduced again to produce energy as ATP. Meanwhile, this process produces hydrogen sulfide. Hydrogen sulfide then reacts with iron or metal to form iron sulfide, or what is known as rust (Mao et al., 2025; Pusparizkita et al., 2023; Putra, 2021)

Corrosion control must be carried out, especially for ferrous metal materials constantly submerged in seawater, to avoid undesirable impacts. One way to control corrosion is to inhibit the corrosion rate so that it does not occur quickly by using natural and artificial inhibitors. The use of artificial inhibitors such as paint and other synthetic materials has been proven to have a detrimental impact on the natural environment, including the marine environment (Km et al., 2024). Therefore, using inhibitors from natural ingredients can be considered an appropriate choice for preserving marine ecosystems.

The coastal waters of Karang Jahe are surrounded by various types of trees, including sea pine, coconut, tengar, and teak trees, which dominate along the coastline. Several local plants in the area have the potential to serve as environmentally friendly bioinhibitors. Still, they have not been utilized by the fishing community there. The tengar tree is a very potent bio-inhibitor. Tengar trees are a type of mangrove with tannin-rich bark. Tengar trees grow in many coastal areas in various regions of Indonesia, including Central Java, East Java, Sulawesi, and Kalimantan, especially in coastal areas. The wood of the tengar tree is used as firewood, while the bark is used as a batik dye for a mixture of soga colors (tegeran wood, tingi bark, and jambal). Tengar bark has a reddish-brown color and a tannin content of 26.5%. The percentage of tannin content compared with avaram, hemlock, oak, and chestnut bark is relatively high (Kasmudjiastuti, 2014)

The use of tannin compounds in tengar trees has also been carried out in various studies, including by (Cui et al., 2022; Shamsuzzaman et al., 2021; Wisdayanti & Sumardi, 2025; Zakeri et al., 2022). In this research, the tannin in tengar leather was used as a natural dye for fabric and was proven to contain antioxidants and anti-corrosion. Local tengar bark as a bioinhibitor has not been widely used in Indonesia. The most significant mangrove utilization is for firewood, charcoal and construction materials (e.g., housing material and fishing gears), medicines, and dye-making (Hamza et al., 2021). Even though Indonesia is a maritime country, many residents live at sea as fishermen. Tengar trees are found in many areas along the coast throughout Indonesia, including at Karangjahe beach, Rembang Regency.

Apart from the tengar trees, there is also a large population of local teak trees in the Karangjahe coastal area. So far, teak trees in the area have only been used for their wood to make household furniture. Meanwhile, the leaves are not widely used by residents. The local teak tree is one of the plants that can be used as a medicinal plant because it contains many compounds in its leaves. The compounds in teak leaves include carbohydrate compounds, alkaloids, tannins, sterols, saponins, proteins, calcium, phosphorus, and raw fiber, and they also contain dyes (yellowish or reddish brown). Several compounds contained in teak leaves have anti-bacterial activity and anti-oxidants acting as medicinal compounds (Montri et al., 2025). Several studies using teak leaf extract have been carried out. In several studies, teak leaves can be used for textile dyes, animal feed mixtures, and have been proven to contain anti-oxidant, anti-bacterial, and anti-corrosion substances. Some of these studies were conducted by (Badruttamam, 2022; Karthikeyan et al., 2021; Kodithuwakku & Edussuriya, 2018; Mukhlisin Saputra & Daniati, 2021; Ovili, A. O., Isaac, E. O., and Ndor, 2020; Ramadhani et al., 2023; Wahyudi et al., 2022).

Tengar tree bark and local teak leaves are often found in the Karangjahe coastal area, Rembang Regency. However, its utilization still needs to be improved. Tengar tree bark and teak leaves contain high levels of tannin compounds, which can be used as environmentally friendly bioinhibitors, especially for equipment made of iron, such as ship nails, anchor chains, anchors, and ship engine support frames. Therefore, this research was conducted to examine the corrosion behavior of iron immersed in natural seawater collected from the Karang Jahe marine environment in the presence of teak leaf extract (Tectona grandis) and tengar bark extract (Ceriops tagal). The study focuses on how different inhibitor concentrations and immersion time affect corrosion rate reduction and inhibition efficiency. In addition, the protective performance of both locally sourced plant extracts was systematically compared to identify the more effective and environmentally sustainable option for marine corrosion protection.

2. RESEARCH METHODOLOGY

2.1. Material

The tools used in this research were digital scales, calipers, rotary vacuum evaporator, magnetic stirrer, label paper, oven, grade 600 sandpaper, glass beaker, 1000 ml Erlenmeyer flask, measuring cup, funnel, plastic container, 250 ml measuring flask, and filter paper. The materials used in this research were Karangjahe seawater, Rembang Regency, 2000 mL ethanol, 100 grams of teak leaves, 100 grams of tengar tree bark and distilled water, and 4'' (10.1 cm) iron nails. All chemicals were of analytical grade and used without further purification.

2.2. Methods

The experimental procedure in this research consisted of three stages: taking and preparing samples and test materials, extraction and evaporation, and immersion testing. The sample preparation stage began with collecting seawater, tengar tree bark, and teak leaves from the Karang Jahe coastal area. The material to be corroded consisted of 120 iron nails specimens measuring 4'' (±10.1 cm), obtained from a hardware store. The nails were cleaned with sandpaper, soaked in distilled water for 2 minutes, dried in an oven, cooled in a desiccator, and then measured and weighed to obtain the initial weight. Each nail was treated as an independent experimental unit for corrosion testing.

Figure 1. Dry Sample

Figure 2. Bio Inhibitor Soaking Test

Tengar tree bark and teak leaf extracts were prepared using the maceration extraction method. Following procedures reported by Bitwell et al (2023), teak leaves and tengar bark were air-dried for 7–10 days without direct sunlight. After drying, each sample (100 g) was ground using a chopper and soaked in 1000 mL of 96% ethanol for seven days in a closed container. The extract was filtered to separate the filtrate from the sediment. The filtrate was then evaporated using a rotary evaporator at 90°C and 60 rpm to remove the solvent. The resulting concentrated filtrate was used as teak leaf extract and tengar tree bark extract for the bio-inhibitor tests. The concentrated extracts were stored at 4°C prior to immersion experiments.

Sample immersion testing was conducted to evaluate the potential of the extracts as corrosion bio-inhibitors and to calculate their inhibition efficiency. Five glass beakers were prepared, each containing 50 mL of seawater. Iron nails were immersed in seawater containing teak leaf extract at concentrations of 0, 5, 10, 15, and 20 ppm. A similar procedure was applied for the tengar bark extract at the same concentration levels. The selected concentration range of 5–20 ppm was chosen based on previous studies reporting that plant-derived green corrosion inhibitors exhibit significant inhibition performance at low ppm levels. For instance, Sivakumar & Srikanth (2020) demonstrated that plant extracts showed increasing inhibition efficiency over the range of 5–20 ppm, with optimal performance at 20 ppm. Similarly, Nour et al. (2024) reported that Trifolium repens extract achieved the highest inhibition efficiency in a saline (3.5% NaCl) medium at 20 ppm. For each concentration level and immersion time, three independent nails were tested (n = 3), ensuring experimental replication and statistical reliability. The immersed nails were observed and weighed after 5, 10, 15, and 20 days of exposure. Separate nail specimens were used for each immersion period to avoid disturbance of corrosion products during repeated measurements.

After each immersion period, the iron nails were washed with acetone, gently sanded to remove adhering corrosion products, rinsed with distilled water, dried in an oven, cooled in a desiccator, and weighed to determine weight loss. Weight loss values were calculated as the difference between initial and final nail mass for each replicate specimen. All immersion experiments were performed in triplicate (n=3), and the results are expressed as mean ± standard deviation (SD). Statistical differences among inhibitor concentration treatments were evaluated using one-way analysis of variance (ANOVA) at the $p < 0.05$ significance level. ANOVA was applied to compare corrosion rate values among different inhibitor concentrations at each immersion time.

When significant differences were detected, post-hoc pairwise comparisons were conducted using Tukey's HSD test. Error bars in the corresponding figures represent the SD values of replicate measurements. The corrosion rate was calculated with and without inhibitor addition at different concentrations and immersion times, together with the inhibition efficiency. The formula for calculating the corrosion rate is as follows:

$$CR\ (mm/y) = \frac{W.K}{D.A.T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

Remark (Pratikno et al., 2018):
CR: Corrosion rate (mm/year)
W: Weight loss (mg)
K: Conversion constant (87.6) to obtain CR in mm/year
D: Density (gram/cm^3)
T: Time of exposure (Hours)
A: Surface area (cm^2)

Inhibitor efficiency in this study was calculated using the following formula:

$$Efficiency\ \frac{CRa - C}{CRa} x100\% \ldots\ldots\ldots.(2)$$

Remark:
CRa : Corrosion rate without inhibitor (mm/year)
C : Corrosion rate with inhibitor (mm/year)

3. RESULT AND DISCUSSIONS

Before using corrosion medium, testing seawater content is an important step to understanding the nature of the test environment and its impact on metal corrosion rates. Research results can be greatly influenced by salinity, pH, dissolved oxygen, ion content, contaminants, and temperature. Testing the content of seawater as a corrosion medium allows researchers to ensure that the results of corrosion experiments and the effectiveness of bio-inhibitors truly reflect natural environmental conditions. Table 1 is the results of testing the Karang Jahe seawater content carried out in this research.

The results indicate that the Karang Jahe seawater has a salinity of 27‰ (ppt), reflecting typical coastal conditions that can promote corrosion due to the presence of chloride ions. Chloride-rich seawater is highly aggressive to iron materials because chloride ions can disrupt the protective oxide layer on the metal surface, accelerating corrosion processes. The measured pH of 8.5 shows that the seawater is slightly alkaline, which is characteristic of marine environments. In addition, the BOD value of 9.05 mg/L suggests moderate organic content, which may contribute to corrosivity through biofilm formation and microbiologically influenced corrosion. Overall, these seawater characteristics confirm that Karang Jahe provides a naturally corrosive medium suitable for evaluating the effectiveness of eco-friendly bio-inhibitors under realistic marine conditions.

Experimental results on the effectiveness of bio-inhibitors from tengar bark and teak leaf extracts using variations in concentration and time. The results can be found in Table 2.

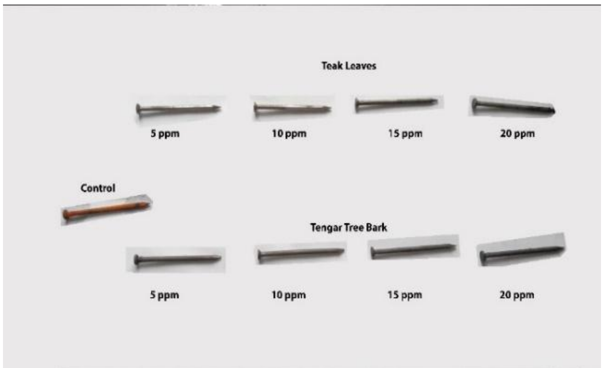

Figure 3. Appearance of Nails on the 20th Day of Soaking

Bio-inhibitors can slow down corrosion by adsorbing onto the metal surface and forming a protective barrier against aggressive seawater ions, particularly chloride (Cl^-). In this study, teak leaf and tengar bark extracts likely contain tannins and other polyphenolic compounds that interact with iron to produce a passive surface layer. This protective adsorption reduces electrochemical reactions at the metal–solution interface, thereby decreasing corrosion rates and improving inhibition efficiency.

Table 1. Karang Jahe Seawater Laboratory Test Results*

No	Parameters	Unit analysis	Result	Standard Index	Analysis Methode
PHYSICS					
1	Temperature	^0C	28	Natural (Coral & Seagrass: 28 - 30, Mangrove: 28 - 32)	SNI 06-6989.23-2005
2	Turbidity	NTU	7,7	5	SNI 06-6989.25-2005
3	Suspended Solids	mg/L	8	Coral: 20, Mangrove: 80, Seagrass: 20	SNI 6989.3-2019
4	Salinity	‰ (ppt)	27	Natural (Coral & Seagrass: 33 -34 ‰, Mangrove: s/d 34)	Lutron YK-2001PHA
CHEMISTRY					
5	pH	-	8,5	7 - 8,5	SNI 6989.11-2019
6	BOD	mg/L	9,05	20	SNI 6989.72-2009
7	DO	mg/L	5,2	> 5	SNI 6989.14-2009
8	Total Ammonia (NH_3-N)	mg/L	0,02	0,3	SNI 06-6989.30-2005
9	Nitrat (NO_3-N)	mg/L	0,67	0,06	SNI 06-2480-1991
10	Sulfida (H_2S)	mg/L	0,06	0,01	SNI 6989.75-2009
11	Krimum Heksavalen (Cr-VI)	mg/L	0,02	0,005	SNI 6989.71-2009
12	Cadmium (Cd)	mg/L	0,01	0,001	SNI 6989.84-2019
13	Copper (Cu)	mg/L	0,001	0,008	SNI 6989.84-2019
14	Lead (Pb)	mg/L	0,06	0,008	SNI 6989.84-2019
15	Zinc (Zn)	mg/L	0,4	0,05	SNI 6989.84-2019

**Sample test results at the UPTD environmental laboratory of the Semarang City environmental service*

Table 2. Bio Inhibitor Test Results

Inhibitor concentration (ppm)	Time (day)	Teak leaf extract			Tengar tree bark extract		
		ΔW (mean±SD)	CR (mean±SD)	Eff%	ΔW (mean±SD)	CR (mean±SD)	Eff%
0	5	0.0150 ± 0.0008	3.68E-02 ± 2.01E-03	-	0.0150 ± 0.0008	3.68E-02 ± 2.01E-03	-
0	10	0.0302 ± 0.0005	3.70E-02 ± 6.30E-04	-	0.0302 ± 0.0005	3.70E-02 ± 6.30E-04	-
0	15	0.0372 ± 0.0011	3.04E-02 ± 8.82E-04	-	0.0372 ± 0.0011	3.04E-02 ± 8.82E-04	-
0	20	0.0425 ± 0.0022	2.61E-02 ± 1.33E-03	-	0.0425 ± 0.0022	2.61E-02 ± 1.33E-03	-
5	5	0.0112 ± 0.0014	2.76E-02 ± 3.35E-03	25.11	0.0084 ± 0.0002	2.07E-02 ± 3.75E-04	43.78
5	10	0.0178 ± 0.0005	2.18E-02 ± 6.49E-04	40.99	0.0106 ± 0.0003	1.30E-02 ± 3.54E-04	64.97
5	15	0.0210 ± 0.0014	1.72E-02 ± 1.14E-03	43.50	0.0126 ± 0.0006	1.03E-02 ± 5.11E-04	66.10
5	20	0.0314 ± 0.0018	1.93E-02 ± 1.12E-03	26.04	0.0158 ± 0.0003	9.69E-03 ± 1.62E-04	62.82
10	5	0.0083 ± 0.0006	2.03E-02 ± 1.50E-03	44.89	0.0053 ± 0.0001	1.29E-02 ± 2.83E-04	64.89
10	10	0.0099 ± 0.0004	1.21E-02 ± 4.42E-04	67.18	0.0075 ± 0.0004	9.20E-03 ± 4.42E-04	75.14
10	15	0.0120 ± 0.0011	9.84E-03 ± 9.01E-04	67.62	0.0096 ± 0.0008	7.88E-03 ± 6.19E-04	74.08
10	20	0.0229 ± 0.0008	1.41E-02 ± 4.60E-04	46.04	0.0110 ± 0.0008	6.77E-03 ± 4.64E-04	74.04
15	5	0.0038 ± 0.0008	9.24E-03 ± 2.06E-03	74.89	0.0020 ± 0.0003	4.91E-03 ± 6.49E-04	86.67
15	10	0.0056 ± 0.0004	6.83E-03 ± 4.96E-04	81.55	0.0048 ± 0.0006	5.89E-03 ± 7.36E-04	84.09
15	15	0.0073 ± 0.0012	5.97E-03 ± 9.92E-04	80.36	0.0071 ± 0.0007	5.78E-03 ± 5.45E-04	80.99
15	20	0.0117 ± 0.0017	7.18E-03 ± 1.03E-03	72.47	0.0089 ± 0.0004	5.48E-03 ± 2.48E-04	78.98
20	5	0.0014 ± 0.0002	3.35E-03 ± 5.11E-04	90.89	0.0010 ± 0.0002	2.45E-03 ± 4.25E-04	93.33
20	10	0.0021 ± 0.0002	2.58E-03 ± 2.45E-04	93.04	0.0015 ± 0.0003	1.80E-03 ± 3.94E-04	95.14
20	15	0.0033 ± 0.0003	2.67E-03 ± 2.36E-04	91.21	0.0018 ± 0.0003	1.50E-03 ± 2.50E-04	95.07
20	20	0.0039 ± 0.0002	2.41E-03 ± 1.28E-04	90.75	0.0028 ± 0.0003	1.70E-03 ± 1.54E-04	93.49

3.1. Weight Loss in Iron Nails in Seawater Media with the Addition of Bioinhibitor

Weight loss measurements were used to evaluate the corrosion behavior of iron nails immersed in Karang Jahe natural seawater with and without plant-based inhibitors. The effect of inhibitor concentration on iron mass loss after 20 days of immersion is presented in Figure 4.

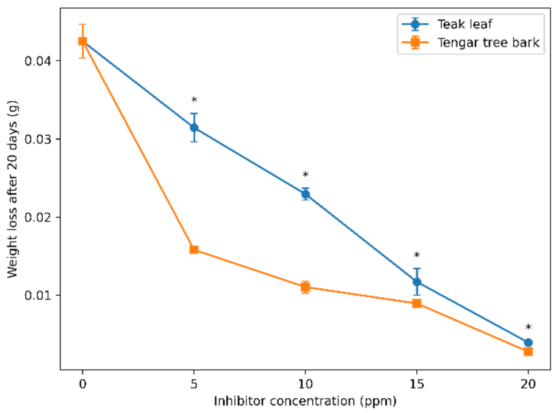

Figure 4. Weight Loss of Iron Nails After 20 Days of Immersion in Karang Jahe Natural Seawater with Teak Leaf (*Tectona grandis*) and Tengar Bark (*Ceriops tagal*) Extracts at Different Inhibitor Concentrations. Values are Presented as Mean ± SD (N = 3). Asterisks Indicate Significant Differences Compared to the Control (0 Ppm) Based on One-Way ANOVA Followed by Tukey's HSD Test (*P < 0.05)

Based on Figure 4, the weight loss of iron nails decreased as the concentration of teak leaf and tengar bark extracts increased from 5 to 20 ppm after 20 days of immersion. Statistical analysis confirmed that inhibitor concentration significantly affected iron weight loss after 20 days (one-way ANOVA; teak: F = 308.3, $p = 2.01 \times 10^{-10}$; tengar: F = 641.9, $p = 5.25 \times 10^{-12}$). Tukey's HSD post hoc test indicated that all inhibitor-treated groups differed significantly from the control condition ($p < 0.05$).

Both bio-inhibitors showed a clear concentration-dependent inhibition effect, where higher concentrations resulted in lower corrosion-induced mass loss. Tengar bark extract consistently produced lower weight loss values than teak leaf extract, indicating stronger surface protection. This protective behavior is likely related to tannins and other polyphenolic compounds in the extracts, which can adsorb onto the iron surface and block the attack of aggressive chloride ions in seawater, thereby suppressing corrosion processes (Ovili, A. O., Isaac, E. O., and Ndor, 2020).

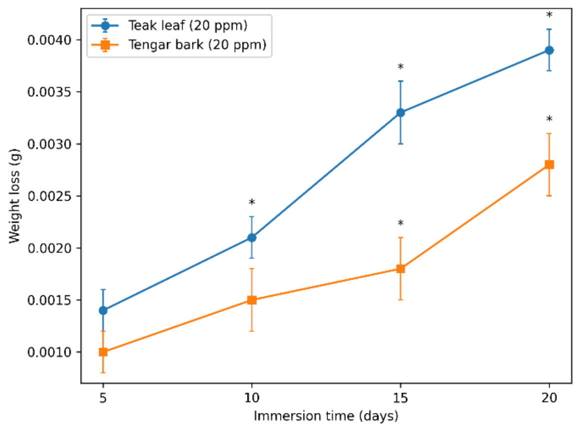

Figure 5. Weight Loss of Iron Nails Immersed in Karang Jahe Natural Seawater Containing 20 Ppm Teak Leaf (*Tectona grandis*) and Tengar Bark (*Ceriops tagal*) Extracts at Different Immersion Times. Values are Presented as Mean ± SD (N = 3). Asterisks Indicate Significant Differences Compared to Day 5 Within Each Extract Group, Based on One-Way ANOVA Followed by Tukey's HSD Test (*P < 0.05)

Based on Figure 5, weight loss increased with immersion time for both teak leaf and tengar bark extracts at 20 ppm, indicating that corrosion progressed gradually during prolonged exposure in natural seawater. Statistical analysis confirmed that immersion duration significantly affected weight loss for both extracts (teak: $F = 75.72$, $p = 3.25 \times 10^{-6}$; tengar: $F = 23.20$, $p = 2.66 \times 10^{-4}$). Tukey's HSD test further revealed that teak-treated specimens showed significant increases in weight loss from Day 10 onward, whereas tengar-treated specimens exhibited significant changes at Days 15 and 20. These findings suggest that tengar bark extract provides relatively more stable protection over the tested immersion period (up to 20 days), as corrosion progression was less pronounced during the early immersion period compared to teak leaf extract. This protective effect may be associated with polyphenolic compounds that adsorb onto the iron surface and reduce electrochemical reactions in the chloride-rich seawater environment.

Corrosion is an electrochemical oxidation process in which iron gradually loses electrons and forms corrosion products such as rust (Fe_2O_3) when exposed to oxygen and seawater. Prolonged immersion increases the exposure time of the metal surface to aggressive ions, leading to progressive mass loss. In this study, iron nails treated with teak leaf extract exhibited higher weight loss than those treated with tengar bark extract, indicating that tengar provides stronger corrosion protection under natural seawater conditions. This difference may be related to variations in the content of tannins and other polyphenolic compounds, which can adsorb onto the iron surface and form a more stable protective barrier. Similar findings have been reported in previous studies, where Ceriops tagal extract effectively reduced metal weight loss in various corrosive environments, including 3.5% NaCl and acidic media (Cui et al., 2022) and (Shamsuzzaman et al., 2021).

3.2. Corrosion Rate

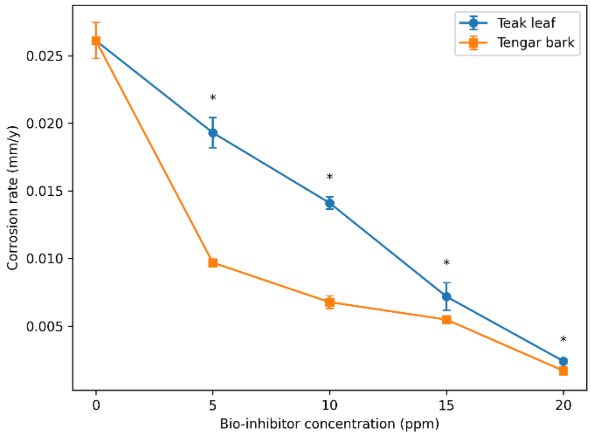

Figure 6. Corrosion Rate of Iron Nails After 20 Days of Immersion in Karang Jahe Natural Seawater with Teak Leaf (*Tectona grandis*) and Tengar Bark (*Ceriops tagal*) Extracts at Different Inhibitor Concentrations. Values are Presented as Mean ± SD (n = 3). Asterisks Indicate Significant Differences Compared to the Control (0 ppm) Based on One-Way ANOVA Followed by Tukey's HSD Test (*$p < 0.05$)

Corrosion rate refers to the speed at which a metal or other material corrodes or oxidizes naturally. Figure 6 below shows the corrosion rate profile of iron nails in seawater with the addition of inhibitors from tengar tree bark and teak leaf extracts.

Figure 6 shows that the corrosion rate of iron nails decreased with increasing concentrations of teak leaf and tengar bark extracts in the natural seawater medium. Statistical analysis confirmed that inhibitor concentration significantly affected corrosion rate after 20 days (one-way ANOVA, $p < 0.001$), and Tukey's HSD test indicated that all inhibitor-treated groups differed significantly from the control condition ($p < 0.05$). This corrosion reduction is likely associated with tannins and other polyphenolic compounds in the extracts, which adsorb onto the iron surface and form protective iron–polyphenol complexes with Fe^{3+}, thereby inhibiting further electrochemical corrosion (Sanchez-cortes & Espina, 2022). After 20 days of immersion, the highest corrosion rate was observed in the control group without inhibitor (2.61×10^{-2} mm/y), whereas the lowest corrosion rates were achieved at 20 ppm, reaching 2.41×10^{-3} mm/y for teak leaf extract and 1.70×10^{-3} mm/y for tengar bark extract.

Bio-inhibitors from teak leaf and tengar bark extracts likely protect iron nails through the adsorption of tannins and other polyphenolic compounds onto the metal surface. These compounds form iron–polyphenol films that limit direct contact with aggressive seawater ions and suppress electrochemical corrosion. Similar protective layer formation has been reported for plant-based corrosion inhibitors (Zakeri et al., 2022). The inhibition mechanism is likely associated with tannin compounds, which are able to form stable complexes with Fe(III) ions on the iron surface, thereby reducing the electrochemical corrosion reaction rate. This tannin–Fe^{3+} complex formation is illustrated in Figure 7.

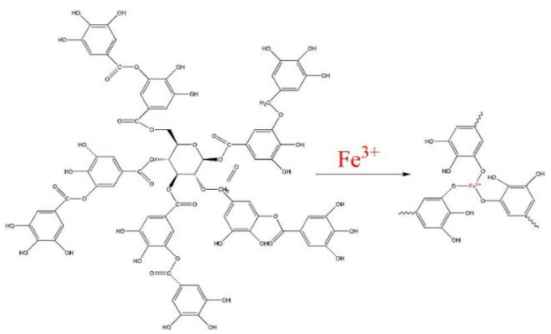

Figure 7. Schematic Illustration Of Tannin Complex Formation with Fe^{3+} Ions on the Iron Surface (Badruttamam, 2022)

The formed tannin–Fe^{3+} complexes can reduce corrosion by blocking the access of aggressive ions to the metal surface. Both Ceriops tagal bark and Tectona grandis leaves contain polyphenolic compounds with functional groups capable of donating lone-pair electrons, such as hydroxyl (–OH) groups. These groups can coordinate with Fe^{3+} ions to form relatively stable complex layers on the iron surface. The resulting protective film limits electrochemical reactions at the metal solution interface and contributes to corrosion inhibition.

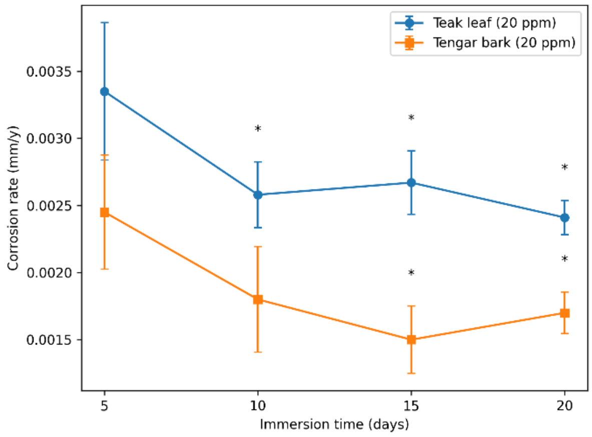

Figure 8. Corrosion Rate of Iron Nails Immersed in Karang Jahe Natural Seawater Containing 20 Ppm Teak Leaf (*Tectona grandis*) and Tengar Bark (*Ceriops tagal*) Extracts at Different Immersion Times. Values are Presented as Mean ± SD (N = 3). Asterisks Indicate Significant Differences Compared to Day 5 Within Each Extract Group, Based on One-Way ANOVA Followed by Tukey's HSD Test (*P < 0.05)

Figure 8 shows the effect of immersion time on the corrosion rate of iron nails in Karang Jahe natural seawater containing 20 ppm teak leaf and tengar bark extracts. Statistical analysis confirmed that immersion duration significantly influenced corrosion rate for both extracts ($p < 0.05$). Teak-treated specimens exhibited significant changes from Day 10 onward, whereas tengar-treated specimens showed significant differences at Days 15 and 20. Overall, tengar bark extract exhibited lower corrosion rates throughout the immersion period, indicating relatively more stable protection over the tested immersion duration (up to 20 days). This time-dependent inhibition behavior may be associated with the gradual formation of a protective adsorption layer from polyphenolic compounds on the iron surface, which limits further electrochemical corrosion reactions. Similar immersion-time effects and protective film formation have also been reported in previous corrosion inhibitor studies (Al-amiery et al., 2023; Parangusan et al., 2025)

3.3. Bio-inhibitory Efficiency of Tengar Bark (Ceriops tagal) and Teak Leaf (Tectona grandis) Extracts

In this study, inhibition efficiency was used to describe how well teak leaf and tengar bark extracts could protect iron nails from corrosion in Karang Jahe natural seawater. The efficiency values were calculated by comparing the corrosion rates of samples without inhibitors and those treated with different extract concentrations. The results are summarized in Figure 9.

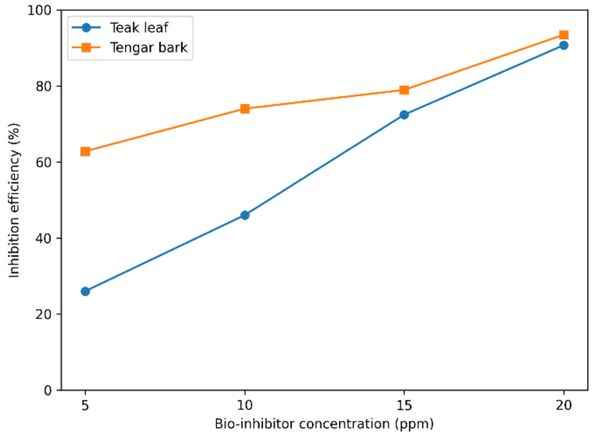

Figure 9. Inhibition Efficiency of Teak Leaf (*Tectona grandis*) and Tengar Bark (*Ceriops tagal*) Extracts at Different Inhibitor Concentrations After 20 Days of Immersion in Karang Jahe Natural Seawater. Efficiency Values Were Calculated Based on the Mean Corrosion Rate of Triplicate Measurements

Based on Figure 9, inhibition efficiency increased with increasing inhibitor concentration for both extracts. Overall, tengar bark extract consistently showed higher efficiency than teak leaf extract at all concentration levels. The highest inhibition efficiency was achieved at 20 ppm after 20 days of immersion, reaching 90.75% for teak leaf extract and 93.49% for tengar bark extract. These results highlight the strong potential of locally sourced tengar bark extract as an eco-friendly bio-inhibitor for protecting iron materials in the Karang Jahe marine environment.

Although inhibition efficiency generally increased with inhibitor concentration (Figure 9), comparison with the time-dependent results (Figures 5 and 8) revealed a slight decline after prolonged immersion (e.g., at 20 days compared to 10 days). This anomaly may indicate partial degradation or desorption of the protective inhibitor film over time under continuous exposure to chloride-rich seawater. In addition, long immersion may allow seawater ions or microbial activity to disrupt the adsorbed layer, reducing its stability. This suggests that while plant-based extracts provide strong short-term protection, their long-term durability in real marine environments may require periodic renewal or improved coating formulations.

Overall, the combined analysis of concentration- and time-dependent results confirms that tengar bark extract provides more effective corrosion protection than teak leaf extract under natural seawater conditions. In addition, tengar showed relatively more stable performance during the tested immersion period. This superior behavior is likely associated with its richer polyphenolic and tannin content, which enhances adsorption stability and promotes the formation of a protective film on the iron surface.

This research shows that bioinhibitors have great potential for use in industries related to the marine environment, such as the marine industry, shipbuilding, and offshore structures. The use of natural bioinhibitors, such as tannin bark and teak leaf extracts, has advantages compared to synthetic chemical inhibitors because they are environmentally friendly and safer for marine ecosystems. These natural bioinhibitor extracts may also be more cost-effective because the raw materials can be obtained from abundant local resources in coastal areas (Rochliadi et al., 2023). The effectiveness of using natural ingredients as metal bioinhibitors using seawater as a medium has also been proven in many studies (Al-rawajfeh et al., 2024)

However, further studies are needed to test the long-term durability of these bioinhibitors and their efficacy under various environmental conditions, such as changes in seawater temperature, salinity and pH. Long-term testing is essential to evaluate the performance of bioinhibitors, especially when used in industrial environments such as ports, ships, and offshore platforms. Although this study showed positive results during the 20-day immersion period, an unanswered question is how these bioinhibitors function over longer periods, such as months or years. Over time, bioinhibitors can be damaged by exposure to sunlight, marine microorganisms, or washing by ocean currents. Therefore, it is very important to know whether tengar bark and teak leaf extracts can continue to form a good protective layer or whether they need periodic recoating. Research on fouling resistance is especially important because marine microorganisms can colonize metal surfaces and affect the performance of bioinhibitor protective coatings.

It should also be noted that seawater quality factors such as organic load (BOD) may influence corrosion behavior in natural marine systems. Although BOD is not a direct parameter in classical corrosion rate calculations, elevated organic matter can promote microbial growth and biofilm formation, potentially contributing to microbiologically influenced corrosion (MIC). Since microbial activity was not specifically evaluated in this study, the role of organic pollution represents a limitation that should be addressed in future work. This highlights the importance of further studies on the combined chemical and biological effects of natural seawater conditions on the long-term stability of plant-based inhibitor layers.

The effectiveness of using inhibitors made from natural ingredients has also been proven by several studies, including inhibitors made from orange and mango peels (Jufri et al., 2022; Khoshsang & Ghaffarinejad, 2021; NoorR, 2015; Nurhaeni et al., 2021; Zhang et al., 2021) and others. On average, these natural ingredients are proven to have more than 70% efficiency. The use of plant extract-based bioinhibitors can reduce water pollution and negative impacts on the marine food chain, but the use of natural bioinhibitors must be balanced with in-depth ecotoxicological studies to ensure that the active ingredients from plant extracts do not have negative cumulative effects on the environment. Future research should focus on improving the stability and durability of these bioinhibitors. This includes developing more robust formulations and evaluating optimal operating conditions for their use. Strategies such as incorporating stabilizing additives or applying protective coating techniques may enhance long-term corrosion protection efficiency.

4. CONCLUSION

This study demonstrates that teak leaf (Tectona grandis) and tengar bark (Ceriops tagal) extracts have strong potential as eco-friendly corrosion inhibitors for iron in natural seawater from the Karang Jahe marine environment. Increasing inhibitor concentration consistently reduced corrosion rate and weight loss, with optimal performance observed at 20 ppm. Overall, tengar bark extract provided more effective and relatively more stable protection than teak leaf extract, supporting its potential as a sustainable alternative to synthetic inhibitors for marine applications.

Nevertheless, this study was limited to short-term laboratory immersion conditions. Future research should investigate long-term durability under dynamic seawater exposure, characterize inhibitor film properties using surface analysis techniques (e.g., SEM or FTIR), and develop practical coating or formulation strategies to improve stability. Such advancements would enhance industrial applicability while promoting environmentally safer corrosion control in coastal ecosystems.

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