Development of a Green Corrosion Inhibitor from Lophatherum Gracile Extract for Steel Protection

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Received: 4 August 2024 | Revised: 26 September 2024 | Accepted: 19 November 2024

ABSTRACT

Corrosion constitutes a significant challenge in the context of infrastructure development, with particular implications for steel materials. One common method for preventing corrosion is the application of inhibitor materials. Inhibitors are classified into two main categories: organic inhibitors and inorganic inhibitors. Inorganic inhibitors are costly and may have adverse environmental effects. Consequently, organic inhibitors that are cost-effective and environmentally benign were developed. One plant that has the potential to be used as an organic inhibitor is Lophatherum gracile B. (Lophatherum gracile Brogn), due to its antioxidant compounds that can prevent corrosion. The objective of this research is to analyze the effect of the Lophatherum gracile B. extract inhibitor on the corrosion rate and its inhibition efficiency on reinforcing steel. The weight loss method was employed to determine the corrosion rate in a 3% sodium chloride (NaCl) medium, with concentration variations of 0%, 2%, and 4% over a duration of 24, 72, and 96 hours. The findings indicated that the lowest corrosion rate was observed at the 4% concentration,

while the highest rate was noted at the 0% concentration. The inhibition efficiency of the Lophatherum gracile B. extract was determined to be greater than 66%. The qualitative analysis of the macro photo material structure indicated that the steel surface treated with Lophatherum gracile B. extract exhibited a reduced level of corrosion in comparison to the control sample. Furthermore, the tensile strength testing demonstrated that the decline in the tensile strength of steel could be attenuated through the use of inhibitors. These findings suggest that the Lophatherum gracile B. extract is an effective inhibitor material for reinforcing steel.

Keywords-Lophatherum gracile; corrosion; coating; inhibitor

I. INTRODUCTION

Steel is a commonly used material in construction due to its high tensile strength, which compensates for the tensile deficiencies inherent in concrete [1]. Despite the numerous advantages of steel, it is highly susceptible to corrosion (rust) when used in humid environments [2]. Corrosion is defined as an oxidation process that deteriorates the ions in metals, thereby reducing the quality and durability of steel and compromising the integrity of constructed materials [3]. As indicated by data from the World Corrosion Organization (WCO), the financial impact of corrosion is estimated at approximately USD 2.2 trillion, representing 3% of the global Gross Domestic Product (GDP). Furthermore, corrosion contributes to an increase in CO_2 emissions on a global scale [4]. Coatings are a widely deployed method for the prevention of corrosion. Coatings are highly valued for their tensile strength, antimicrobial contents, and effectiveness in resisting corrosion. The coating serves to safeguard the steel surface by forming a protective layer that inhibits corrosion [5]. Inhibitors can be employed to forestall acid-induced corrosion and to attenuate its deleterious effects on steel [6]. Inhibitors are defined as substances that function to impede the oxidation reactions in steel, thereby preventing corrosion. Inhibitors can be classified into two main categories: organic and inorganic [7]. Inorganic inhibitors are composed of toxic substances that can be detrimental to human health and costly to produce. [8] Organic inhibitors are the most viable and cost-effective means of preventing corrosion [9]. Accordingly, a highly efficacious, cost-effective, and environmentally benign organic inhibitor was developed for corrosion protection [8]. Flavonoids and organic acids present in plants have been demonstrated to inhibit oxidation reactions [10].

One plant that contains these compounds is Lophatherum gracile B. Lophatherum gracile B. is a species that exhibits optimal growth in humid tropical biomes [11], like in Indonesia. Despite its reputation as a weed due to its detrimental impact on agricultural crops, Lophatherum gracile B. possesses a considerable potential as an organic inhibitor, largely due to its antioxidant properties. Lophatherum gracile B. contains a variety of bioactive components, including flavonoids, polysaccharides, amino acids, and phenolic acids, which have been demonstrated to possess antioxidant properties [12]. Flavonoids are a class of compounds found in Lophatherum gracile B, that have been demonstrated to possess antioxidant effects and have the potential to serve as eco-friendly corrosion inhibitors. Flavonoids are naturally occurring compounds that are present within the Lophatherum gracile plant. These compounds are known for their diverse biological properties and are particularly effective at combating harmful free radicals due to their potent antioxidant capabilities. Given these characteristics, flavonoids have emerged as a promising material for the prevention of corrosion. Their capacity to form a protective barrier on metal surfaces renders them a promising class of inhibitors for the corrosion process [13]. The antioxidant properties of flavonoids provide an inhibitory effect, and the formation of a protective layer can reduce the corrosion rate and mitigate the formation of rust [14]. The objective of this research is to evaluate the effectiveness of Lophatherum gracile B. extract as a corrosion inhibitor in addressing corrosion-related issues. The research entails a comparison of the corrosion rates of steel in the presence and absence of Lophatherum gracile B. inhibitors, with the objective of deriving inhibition efficiency values for the extract.

II. MATERIALS AND METHODS

A. Materials

The materials used for the Lophatherum gracile B. extract inhibitors included Lophatherum gracile B. (the sample to be extracted), water for sample washing, ethanol 96%, and acetone for cleaning steel. To assess the corrosion rate of the steel, 13 mm diameter reinforcing steel rods were utilized in conjunction with a 3% NaCl corrosion medium.

B. Methods

A total of 27 deformed bars, with a diameter of 13 mm and a length of 34 cm each, were prepared in accordance with the Indonesian National Standard (SNI) 2052:2017 [15]. The steel was then subjected to a cleaning process involving soaking in an acetone solution. Following this, the steel was dried at room temperature for 24 hours. Subsequently, the mass of the steel was determined through a weighing procedure.

C. Preparation of Inhibitor Materials

Two kilograms of Lophatherum gracile B. were cleaned with distilled water and subsequently dried in an oven for a period of 24 hours, resulting in the production of 306.7 grams of dried material. The dried Lophatherum gracile B. was ground using a blender and extracted with 96% ethanol by maceration. The mixture was filtered through filter paper to obtain the liquid extract, which was subsequently concentrated using a rotary evaporator at 80 rpm and 80°C to produce a concentrated extract [16], as presented in Figure 1. As shown in Figure 2, the final concentrated extract represents a purified form of the original mixture, exhibiting a higher concentration of the active compounds following the rotary evaporator process [16].

D. Coating Application

The coating of the reinforcing steel commenced with the preparation of the coating solution, which involved the reduction of the concentrated extract. The dilution of the extract with ethanol ensured the uniform application of the coating to the steel surfaces. The coating procedure was applied to 27 pieces of steel bars, which were organized into three distinct groups based on the concentration of the extract used. The concentrations tested were 0%, 2%, and 4%, with each concentration level having been applied to nine individual steel bars, as detailed in Table I.

Fig. 1. Preparation of Corrosion Inhibitor: (a) separation, (b) cleaning, (c) drying, (d) maceration, (e) filtering, (f) extraction.

Fig. 2. Concentrated extract of Lophatherum gracile B.

E. Chemical Content Testing

To identify the specific constituents of Lophatherum gracile B. extracts, chemical content tests were conducted using Liquid Chromatography-Mass Spectrometry (LC-MS) [17]. This method enabled the separation and detection of a range of compounds within the extract, resulting in the generation of an ion mass spectrum graph. Subsequently, the spectrum was subjected to quantitative analysis to ascertain the presence and concentration of pivotal bioactive compounds.

TABLE I. NUMBER AND VARIABLE OF TEST SPECIMENS

Soaking Time (h)	Inhibitor Concentration (%)	Number of Test Specimens	Description
24	0	3	Without Inhibitor
	2	3	Inhibitor
	4	3	
72	0	3	Without Inhibitor
	2	3	Inhibitor
	4	3	
96	0	3	Without Inhibitor
	2	3	Inhibitor
	4	3	

F. Corrosion Rate and Inhibition Efficiency Testing

The corrosion testing was conducted by immersing the coated steels in a 3% NaCl solution, which served as the corrosion medium, as evidenced in Figure 3. The 3% NaCl solution was prepared by dissolving 30 ml of NaCl in 970 ml of distilled water [18]. This test also yielded the inhibition efficiency value, which was obtained to ascertain the efficacy of the usage of Lophatherum gracile B. extract inhibitors in the reinforcement of steel.

Fig. 3. Corrosion rate and inhibition efficiency test.

G. Material Structure Testing Macro Photos

Material structure tests were conducted using a 200x macro lens to examine the steel surface treated with 2% and 4% Lophatherum gracile B. extract inhibitor, in comparison to steel without the inhibitor, after a 96-hour immersion period. The results of the test demonstrated that the steel surface had sustained damage as a consequence of exposure to the corrosive environment.

H. Steel Tensile Strength Testing

The tensile strength of the steel was evaluated through a tensile testing procedure, as depicted in Figure 4. Each 34 cm steel piece was marked at both ends to facilitate the positioning of the tool. Once the apparatus was activated, the steel was pulled at both ends until fracture occurred, and the elongation of the steel was subsequently measured. This test was employed to ascertain the tensile strength of the reinforcing steel and to delineate its intrinsic characteristics. The resulting tensile strength data were subjected to mathematical processing in accordance with the equations set forth in SNI 8389:2017 for metal tensile testing [19]:

$$R_m = \frac{F_m}{S_0} \quad (1)$$

where R_m is the tensile strength (MPa), F_m is the maximum load (N), and S_0 is the initial cross-sectional area of parallel section (mm^2).

Fig. 4. Steel tensile strength test.

I. Determination of Corrosion Rate of Steel

Once the requisite corrosion time had elapsed, the steel samples were subjected to a cleansing process involving soaking in acetone, followed by a 24-hour drying period at room temperature. Thereafter, the samples were weighed in order to ascertain their final weight. The loss in weight was employed to calculate the corrosion rate [20]. The data were analyzed using mathematical equations based on the ASTM G31-72 standards for laboratory corrosion rate testing [21].

$$Corrosion\ rate = \frac{\text{k-w}}{\text{A×T×ρ}} \quad (2)$$

where k is the constant value (3.14×10^6 mpy), T is the soaking time (hours), A is the sample area (cm^2), w is the mass difference (mg), and ρ is the density (7.85 mg/mm^3). Furthermore, the inhibition efficiency value of Lophatherum gracile B. extract has been calculated using:

$$IE(\%) = \frac{W_0\text{-}W_1}{W_1} \text{ x } 100 \quad (3)$$

where IE (%) is the inhibition efficiency, W_0 is the corrosion rate of variation 1 (mpy), W_1 is the corrosion rate of variation 2 (mpy).

III. RESULTS AND DISCUSSION

A. Phytochemical Screening Test Analysis

The identification of extract compounds was conducted through the use of a variety of reagents. The presence of tannins was indicated by a green-black color resulting from the use of ferric chloride ($FeCl_3$) as a test reagent [22]. The presence of flavonoid compounds was identified through the use of citric acid and boric acid (H_3BO_3), which resulted in the formation of a yellow-green coloration [23]. The identification of alkaloids was achieved through the use of Dragendorff's reagent, which underwent a color change from orange-red, thus confirming the presence of alkaloids [24]. The presence of saponins was confirmed through the use of distilled water and heating, which resulted in the formation of a stable froth, indicative of the compound's presence [25]. The Lophatherum gracile B. extract was found to contain tannins, flavonoids, alkaloids, and saponins. Authors in [25] reported that Lophatherum gracile B. contains various bioactive compounds, including polyphenols, alkaloids, and flavonoids, which can provide antioxidant effects and inhibit corrosion rates. The content of Lophatherum gracile B. is shown in Table II.

TABLE II. PRELIMINARY PHYTOCHEMICAL ANALYSIS OF LOPHATHERUM GRACILE BROGN EXTRACT

No	Phytochemicals	Result	Phytochemical test
1.	Tannins	+	$FeCl_3$
2.	Flavonoids	+	H_3BO_3
3.	Alkaloids	+	Dragendorf
4.	Saponins	+	Froth test
5.	Triterpenoids	-	Liebermann-Burchard

The "+" symbol indicates the successful detection of these phytochemicals in the *Lophatherum gracile* B

B. Chemical Content Test Analysis

The LC-MS test revealed that the organic compound contains the following chemical groups: chlorine, phenyl, and alkyl (Figure 5). Both the alkyl and phenyl groups were found to exhibit ideal antioxidant properties and a strong antioxidant capacity at elevated temperatures [26]. It can be, therefore, reasonably concluded that these compounds have the potential to be developed into coatings that prevent corrosion and can be used as corrosion inhibitors. The extract contains ethyl(dimethyl)sulfonium, a derivative of chitosan acetate. Derivatives of chitosan acetate with sulfonium salts are known to possess antioxidant properties and low toxicity [27]. These findings indicate that the Lophatherum gracile B. extract has significant potential for effectively inhibiting the corrosion rate of reinforcing steel.

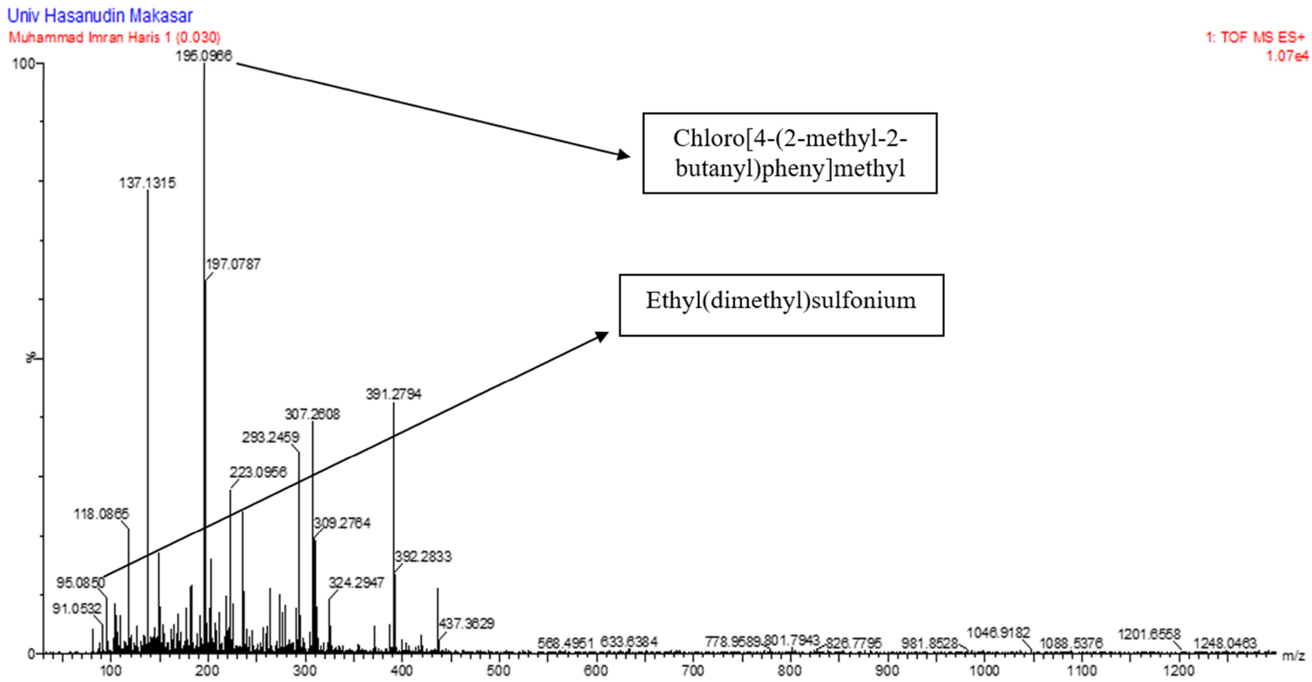

Fig. 5. LC-MS ion mass spectrum graph.

C. *Corrosion Rate and Inhibition Efficiency Test Results*

The quantitative results of the corrosion rate test and the inhibition efficiency value of the Lophatherum gracile B. extract are presented in Table III.

TABLE III. WEIGHT LOSS AND CORROSION RATE OF STEEL

Inhibitor Concentration (%)	Soaking Time (Hour)	Initial Weight (G)	Final Weight (G)	Weight Change (G)	Corrosion Rate (mpy)	Inhibition Efficiency (%)
0%	24	328.3	328.2	0.13	0.025	-
2%		327.5	327.4	0.03	0.006	75
4%		324.4	324.4	0.00	0.000	100
0%	72	327.0	326.8	0.20	0.012	-
2%		326.9	326.9	0.07	0.004	66.7
4%		332.2	332.2	0.07	0.004	66.7
0%	96	328.8	328.5	0.27	0.012	-
2%		324.5	324.5	0.07	0.003	75
4%		331.9	331.9	0.07	0.003	75

D. *Effect of Immersion Duration on Weight Loss of Steel*

As shown in Figure 6, the greatest reduction in weight is observed in steel samples with a 0% concentration after 96 hours of immersion, amounting to 0.27 grams. Conversely, steel samples treated with 2% and 4% of the Lophatherum gracile B. extract inhibitor demonstrated a weight loss of 0.07 grams. This suggests that steel treated with Lophatherum gracile B. inhibitors demonstrated a markedly reduced rate of weight loss. The data indicate that the use of Lophatherum gracile B. inhibitors is an effective method for protecting metal surfaces, reducing weight loss, and slowing the corrosion rate of reinforcing steel. This finding demonstrated that inhibitors can provide a protective shielding effect that minimizes corrosion [28], as portrayed in Figure 7.

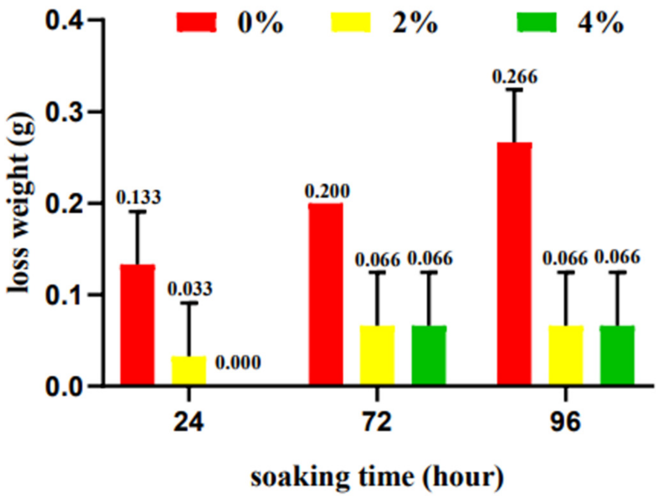

Fig. 6. Reinforcing steel weight loss diagram.

E. *Effect of Inhibitors on Corrosion Rate*

Figure 8 shows that the highest corrosion rate was observed at a 0% concentration of 0.025 mpy, while the lowest corrosion rate was observed at a 4% concentration of 0 mpy over a 96-hour duration, exhibiting an outstanding corrosion resistance level of <1 mpy, as documented in the Corrosion Engineering textbook. This indicates that steel with inhibitors exhibits a diminished corrosion rate in comparison to steel lacking such inhibitors. In particular, the corrosion rate of steel with inhibitors is significantly reduced in comparison to that of untreated steel, emphasizing the efficacy of these green inhibitors in enhancing the longevity and durability of steel components.

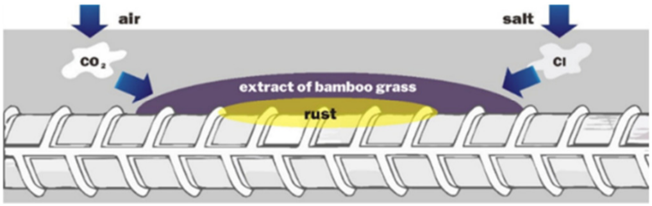

Fig. 7. Corrosion protection on steel.

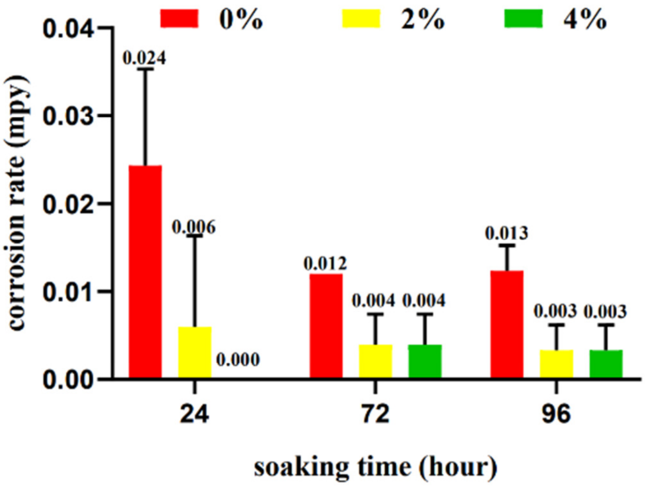

Fig. 8. Corrosion rate diagram.

F. *Inhibitor Efficiency*

The capacity of Lophatherum gracile B. extract to impede corrosion on reinforcing steel was evaluated through the calculation of its inhibition efficiency, as presented in Figure 9. The Lophatherum gracile B. extract inhibitors demonstrated efficacy values exceeding 66% across all test specimen variations. The highest efficiency of 100% was observed at a 4% concentration, while a 75% efficiency was achieved at a 2% concentration. This finding is consistent with the results reported by in [29], where an efficiency of 71.43% for the green tea extract was observed. This suggests that the extract is more effective in preventing corrosion than previous studies have indicated and is a more cost-effective solution. At immersion durations of 72 hours and 96 hours, the efficiency values for the 2% and 4% concentrations were found to be similar, indicating that a 2% concentration of the inhibitor extract may be the optimal choice for preventing the corrosion of reinforcing steel.

G. *Material Structure Test Results Macro Photo*

Macro photographs of the steel surface structure were obtained using an 100 mm macro lens with a magnification at twice the original size, as displayed in Figures 10 and 11.

Figure 10 provides a detailed macro-photographic representation of the steel surface that was subjected to immersion in a corrosive NaCl solution for 96 hours without the application of any inhibitor. This revealed pronounced deterioration, which is characterized by extensive pitting and surface degradation. This considerable deterioration can be attributed to the aggressive nature of the NaCl solution, which facilitates corrosive reactions that result in the breakdown of the steel's protective oxide layer.

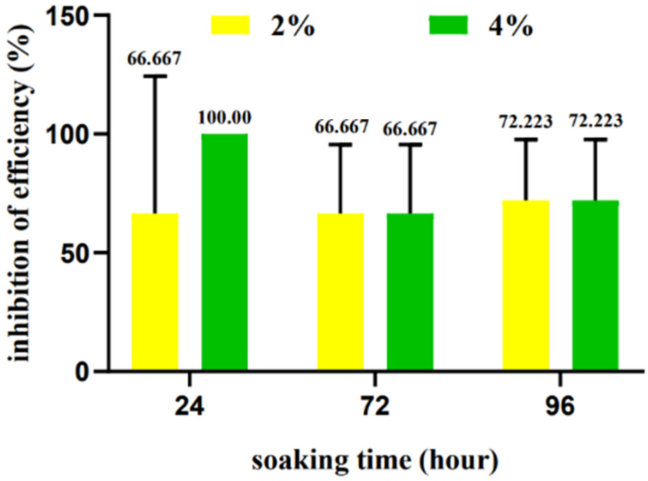

Fig. 9. Inhibition efficiency *Lophatherum gracile* B.

Fig. 10. The 0% concentration steel at 96 hours immersion.

Fig. 11. The 2% concentration steel at 96 hours of immersion.

Figure 11 depicts the steel surface treated with a 2% inhibitor concentration under identical immersion conditions for 96 hours. The macro-photographs demonstrate a markedly improved preservation of the steel surface, with significantly less corrosion and minimal pitting, indicative of the inhibitor's effective protective role in mitigating the corrosive effects of the NaCl solution. As shown in Figure 11, macro images of the steel surface with a 2% inhibitor concentration after 96 hours of immersion demonstrated a notable reduction in corrosion compared to the steel with a 0% inhibitor concentration. The presence of corrosion is evident on the steel surface in the absence of inhibitor protection, while the corrosion rate decreases with increasing inhibitor concentration. This observation is consistent with the findings in [29], where it was reported that corrosion inhibitors can form a protective layer, thereby providing enhanced corrosion protection for metals exposed to aggressive environments [30]. It can be thus concluded that the Lophatherum gracile B. extract is effective in reducing the corrosion rate of reinforcing steel.

H. Steel Tensile Strength Test Result

Tensile strength testing was conducted on the steel in order to evaluate the mechanical properties of the material following the exposure to corrosion. Figure 12 depicts the correlation between the tensile strength of steel and alterations in inhibitor concentration, as well as the duration of immersion.

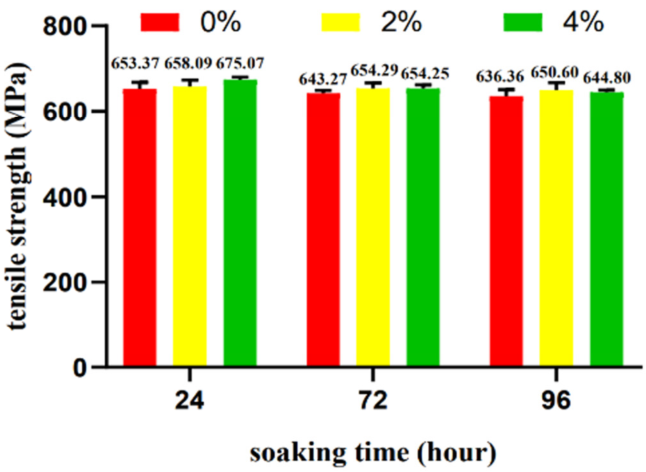

Fig. 12. Steel tensile strength test.

Figure 12 displays that the tensile strength of steel exhibits a decline with the prolongation of immersion periods. For samples immersed for 24 hours, the highest tensile strength of 675 N/mm² was observed at both 2% and 4% inhibitor concentrations. At 72 hours of immersion, the highest tensile strength of 654 N/mm² was achieved at the same concentrations. A 96-hour immersion period yielded the highest tensile strength of 650.6 N/mm², which was observed at a 2% concentration. These findings suggest that the incorporation of inhibitors can effectively mitigate the decline in tensile strength observed in steel specimens. Although there is no significant difference in tensile strength between the 2% and 4% concentrations, the 2% concentration is recommended as it is more effective in minimizing the decline in tensile strength. These findings are consistent with those in [30], which highlight that corrosion not only causes weight loss, but also affects the quality of steel materials [31].

IV. CONCLUSIONS

This research project examined the potential of Lophatherum gracile B. extract as a natural, environmentally friendly alternative to traditional chemical corrosion inhibitors. The impetus for this study was the mounting necessity for sustainable and non-toxic corrosion prevention methodologies. The findings indicated that the Lophatherum gracile B. extract is an effective inhibitor of corrosion in steel. Based on the findings of the research, the following conclusions were drawn:

- The usage of Lophatherum gracile B. extract as a corrosion inhibitor for steel has been demonstrated to markedly diminish weight loss, thereby effectively inhibiting the corrosion rate. This is likely due to the presence of phytochemicals in the extract, including alkaloids, flavonoids, and tannins, which can form a protective film on the steel surface, preventing direct contact with the corrosive environment.
- The corrosion inhibition efficiency of the Lophatherum gracile B. extract was found to be comparable to that of conventional inhibitors, with inhibition values ranging from 66.67% to 100%. This indicates that the natural extract is a promising alternative to synthetic inhibitors for the protection of steel from corrosion.
- The Lophatherum gracile B. extract has exhibited considerable potential as a corrosion inhibitor for steel, effectively preserving its mechanical strength. The extract was found to be most efficacious at a concentration of 2%.

ACKNOWLEDGMENT

The authors would like to genuinely thank the Student Creativity Program (PKM), Directorate General of Higher Education, Ministry of Education and Culture of Indonesia for fully funded to supporting this work.

REFERENCES

[1] S. Singthanu and T. Nilsonthi, "A Comparative Study of the Oxidation Behavior of Hot-Rolled Steel established from Medium and Thin Slabs oxidized in 20% H2O-N2 at 600-900°C," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12646–12651, Feb. 2024, https://doi.org/10.48084/etasr.6168.

[2] C. Zeng, Z. Zheng, H. Zhang, Y. Huang, X. Wang, and G. Liu, "3D mesoscale investigation of non-uniform steel corrosion in reinforced concrete under chloride environments," *Construction and Building Materials*, vol. 411, Jan. 2024, Art. no. 134273, https://doi.org/10.1016/j.conbuildmat.2023.134273.

[3] P. Liu, Q.-H. Zhang, Y. Watanabe, T. Shoji, and F.-H. Cao, "A critical review of the recent advances in inclusion-triggered localized corrosion in steel," *NPJ Materials Degradation*, vol. 6, no. 1, pp. 1–17, Sep. 2022, https://doi.org/10.1038/s41529-022-00294-6.

[4] R. Camaratta *et al.*, "Electrodeposition of organic corrosion inhibitor prepared from *eucalyptus robusta* leaves," *Journal of Building Engineering*, vol. 94, Oct. 2024, Art. no. 109944, https://doi.org/10.1016/j.jobe.2024.109944.

[5] S. B. Ulaeto, R. P. Ravi, I. I. Udoh, G. M. Mathew, and T. P. D. Rajan, "Polymer-Based Coating for Steel Protection, Highlighting Metal–Organic Framework as Functional Actives: A Review," *Corrosion and Materials Degradation*, vol. 4, no. 2, pp. 284–316, Jun. 2023, https://doi.org/10.3390/cmd4020015.

[6] V. P. Vijeesh, M. R. Ramesh, and A. D. Anoop, "Inconel 625 Coatings on AISI 304 Steel using Laser Cladding: Microstructure and Hardness,"

Engineering, Technology & Applied Science Research, vol. 13, no. 5, pp. 11911–11916, Oct. 2023, https://doi.org/10.48084/etasr.6297.

[7] P. D. Desai, C. B. Pawar, M. S. Avhad, and A. P. More, "Corrosion inhibitors for carbon steel: A review," *Vietnam Journal of Chemistry*, vol. 61, no. 1, pp. 15–42, 2023, https://doi.org/10.1002/vjch.202200111.

[8] Shehnazdeep and B. Pradhan, "A study on effectiveness of inorganic and organic corrosion inhibitors on rebar corrosion in concrete: A review," *Materials Today: Proceedings*, vol. 65, pp. 1360–1366, Jan. 2022, https://doi.org/10.1016/j.matpr.2022.04.296.

[9] P. Li *et al.*, "Enhancing corrosion resistance of magnesium alloys via combining green chicory extracts and metal cations as organic-inorganic composite inhibitor," *Corrosion Communications*, vol. 9, pp. 44–56, Mar. 2023, https://doi.org/10.1016/j.corcom.2022.06.002.

[10] J.-H. Zheng, S.-X. Lin, X.-Y. Li, C.-Y. Shen, S.-W. Zheng, and W.-B. Chen, "Flavonoids from Lophatherum gracile Brongn. Ameliorate Liver Damages in High-Fat Diet and Streptozotocin-Induced Diabetic Mice by Regulating PI3K/AKT and NF-Kappa B Pathways," *Journal of Food Biochemistry*, vol. 2023, no. 1, 2023, Art. no. 5273349, https://doi.org/10.1155/2023/5273349.

[11] Z. Li *et al.*, "*Lophatherum gracile* Brongn.: A review on phytochemistry, bioactivity and food applications," *Food Chemistry Advances*, vol. 4, Jun. 2024, Art no.100688, https://doi.org/10.1016/j.focha.2024.100688.

[12] Y. Cheng *et al.*, "Bamboo leaf: A review of traditional medicinal property, phytochemistry, pharmacology, and purification technology," *Journal of Ethnopharmacology*, vol. 306, Apr. 2023, Art. no. 116166, https://doi.org/10.1016/j.jep.2023.116166.

[13] T. Sithuba *et al.*, "Corrosion inhibitory potential of selected flavonoid derivatives: Electrochemical, molecular···Zn surface interactions and quantum chemical approaches," *Results in Engineering*, vol. 16, Dec. 2022, Art. no. 100694, https://doi.org/10.1016/j.rineng.2022.100694.

[14] V. Vorobyova, O. Sikorsky, M. Skiba, and G. Vasyliev, "Quebracho tannin as corrosion inhibitor in neutral media and novel rust conversion agent for enhanced corrosion protection," *South African Journal of Chemical Engineering*, vol. 44, pp. 68–80, Apr. 2023, https://doi.org/10.1016/j.sajce.2023.01.003.

[15] *SNI 2052:2017 Baja tulangan beton*. Badan Standardisasi Nasional, 2017.

[16] B. Hamzah *et al.*, "Determination of thick tannine extract levels of Guava leaves (Psidium guajava L.) by using acetone solution, ethanol, and methanol," *AIP Conference Proceedings*, vol. 3058, no. 1, Apr. 2024, Art. no. 050009, https://doi.org/10.1063/5.0206586.

[17] G. N. Manjesh *et al.*, "Diversity of flavonoids profile in sexually dimorphic clones of betle vine [*Piper betle* L.] genotypes based on liquid chromatography-mass spectrometry [LCMS/MS]," *Industrial Crops and Products*, vol. 187, Nov. 2022, Art. no. 115363, https://doi.org/10.1016/j.indcrop.2022.115363.

[18] R. W. Sari, E. G. Suka, and P. K. Karo, "Ekstrak Daun Sawo (Manilkara Zapota L) Sebagai Inhibitor Terhadap Laju Korosi Baja AISI 1018 Dalam Medium Korosif NaCl 3%," *Journal of Energy, Material, and Instrumentation Technology*, vol. 3, no. 1, Feb. 2022, https://doi.org/10.23960/jemit.v3i1.86.

[19] *SNI 8389:2017 Cara uji tarik logam*. Badan Standardisasi Nasional, 2017.

[20] I. Alenezi, "Effects of Heat Treatment on the Corrosion Behavior of ASTM A-36 Steel," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5320–5324, Feb. 2020, https://doi.org/10.48084/etasr.3326.

[21] G 31-72 Standard Practice for Laboratory Immersion Corrosion Testing of Metals. ASTM International, 2020.

[22] A. Krishnan and A. S. B. Packirisamy, "Exploration of therapeutic potential and pesticidal activity of *Sapindus mukorossi* by In vitro and *Insilico* profiling of phytochemicals," *Journal of Molecular Structure*, vol. 1315, Nov. 2024, Art. no. 138866, https://doi.org/10.1016/j.molstruc.2024.138866.

[23] Ş. S. Çatav, E. Çetin, E. Vural, and B. Bürün, "Boron toxicity tolerance in barley may be related to intrinsically higher levels of reactive oxygen species in the shoots," *Botanica Serbica*, vol. 47, no. 1, pp. 113–124, Apr. 2023, https://doi.org/10.2298/BOTSERB2301113C.

[24] J. E. Mbosso Teinkela *et al.*, "Evaluation of *in vitro* antiplasmodial, antiproliferative activities, and *in vivo* oral acute toxicity of *Spathodea campanulata* flowers," *Scientific African*, vol. 21, Sep. 2023, Art. no. e01871, https://doi.org/10.1016/j.sciaf.2023.e01871.

[25] Y.-L. Ma *et al.*, "In vitro digestibility and hepato-protective potential of Lophatherum gracile Brongn. leave extract," *Food Chemistry*, vol. 433, Feb. 2024, Art. no. 137336, https://doi.org/10.1016/j.foodchem.2023.137336.

[26] J. Chen, L. Zhang, P. Zhao, G. Ma, Q. Li, and X. Yu, "Synthesized alkyl ferulates with different chain lengths inhibited the formation of lipid oxidation products in soybean oil during deep frying," *Food Chemistry*, vol. 410, Jun. 2023, Art. no. 135458, https://doi.org/10.1016/j.foodchem.2023.135458.

[27] X. Sun *et al.*, "Synthesis, characterization, and the antioxidant activity of the acetylated chitosan derivatives containing sulfonium salts," *International Journal of Biological Macromolecules*, vol. 152, pp. 349–358, Jun. 2020, https://doi.org/10.1016/j.ijbiomac.2020.02.177.

[28] S. Bilgiç, "Plant extracts as corrosion inhibitors for mild steel in H2SO4 and H3PO4 media – Review II," *International Journal of Corrosion and Scale Inhibition*, vol. 11, no. 1, pp. 1–42, 2022, https://doi.org/10.17675/2305-6894-2022-11-1-1.

[29] M. A. Chowdhury, N. Hossain, M. M. S. Ahmed, M. A. Islam, S. Islam, and M. M. Rana, "Green tea and tulsi extracts as efficient green corrosion inhibitor for aluminum alloy in alkaline medium," *Heliyon*, vol. 9, no. 6, Jun. 2023, Art. no. e16504, https://doi.org/10.1016/j.heliyon.2023.e16504.

[30] H. M. C. Abubakr, M. E. Ghaith, A. A. El-Sherif, and M. S. El-Deab, "Influence of metal ions on cysteine as a corrosion inhibitor for low carbon steel in sulfuric acid: Polarization, EIS, XPS, and DFT analysis," *International Journal of Electrochemical Science*, vol. 19, no. 7, Jul. 2024, Art. no. 100620, https://doi.org/10.1016/j.ijoes.2024.100620.

[31] A. Dantas *et al.*, "A methodology to evaluate seawater corrosion on quasi-static tensile properties of a structural steel," *Engineering Failure Analysis*, vol. 164, Oct. 2024, Art. no. 108613, https://doi.org/10.1016/j.engfailanal.2024.108613.