



Atmospheric Corrosion Inhibition of Steel Using Tea Leaf Extract in the Coastal Environment of Air Tawar, Padang

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Abstract

This study evaluates the effectiveness of tea leaf extract as a corrosion inhibitor for steel under real coastal atmospheric exposure. The novelty of this work lies in its direct assessment of a plant-derived inhibitor in an open-air marine environment, a setting that has not been adequately addressed in previous studies, which have largely focused on controlled aqueous systems. In addition, this study employs mature tea leaves, an abundant agricultural byproduct with naturally high tannin content, processed through a simple, solvent-free extraction method, thereby offering a sustainable route for green inhibitor development. The extract was obtained from mature tea leaves through aqueous boiling, and its tannin content was quantified using UV-Vis spectrophotometry. ASSAB 760 steel specimens were coated by immersion in tea extract at varying concentrations and soaking durations, followed by natural exposure in a coastal environment for 1 to 30 days. Corrosion behavior was evaluated using the weight loss method. The results showed that mature tea leaves contained the highest tannin concentration (29530.95 ppm), supporting their selection for inhibitor application. The optimum extract concentration was identified as 11000 ppm with a 5-hour immersion time. Under these conditions, treated steel exhibited a substantially lower corrosion rate (7.78×10^{-5} g/cm²/day) compared to untreated steel (1.66×10^{-4} g/cm²/day), corresponding to a maximum inhibition efficiency of 84.71%. The inhibition mechanism is attributed to the formation of a stable Fe³⁺-tannin chelate complex that adsorbs onto the steel surface, forming a protective film that restricts the ingress of aggressive chloride-rich moisture in the coastal atmosphere. Overall, the findings demonstrate the practical viability of mature tea leaf extract as an effective and environmentally benign atmospheric corrosion inhibitor, providing field-relevant insight into sustainable protection strategies for marine-exposed steel infrastructure.

Keywords: Coastal atmospheric corrosion, green tea leaf-based inhibitor, steel surface protection, tannin

Introduction

Steel is one of the most widely used metallic materials in building construction, the automotive industry, and various technical applications (Braun et al., 2024). Composed primarily of iron, its chemical behavior is strongly influenced by the inherent tendency of iron to oxidize when exposed to humid or corrosive environments. This oxidation process leads to the formation of rust (iron oxides), which progressively reduces the structural integrity of the material. Such characteristics render steel highly susceptible to corrosion, particularly in atmospheric conditions rich in water vapor, chloride ions, and oxygen, as commonly found in coastal regions. Corrosion not only diminishes the economic value of steel but may also compromise structural safety if not effectively mitigated (Hatamov, 2022).

Multiple strategies have been developed to mitigate the rate of metal corrosion, one of which is the application of corrosion inhibitors, which are

substances capable of slowing the reaction rate between a metal and its environment (Al-Baghdadi et al., 2023). Such inhibitors may consist of either inorganic or organic compounds (Ma et al., 2022). In practice, metal protection can also be achieved by forming a barrier layer on its surface, such as through coating or painting (Ziganshina et al., 2020). Traditional paints containing compounds like lead oxide or chromates act as inhibitors by preventing direct interaction between the metal and surrounding corrosive agents (Soltanov et al., 2023). However, these compounds are known for their high toxicity and potential to cause environmental pollution (Sodiya & Dawodu, 2022). Consequently, the search for environmentally benign, non-toxic, and cost-effective alternatives has become a major focus in green chemistry approaches over the past few decades (Răuță et al., 2025).

In recent years, plant-derived organic compounds such as tannins, alkaloids, organic acids, amino acids, and natural pigments have been

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extensively investigated as potential green corrosion inhibitors (Holla et al., 2024). Tannins, belonging to the polyphenol group, exhibit notable potential as corrosion inhibitors due to their ability to form stable complexes with metal ions, coupled with their biodegradability and environmental friendliness (Lebrini, 2024). These complexes adsorb onto the metal surface, thereby acting as a barrier that limits the ingress of oxygen and other aggressive ions. Consequently, the corrosion rate can be effectively reduced (Shilkamy et al., 2025).

Tannins can be extracted from various parts of plants, including bark, stems, seeds, roots, buds, and leaves (Das et al., 2020). Examples of plant sources rich in tannins include gambier leaves (Andini et al., 2023), guava leaves (Faradilla & Rizal, 2023), plant galls, oak, chestnut, hemlock, mangrove, grapes, pomegranates, cranberries, red wine, tea extract, coffee (Pourmadadi et al., 2024), as well as pine and other coniferous species (Molnar et al., 2024). This compound can be obtained through a simple extraction process, such as boiling with water as the solvent (Pourmadadi et al., 2024).

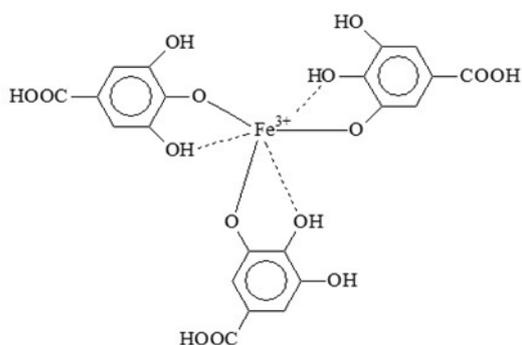


Figure 1. A stable iron–tannin chelate complex formed via coordination bonding between Fe^{3+} ions and the hydroxyl

Previous studies have extensively examined the effectiveness of tea leaf extracts as corrosion inhibitors, primarily in aqueous environments such as acidic or saline media. It has been reported that phenolic compounds from White tea effectively reduce the corrosion rate of mild steel under 1M Hydrochloric acid solution (Kaban et al., 2021). In a similar study, the use of green tea polyphenols was found to mitigate the corrosion of CT3 steel in an artificial marine environment through salt spray and electrochemical methods. The results indicated that tea extracts in 3.5% NaCl solution facilitated the formation of a protective layer through the adsorption of tannin–metal complexes, which served as corrosion barriers (Tien et al., 2025).

There remains a significant knowledge gap concerning the performance of tannin-based inhibitors under real atmospheric exposure, particularly in coastal microclimates that are enriched with moisture and airborne chloride.

These environments involve complex phenomena such as chloride transport, cyclic wetting and drying, and aerosol deposition, none of which can be fully reproduced under standard laboratory conditions.

To the best of our knowledge, no prior study has evaluated the effectiveness of tea leaf extract as a corrosion inhibitor for steel under natural open-air coastal exposure. This work further introduces the novel use of mature tea leaves, an abundant agricultural byproduct with high tannin content, processed through a simple solvent-free extraction method. By integrating a sustainable feedstock with direct atmospheric testing, this study advances the field by providing field-relevant insight into green corrosion mitigation strategies for marine-adjacent infrastructure.

Methods

The present study was designed to evaluate the performance of tea leaf extracts as atmospheric corrosion inhibitors for steel in a coastal environment. The experimental workflow comprised four key stages: preparation of materials, extraction and quantification of tannin, optimization of coating parameters, and field exposure testing under natural atmospheric conditions. Each stage was carefully designed to ensure reproducibility and reliability of the results.

Materials

The primary material used in this study was steel (ASSAB 760, AISI 1148, 0.5% C) supplied by PT Tira Austenite, Padang, Indonesia. The plant material used was tea leaves (*Camellia sinensis*) collected from the Kayu Aro tea plantation, Solok Regency, West Sumatra, Indonesia. Both mature (older) and young (bud) leaves were selected to compare tannin content and inhibitory efficiency. The leaves were thoroughly cleaned, air-dried, finely cut, and extracted using deionized water as the solvent.

The following reagents and chemicals were used, all of analytical grade: Potassium ferricyanide ($\text{K}_3\text{Fe}(\text{CN})_6$, 0.016 M), iron(III) chloride (FeCl_3 , 0.02 M), phosphoric acid (H_3PO_4 , 6.03 M), nitric acid (HNO_3 , 1%), and acetone (p.a., Merck, Germany) for colorimetric determination of tannin and surface cleaning; A 1% gelatin solution was freshly prepared before use; while distilled water (aquades) was used for all dilutions and rinsing steps; Standard tannic acid (Sigma-Aldrich, USA) was employed to construct calibration curves for quantitative spectrophotometric analysis.

The main equipment and instruments used included: an analytical balance (Ohaus PA214C, readability 0.0001 g) for precise mass determination; a UV–Visible spectrophotometer (Shimadzu UV-1800, Japan) for measuring absorbance at 670 nm during tannin analysis; an oven (Memmert UN55) for controlled drying at 40 °C; a desiccator with silica gel for sample cooling before weighing. Additional equipment comprised a mechanical grinder and polishing unit for surface preparation,

class-A borosilicate glassware (Pyrex) for volumetric analyses, and a corrosion exposure rack installed approximately 100 m from the shoreline at Air Tawar Beach, Padang.

The corrosion tests were conducted under natural atmospheric conditions without artificial control of temperature or humidity, thereby closely representing real coastal exposure environments.

Preparation of Steel Specimens

Steel bars were cut into discs approximately 2.5 cm in diameter and 0.5 cm in thickness. The surfaces were sequentially polished with emery papers of progressively finer grit to remove surface irregularities and achieve a uniform metallic sheen. The specimens were then degreased using detergent, rinsed with distilled water, and immersed in 1% nitric acid to remove oxide residues. Subsequently, the discs were washed with analytical-grade acetone, oven-dried at 40 °C for 5 minutes, cooled in a desiccator for 15 minutes, and weighed to record their initial mass (W_0) (Putra et al., 2022).

Extraction and Quantification of Tannins

Mature and young tea leaves (350 g each) were chopped into small pieces and subjected to aqueous extraction by boiling in 2 L of distilled water. The filtrate obtained was diluted, and a 10 mL aliquot was transferred into a 100 mL volumetric flask with distilled water (Fraga-Corral et al., 2020). From this solution, 3 mL was pipetted into a 25 mL volumetric flask, followed by sequential addition of 1 mL $K_3Fe(CN)_6$ (0.016 M) and $FeCl_3$ (0.02 M). After gentle shaking and a 15-minute rest period, 3 mL of H_3PO_4 (6.03 M) was added, and the solution was allowed to stand for 2 minutes before the addition of 1% gelatin solution. The mixture was shaken and made up to volume with distilled water. Absorbance was measured at 670 nm using a UV-Vis spectrophotometer, and tannin content was calculated from a previously established calibration curve (Hagerman, 2002). The extract with the highest tannin concentration was selected for coating applications.

Optimization of Coating Parameters

To determine the optimum inhibitor concentration, steel specimens were immersed in 50 mL of tea extract at concentrations ranging from 1000 to 13000 ppm for 3 hours. After immersion, specimens were oven-dried (40 °C, 5 minutes), cooled in a desiccator (15 minutes), and weighed (W_i). The percentage weight gain (WG) was calculated using equation 1 (Solanki et al., 2025):

$$WG(\%) = \frac{W_i - W_0}{W_0} \times 100\% \quad (1)$$

where W_0 and W_i are the steel mass before and after coating, respectively (g).

Similarly, the optimum immersion time was established by exposing steel specimens to the optimum concentration extract for durations

ranging from 1 to 8 hours, followed by the same drying and weighing protocol.

Atmospheric Corrosion Testing

Field exposure testing was conducted at a coastal site approximately 100 m from the shoreline of Air Tawar Beach, Padang, West Sumatra. Steel specimens coated under optimum conditions, alongside uncoated controls, were suspended in the open air for exposure periods ranging from 1 to 30 days (Jiao et al., 2022). Corrosion rates (CR) were determined using the weight loss method according to equation 2 (Boukhedena et al., 2024).

$$CR = \frac{W_0 - W_b}{A \times t} \quad (2)$$

where W_0 is the initial mass before exposure (g), W_b is the mass after exposure (g), A is the exposed surface area (cm^2), and t is the exposure time (days).

The inhibition efficiency (η) was calculated according to equation 3 (Lin et al., 2024).

$$\eta(\%) = \frac{CR_u - CR_o}{CR_u} \times 100 \quad (3)$$

where CR_u and CR_i are the corrosion rates of uncoated and coated specimens, respectively ($g/cm^2/day$).

This integrated approach allowed a direct comparison between treated and untreated steel under identical environmental conditions, ensuring that the reported inhibition efficiencies accurately reflect the performance of the tea leaf extract under real-world atmospheric exposure.

Results and Discussion

Tannin content analysis revealed that mature tea leaves contained a significantly higher tannin concentration (29530.95 ppm) compared to young tea shoots (24326.19 ppm). This result aligns with previous findings showing that the tannin concentration in dried tea leaves tends to be higher than that in fresh ones (Rusita et al., 2019). The higher tannin level in mature tea leaves supports their selection as the primary source for the corrosion inhibitor in subsequent experiments.

The influence of tea leaf extract concentration on the coating performance is shown in **Table 1** and illustrated in **Figure 2**. The percentage of steel weight gain increased with extract concentration, reaching an optimum at 11000 ppm. This trend indicates that the formation of the tannin-iron complex layer is concentration-dependent, where higher tannin availability enhances surface adsorption and chelation with Fe^{3+} ions. At the optimum concentration, the steel surface exhibited a distinct dark purple color, which

is characteristic of iron–tannin complex formation. (Yıldız & Sahiner, 2021). A similar observation was reported that polyphenolic extracts from green tea promote the formation of protective Fe–O–C coordination bonds that suppress electrochemical dissolution (Tien et al., 2025).

Table 1. Steel weight gain at different tea leaf extract concentrations

Concentration of tea extract (ppm)	%WG	Average ± SD
5000	0.0118 0.0093 0.0087	0.0099 ± 0.0016
6000	0.0112 0.0124 0.0100	0.0112 ± 0.0012
7000	0.0196 0.0202 0.0173	0.0190 ± 0.0015
8000	0.0208 0.0188 0.0191	0.0196 ± 0.0011
9000	0.0192 0.0211 0.0186	0.0197 ± 0.0013
10000	0.0178 0.0201 0.0216	0.0198 ± 0.0019
11000	0.0276 0.0252 0.0267	0.0265 ± 0.0012
12000	0.0244 0.0269 0.0238	0.0250 ± 0.0017
13000	0.0251 0.0240 0.0228	0.0240 ± 0.0011
14000	0.0235 0.0244 0.0222	0.0234 ± 0.0011

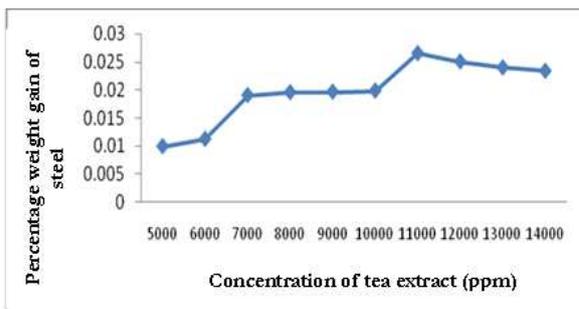


Figure 2. Effect of Tea Leaf Extract Concentration on Steel Weight Gain after 3 hours Immersion

At concentrations below 11000 ppm, incomplete coating coverage likely occurred, leading to lower weight gain. Conversely, exceeding this concentration resulted in a decline in mass gain, suggesting that the surface had reached saturation. Excess tannin–iron complexes likely remained suspended in the bulk solution rather than depositing on the steel surface. Such over-saturation behavior is also reported in plant-based inhibitor systems, where excessive organic molecules hinder compact film formation due to aggregation or solubility limits (Bhardwaj et al., 2021). Therefore, 11000 ppm was identified as the optimum concentration that balances adsorption density and film stability.

The effect of immersion time on coating formation at this optimum concentration is presented in **Table 2** and **Figure 3**.

Table 2. Steel weight gain at different immersion times (11000 ppm extract)

Immersion Time (Hours)	%WG	Average ± SD
1	0.0131 0.0158 0.0147	0.0145 ± 0.0013
2	0.0112 0.0128 0.0134	0.0124 ± 0.0012
3	0.0205 0.0188 0.0197	0.0197 ± 0.0008
4	0.0319 0.0256 0.0280	0.0285 ± 0.0032
5	0.0335 0.0321 0.0354	0.0337 ± 0.0016
6	0.0189 0.0177 0.0203	0.0190 ± 0.0013
7	0.0161 0.0183 0.0158	0.0167 ± 0.0014

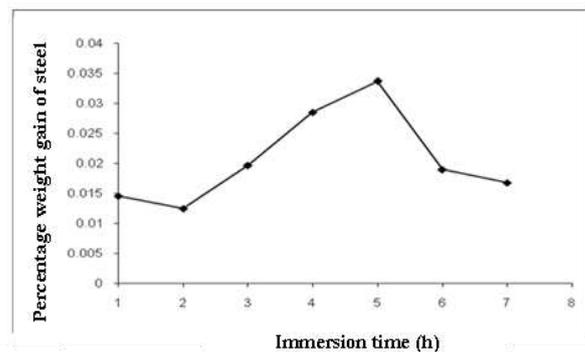


Figure 3. Effect of Immersion Time in Tea Leaf Extract on Steel Weight Gain

The steel weight gain increased with immersion duration, peaking at 5 hours, after which it began to decline. This indicates that sufficient contact time is crucial for uniform adsorption and chelate film formation. Similar kinetic behavior was observed in the optimum immersion period for the equilibrium between adsorption and desorption processes (Bian et al., 2019). Shorter immersion times (<5 h) likely produced incomplete surface

coverage, while longer exposure may have led to desorption or hydrolysis of weakly bound complexes, resulting in decreased film mass. Prolonged immersion can also increase the acidity or organic content of the solution, inducing partial corrosion of the protective layer. The effect of exposure time on the corrosion rate of steel in an open-air coastal environment is presented in **Table 3** and **Figure 4**.

Table 3. Corrosion rate of uncoated and tannin-coated steel under open-air coastal exposure

Corrosion Exposure Time (days)	Corrosion Rate	
	Without Tannin	With Tannin
1	$1.91 \times 10^{-3} \pm 1.66 \times 10^{-4}$	$1.95 \times 10^{-3} \pm 4.32 \times 10^{-4}$
3	$4.56 \times 10^{-4} \pm 7.00 \times 10^{-5}$	$1.97 \times 10^{-4} \pm 5.68 \times 10^{-6}$
6	$6.40 \times 10^{-4} \pm 1.56 \times 10^{-4}$	$1.93 \times 10^{-4} \pm 1.50 \times 10^{-4}$
9	$2.95 \times 10^{-4} \pm 1.23 \times 10^{-4}$	$1.26 \times 10^{-4} \pm 1.19 \times 10^{-4}$
12	$1.30 \times 10^{-4} \pm 9.82 \times 10^{-6}$	$1.89 \times 10^{-4} \pm 2.22 \times 10^{-6}$
15	$1.66 \times 10^{-4} \pm 2.97 \times 10^{-5}$	$7.78 \times 10^{-5} \pm 5.64 \times 10^{-5}$
20	$1.61 \times 10^{-4} \pm 2.49 \times 10^{-5}$	$5.83 \times 10^{-5} \pm 2.64 \times 10^{-5}$
21	$1.72 \times 10^{-4} \pm 4.11 \times 10^{-5}$	$5.60 \times 10^{-5} \pm 2.54 \times 10^{-5}$
24	$1.01 \times 10^{-4} \pm 1.12 \times 10^{-5}$	$2.92 \times 10^{-5} \pm 7.13 \times 10^{-6}$
27	$1.19 \times 10^{-4} \pm 2.00 \times 10^{-5}$	$1.83 \times 10^{-5} \pm 1.32 \times 10^{-5}$
30	$9.37 \times 10^{-5} \pm 3.99 \times 10^{-6}$	$1.63 \times 10^{-5} \pm 2.61 \times 10^{-7}$

The highest corrosion rates occurred within the first three days for both coated and uncoated steel, a phenomenon attributed to the high aggressiveness of chloride (Cl^-) and sulfate (SO_4^{2-}) ions during the early exposure period, which can penetrate and damage the initial protective film

(Bernardi et al., 2020). After this initial stage, corrosion rates decreased and stabilized, likely due to the formation of a passive oxide film that inhibited the diffusion of oxygen and aggressive ions to the metal surface (Gui-Rong et al., 2019).

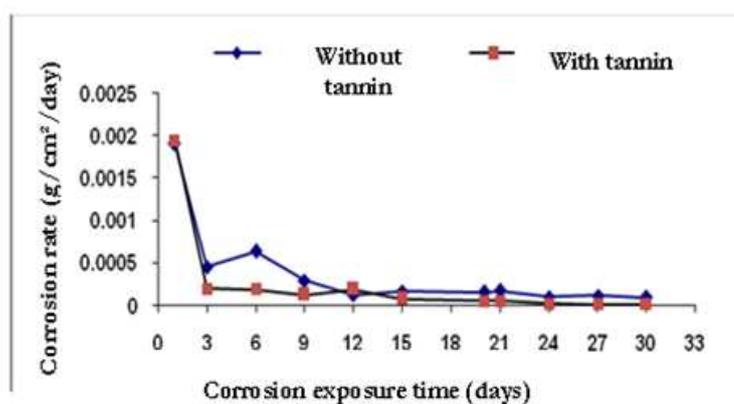


Figure 4. Effect of Atmospheric Exposure Time on the Corrosion Rate of Steel

A temporary increase in the corrosion rate of uncoated steel on day six was observed, possibly due to the mechanical disruption of the passive layer, as evidenced by visible oxide deposits at the bottom of the container. Quantitative analysis confirmed that tannin-coated steel exhibited a much lower corrosion rate (7.78×10^{-5} g/cm²/day) compared to uncoated steel (1.66×10^{-4} g/cm²/day),

demonstrating the effectiveness of the tannin-based film in mitigating corrosion. This finding aligns with recent studies showing that polyphenolic inhibitors can reduce corrosion rates by up to 70–90% depending on their surface binding strength and environmental conditions (Sheokand et al., 2024). The variation in inhibition efficiency throughout the exposure period is shown in **Table 4** and **Figure 5**.

Table 4. Inhibition efficiency of tannin-coated steel during atmospheric exposure

Corrosion Exposure Time (days)	Inhibition Efficiency (%)
3	56.92
6	69.77
9	57.22
12	51.13
15	53.00
18	63.82
21	67.39
24	80.98
27	84.72
30	82.55

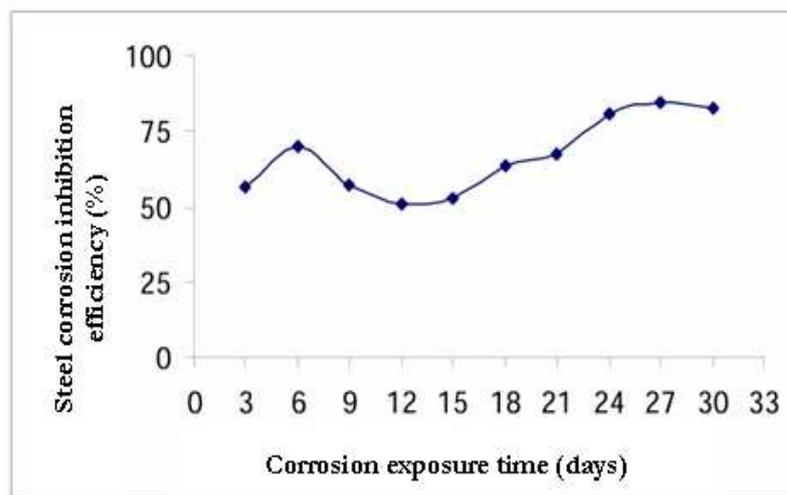


Figure 5. Variation of Inhibition Efficiency Over the Atmospheric Exposure Period

The maximum efficiency (84.71%) was recorded on day 27, followed by a slight decline on day 30. This minor decrease may be attributed to the reduced stability of the protective film or a saturation effect, where the extract's ability to form additional tannin–metal complexes had reached its limit. Nevertheless, the decrease was not significant, indicating that the inhibitor maintained strong protective performance toward the end of the testing period. A comparable study reported an inhibition efficiency of 81.71% for *Commelina benghalensis* leaf extract in 1 M HCl solution,

demonstrating a similar trend of sustained protection despite varying corrosion environments (Akaaza et al., 2023). Both findings highlight the promising potential of plant-derived organic compounds as efficient and sustainable corrosion inhibitors.

The overall inhibition mechanism can be rationalized in three main stages: First, Fe atoms at the steel surface oxidize to Fe²⁺ and subsequently to Fe³⁺ to achieve a half-filled 3d⁵ configuration, which is thermodynamically more stable. Second, Fe³⁺ ions form coordination bonds with the

hydroxyl and carbonyl groups of tannins, producing stable Fe–O–C chelate complexes. Finally, these complexes adsorb onto the steel surface through both physisorption and chemisorption, generating a compact, adherent barrier that prevents the ingress of aggressive ions such as Cl^- and SO_4^{2-} (Bacca et al., 2022). The strong correlation between the observed inhibition efficiency and the stability of the Fe–tannin chelate supports this mechanistic interpretation, consistent with findings from other natural inhibitor systems involving flavonoids and lignin derivatives (Sesia et al., 2023).

Conclusions

This study demonstrates that tannin-rich extracts from mature tea leaves are highly effective as a green corrosion inhibitor for steel in open-air coastal environments. The extract, containing 29530.95 ppm tannins, exhibited optimal coating performance at a concentration of 11000 ppm with a 5-hour immersion period, resulting in the formation of a dense and adherent iron–tannin complex layer. Under these conditions, the corrosion rate of coated steel was reduced to 7.78×10^{-5} g/cm²/day, significantly lower than that of uncoated steel (1.66×10^{-4} g/cm²/day), with a maximum inhibition efficiency of 84.71% observed on day 27.

The protective action is attributed to the strong coordination between Fe^{3+} ions and tannin hydroxyl groups, producing a stable chelate film that effectively impedes the ingress of aggressive chloride and sulfate ions. The sustained high efficiency over the 30-day exposure highlights the durability of this natural protective barrier.

Beyond its scientific relevance, these findings underscore the untapped potential of mature tea leaves, an agricultural byproduct often treated as waste, as a cost-effective, biodegradable, and environmentally benign alternative to synthetic corrosion inhibitors. This work not only expands the scope of atmospheric corrosion mitigation strategies but also aligns with the principles of green chemistry, offering a viable path toward sustainable materials protection in marine-adjacent infrastructures.

Conflict of Interest

The authors confirm that there is no conflict of interest regarding the publication of this research.

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