

CORROSION PROTECTION OF ST-37 STEEL USING RED DRAGON FRUIT PEEL EXTRACT: EFFECTS OF INHIBITOR CONCENTRATION AND COATING DURATION

Muh. Azis Albar. J^{1*}, Stevina Kantohe², Ardiansah³, Rismul Trianto Salawali⁴

^{1,2,3}Mineral Chemical Engineering Study Program, Politeknik Industri Logam Morowali, Sulawesi Tengah, 94974, Indonesia

⁴Chemical Analysis Study Program, AK-Manufaktur Bantaeng, Sulawesi Selatan, 92461, Indonesia

*E-mail: azis.albar.j@gmail.com

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Abstract

Corrosion of ST-37 steel in acidic rainwater can compromise material durability, particularly in industrial environments where local atmospheric conditions may contribute to corrosive exposure. This study investigated the effect of red dragon fruit (*Hylocereus polyrhizus*) peel extract concentration and coating duration on the corrosion protection of ST-37 steel exposed to actual rainwater collected from the Morowali industrial area. The collected rainwater had a measured pH of 4.88 and was used to represent the local corrosive environment. The inhibitor was prepared by macerating 100 g of dried red dragon fruit peel powder in 1 L of 96% ethanol for 3 × 24 h. The filtrate was concentrated at 80 °C and 300 rpm and subsequently diluted with 96% ethanol to obtain inhibitor concentrations of 6%, 8%, 10%, and 12% (v/v). The extract was applied to ST-37 specimens with coating durations of 2 and 4 days. After coating, the specimens were exposed to rainwater for 504 h, and corrosion performance was evaluated using the weight loss method with an uncoated specimen as the control. The corrosion rate of the uncoated control was 4.2731 mpy and was used as the reference for calculating inhibition efficiency. The corrosion rate decreased with increasing extract concentration up to 10%, but increased at 12%. The lowest corrosion rate was obtained at 10% (v/v) extract concentration with a 4-day coating, reaching 1.5153 mpy, corresponding to an inhibition efficiency of 64.54%. The decrease in protection at 12% may be associated with less uniform film formation or aggregation of extract constituents at excessive concentration. The higher protection obtained after 4 days of coating indicates that longer contact with the steel surface may facilitate the formation of a more effective protective layer. These results demonstrate the potential of red dragon fruit peel extract as a biomass-derived corrosion inhibitor for ST-37 steel under the investigated rainwater exposure conditions.

Keywords: Red Dragon Fruit Peel, Corrosion Inhibitor, ST-37 Steel, Coating Time, Inhibition Efficiency

Abstrak

Korosi pada baja ST-37 dalam air hujan yang bersifat asam dapat menurunkan ketahanan material, khususnya pada lingkungan industri yang memiliki kondisi atmosfer yang berpotensi meningkatkan paparan korosif. Penelitian ini bertujuan untuk mengkaji pengaruh konsentrasi ekstrak kulit buah naga merah (*Hylocereus polyrhizus*) dan lama pelapisan terhadap perlindungan korosi baja ST-37 yang terpapar air hujan aktual yang dikumpulkan dari kawasan industri Morowali. Air hujan yang digunakan memiliki pH terukur sebesar 4,88 dan digunakan untuk merepresentasikan kondisi lingkungan korosif setempat. Inhibitor dibuat melalui proses maserasi menggunakan 100 g serbuk kulit buah naga merah kering dalam 1 L etanol 96% selama 3 × 24 jam. Filtrat kemudian dipekatkan pada suhu 80 °C dengan kecepatan pengadukan 300 rpm dan selanjutnya diencerkan menggunakan etanol 96% untuk memperoleh konsentrasi inhibitor sebesar 6%, 8%, 10%, dan 12% (v/v). Ekstrak diaplikasikan pada spesimen baja ST-37 dengan lama pelapisan 2 dan 4 hari. Setelah proses pelapisan, spesimen direndam dalam air hujan selama 504 jam, kemudian kinerja perlindungan terhadap korosi dievaluasi menggunakan metode kehilangan berat (*weight loss*) dengan spesimen tanpa pelapisan sebagai kontrol. Laju korosi pada spesimen kontrol tanpa pelapisan sebesar 4,2731 mpy dan digunakan sebagai nilai acuan dalam perhitungan efisiensi inhibisi. Laju korosi menurun seiring dengan peningkatan konsentrasi ekstrak hingga 10%, tetapi kembali meningkat pada konsentrasi 12%. Laju korosi terendah diperoleh pada konsentrasi ekstrak 10% (v/v) dengan lama pelapisan 4 hari, yaitu sebesar 1,5153 mpy, dengan efisiensi inhibisi sebesar 64,54%. Penurunan efektivitas perlindungan pada konsentrasi 12% berkaitan dengan

pembentukan lapisan yang kurang seragam atau terjadinya agregasi senyawa penyusun ekstrak pada konsentrasi yang terlalu tinggi. Perlindungan yang lebih tinggi setelah pelapisan selama 4 hari menunjukkan bahwa waktu kontak yang lebih lama dengan permukaan baja dapat mendukung pembentukan lapisan pelindung yang lebih efektif. Hasil penelitian menunjukkan bahwa ekstrak kulit buah naga merah berpotensi dimanfaatkan sebagai inhibitor korosi berbasis biomassa untuk melindungi baja ST-37 pada kondisi paparan air hujan yang diteliti.

Keywords: Kulit Buah Naga Merah, Inhibitor Korosi, Baja ST-37, Waktu Pelapisan, Efisiensi Inhibisi.

1. Introduction

Corrosion is one of the major challenges associated with the use of carbon steel because it can compromise material integrity and service life, particularly in acidic and electrolyte-containing environments (Royani *et al.*, 2019) (Akmal, Za and Ishak, 2019). In industrial areas, rainwater can contain dissolved ions and atmospheric pollutants originating from industrial activities, combustion processes, transportation, and particulate emissions. Such atmospheric constituents can alter the physicochemical characteristics of precipitation and potentially increase its corrosivity toward metallic materials (Bernardi *et al.*, 2020). Therefore, the corrosion behavior of steel exposed to naturally collected rainwater may differ from that observed in laboratory-prepared acidic solutions because the composition of actual rainwater is influenced by local atmospheric and environmental conditions (Grzegorzec *et al.*, 2025).

The use of corrosion inhibitors is an established approach for reducing metal degradation. Recently, plant-derived extracts and biomass wastes have received increasing attention as green corrosion inhibitors because they contain diverse phytochemicals capable of interacting with metal surfaces and forming protective layers (Al Jahdaly *et al.*, 2022). In addition to their corrosion-inhibition potential, biomass-based inhibitors can provide environmental and economic benefits through the utilization of renewable and readily available organic resources (Satria Jati and Ayu Triwuri, 2023) (Dewi, Asih and Wijana, 2026) (Budi Utomo *et al.*, 2018). Previous reviews have reported that plant extracts are generally considered biodegradable, renewable, and relatively accessible, while biomass waste can be valorized as a source of corrosion-protection materials (Marzorati, Verotta and Trasatti, 2018).

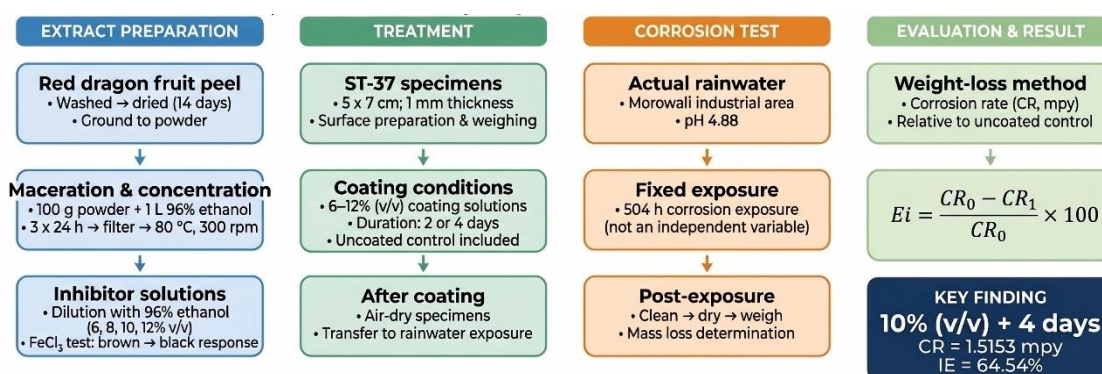
Red dragon fruit peel (*Hylocereus polyrhizus*) is an agricultural biomass waste containing bioactive compounds, including phenolic compounds, flavonoids, and tannins, which may contribute to corrosion inhibition through interactions with metallic surfaces (Yufita *et al.*, 2022) (Oriana Jawa La *et al.*, 2020). Previous studies have demonstrated the potential of red dragon fruit peel extract as a corrosion inhibitor for steel. Nanda Sari *et al.* (2019a), for example, reported the potential of red dragon fruit peel as a corrosion inhibitor for A36 steel using the weight loss method. Macadangdang (2022), also investigated ethanolic red dragon fruit peel extract on mild steel in an acidic medium and reported that inhibitor concentration and immersion time influenced inhibition performance, with adsorption of extract constituents contributing to corrosion protection. These findings support the potential application of red dragon fruit peel as a biomass-derived corrosion inhibitor, although its performance remains dependent on the metal substrate, corrosive medium, extract preparation, inhibitor concentration, and application conditions (Ronaldo Simanjuntak *et al.*, 2020) (Yuniar *et al.*, 2026) (Mulyaningsih and Mujiarto, 2019).

Recent studies have also examined red dragon fruit peel extract for steel protection under laboratory-controlled corrosive media, including acidic and saline environments (Macadangdang, 2022) (Maulana *et al.*, 2026). However, limited studies have addressed the combined effects of inhibitor concentration and coating duration on ST-37 steel exposed to naturally collected rainwater from an industrial environment (Tanti *et al.*, 2025). In particular, the use of actual rainwater provides an exposure condition that incorporates the physicochemical characteristics of the local environment rather than relying solely on a predefined laboratory electrolyte. This approach is relevant to the Morowali industrial area because atmospheric and industrial activities can influence the composition and corrosivity of precipitation. In the present study, the collected rainwater had a measured pH of 4.88, indicating an acidic exposure condition. The use of this rainwater was therefore intended to provide a more representative corrosive medium for

evaluating the performance of the inhibitor under environmental conditions relevant to the study area.

Accordingly, this study investigated the effect of red dragon fruit peel extract concentration and coating duration on the corrosion protection of ST-37 steel. The extract was prepared by maceration using 100 g of dried red dragon fruit peel powder and 1 L of 96% ethanol for 3 × 24 h, followed by concentration and dilution to obtain 6%, 8%, 10%, and 12% (v/v) inhibitor concentrations. The extract was applied to ST-37 specimens with coating durations of 2 and 4 days. After coating, the specimens were exposed to naturally collected rainwater from the Morowali industrial area for a fixed exposure period of 504 h. The dependent variables were corrosion rate and inhibition efficiency, which were determined using the weight loss method relative to an uncoated control specimen. The study aimed to evaluate the influence of inhibitor concentration and coating duration on the corrosion protection of ST-37 steel and to identify the treatment condition that provided the highest inhibition performance under the investigated conditions.

2. Methodology



Graphical Abstract. Experimental workflow for evaluating the corrosion inhibition performance of red dragon fruit peel extract on ST-37 steel in industrial rainwater.

2.1. Materials and Equipment

The materials used in this study were red dragon fruit peel (*Hylocereus polyrhizus*), 96% ethanol, ST-37 steel, 10% FeCl₃ solution, abrasive paper, aluminum foil, filter paper, tissue paper, and rainwater collected from Labota Village, Bahodopi District, Morowali Regency. The rainwater served as the corrosive medium and had a measured pH of 4.88. The experimental equipment comprised an analytical balance, blender, glass funnel, Erlenmeyer flask, volumetric flask, beakers, graduated cylinders, magnetic stirrer, volumetric pipette, pipette bulb, hot plate, retort stand, thermometer, and vernier caliper.

2.2. Preparation of Red Dragon Fruit Peel Extract

Fresh red dragon fruit peels were washed with water to remove adhering dirt and other contaminants and subsequently dried at room temperature for 14 days. The dried peels were ground using a blender to obtain a relatively homogeneous powder. A 100 g portion of the powdered material was then extracted with 1 L of 96% ethanol using a maceration procedure for 3 × 24 h. Following extraction, the mixture was filtered through filter paper, and the resulting filtrate was collected for concentration.

The filtrate was concentrated using a magnetic stirrer hot plate at 80 °C and 300 rpm until a concentrated extract was obtained. The extract was subsequently diluted with 96% ethanol to prepare inhibitor solutions with concentrations of 6%, 8%, 10%, and 12% (v/v). These concentrations were selected to investigate the effect of inhibitor concentration on the corrosion protection of ST-37 steel.

A qualitative identification of phenolic compounds was conducted using 10% FeCl₃. A drop of FeCl₃ solution was added to the extract, and the color response was visually observed as an indication of phenolic constituents.

2.3. Preparation of ST-37 Steel Specimens

ST-37 steel sheets were cut into specimens measuring approximately 5 × 7 cm with a thickness of 1 mm. Before treatment, the specimen surfaces were mechanically prepared using abrasive paper to remove surface oxides and impurities and to obtain a relatively uniform surface. The specimens were subsequently cleaned, dried, and weighed using an analytical balance. The initial mass of each specimen was recorded as the basis for calculating mass loss after corrosion exposure.

2.4. Inhibitor Coating Treatment

A total of nine ST-37 steel specimens were prepared for the corrosion test, comprising one untreated control specimen and eight inhibitor-treated specimens. The treated specimens represented a factorial combination of four inhibitor concentrations (6%, 8%, 10%, and 12%) and two coating durations (2 and 4 days). Each specimen was immersed in the corresponding red dragon fruit peel extract according to the predetermined concentration and coating duration. Upon completion of the coating treatment, the specimens were removed from the inhibitor solution and allowed to dry at room temperature for approximately 2 h before corrosion exposure.

2.5 Corrosion Exposure

The coated and untreated ST-37 specimens were subsequently exposed to rainwater collected from Labota Village, Bahodopi District, Morowali Regency. The rainwater was used directly as the corrosive medium and had a measured pH of 4.88. All specimens were immersed under the same conditions for 504 h (21 days). The corrosion exposure time was kept constant for all treatments to allow the effects of inhibitor concentration and coating duration on the corrosion behavior of ST-37 steel to be evaluated. After 504 h, the specimens were removed from the corrosive medium, cleaned to remove corrosion products and deposits, rinsed, dried, and weighed to determine the final mass.

2.6 Determination of Corrosion Rate and Inhibition Efficiency

The corrosion rate was determined using the gravimetric *weight loss* method. Mass loss was obtained from the difference between the initial mass of the specimen before corrosion exposure and its final mass after the 504 h test period. The corrosion rate was calculated using:

$$CR = \left(\frac{K.W}{A.T.D} \right) \quad (1)$$

where:

CR = corrosion rate (mpy)
 K = corrosion rate conversion constant
 W = mass loss (g)
 A = exposed surface area (cm²)
 T = corrosion exposure time (hours)
 D = density of ST-37 steel (g/cm³)

The inhibition efficiency was calculated by comparing the corrosion rate of the untreated control with that of the inhibitor-treated specimens according to:

$$Ei = \frac{CR_0 - CR_1}{CR_0} \times 100 \quad (2)$$

where:

Ei = inhibition efficiency
 CR₀ = corrosion rate of the uninhibited specimen
 CR₁ = corrosion rate of the inhibited specimen

3. Results and Discussion

The corrosion inhibition performance of red dragon fruit peel extract was evaluated using the weight loss method by measuring the mass loss of ST-37 steel specimens after exposure to the corrosive medium. Before the corrosion test, a qualitative phytochemical test using 10% FeCl₃

solution was performed to indicate the presence of phenolic compounds in the extract. After the addition of FeCl_3 , the extract changed from brown to blackish, indicating a positive qualitative response for phenolic constituents. Ferric chloride tests are commonly used as a preliminary qualitative test for phenolic compounds because Fe^{3+} can interact with phenolic hydroxyl groups to produce colored complexes. However, this color response should be interpreted only as a qualitative indication of phenolic compounds and not as a definitive identification or quantification of specific phenolic constituents (Tchamgoue *et al.*, 2015).

The presence of phenolic constituents is relevant to the corrosion-inhibition behavior of plant extracts because oxygen-containing functional groups and other electron-donating sites can interact with metallic surfaces and contribute to the formation of an adsorbed protective layer (Wahyuni, 2022). Previous research on red dragon fruit peel has also reported the presence of antioxidant compounds, including flavonoids and tannins, and demonstrated its potential as a corrosion inhibitor for steel (Nanda Sari *et al.*, 2019) (Macadangdang, 2022). Therefore, the positive FeCl_3 response obtained in the present study provides qualitative supporting evidence that the extract contains compounds that may contribute to its corrosion-inhibition performance.

The potential contribution of these active compounds was subsequently evaluated quantitatively based on the mass loss of the specimens after 504 h of exposure to rainwater. The measured mass loss was used to determine the corrosion rate, while inhibition efficiency was calculated by comparing the corrosion rate of the uninhibited specimen with that of the inhibitor-treated specimens. The extract concentrations investigated were 6%, 8%, 10%, and 12% (v/v), with coating durations of 2 and 4 days. The calculated mass loss, corrosion rate, and inhibition efficiency for each treatment condition are presented in Tables 1 and 2.

Table 1. Corrosion rate and inhibition efficiency of red dragon fruit peel extract after a 2-day coating treatment

Inhibitor concentration (v/v)	Mass loss (g)	Corrosion rate (mpy)	Inhibition efficiency (%)
0 %	0.0975	4.2731	0
6 %	0.0547	2.2953	46.29
8 %	0.0532	2.2564	47.20
10 %	0.0512	2.0995	50.87
12 %	0.0567	2.4339	43.04

Table 2. Corrosion rate and inhibition efficiency of red dragon fruit peel extract after a 4-day coating treatment

Inhibitor concentration (v/v)	Mass loss (g)	Corrosion rate (mpy)	Inhibition efficiency (%)
0 %	0.0975	4.2731	0
6 %	0.0393	1.6903	60.44
8 %	0.0347	1.5277	64.25
10 %	0.0338	1.5153	64.54
12 %	0.0427	1.9220	55.02

3.1. Effect of Red Dragon Fruit Peel Extract Concentration and Coating Time on the Corrosion Rate of ST-37 Steel

The corrosion behavior of ST-37 steel was evaluated using the *weight loss* method after exposure to rainwater for 504 h. The analysis was conducted by comparing the mass loss of the untreated specimen with that of specimens coated with red dragon fruit peel extract at concentrations of 6%, 8%, 10%, and 12% for 2 and 4 days. The resulting mass loss was used to determine the corrosion rate, expressed in mils per year (mpy), as an indicator of the protective performance of the inhibitor. The relationship between inhibitor concentration, coating time, and the corrosion rate of ST-37 steel is presented in Figure 1.

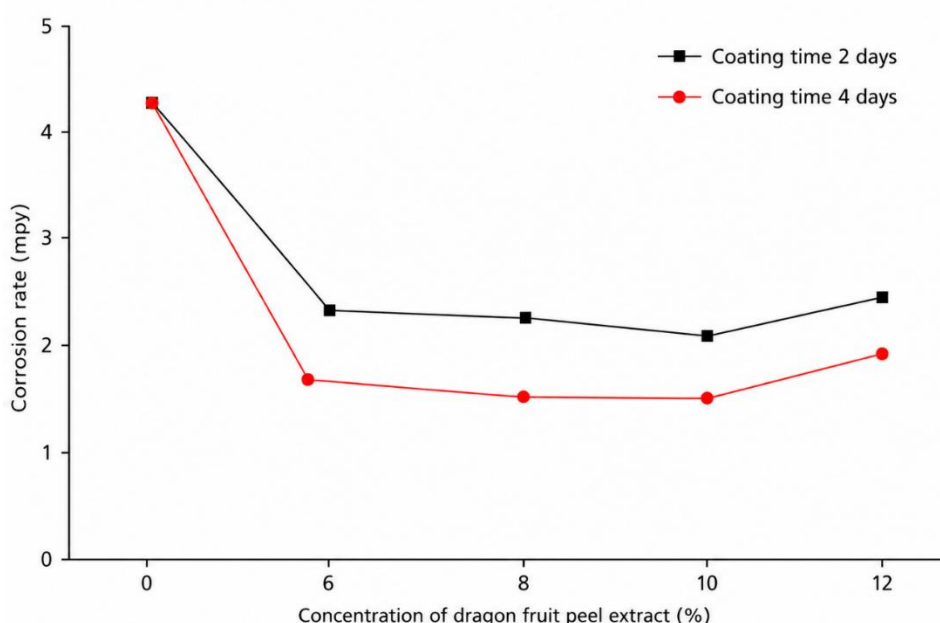


Figure 1. Corrosion rate of ST-37 steel as a function of red dragon fruit peel extract concentration at coating times of 2 and 4 days.

Figure 1, shows that the corrosion rate of ST-37 steel generally decreased with increasing red dragon fruit peel extract concentration from 6% to 10%, followed by an increase at 12%. At a coating time of 2 days, the corrosion rate decreased from 2.2953 mpy at 6% to 2.0995 mpy at 10%, before increasing to 2.4339 mpy at 12%. A similar trend was observed for the 4-day coating, in which the corrosion rate decreased from 1.6903 mpy at 6% to 1.5153 mpy at 10%, followed by an increase to 1.9220 mpy at 12%. This indicates that a 10% inhibitor concentration provided the most effective protection under the conditions investigated.

The reduction in corrosion rate from 6% to 10% (v/v) can be attributed to the increasing availability of phytochemical constituents in the extract that can interact with the steel surface and contribute to the formation of a protective layer. Organic compounds containing functional groups such as hydroxyl ($-OH$), carbonyl ($C=O$), and other oxygen-containing groups can interact with the metal surface through adsorption, thereby increasing surface coverage and reducing the electrochemically active surface area available for corrosion reactions. The adsorption of these organic constituents can act as a barrier that limits the interaction between the steel surface and corrosive species in the rainwater. Plant extracts have been widely reported to inhibit corrosion through adsorption and the formation of protective films on metallic surfaces (Parangusan *et al.*, 2025). This behavior is consistent with previous studies on red dragon fruit peel, which have demonstrated its ability to reduce corrosion of steel and attributed its inhibitive action to adsorption of extract constituents on the metal surface (Macadangang, 2022).

The increase in corrosion rate at 12% suggests that increasing inhibitor concentration does not necessarily produce a continuous improvement in protection. At excessive concentrations, the additional extract constituents may not contribute proportionally to surface protection and may instead promote a less uniform or less compact protective layer. Consequently, the optimum concentration under the present experimental conditions was 10%. The longer coating duration also improved protection: at 10% concentration, increasing the coating time from 2 to 4 days reduced the corrosion rate from 2.0995 to 1.5153 mpy, corresponding to a reduction of approximately 27.82%. The improved performance can be associated with a longer interaction period between inhibitor constituents and the steel surface, allowing more effective surface coverage and development of the protective layer. Similar dependence of inhibition performance on immersion/contact time has been reported for red dragon fruit peel extract, where longer exposure promoted adsorption of the extract constituents onto mild steel (Macadangang, 2022).

3.2. Effect of Red Dragon Fruit Peel Extract Concentration and Coating Time on Inhibition Efficiency

The inhibition efficiency of red dragon fruit peel extract was evaluated based on the corrosion rate obtained from the *weight loss* measurements after 504 h of exposure to rainwater. The efficiency was determined by comparing the corrosion rate of the untreated ST-37 specimen with those of specimens coated with the inhibitor at concentrations of 6%, 8%, 10%, and 12% for 2 and 4 days. A higher inhibition efficiency indicates a greater reduction in corrosion rate relative to the uninhibited specimen. The relationship between inhibitor concentration, coating time, and the inhibition efficiency of ST-37 steel is presented in Figure 2.

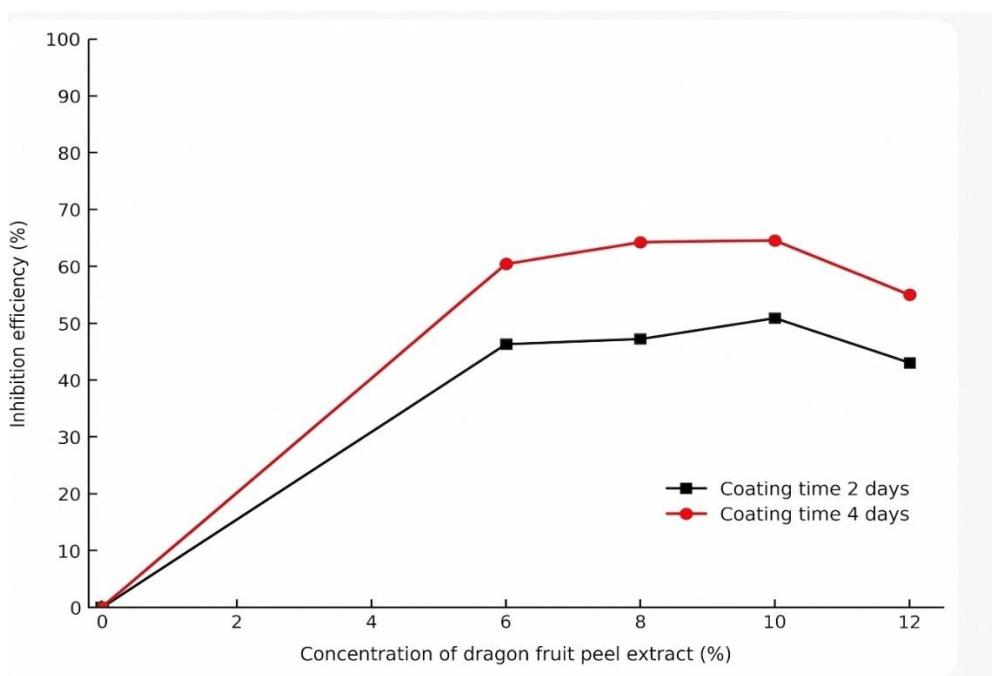


Figure 2. Inhibition efficiency of ST-37 steel as a function of red dragon fruit peel extract concentration at coating times of 2 and 4 days.

Figure 2 shows the effect of red dragon fruit peel extract concentration and coating time on the inhibition efficiency of ST-37 steel. At a coating time of 2 days, the inhibition efficiency increased from 46.29% at 6% inhibitor concentration to 50.87% at 10%, but subsequently decreased to 43.04% at 12%. A similar trend was observed for the 4-day coating, with the inhibition efficiency increasing from 60.44% at 6% to 64.54% at 10%, followed by a decrease to 55.02% at 12%. Thus, the 10% concentration provided the highest inhibition efficiency for both coating durations, with the maximum value of 64.54% obtained after 4 days of coating.

The increase in inhibition efficiency from 6% to 10% can be associated with the greater availability of active phytochemical constituents capable of interacting with the ST-37 surface. These compounds can adsorb onto the metal surface and form a protective film, thereby reducing the area directly exposed to the corrosive medium. Plant extracts containing oxygenated and other electron-donating functional groups are commonly reported to inhibit corrosion through surface adsorption and formation of a protective barrier (R. Holla *et al.*, 2024). The present result is also consistent with research conducted by Macadangdang (2022) on red dragon fruit peel extract, which demonstrated corrosion inhibition of mild steel through adsorption of extract constituents on the metal surface. Macadangdang reported that increasing immersion time enhanced the adsorption of red dragon fruit peel constituents and consequently improved inhibition efficiency.

The decrease in inhibition efficiency at 12% indicates that increasing the inhibitor concentration beyond the optimum level did not further improve surface protection. This behavior may occur when additional extract constituents no longer increase effective surface coverage proportionally, resulting in a less uniform or less effective protective layer. Therefore, under the conditions investigated, 10% can be considered the optimum inhibitor concentration. The higher inhibition efficiency obtained after 4 days compared with 2 days further indicates that coating duration

contributes to the development of the protective layer. At 10% concentration, extending the coating duration from 2 to 4 days increased the inhibition efficiency from 50.87% to 64.54%, corresponding to an increase of 13.67 percentage points. This observation is consistent with the findings of Macadangdang (2022) which showed that longer contact time can facilitate the adsorption of red dragon fruit peel constituents onto steel surfaces and consequently improve corrosion protection.

4. Conclusion

Red dragon fruit peel extract provided corrosion protection for ST-37 steel exposed to rainwater from the Morowali industrial area. The corrosion rate decreased with increasing inhibitor concentration up to 10% (v/v), but increased at 12%, indicating that 10% was the optimum concentration under the investigated conditions. Increasing the coating duration from 2 to 4 days resulted in lower corrosion rates and higher inhibition efficiencies at all tested concentrations. The optimum treatment, 10% (v/v) extract with a 4-day coating duration, produced a corrosion rate of 1.5153 mpy and an inhibition efficiency of 64.54% relative to the uncoated control. Thus, red dragon fruit peel extract shows potential as a biomass-derived corrosion inhibitor for ST-37 steel under the experimental conditions investigated.

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