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ARTICLE

Investigation on *Ficus carica* and *Punica granatum* Extracts as Eco-Friendly Corrosion Inhibitors for C1018 Carbon Steel in Acidic and Marine Environments

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ABSTRACT

This study evaluates the corrosion behavior of carbon steel in acidic medium and seawater in the presence of natural plant extracts derived from pomegranate peels and fig leaves as environmentally friendly corrosion inhibitors. The weight loss technique was employed to determine the corrosion rate and inhibition efficiency after an immersion period of 624 h, in the absence and presence of different inhibitor concentrations ranging from 12.5 to 100 ppm. The results demonstrated that pomegranate peels and fig leaves extracts were ineffective in the acidic medium, as negative inhibition efficiency values were recorded, indicating an increase in the corrosion rate compared to the blank solution. In contrast, the extracts exhibited noticeable corrosion inhibition performance in seawater, where positive inhibition

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efficiency values were observed and improved with increasing inhibitor concentration. Fig leaves extract showed superior performance, achieving a maximum inhibition efficiency of approximately 27.47% at a concentration of 100 ppm. This improvement is mainly attributed to the adsorption of organic compounds present in the extracts onto the steel surface. resulting in the formation of a protective film that reduces metal dissolution in the marine environment. The findings of this study indicate that pomegranate peels and fig leaves extracts are ineffective under the studied conditions in acidic environments but demonstrate promising potential as eco-friendly inhibitors in marine or saline conditions. These results highlight the critical influence of the corrosive medium on inhibitor performance and support the use of natural plant extracts as sustainable alternatives to conventional chemical inhibitors of corrosion.

Keywords: *Ficus carica*; *Punica granatum*; Green Inhibitors; Fig Leaf Extract; Pomegranate Leaf Extract; Corrosion Inhibition Rate; Corrosion Inhibition Efficiency

1. Introduction

The damage that metals and alloys experience from chemical or electrochemical interactions with their surroundings is known as corrosion [1]. Wet and dry corrosion are two categories of corrosion reactions based on the types of corrosive environments [2,3]. General corrosion, pitting corrosion, crevice corrosion, intergranular corrosion, environmentally induced fracture, de-alloying, galvanic, and erosion-corrosion can all be categorized based on the morphology of metal damage [4,5]. The use of treated *Rhizophora mucronata* tannin (RMT) as a corrosion inhibitor for copper and carbon steel in oil and gas facilities was studied. Using chemical (weight loss method) and spectroscopic (FTIR) techniques, the corrosion rate of carbon-steel and copper in 3 wt% NaCl solution by RMT was investigated at different temperatures between 26 and 90 °C [6]. The ability of three flavonoid derivatives, Naringenin (NRNG), Morin Hydrate (MNHD), and 6-Hydroxyflavone (6-HFN) to inhibit corrosion on aluminum in a hydrochloric acid solution was studied and investigated. A variety of experimental methods were used, such as Potentiodynamic Polarization (PDP) [7].

Since they are widely used to reduce metallic waste during production and lower the risk of material failure—both of which can result in the abrupt closure of industrial processes, which in turn results in additional costs—corrosion inhibitors are of significant practical importance. To stop minerals from dissolving and lower acid consumption, corrosion inhibitors are also crucial [8,9]. The inhibitory effect of wood ash (olive and palm) on mild carbon steel was investigated in a hydrochloric acid solution with a pH of approximately 5, or 10 μM. By performing the inhibition efficiency test for 10% aqueous wood ash solutions for both olive and palm using the weight loss method, the corrosion rate and inhibitor efficiency were determined. In the temperature range of 25–50 °C, the impact of temperature on the corrosion behavior of mild carbon steel was investigated at 10 μM and pH = 5 hydrochloride with the addition of 10% aqueous wood ash solutions (olive and palm) [10]. Reviews of the most recent research on corrosion inhibitors derived from natural products, plants, leaves, fruit, and fruit peels are the sources of the inhibitors. A review of corrosion inhibitor concentrations, media, metal types, and corrosion efficiency is provided [11]. A promising green building method is the use of *Punica granatum* peel extract to stop thermo-mechanically treated steel bar (TMT) from corroding in 1 M HCl. Compared to traditional methods like Tafel and EIS (electrochemical impedance spectroscopy), the untested electrochemical noise test provides a quicker and simpler way to assess the extract's inhibitory efficacy [12]. Fig leaf extract (FLE) was prepared quickly at a low temperature (313 K) to preserve the main chemical composition and distilled water was used as the solvent of extraction. This green inhibitor was employed to prevent steel corrosion in hydrochloric acid 1 M [13].

The Langmuir adsorption isotherm has been studied. Electrochemical impedance spectra (Alternating Current (AC) impedance spectra) have been used to study the mechanistic aspect of corrosion inhibition. Atomic Force Microscopy (AFM), FTIR, and fluorescence spectroscopy have all been used to analyze the protective film [14]. The Weight Loss (WL) method and PPD technique were used to assess the inhibitory effect of a seaweed (SM) alcoholic extract on mild steel (MS) corrosion immersed in 1 M HCl for 30 min [15]. Pipelines composed of various alloys, such as mild steel L80, carry simulated oil well water (SOWW). Because SOWW contains a variety of aggressive ions, these alloys may corrode in simulated oil well water. Numerous inhibitors have been used to stop this. Electrochemical studies, such as polarization studies and AC impedance spectra (EIS), have been used to assess the inhibition of corrosion of L80 alloy pipelines carrying simulated oil well water by succinic acid [16]. The ship's mild steel (MS) hull plates are constantly in contact with aggressive ions found in seawater, such as chloride ions. Polarization research has been used to examine the mild steel ship's hull plates' resistance to corrosion [17]. The inhibitory performance of the *Melissa officinalis* ethanolic extract (MO) has been evaluated using a wide range of techniques, such as weight loss, potentiodynamic polarization, electrochemical impedance spectroscopy, and surface analysis. The extract successfully inhibits corrosion under the tested conditions, as demonstrated by the highest level of inhibition at 500 ppm, which reached 89.0% in weight loss measurement, 93.5% in potentiodynamic polarization, and 91.7% in electrochemical impedance spectroscopy after testing a range of concentrations in a 1 M HCl medium [18]. Potentiodynamic polarization and electrochemical impedance spectroscopy were used to examine the inhibitory effect of *Mentha pulegium* extract (MPE) on steel corrosion in a 1 M HCl solution. It was discovered that MPE's inhibition efficiency rose with concentration, reaching 88% at 33% (v/v) [19]. Using weight loss techniques, the impact of a combination of different KI and *Mentha pulegium* extract concentrations on steel corrosion in 1 M HCl has been examined [20]. The corrosion protection of pipeline steel API 5L X52 in hydrochloric acid solution was compared between a green corrosion inhibitor extract from *Ruta chalepensis* leaves (LERC) and a synthetic commercial corrosion inhibitor. The ability of LERC to inhibit corrosion has been found to be fairly high and to be highly dependent on its concentration in the corrosive solution [21]. 4 different extracts from the plant *Ruta chalepensis* using methanol, chloroform, ethyl acetate, and aqueous ethyl acetate solvent systems. The flavonoid content, as well as the other oxygenated compounds, in the 4 extracts was carefully screened using the gas chromatographic-mass spectrometry (GC-MS) technique. The corrosion inhibition property of all extracts for API 5L X52 steel in the hydrochloric acid medium has been carefully assessed using electrochemical techniques and surface-morphological characterizations [22].

2. Materials and Methods

2.1. Materials

2.1.1. Chemical Reagents

- Ethanol (99%) as a solvent for extracting bioactive compounds.
- Distilled water for washing plant materials and diluting ethanol.
- Diluted hydrochloric acid (HCl) to adjust the acidic medium to pH 5.

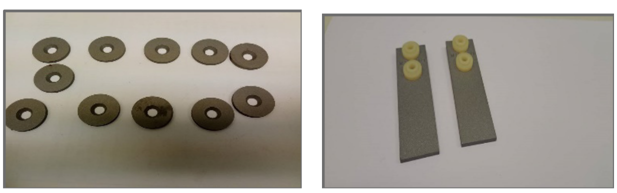
2.1.2. Plant Materials

- Fresh fig leaves (*Ficus carica*), collected from Brega, Libya.
- Fresh pomegranate peels (*Punica granatum*), collected from Brega, Libya (**Figure 1**).

Figure 1. Fresh plant samples used for extraction: Fig leaves and pomegranate peels.

2.1.3. Corrosion Coupons

- Carbon steel C1018 coupons, a total of 18, divided as follows:
- Disc coupons (**Figure 2a**): 1.25 in diameter × 0.125 in thickness, exposed surface 16.1 cm^2, for seawater.
- Strip coupons (**Figure 2b**): 2.875 × 0.875 × 0.125 in, exposed surface 33.5 cm^2, for acidic medium.



(**a**) (**b**)

Figure 2. Coupons used in the tests: (**a**) disc; (**b**) strip.

2.1.4. Test Media

- Acidic Solution: Diluted HCl to pH 5.
- Natural Seawater: Collected from Al-Breqa shore (Zone 3) with the following characteristics: pH = 8.02 at 27 °C, Cl^- = 226 ppm, conductivity = 59 mS/cm, Total Dissolved Solids (TDS) = 53,000 ppm (**Figure 3**).

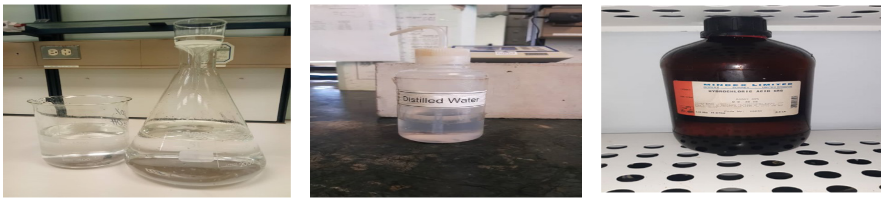


Figure 3. Experimental materials and chemical constituents utilized for corrosion testing.

2.1.5. Equipment

Electric grinder, filter paper, precise digital balance ±0.0001 mg, shaded drying area, incubator/oven, soft brush, acetone.

2.2. Experimental Procedures

2.2.1. Extraction of Natural Inhibitor from Fig Leaves

The preparation of the *Ficus carica* leaf extract was conducted according to a systematic laboratory procedure, as illustrated in the stepwise workflow in **Figure 4**:

- Collection: Fresh fig leaves were collected from a home garden (Municipality of Brega, El Marsa, Libya).
- Washing & Drying: Leaves were thoroughly washed with distilled water and shade-dried.
- Grinding: Dried leaves were powdered using an electric grinder.
- Solvent Preparation: 10% ethanol solution was prepared by mixing 100 mL of ethanol with 900 mL of distilled water.
- Extraction: 50 g of leaf powder mixed with 500 mL of the solution, left at room temperature for 24 h with occasional stirring.
- Filtration & Storage: Mixture filtered, and the clear extract was stored in labeled bottles at 4 °C.

Figure 4. Showing the Stepwise Preparation of Fig Leaf Extract.

2.2.2. Extraction of Natural Inhibitor from Pomegranate Peels

The extraction process for the *Punica granatum* peel inhibitor followed a standardized experimental protocol, the stages of which are depicted in **Figure 5**.

- Collection & Washing: Fresh peels were washed

with distilled water.
- Drying: Shade-dried.
- Grinding: Cut into small pieces and powdered using an electric grinder.
- Solvent Preparation: 10% ethanol solution.
- Extraction: 50 g of peel powder mixed with 500 mL of solution, left for 24 h at room temperature with occasional stirring.
- Filtration & Storage: Filtered and stored in the refrigerator until use.

Figure 5. Showing the stepwise preparation of pomegranate peel extract.

2.3. Weight Loss Method for Corrosion Rate Determination

- Initial Preparation & Weight (**Figure 6**): Coupons were cleaned and weighed accurately using a digital balance ±0.0001 mg.
- Immersion (**Figures 7–9**): Coupons were immersed in test solutions (with or without plant extracts) for 26 days at 50 °C.
- Post-Exposure Cleaning: Coupons were gently cleaned with a soft brush, rinsed with distilled water, and dried using acetone.
- Final Weight & Corrosion Rate Calculation (**Figure 10**): Coupons were reweighed, and the corrosion rate (CR) was calculated using the formula:

$$CR\ (mpy) = 534 \times W/(\rho \times A \times t)$$

Where :

W = weight loss (mg),

ρ = density of carbon steel (g/cm^3),

A = exposed area (in^2),

t = exposure time (hours).

Figure 6. Initial preparation and weighing of coupons using a digital balance (±0.0001 mg).

Figure 7. Test containers prepared for immersion of coupons in solutions.

Figure 8. Coupons immersed in test solutions at 50 °C during the 26-day exposure period.

Figure 9. Oven used to maintain the coupons at 50 °C for 26 days during immersion in the inhibitor-containing solutions, simulating long-term exposure conditions.

Figure 10. Coupons after 26 days of immersion in test solutions (with/without plant extracts) at 50 °C.

3. Results and Discussion

In this work, the results of the experiments conducted on low-carbon steel using pomegranate peel and fig leaf extracts in both acidic medium and seawater are presented. The experiments focused on measuring the corrosion rate and evaluating the inhibition efficiency of each extract at different concentrations. The data are presented primarily in graphs, with tables included where detailed numerical values are needed to illustrate the experimental behavior of the extracts. The results are discussed based solely on these data, highlighting possible reasons for the differences in performance between the two media and between the two extracts.

3.1. Performance of Pomegranate Peel Extract

3.1.1. In Acidic Medium (pH = 5)

The corrosion behavior of low-carbon steel in the acidic medium (pH = 5) in the presence of pomegranate peel extract is presented in this section. As is well known, pH has a vital impact on the solution behavior and corrosion of metals [23]. Therefore, the experiments were conducted in acidic medium [23]. The experimental results revealed that increasing the concentration of the extract led to a noticeable increase in the corrosion rate compared to the blank solution (**Table 1**). This behavior was reflected by negative inhibition efficiency values at all tested concentrations (**Figure 11**).

The negative inhibition efficiency indicates that the pomegranate peel extract failed to function as a corrosion inhibitor under acidic conditions and instead acted as a corrosion activator. This behavior may be attributed to the instability of the active organic compounds present in the extract when exposed to acidic environments. Under such conditions, protonation of functional groups can occur, which weakens the adsorption of inhibitor molecules on the steel surface. Additionally, some extract components may interact with iron ions to form soluble complexes, facilitating metal dissolution and accelerating corrosion [24].

Table 1. Corrosion rate and inhibition efficiency of low-carbon steel in acidic medium (pH = 5) with pomegranate peel extract.

Sample	Conc. (ppm)	Initial Weight	Final Weight	Δm (mg)	Density (g/cm^3)	Area (in^2)	Time (h)	Corrosion Rate (mpy)	Corrosion Efficiency (%)
Blank	0	37.3188	37.1925	126.3	7.87	5.2	624	2.641	0.00
p. peels	12.5	37.1203	36.8603	260	7.87	5.2	624	5.437	−105.86
p. peels	25	37.1043	36.87387	230.43	7.87	5.2	624	4.819	−82.45
p. peels	50	37.5842	37.3321	252.1	7.87	5.2	624	5.272	−99.60
p. peels	100	37.5732	37.3144	258.8	7.87	5.2	624	5.412	−104.91

Note: Negative inhibition efficiency indicates that pomegranate peel extract acts as a corrosion activator in acidic medium (pH = 5).

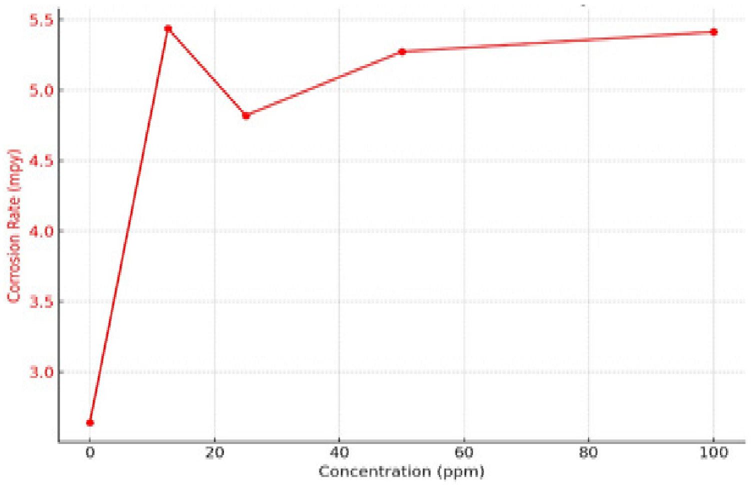


Figure 11. Effect of pomegranate peel extract concentration on corrosion rate in acidic medium.

These findings suggest that pomegranate peel extract has limited applicability as a corrosion inhibitor in acidic media.

3.1.2. In Seawater

In contrast to the acidic medium, the use of pomegranate peel extract in natural seawater resulted in a noticeable reduction in the corrosion rate of low-carbon steel. The inhibition efficiency values ranged from 10.57% to 19.13%, with the highest efficiency achieved at a concentration of 50 ppm. The improved performance in seawater can be attributed to the mildly alkaline nature of the medium, which enhances the stability of the active organic compounds and promotes their adsorption onto the steel surface. This adsorption likely leads to the formation of a partial protective film that reduces metal dissolution. However, when the concentration was increased to 100 ppm, a significant decrease in inhibition efficiency was observed. This decline may be explained by the aggregation of extract molecules in the solution at higher concentrations, which can hinder effective surface coverage and disrupt the protective layer. This behavior indicates the presence of a critical concentration, beyond which the protective effect of the extract diminishes. **Table 2** presents the inhibition efficiency of pomegranate peel extract in seawater while **Figure 12** shows the corrosion rate.

Table 2. Corrosion rate and inhibition efficiency of low-carbon steel in seawater with pomegranate peel extract.

Sample	Concen. (ppm)	Initial Weight (g)	Final Weight (g)	Δm (mg)	Density (g/cm^3)	Area (in^2)	Time (h)	Corrosion Rate (mpy)	Efficiency (%)
Blank	0	37.3659	37.0619	304	7.87	5.2	624	6.3570	0.00
p. peels	12.5	18.1629	18.0322	130.7	7.87	2.5	624	5.6848	10.57
p. peels	25	17.8259	17.6969	129	7.87	2.5	624	5.6109	11.74
p. peels	50	18.0224	17.9042	118.2	7.87	2.5	624	5.1411	19.13
p. peels	100	18.0571	17.9107	146.4	7.87	2.5	624	6.3677	−0.17

Note: Inhibition efficiency decreases at higher concentrations due to aggregation of extract molecules.

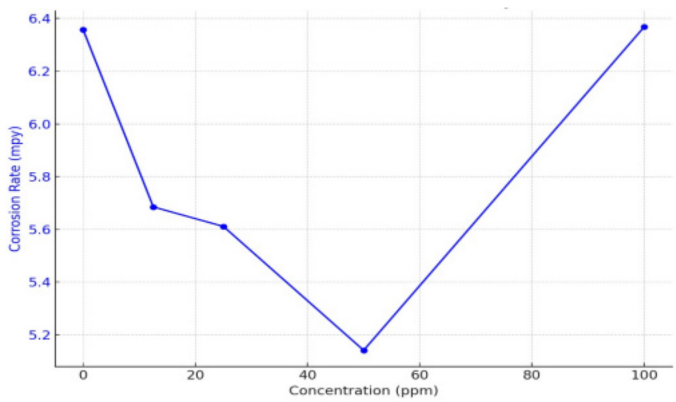


Figure 12. Effect of pomegranate peel extract concentration on corrosion rate in seawater.

3.2. Performance of Fig Leaf Extract

3.2.1. In Acidic Medium (pH = 5)

The corrosion results obtained using fig leaf extract in the acidic medium showed a pronounced increase in corrosion rate compared to the blank solution. All tested concentrations resulted in negative inhibition efficiency values, reaching a maximum negative value of −110.53% at a concentration of 12.5 ppm (see **Table 3** and **Figure 13**). This behavior confirms that fig leaf extract is ineffective as a corrosion inhibitor in acidic environments. The poor performance can be attributed to the weak adsorption of the active compounds on the steel surface and their instability under acidic conditions. Similar to pomegranate peel extract, the active constituents may undergo protonation or act as chelating agents, facilitating the removal of iron ions from the metal surface and accelerating corrosion.

Table 3. Corrosion rate and inhibition efficiency of low-carbon steel in acidic medium (pH = 5) with fig leaf extract.

Sample	Concentration (ppm)	Initial Weight (g)	Final Weight (g)	Δm (mg)	Density (g/cm^3)	Area (in^2)	Time (h)	Corrosion Rate (mpy)	Efficiency (%)
Blank	0	37.3188	37.1925	126.3	7.87	5.2	624	2.641	0.00
Fig leaves	12.5	37.2177	36.9518	265.9	7.87	5.2	624	5.560	−110.53
Fig leaves	25	37.395	37.1483	246.7	7.87	5.2	624	5.159	−95.33
Fig leaves	50	37.0947	36.8774	217.3	7.87	5.2	624	4.544	−72.05
Fig leaves	100	37.1744	36.9565	217.9	7.87	5.2	624	4.557	−72.53

Note: Negative values confirm that fig leaf extract is ineffective in acidic medium.

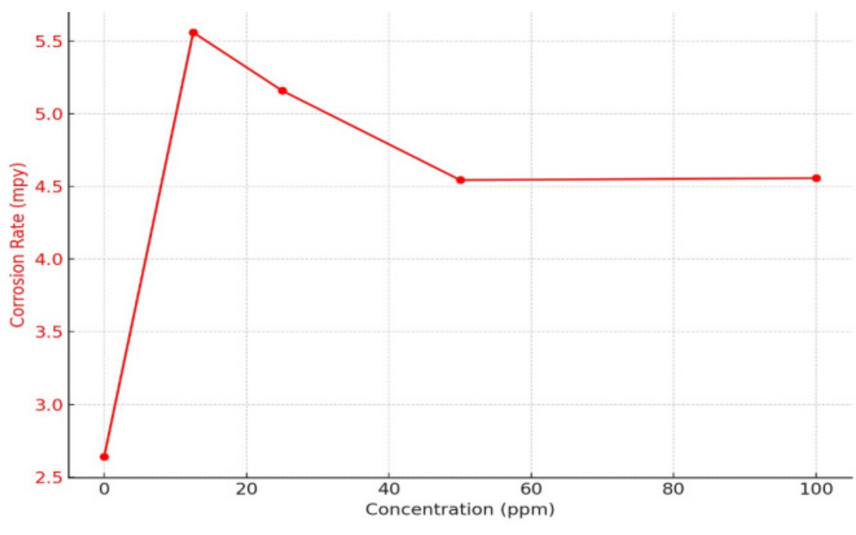


Figure 13. Effect of fig leaf extract concentration on corrosion rate in acidic medium.

3.2.2. In Seawater

This consistent improvement indicates that the active compounds in fig leaf extract are stable in mildly alkaline seawater and possess a strong affinity for adsorption onto the steel surface [25]. The gradual increase in efficiency suggests the formation of a more uniform and stable protective layer, which effectively reduces the corrosion rate. The absence of efficiency deterioration at higher concentrations highlights the high stability and reliability of fig leaf extract as a corrosion inhibitor in marine environments. The results are presented in **Table 4** and **Figure 14**.

3.3. Comparative Analysis of Extract Performance

To provide a clearer evaluation of the corrosion inhibition behavior of the studied extracts, a comparative summary is presented in **Table 5**.

Table 4. Corrosion rate and inhibition efficiency of low-carbon steel in seawater with fig leaf extract.

Sample	Concentration (ppm)	Initial Weight (g)	Final Weight (g)	Δm (mg)	Density (g/cm^3)	Area (in^2)	Time (h)	Corrosion Rate (mpy)	Efficiency (%)
Blank	0	37.3659	37.0619	304	7.87	5.2	624	6.357	0.00
Fig leaves	12.5	17.8922	17.7837	108.5	7.87	2.5	624	4.719	25.76
Fig leaves	25	17.8978	17.7807	117.1	7.87	2.5	624	5.093	19.88
Fig leaves	50	17.9501	17.835	115.1	7.87	2.5	624	5.006	21.25
Fig leaves	100	17.8608	17.7548	106	7.87	2.5	624	4.610	27.47

Note: Inhibition efficiency improves consistently with increasing concentration, showing strong adsorption and stability of fig leaf extract in seawater.

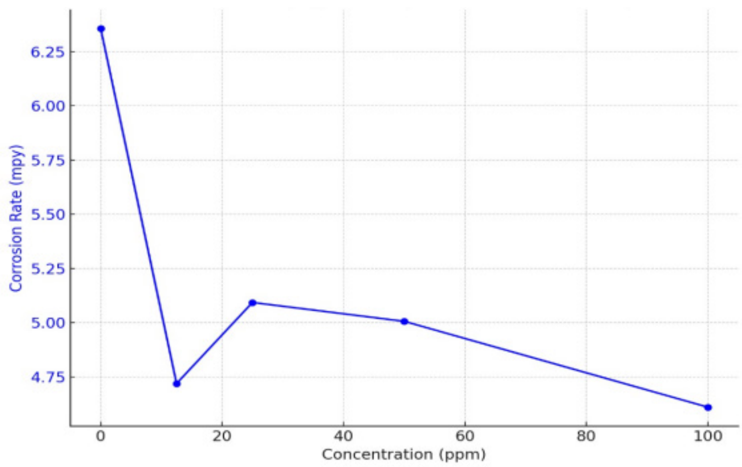


Figure 14. Effect of fig leaf extract concentration on corrosion rate in seawater.

Table 5. Comparative performance of pomegranate peel and fig leaf extracts.

Process Parameter	Fig Leaves (Seawater)	Pomegranate Peels (Seawater)
Optimal Concentration	100 ppm	50 ppm
Max Efficiency (%)	27.47%	19.13%
Stability	Highly stable and consistent	Unstable at high concentrations
Acidic Performance	Failed (Corrosion Activator)	Failed (Corrosion Activator)

3.4. Comparative Analysis and General Discussion

The results indicate that the effectiveness of natural inhibitors strongly depends on the chemical nature of the medium and the properties of the organic compounds.

3.4.1. Performance in Seawater

Fig leaf extract exhibited higher inhibition efficiency and stable performance across all concentrations compared to pomegranate peel extract, which reached its maximum efficiency at 50 ppm and then decreased at 100 ppm due to aggregation of the molecules. This indicates the strong adsorption and stability of the active compounds in fig leaves.

3.4.2. Performance in Acidic Medium (pH = 5)

Both extracts failed to inhibit corrosion, as all values showed negative inhibition efficiency, indicating that the organic compounds are affected by protonation or interact with iron ions, which accelerates the corrosion rate

This reflects that both concentration and the chemical environment have a significant effect on inhibitor performance, where efficiency can increase with concentration up to a certain point, then decrease in cases of molecule aggregation, as observed with pomegranate peel extract.

3.5. Future Recommendations

- Investigate the effect of different temperatures on inhibition efficiency to understand the thermal stability of the compounds.
- Study blending extracts or adding other natural compounds to enhance inhibition performance in seawater or acidic media.
- Evaluate the inhibitors under natural marine conditions to validate laboratory results and improve practical recommendations.
- Overall, the results suggest that fig leaf extract is a more suitable and eco-friendly inhibitor for marine applications, while pomegranate peel extract requires careful concentration control to avoid adverse effects.

4. Conclusions

4.1. Relative Effectiveness of Natural Extracts

The results indicated that the fig leaf extract outperformed the pomegranate leaf extract in reducing the corrosion rate in seawater. This is attributed to its high content of phenolic and flavonoid compounds, which form a coherent protective layer on the metal surface, limiting its interaction with corrosive ions.

4.2. Effect of Environmental Medium

Acidic Medium: The experiment recorded a high corrosion rate with negative inhibition percentages, indicating an increase in corrosion when using the extracts. This suggests that high acidity affects the effectiveness of the compounds, potentially causing their degradation or altering their chemical behavior, thus reducing their protective capability.

Seawater: A lower corrosion rate was observed compared to the acidic medium, with a clear superiority of pomegranate peel extract over fig leaves. This is due to the formation of a protective layer from phenolic and flavonoid compounds on the metal surface, enhancing corrosion resistance in the chloride-rich marine environment.

4.3. Effect of Concentration

The effect of increasing the extract concentration on the corrosion rate varied according to the medium:

Seawater: Increasing the concentration led to a decrease in corrosion rate up to a certain limit, beyond which performance did not improve significantly, indicating surface saturation by the protective layer.

Acidic Medium: Increasing the concentration had no clear effect on reducing corrosion, reflecting that the medium's acidity impacts compound effectiveness more than the extract amount.

4.4. Chemical Mechanism

Phenolic and flavonoid compounds form a protective layer that prevents direct interaction between the metal and corrosive ions, along with antioxidant properties that reduce corrosion-causing chemical reactions. However, in acidic media, these compounds may degrade or lose effectiveness, explaining the increased corrosion rate.

4.5. Comparison with Previous Studies

Acidic Medium: Results differ from previous studies, as the current study showed increased corrosion with extract use, whereas other studies typically reported decreased corrosion.

Seawater: Results are consistent with previous studies, demonstrating the effectiveness of pomegranate peel extract in reducing corrosion through the formation of a protective layer on the metal surface.

4.6. Challenges and Limitations

- Limited number of coupons and available materials, which prevented repeating experiments to verify results or study the effect of medium and concentration variations.
- The need to employ advanced analytical techniques such as EIS and Scanning Electron Microscopy (SEM) to precisely determine the nature and thickness of the protective layer.
- Difficulty in explaining increased corrosion in acidic media, as corrosion sometimes increased when extracts were applied. The reason is not entirely clear and requires further studies to understand the impact of acidity on active compounds.

4.7. Practical and Future Recommendations

- Utilize pomegranate peel and fig leaves extracts as environmentally friendly inhibitors in low-risk industrial applications, considering the nature of the medium.
- Investigate additional plant extracts to expand the database on natural inhibitors.
- Assess the effect of extracts on different metals and under varying temperatures.
- Apply advanced analytical techniques to determine the protective layer's nature and thickness accurately.

4.8. Final Summary

The study confirms that plant extracts, especially pomegranate peel, represent effective and safe alternatives to conventional chemical inhibitors. They are more effective in marine environments than in highly acidic media, where the latter may increase corrosion rates. Performance can be enhanced by adjusting extract concentration and medium conditions, allowing their use in sustainable and environmentally friendly industrial applications.

Author Contributions

Methodology, O.N.; validation, A.H.O.S. and S.M.S.; formal analysis, G.A.; data curation, G.A.; writing—original draft preparation, M.Y.A.; writing—review and editing, A.S.A.E., G.A. and O.N.; supervision, A.S.A.E. and R.G.R. All authors have read and agreed to the published version of the manuscript.

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The data are available upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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