Performance of natural plant-based inhibitors: Effect of *Psidium guajava* extract concentration and immersion time on corrosion rate of boiler tubes

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Abstract. Corrosion in boiler header tubes poses a major operational challenge in steam-based power generation, especially in systems exposed to chloride-rich feedwater. Environmentally benign corrosion inhibitors have gained attention as alternatives to synthetic chemicals. This study examines the effectiveness of *Psidium guajava* leaf extract as a natural corrosion inhibitor for boiler tube carbon steel immersed in a 4% NaCl medium. Corrosion rates were measured using the gravimetric method supported by optical microscopy. The results showed that increasing inhibitor concentration up to 1500 ppm significantly reduced the corrosion rate and increased inhibition efficiency at all immersion times. The optimum performance was achieved at 1500 ppm after 7 days of immersion, where the corrosion rate decreased and the inhibition efficiency reached 82.7%. A slight decline in performance at 2000 ppm indicated that excessive inhibitor concentration may reduce film stability due to multilayer formation or competitive adsorption. Optical micrographs supported these findings by showing severe pitting on the uninhibited surface and a smoother, more homogeneous morphology on the inhibited specimen. These results demonstrate that *Psidium guajava* leaf extract is a promising environmentally friendly inhibitor for boiler tube protection in saline media.

1 Introduction

Boiler tubes are indispensable components in industrial thermal systems because they simultaneously ensure heat transfer and pressure containment during steam generation. Their performance directly influences thermal efficiency, operational continuity, and plant safety in power stations, refineries, and other process industries. During service, boiler tubes are exposed to severe environments involving high-temperature water and steam, dissolved oxygen, chloride and sulfate ions, and other corrosive species that can accelerate material

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degradation. Under such conditions, corrosion becomes one of the main causes of tube wall thinning, loss of heat-transfer efficiency, and premature failure, driven by mechanisms such as uniform corrosion, pitting, crevice corrosion, and flow-accelerated corrosion (FAC), with oxide scales and deposits acting as sites for accelerated attack or protective-film breakdown. As a result, maintaining the integrity of boiler-tube materials is essential not only for sustaining process performance but also for extending equipment service life, given the clear associations between corrosion, decreased heat-transfer performance, and increased risk of failures in boiler systems.

Conventional corrosion control methods commonly include the use of corrosion-resistant alloys, optimization of feedwater chemistry and operating parameters, surface protection, and the application of chemical inhibitors. Among these approaches, corrosion inhibitors remain attractive because they can suppress corrosion at relatively low concentrations while being readily integrated into existing systems [1]. In general, inhibitors act by adsorbing on the metal surface, forming a protective barrier film, scavenging aggressive species, or altering anodic and cathodic reactions at the metal–solution interface [2]. However, many commercial synthetic inhibitors suffer from significant drawbacks, including toxicity, poor biodegradability, environmental persistence, and risks associated with handling and disposal. Increasing environmental awareness and stricter regulations on hazardous chemicals have therefore stimulated growing interest in green corrosion inhibitors derived from natural resources, including plant-derived extracts and related phytochemicals [3].

Plant-based inhibitors have emerged as promising alternatives because they are renewable, biodegradable, relatively inexpensive, and rich in organic compounds capable of interacting with metallic surfaces. Their inhibitory performance is commonly associated with phytochemicals such as tannins, flavonoids, phenolic compounds, and alkaloids, which contain heteroatoms and π-electron systems that promote adsorption and protective film formation. Among these natural sources, *Psidium guajava* leaves are particularly attractive due to their abundance, low cost, and high polyphenolic content. The presence of tannins, flavonoids, and phenolic constituents suggests a strong potential for surface adsorption and corrosion inhibition. Nevertheless, studies specifically addressing the use of *Psidium guajava* extract for boiler-tube materials remain limited, especially with respect to the combined influence of inhibitor concentration and immersion time on corrosion performance. Accordingly, This study aims to investigate the effectiveness of *Psidium guajava* leaf extract as a green corrosion inhibitor for boiler header tubes exposed to 4% NaCl, simulating a corrosive feedwater condition. Weight loss methods were employed to measure corrosion rates across different extract concentrations and immersion times. The objectives include evaluating the impact of extract concentration on corrosion inhibition efficiency, the role of immersion time in corrosion progression, and the optimal dosage for achieving maximum corrosion resistance.

2 Methods

2.1 Sample preparation

The preparation of test specimens began with the procurement of a commercial boiler tube with an initial length of 30 cm. The pipe was sectioned into rectangular coupons measuring 30 × 20 × 4 mm using a precision cutting tool to ensure uniform dimensions. A total of 60 specimens were prepared to accommodate all experimental conditions and replicates. Prior to corrosion testing, the surface of each coupon was mechanically polished using successive grades of silicon carbide abrasive paper to remove surface impurities, oxide layers, and residual rust, thereby obtaining a smooth and uniform surface finish. The specimens were subsequently washed with detergent solution to eliminate any remaining abrasive particles, grease, or contaminants adhering to the surface. After thorough rinsing with distilled water, the specimens were dried at room temperature before further experimental procedures. The chemical composition of specimen was identified using X-ray fluorescence (XRF).

2.2 Preparation of inhibitor

Fresh leaves of *Psidium guajava* Linn were cleaned to remove impurities and separated from the stems. The leaves were air-dried under direct sunlight for 48 hours to reduce moisture content, then ground into powder using a laboratory blender. The powdered material was sieved through a 40-mesh sieve to obtain uniform particle size. For extraction, 200 g of the sieved powder was immersed in 1 L of 96% ethanol (solid-to-solvent ratio 1:5 w/v) and subjected to maceration for 48 hours at room temperature in a closed container. After maceration, the mixture was filtered to separate the filtrate from the solid residue. The filtrate was concentrated using a rotary vacuum evaporator at 78 °C for 4 hours to remove the solvent under reduced pressure, yielding a crude extract. A total of 59.33 g of concentrated extract was obtained. The extract subsequently stored in airtight glass bottles for further analysis and corrosion inhibition testing.

2.3 Phytochemical determination

A qualitative test was performed to determine the presence of tannins in the *Psidium guajava* leaf extract using the ferric chloride ($FeCl_3$) method. The crude extract was first dissolved in distilled water to facilitate solubility and ensure homogeneous mixing. Subsequently, a few drops of 1% (w/v) $FeCl_3$ solution were added to the aqueous extract, and the resulting color change was carefully observed.

2.4 Gravimetric test

The corrosion rate was determined using the weight loss (gravimetric) method. Prepared steel specimens were immersed in inhibitor solutions at concentrations of 0 (blank), 500, 1000, 1500, and 2000 ppm. Each concentration was tested at immersion periods of 3, 5, 7, and 10 days. All experimental conditions were conducted in triplicate, resulting in a total of 60 specimens to ensure reproducibility and statistical reliability. After the designated immersion time, the specimens were removed from the solution, rinsed with distilled water to eliminate corrosion products, dried, and weighed to obtain the final mass. The corrosion rate (CR) was calculated using the standard weight loss equation:

$$CR = \frac{K \times W}{A \times t \times D} \tag{1}$$

where K is a constant, $W$is the weight loss (g), A is the surface area of the specimen (cm^2), t is the immersion time (h or days), and D is the density of the metal (g/cm^3). The inhibition efficiency (I, %) was calculated to evaluate the effectiveness of the inhibitor using:

$$IE(\%) = \frac{CR_0 - CR_i}{CR_0} \times 100 \tag{2}$$

where CR_0 and CR_i represent the corrosion rates in the absence and presence of inhibitor, respectively. This approach allowed quantitative assessment of the corrosion protection performance of the *Psidium guajava* leaf extract at different concentrations and exposure times.

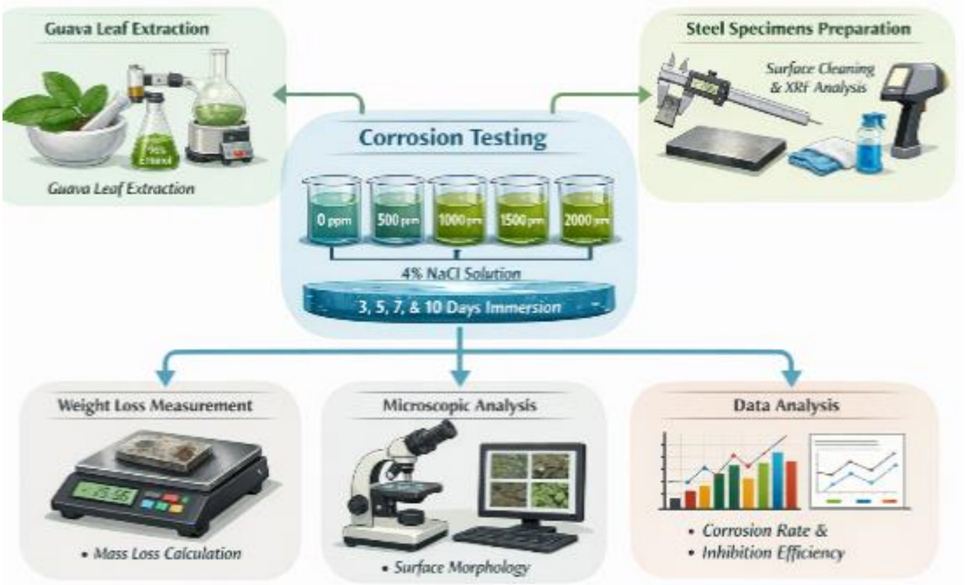


Fig. 1. Experimental methodology

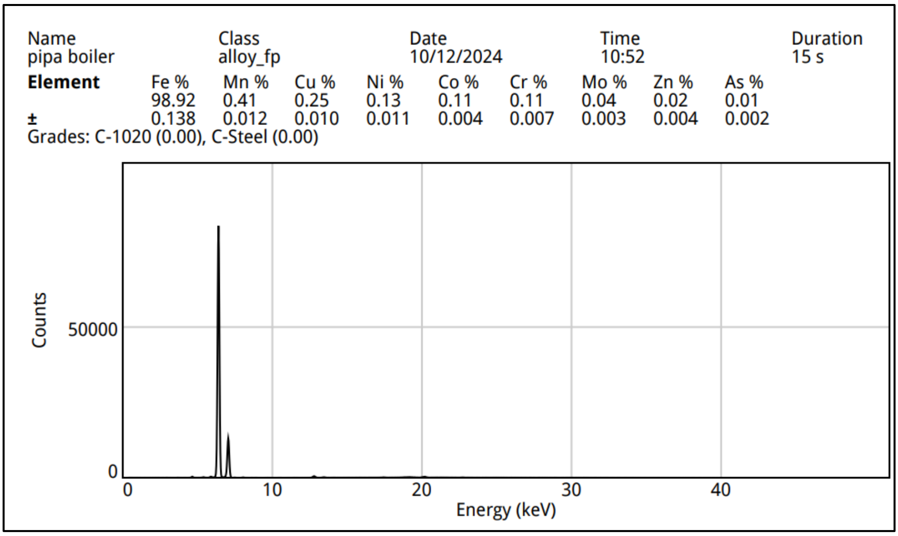
3 Results and discussion

3.1 XRF analysis

The EDS spectrum indicates that the boiler pipe specimen is predominantly composed of iron (Fe), with a measured content of 98.92 wt.%, confirming that the material is mainly a ferrous alloy. Minor alloying and trace elements detected include Mn (0.41 wt.%), C (0.25 wt.%), Ni (0.13 wt.%), Cu (0.11 wt.%), Co (0.05 wt.%), Cr (0.11 wt.%), Mo (0.04 wt.%), W (0.03 wt.%), Zn (0.04 wt.%), As (0.02 wt.%), and S (0.00 wt.%). The spectrum is dominated by a strong Fe peak, while the other elements appear only as very small peaks, indicating their presence in low concentrations.

Based on this elemental composition, the specimen can be classified as low-carbon steel, which is consistent with the label shown in the figure, namely C-Steel with grade C-1020. The carbon content of 0.25 wt.% suggests that the material belongs to the low-carbon steel category, which is commonly used for boiler tubes because of its good formability, weldability, and reasonable mechanical strength. However, due to its high iron content and relatively low alloying-element content, this type of steel remains susceptible to corrosion, especially in aggressive environments containing chloride ions.

The very high iron fraction confirms that Fe is the principal metal undergoing oxidation during corrosion exposure. Meanwhile, the small amounts of Mn, Cr, Ni, and Cu may slightly contribute to the overall properties of the alloy, but their concentrations are too low to provide significant corrosion resistance compared with stainless or highly alloyed steels. Therefore, the EDS result supports the assumption that the tested material is a carbon-steel boiler tube with limited inherent corrosion resistance, making it suitable for evaluating the effectiveness of *Psidium guajava* leaf extract as a natural corrosion inhibitor.



Name	Class	Date	Time	Duration
pipa boiler	alloy_fp	10/12/2024	10:52	15 s

Element	Fe %	Mn %	Cu %	Ni %	Co %	Cr %	Mo %	Zn %	As %
	98.92	0.41	0.25	0.13	0.11	0.11	0.04	0.02	0.01
±	0.138	0.012	0.010	0.011	0.004	0.007	0.003	0.004	0.002

Grades: C-1020 (0.00), C-Steel (0.00)

Fig. 2. XRF spectrum of the boiler tube specimen

3.2 Phytochemical analysis

The extract solution exhibited a light green to brownish coloration; however, upon the addition of $FeCl_3$, the solution turned dark green, indicating a positive reaction for tannins [4]. The formation of a dark green to greenish-black color confirms the presence of tannin compounds, which are polyphenolic substances containing multiple hydroxyl (–OH) functional groups [5]. These hydroxyl groups enable tannins to form coordination complexes with ferric ions (Fe^{3+}), resulting in the characteristic dark coloration. The polarity of tannins, attributed to the abundance of hydroxyl groups, facilitates their interaction with $FeCl_3$, thereby supporting the qualitative identification of condensed tannins in the extract

3.3 Gravimetric analysis studies

The addition of *Psidium guajava* leaf extract markedly reduced the corrosion rate of boiler tube steel in 4% NaCl solution. In this study, corrosion rates were measured via weight loss and expressed in millimeters per year (mmpy). Without inhibitor, the steel corroded rapidly (e.g. 0.2533 mmpy after 3 days immersion). With increasing inhibitor concentration from 0 to 1500 ppm, the corrosion rate decreased significantly at all immersion times. For instance, at 3 days the corrosion rate dropped from 0.2533 mmpy (no inhibitor) to 0.0470 mmpy at 1500 ppm – an over 80% reduction. At 7 days immersion, the uninhibited sample's corrosion rate was 0.0765 mmpy, whereas only 0.0132 mmpy was recorded with 1500 ppm extract (an 83% decrease, corresponding to the highest inhibition efficiency of 82.7%). This trend demonstrates the effectiveness of guava leaf extract in suppressing steel corrosion. The optimal concentration was found to be 1500 ppm, which yielded the lowest corrosion rates across all time periods. Notably, pushing the concentration to 2000 ppm did not further improve protection – in fact, a slight increase in corrosion rate was observed at 2000 ppm compared to 1500 ppm. For example, at 7 days the corrosion rate at 2000 ppm rose to 0.0156 mmpy from 0.0132 mmpy at 1500 ppm, and the inhibition efficiency dropped from 82.7% to ~79.6%. This indicates that an overdose of inhibitor can diminish performance, a behavior reported in other plant-based inhibitors as well. Guava leaf extract in acid, that inhibition efficiency increased up to an optimum (~800 ppm) and then slightly decreased at higher dose

[6]. Such behavior is often explained by the saturation of the metal surface with inhibitor molecules: once an optimal monolayer is adsorbed, excess inhibitor may aggregate or form multilayers that do not adhere as well, leading to partial desorption of the protective film [7]. In our system, the 1500 ppm extract likely produces a compact, adherent inhibitor layer, whereas 2000 ppm may induce a loosely bound multilayer or competitive adsorption of inhibitor constituents, slightly compromising the protective barrier [7]. This finding underlines the importance of determining an optimum inhibitor concentration for maximal efficacy [8].

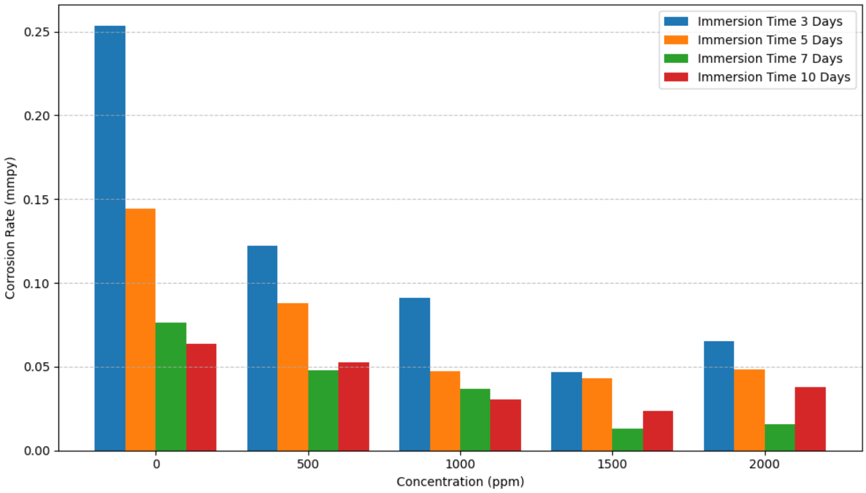


Fig. 3. Effect of inhibitor concentration and immersion time on corrosion rate

Figure 4 shows that the inhibition efficiency (IE) increased markedly with extract concentration from 500 to 1500 ppm for all immersion periods, confirming a clear concentration-dependent improvement in corrosion protection. At 500 ppm, the IE remained relatively low, particularly at longer immersion times, indicating that the amount of adsorbed inhibitor was still insufficient to generate a dense and continuous barrier film on the metal surface. This suggests incomplete surface coverage, so that active sites remained exposed to the corrosive medium and corrosion could still proceed locally. As the concentration increased to 1000 and 1500 ppm, the IE rose substantially, implying progressive occupation of the surface by active phytochemical constituents and the formation of a more compact protective layer. The highest performance was observed at 1500 ppm, where the 7-day immersion produced the maximum IE, followed by the 3-day immersion, indicating that this concentration provided the most favorable condition for stable inhibitor adsorption and effective surface protection.

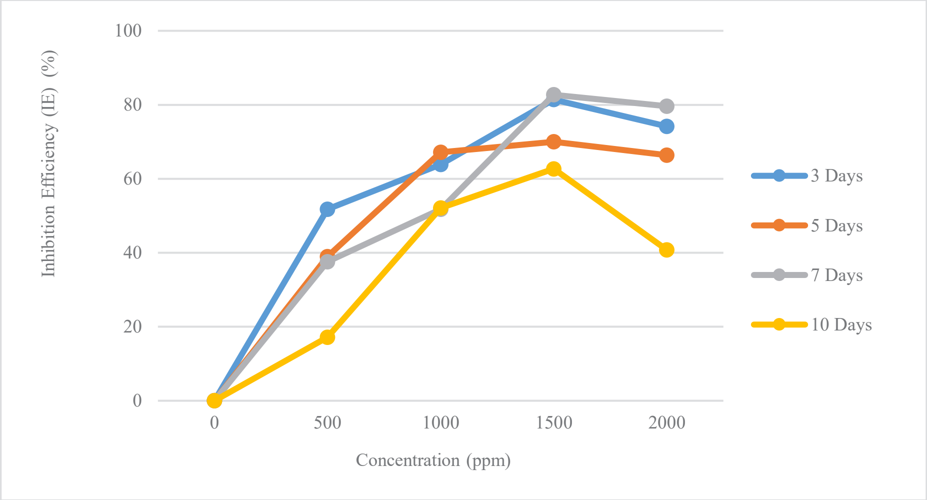


Fig. 4. Effect of inhibitor concentration and immersion time on Inhibition Efficiency (IE)

The overall trend is consistent with adsorption-controlled inhibition, which is commonly interpreted using Langmuir-type adsorption behavior for organic and plant-based inhibitors. In this framework, the increase in IE with concentration reflects greater surface coverage by adsorbed inhibitor molecules, leading to the development of a protective monolayer that suppresses contact between the metal substrate and aggressive species in solution. The immersion-time dependence further indicates that film formation was not instantaneous, but rather involved a gradual adsorption and reorganization process in which the active components of the extract became more uniformly distributed over the metal surface with time. This explains why the inhibition performance improved up to an optimum immersion period, especially at 7 days, where the protective film appeared to be the most mature and effective. Such behavior is in line with previous studies on natural inhibitors, where multi-component phytochemicals progressively adsorb and consolidate on the metal surface, thereby restricting anodic metal dissolution and cathodic reactions through a surface-blocking mechanism [9].

However, the decline in IE at 2000 ppm, particularly for the 10-day immersion period, indicates that increasing inhibitor concentration beyond the optimum level did not further enhance protection and may even have destabilized the adsorbed layer. This decrease may be associated with partial desorption, intermolecular repulsion within an overcrowded adsorbed film, competitive adsorption among extract constituents, or reduced film integrity during prolonged exposure. Such behavior highlights that, although Langmuir adsorption is often used as a first approximation, the adsorption of complex plant extracts may deviate from ideal monolayer behavior because of lateral interactions and surface heterogeneity. Therefore, the present results suggest that the extract acts through adsorption-mediated film formation, with the most effective protection obtained at 1500 ppm and an immersion time of 7 days. This optimum condition likely reflects the best balance between inhibitor availability, surface coverage, and film stability, and thus represents the most favorable operational window for applying the extract as a green corrosion inhibitor [10].

3.4 Optical micrograph

The figure 4 presents an optical micrograph (20× magnification) of a steel specimen immersed in a 4% NaCl solution without the addition of *Psidium guajava* leaf extract inhibitor (0 ppm). Observations were conducted on three different regions—left, middle, and right—to provide a comprehensive representation of the overall surface condition. In all three regions, clear evidence of localized corrosion in the form of pitting corrosion can be observed, as highlighted by the red circles. The circled areas indicate the presence of cavities, small pits, and non-uniform corrosion products with brownish to dark coloration. The metal surface appears rough and heterogeneous, with extensive accumulation of iron oxidation products. The yellowish to dark brown coloration suggests the formation of iron oxides and hydroxides resulting from the oxidation of Fe-to-Fe^{2+} and subsequently to Fe^{3+} in a chloride-containing environment [11]

The presence of Cl^- ions in the 4% NaCl solution accelerates the breakdown of the natural passive film on the steel surface, thereby initiating and propagating pit formation. The distribution of pits across the left, middle, and right regions indicates significant surface degradation in the absence of inhibitor protection. This morphological condition corroborates the high corrosion rate measured for the uninhibited specimen and confirms the absence of a protective layer capable of preventing the penetration of aggressive chloride ions and water molecules into the metal surface, consistent with the well-established role of chloride in passivity breakdown and pit nucleation on carbon and alloy steels [12].

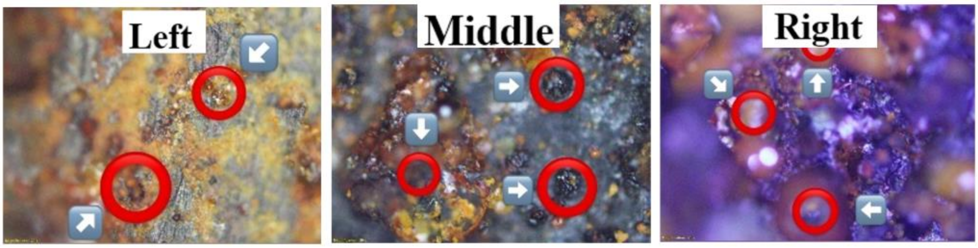


Fig. 5. Optical micrograph (20×Magnification) of the specimen in the absence of *Psidium guajava* leaf extract.

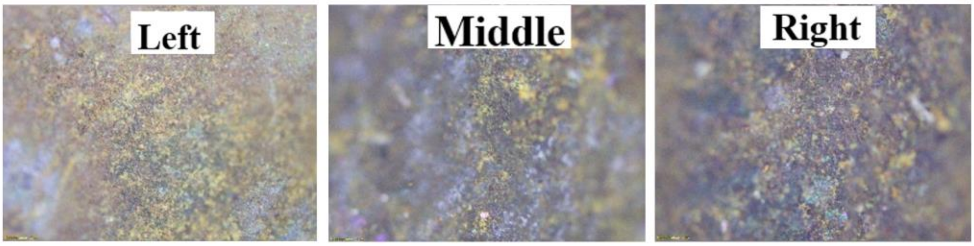


Fig. 6. Optical micrograph (20×Magnification) of the specimen treated with *Psidium guajava* leaf extract.

The figure 6 presents an optical micrograph (20× magnification) of a steel specimen treated with *Psidium guajava* leaf extract as a corrosion inhibitor. Observations were carried out in three distinct regions—left, middle, and right—to ensure that the surface morphology represents the overall condition of the specimen. In contrast to the uninhibited sample, the treated specimen exhibits a significantly more homogeneous and relatively smoother surface. No prominent cavities or clearly defined pits are observed, indicating a substantial reduction in localized corrosion. The metal surface appears to be covered by a more uniform thin layer, with a relatively even color distribution and without evident signs of severe surface degradation. This morphology suggests the formation of a protective adsorbed film derived from the phytochemical constituents of the P. guajava extract [13].

The protective layer acts as both a physical and chemical barrier, minimizing direct contact lotbetween the metal surface and aggressive species such as Cl^- ions and water molecules in the 4% NaCl solution. The improved surface integrity confirms a significant decrease in corrosion activity compared to the specimen without inhibitor. Overall, the microstructural features observed in this figure provide clear evidence of the effectiveness of *Psidium guajava* leaf extract as a green corrosion inhibitor, capable of suppressing pit formation and enhancing surface stability under saline conditions [14].

4 Conclusions

Psidium guajava leaf extract proved to be an effective green corrosion inhibitor for boiler tube steel in 4% NaCl solution. The $FeCl_3$ test confirmed the presence of tannins in the extract, while gravimetric measurements showed that corrosion resistance improved with increasing inhibitor concentration up to an optimum level. The best performance was obtained at 1500 ppm and 7 days of immersion, where the corrosion rate decreased to 0.0132 mmpy and the inhibition efficiency reached 82.7%. These results indicate that the extract formed an adsorbed protective film capable of significantly suppressing steel dissolution in the corrosive medium. A further increase in concentration to 2000 ppm did not improve protection and instead caused a slight decline in inhibition efficiency, suggesting that excessive extract concentration may lead to a less compact or less stable adsorbed layer. Optical micrograph observations confirmed the protective role of the inhibitor, as the uninhibited specimen showed severe pitting and abundant corrosion products, whereas the inhibited surface appeared smoother and more uniform. Overall, the study demonstrates that *Psidium guajava* leaf extract has strong potential as a sustainable alternative to conventional synthetic inhibitors for boiler tube protection. Further studies using electrochemical methods and advanced surface characterization are recommended to better elucidate the adsorption mechanism and long-term protective behavior.

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