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Evaluation of Banana-Derived Inhibitor for Corrosion Control in Mild Steel

Diego Hidalgo*, Carlos Montero, Daniel Luna, Vladimir Pazmiño, Jessica Brito

Faculty of Engineering, Universidad Nacional de Chimborazo, Ecuador

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Abstract This study investigates the effectiveness of banana peel extract as a corrosion inhibitor for A36 steel, addressing the need for sustainable solutions in infrastructure maintenance. Controlled corrosion exposure tests were conducted on steel plates treated with banana peel extract at varying concentrations (0%, 5%, 10%, and 15%). Surface characteristics were evaluated through scanning electron microscopy (SEM) and colorimetry. The pH and conductivity were monitored throughout the tests. The corrosion rate was determined using gravimetric characterization. Mechanical testing, including stress-strain behavior analysis, was performed using a universal testing machine. The results demonstrate that banana peel extract significantly enhances the corrosion resistance of A36 steel. Higher inhibitor concentrations, particularly at 15%, resulted in improved mechanical properties, such as ultimate stress, yield stress, modulus of elasticity, resilience, and toughness. SEM analysis revealed the formation of a protective chemisorbed layer, while colorimetry indicated better preservation of the steel's surface characteristics with increasing inhibitor concentration. Banana peel extract is a promising and sustainable alternative for corrosion protection in civil infrastructure. The effectiveness of the inhibitor increases with higher concentrations, providing robust protection against corrosion and enhancing the mechanical integrity of the steel. The utilization of agricultural waste as a functional corrosion inhibitor promotes circular economy principles. By repurposing banana peels, the study contributes to sustainable engineering practices and supports the achievement of the United Nations Sustainable Development Goals. This approach not only mitigates the environmental impact of traditional corrosion protection methods but also offers a viable, eco-friendly solution for extending the lifespan of steel structures.

Keywords Banana-Derived Inhibitors, Corrosion Control, Mild Steel, Sustainable Solutions, Plant-Based Compounds

1. Introduction

1.1. Problem

In Latin America, a pervasive lack of maintenance culture prevails, particularly evident in the neglect of infrastructure assets such as bridges and roads [1][2]. Corrosion poses a significant risk to carbon steel bridges, necessitating meticulous maintenance and corrosion assessment to prevent structural failure and mitigate adverse societal consequences [3]. Traditional methods of corrosion protection, primarily reliant on costly and environmentally harmful coatings, contribute to this issue [4]. Addressing these challenges aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

1.2. Introduction to Corrosion in Mild Steel

Corrosion in mild steel is a significant challenge across industries, leading to economic losses and environmental degradation [5]. It can be defined as the progressive deterioration of a metal surface due to chemical and/or electrochemical reactions with its environment. These reactions cause the metal to be oxidized and transformed into more chemically stable compounds, typically metal oxides [6].

To promote sustainable development and circular economy principles, this research endeavors to explore an alternative corrosion inhibition approach utilizing banana peel extract. Ecuador, a major banana producer, offers an abundant supply of this agricultural byproduct, making its utilization environmentally friendly and economically viable [7]. By repurposing banana waste into a corrosion inhibitor, we aim to contribute to the principles of sustainability and circular economy while addressing the pressing need for infrastructure maintenance.

1.3. Overview of Current Inhibitors and Their Limitations

Traditional inhibitors, though somewhat effective, pose environmental and health risks due to their toxicity [8]. Thus, demand is growing for sustainable, eco-friendly alternatives in corrosion control strategies. The problem arises from persistent mild steel corrosion and concerns over traditional inhibitors, emphasizing the need for innovative, sustainable solutions capable of mitigating corrosion while minimizing environmental impact [9] [10] [11].

1.4. Introduction of Banana-Derived Inhibitor Concept

The concept of banana-derived inhibitors integrates corrosion science, electrochemistry, and green chemistry, presenting a promising approach to mild steel corrosion control [12]. *Musa paradisiaca (M. paradisiaca)*, commonly known as *banana*, is recognized for its rich phenolic content, including natural antioxidants such as *gallo catechion, catechin, hydroxyl groups, and phenols*. These compounds are known for their ability to adsorb onto metal surfaces, forming protective layers that inhibit corrosion processes.

This study focuses on exploring plant-based inhibitors, particularly those derived from bananas, as potential alternatives for mild steel corrosion control. The objectives are to investigate the effectiveness, mechanisms, and applications of banana-derived inhibitors for mild steel corrosion control. Through critical literature review, the study aims to evaluate corrosion inhibition efficiency, understand underlying mechanisms, and identify potential applications and limitations of banana-based inhibitors. The comprehensive classification of inhibitors is illustrated in Figure 1, which includes eco-friendly options such as banana-based inhibitors utilizing adsorption mechanisms.

1.5. Previous Investigation about Banana Peel

In a prior investigation, researchers delved into the inhibitory and adsorptive effects, evaluating changes in inhibition efficiency across different ripening stages of the peels. Various analytical techniques, including weight loss measurement, electrochemical impedance spectroscopy (EIS), Tafel polarization, and atomic force microscopy (AFM), were utilized. Results revealed a diminishing inhibition capacity as the peels matured effects [13].

In a subsequent study, electrochemical analyses uncovered the presence of a protective film on the steel surface. This protective film was attributed to the protonation of the corrosion inhibitor, coupled with rust formation, particularly in fluctuating acidic conditions. Notably, the investigation highlighted UBPE as a promising corrosion inhibitor for steel, especially in highly acidic environments containing chloride and sulfate ions [14].

While various studies have explored the potential of green corrosion inhibitors, few have comprehensively analyzed their effectiveness in enhancing material resistance [11]. Moreover, contemporary trends in engineering emphasize the importance of rehabilitation over new construction to minimize ecological impact. By assessing the corrosion resistance of steel treated with banana peel extract, this study seeks to provide valuable insights into a sustainable solution for infrastructure maintenance.

Through experimental investigations, including controlled corrosion exposure and mechanical testing, coupled with advanced analytical techniques such as colorimetry and scanning electron microscopy, we aim to elucidate the protective mechanisms of the banana peel-derived inhibitor. Additionally, finite element modeling will be employed to simulate and validate the observed stress-strain behavior, enhancing our understanding of the inhibitor's performance under various loading conditions.

1.6. Contribution

By bridging the gap between sustainable development goals and innovative engineering solutions, this research endeavors to offer a practical and environmentally conscious approach to corrosion protection in civil infrastructure. Ultimately, the findings of this study aspire to inform policymakers, engineers, and stakeholders on the potential of banana peel extract as a sustainable alternative for infrastructure maintenance, fostering resilient and sustainable communities in Latin America and beyond.

The classification of corrosion inhibitors is shown in Figure 1, which includes environmentally friendly options that use adsorption mechanisms.

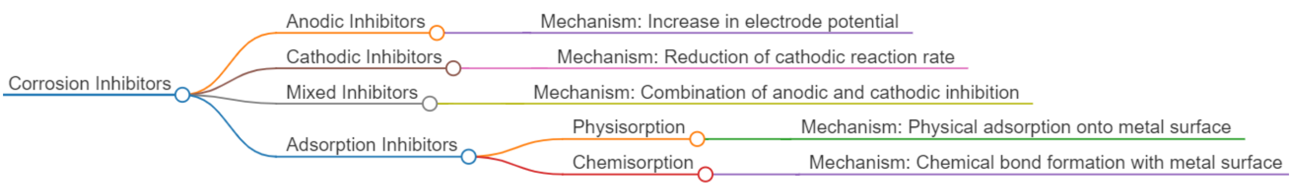


Figure 1. Corrosion inhibitors and their mechanisms

2. Materials and Methods

The methodology in this study was organized into distinct phases, each supported by specific literature references. It followed four key stages: sample preparation, experimental setup, and testing and analysis.

The experimental development was divided into two parts: the first part involved the extraction and preparation of the green inhibitor from banana peels in the form of a liquid suspension; the second part consisted of evaluating the steel plates' characteristics. For the surface morphology analysis and mechanical testing, protocols outlined in [15] were followed. Colorimetry procedures were based on [16].

For the accelerated corrosion experimental procedure and the evaluation of the gravimetric mechanism, the methodologies described in the literature were taken into consideration [11], [12], [13], [14], [17], [18], [19]. Statistical procedures were based on the studies outlined in [20].

2.1. Chemical Preparations

2.1.1. Banana Peel Extracts Preparation

The plant material, *M. paradisiaca*, was attained from the local market, considering the same size and without visible blights were chosen. The *M. paradisiaca* was washed with distilled water to remove dirt and face remainders. Also, they were precisely hulled to separate the pulp from the peel.

The *M. paradisiaca* peel was cut into small pieces and blended with distilled water in a rate of 150 g per 500 ml of water. The admixture was blended for 5 twinkles until a homogeneous suspense was attained. Latterly, the suspense was filtered to separate the undoable solids.

To prepare experimental solutions, dilutions of 5%, 10%, and 15% were made by mixing specific volumes of the original extract with distilled water. These extracts contain active compounds such as phenolic compounds, flavonoids (gallocatechin and catechin), and natural antioxidants, which are responsible for inhibiting corrosion. These compounds work by forming a protective chemisorbed layer on the steel surface, reducing its susceptibility to corrosion.

2.1.2. Details of Banana Peel Extract

The banana peel extract (*Musa paradisiaca*) used in this study was prepared following a standard process of washing, drying, and grinding the peels. The specific gravity of the extract was measured at 1.03g/cm^3, aligning with values reported for similar plant-based inhibitors. The pH of the extract was recorded at 5.2, indicating its slightly acidic nature, which enhances its corrosion inhibition properties. Conductivity measurements showed a value of 9.82 S/cm for the 15% inhibitor concentration, reflecting a suitable ionic environment for corrosion inhibition. These parameters were carefully monitored to ensure consistency in the corrosion tests and across the different concentrations of inhibitor solutions (0%, 5%, 10%, and 15%).

2.1.3. Preparation of Corrosive Solution

A 0.5 M hydrochloric acid (HCl) solution was prepared to generate accelerated oxidation conditions [21], simulating those that the study material might be exposed to. Reagent-grade HCl with a purity of 37% and distilled water were used. The solutions were placed in flasks for each of the samples.

2.1.4. Corrosion Testing

In this corrosive medium, a control plate (CP) without inhibitor is used to establish a baseline. The inhibitor is then applied at different concentrations of 0%, 5%, 10%, and 15%. Each specimen is exposed to one of these concentrations to determine its ability to protect A36 steel from corrosion over a period of two weeks. During this time, the mass loss of the steel plates is recorded.

2.1.5. PH and Temperature Conditions

The pH of the corrosion solution was measured at the start of the experiment using a calibrated pH meter at room temperature (approximately 25 ℃). During the corrosion testing, the steel specimens were kept in a controlled environment at a consistent temperature of 25 ℃ to ensure uniform test conditions. This temperature was selected to simulate standard laboratory conditions, minimizing the influence of temperature fluctuations on the corrosion rate and inhibitor performance.

2.2. Test Specimen

Mild steel plates specimens of grade A36 were used with the dimensions depicted in Figure 2, complied with the specifications outlined in ASTM A370 standard, which ensured conformity with established guidelines for mechanical testing with thickness of 3 mm. For the corrosion tests, PVC tubes with a diameter of 64 mm (2.5 inches) and a height of 550 mm were used for their corrosion resistance and ease of handling. Each tube was sealed with a male cap at the top and a female cap at the bottom to ensure a tight seal and prevent solution leakage during the experiment. In addition, a 10 mm x 10 mm square was cut from each specimen to facilitate scanning electron microscopy analysis.

2.2.1. Surface Roughness (Ra) of A36 Steel Plates

The A36 steel plates used in this study were sourced with an average surface roughness of approximately 3.2 to 6.3 micrometers Ra, as per standard industrial practice for hot-rolled steel. The surface roughness is crucial as it can affect the material’s susceptibility to corrosion, with rougher surfaces having higher friction and nucleation sites that promote corrosion. The surface preparation followed ASTM A370, ensuring consistency in surface texture for all specimens before corrosion testing.

2.2.2. Experimental Setup with PVC Pipe

In this study, the PVC pipes used for corrosion testing were sealed at both ends with threaded caps to ensure a hermetic seal, maintaining a controlled environment for the specimens throughout the test duration. Each pipe contained three steel specimens with an exposed surface area of approximately 20 cm^2, submerged in 500 mL of the prepared corrosion solution. The initial pH of the solution was set at 5.3 to replicate a realistic corrosive environment. To simulate long-term, real-world corrosion conditions, the solution was not changed over the 75-day test period, allowing continuous observation of the steel's corrosion behavior as the solution gradually reacted with the specimens. The solution level was monitored, and any evaporative losses were compensated with distilled water, ensuring consistency in the exposure conditions throughout the test.

2.2.3. Specimen Testing and Statistical Analysis

For each condition, including inhibitor concentrations of 0%, 5%, 10%, and 15%, a total of three steel specimens were tested to ensure the reliability of the data. The manuscript presents the average results for each condition. The term 'Ef' or Modulus of Elasticity at Failure, represents the stress-strain response at the ultimate point where material deformation becomes permanent. Standard deviation and error bars were not included in the figures because the consistency between replicates was high, with minor deviations in results across the three specimens. The dimensions of the steel samples and PVC tubes used in the corrosion tests are shown in Figure 2. These configurations ensure standard compliance and test stability.

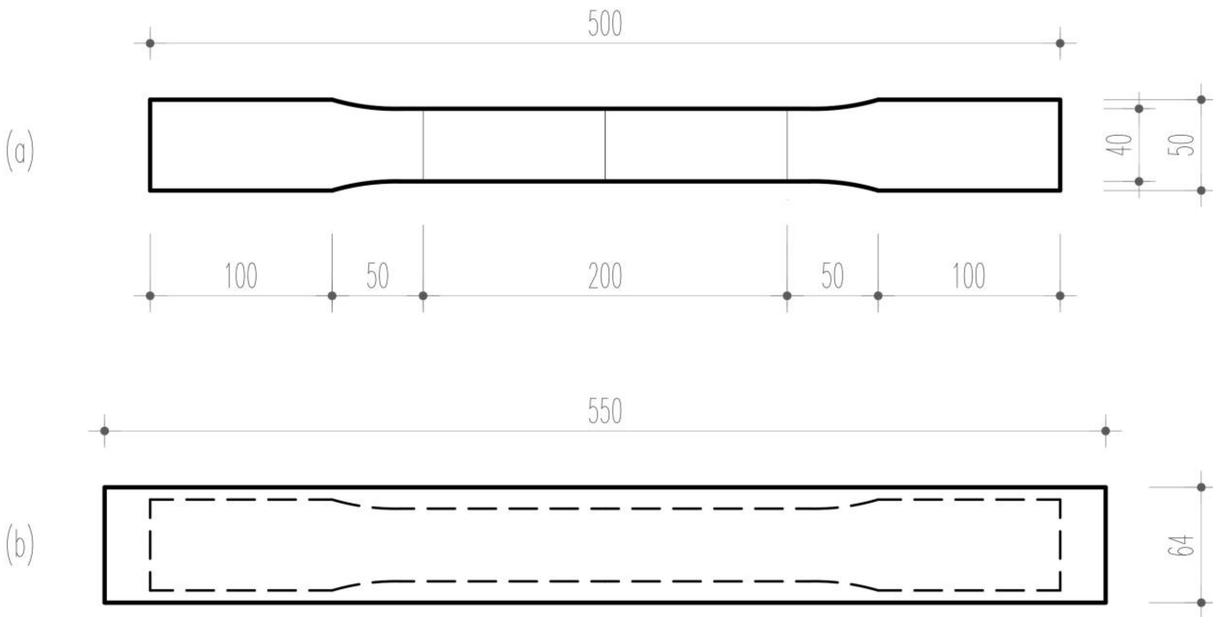


Figure 2. Dimensions (mm). (a) tension test specimen according to ASTM A370, (b) PVC tube for corrosion testing

3. Results

3.1. Morphological Characterization

3.1.1. Scanning Electron Microscopy (SEM)

The high magnification scanning electron microscopy (SEM) results depict the surface analysis of steel samples immersed for 75 days in a 0.5M HCl solution. Figure 5 illustrates the surface morphology at various magnifications: (a)-(d) represent the control plate (CP) without inhibitor, while subsequent rows depict plates treated with inhibitors at concentrations of 0%, 5%, 10%, and 15%, respectively. Each image provides insights into the structural changes induced by corrosion and the protective effects of the inhibitors under study.

3.2. Optical Characterization

3.2.1. Colorimetry Analysis

The KONICA Minolta CM-760d colorimeter uses a principle of spectral reflectance to measure color. This principle relies on how light interacts with a surface. On impacting the surface, light is partly absorbed and partly reflected back off. It is important to notice that the amount of reflected light varies according to different colors in the material.

The color results are expressed on the scale CIE Lab. This three-dimensional scale defines color through three coordinates: L* Lightness (bright/dark), a* Red-green color coordinate (positive red, negative green) and b* Yellow-blue color coordinate (positive yellow, negative blue) [22].

For color measurement, each of the samples was taken and three measurements were made in different places. The same procedure was followed for each of the treatments, obtaining the results that can be observed in Table 1.

The color variation among treatments with different inhibitor concentrations is illustrated in Figure 3, providing visual evidence of the inhibitor's protective effect.

Figure 4 shows a visual comparison of A36 steel samples treated with different inhibitor concentrations after corrosion testing, highlighting differences in surface appearance.

Table 1. Colorimetry results at CIE L*a*b*

	L*	a*	b*	△E*
CP	55,47595	5,212804	3,530164	V REF
0%	37,02911	7,243639	7,563207	18,99146
5%	30,45674	4,36009	3,164386	25,03641
10%	31,68726	4,973881	3,931917	23,79328
15%	31,74258	4,602641	3,896529	23,74404

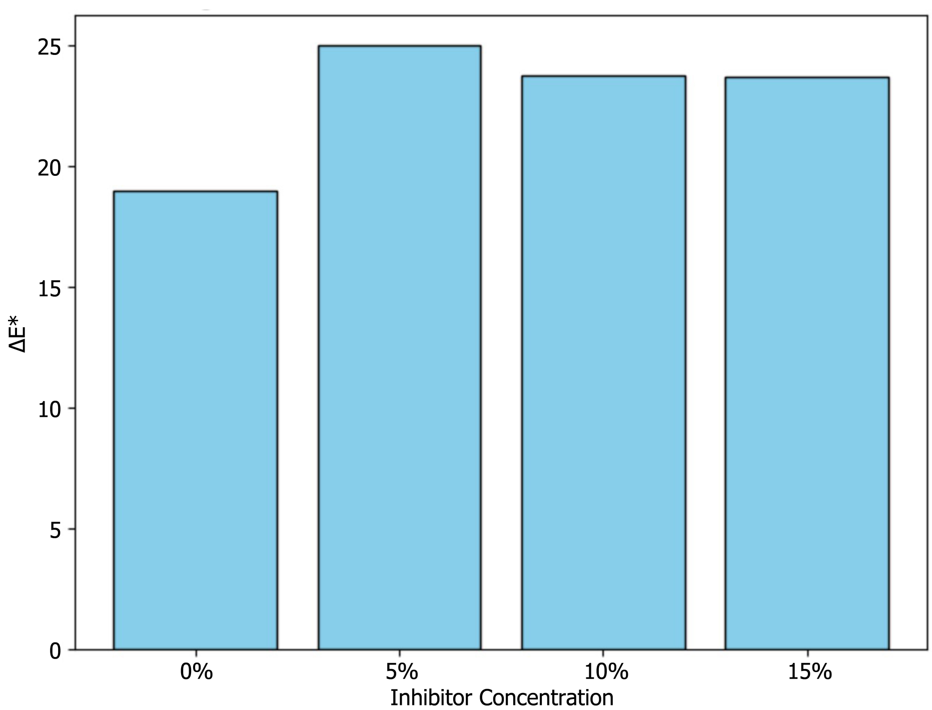
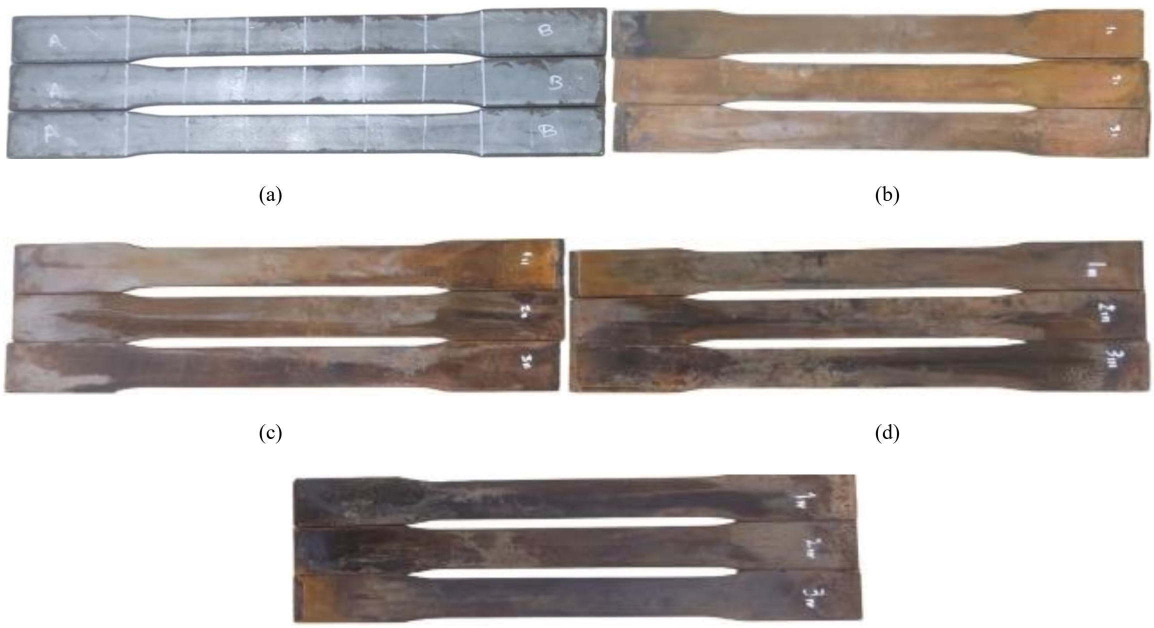


Figure 3. Color variation between treatments



(a) (b) (c) (d) (e)

Figure 4. Visual Comparison of A36 Steel Specimens Treated with Different Inhibitor Concentrations After Corrosion Testing. (a) CP, (b) 0%, (c) 5%, (d) 10%, (e) 15%

3.3. PH and Conductivity Analysis

The final pH and conductivity of the solution for each study group were measured to evaluate the chemical stability of the corrosive medium, detect additional reactions, and ensure the consistency and reproducibility of the test conditions. After two weeks of the study, the data obtained is summarized in Table 2.

Table 2. PH and conductivity values

Solution	pH (-)	Conductivity (S/cm)
0.5M HCl + I 0%	5.3	10.13
0.5M HCl + I 5%	5.1	9.93
0.5M HCl + I 10%	5.3	9.89
0.5M HCl + I 15%	5.2	9.82

3.4. Gravimetric Characterization

3.4.1. Weight Loss Test

According to the methodology described in [19], the weight loss test was conducted by placing material samples in jars containing approximately 500 mL of each of the previously prepared HCl solutions. The steel plates were subjected to this advanced oxidation process for 15 days, with daily weight measurements recorded using an analytical balance with a sensitivity of ±0.1 mg. Prior to weighing, the corroded layer on each sample was cleaned according to the standard ASTM G-103 procedure. The samples were removed from the acidic solution, mechanically cleaned with cloths to remove the oxide layer, immersed in Clarke's solution for 5 minutes, thoroughly washed with water, rinsed with ethanol, dried using dry air, and then weighed. This process ensured accurate mass loss measurements due to corrosion, without interference from residual corrosion products.

3.4.2. Corrosion Rate

The weight loss of the samples can be used to calculate the average corrosion rate of the steel by the following equation:

$$V_{CR} = \frac{8.76\times10^{4}\Delta W}{\rho St} \quad (1)$$

where the V_{CR} is the corrosion rate, $mm.y^{-1}$; ΔW is the average weight loss of samples, g; S represents the total area of the sample, cm^2; t is the immersion time, h; ρ is the density of the samples, g/cm^3; 8.76×10^4 is the unit conversion constant [21].

According to the values of the V_{CR}, the inhibition efficiency (η_w) of the corrosion inhibitors can be obtained as follows:

$$\eta_w = \left(1 - \frac{V_{CR\ (inh)}}{V_{CR(uninh)}}\right) \times 100\% \quad (2)$$

where the $V_{CR(inh)}$ and $V_{CR(uninh)}$ are the corrosion rates in the presence and absence of inhibitor, respectively [21].

The results of the corrosion rate and inhibition efficiency, calculated from the weight loss tests, are presented in Table 3. These data allow for evaluating the inhibitor's effectiveness based on concentration.

The corrosion rate over time for each inhibitor concentration is shown in Figure 5, allowing a comparison of concentration effectiveness.

Table 3. Corrosion rate and inhibition efficiencies, ηw, obtained from weight- loss tests in solution containing different inhibitors concentration

Treatment	Corrosion rate (mm y^{-1})	η_W (%)
CP.	1.395 ±0.23	
5%	1.252 ±0.88	10.25
10%	1.143 ±1.1	18.06
15%	1.054 ±1.03	24.44

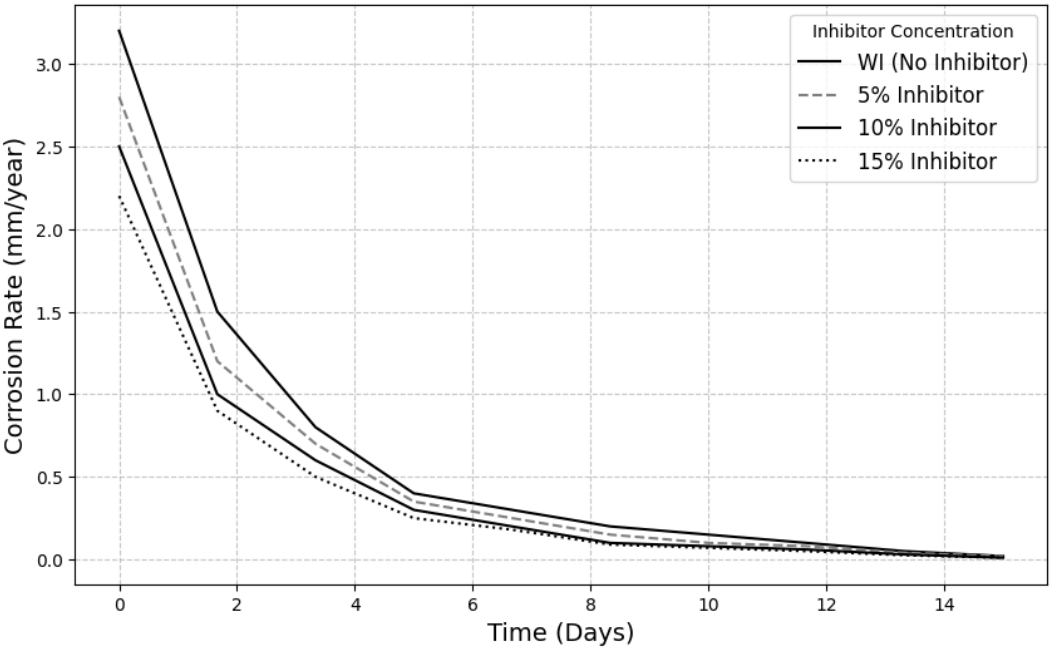


Figure 5. Corrosion rate over time for different inhibitor concentrations

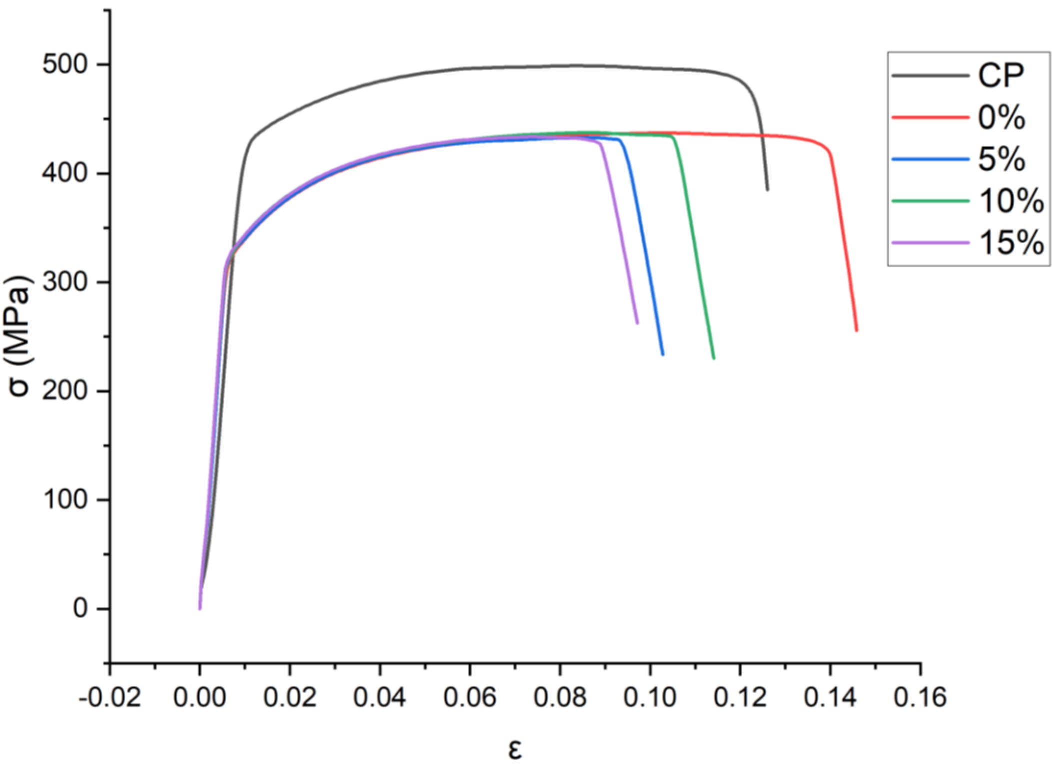


Figure 6. Average stress-strain curves of corroded A36 steel. Control Plate CP, 0% inhibitor, 5% inhibitor, 10% inhibitor, 15% inhibitor

3.5. Mechanical Characterization

3.5.1. Tensile Testing and Analysis of Stress-Strain Behavior

The average stress-strain curves for corroded A36 steel specimens treated with different concentrations of the banana peel extract inhibitor are presented in Figure 6. The control plate (CP) without inhibitor, the plate with 0% inhibitor, and plates with 5%, 10%, and 15% inhibitor concentrations were tested. For each group, three samples were subjected to tensile testing using a universal testing machine. The stress-strain curves from these tests were averaged to produce a representative curve for each group. The variations in the mechanical properties of each study group are shown in Figure 7.

Figure 8 presents the high magnification scanning electron microscopy (SEM) results, allowing observation of morphological differences on the surfaces of treated samples.

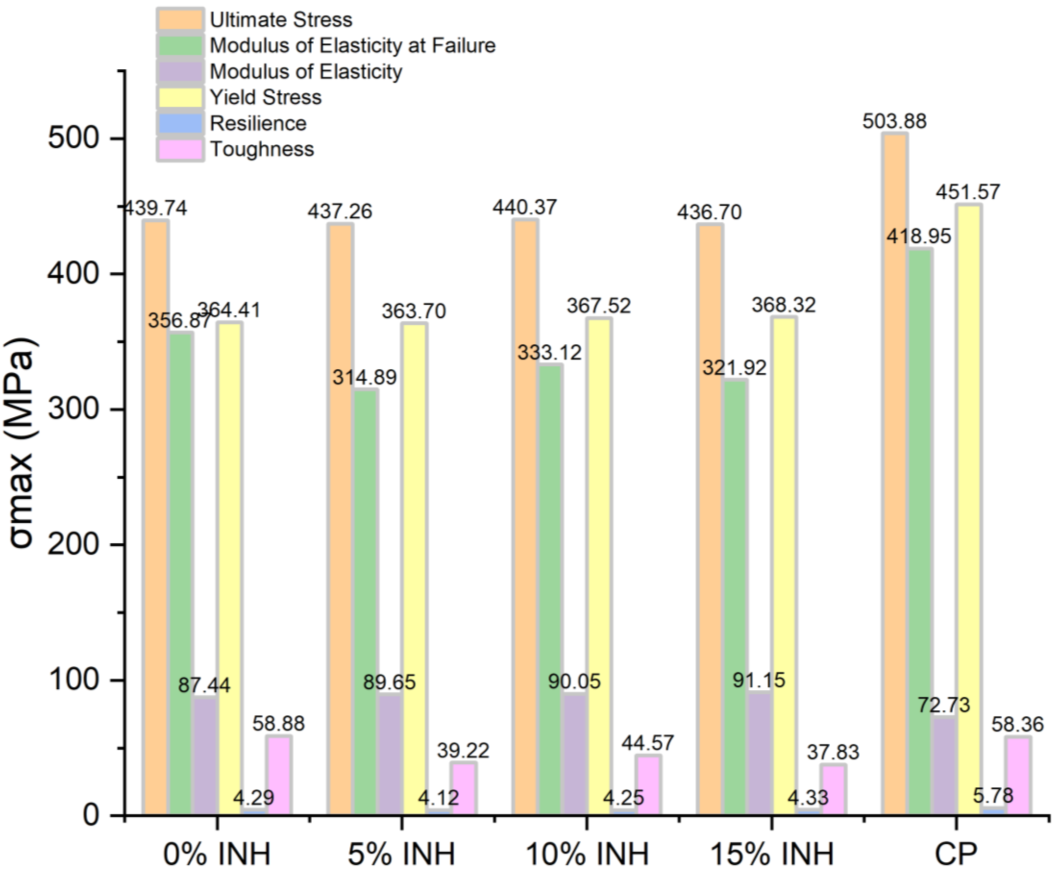
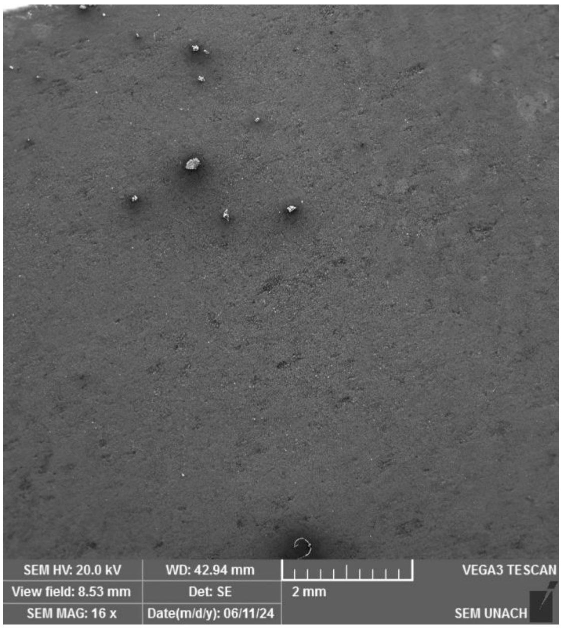


Figure 7. Variations in Mechanical Properties of A36 Steel with Different Inhibitor Concentrations. (a) Ultimate stress, (b) Modulus of Elasticity at Failure, (c) Modulus of Elasticity, (d) Yield Stress, (e) Resilience, (f) Toughness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WD: 42.94 mm
VEGA3 TESCAN
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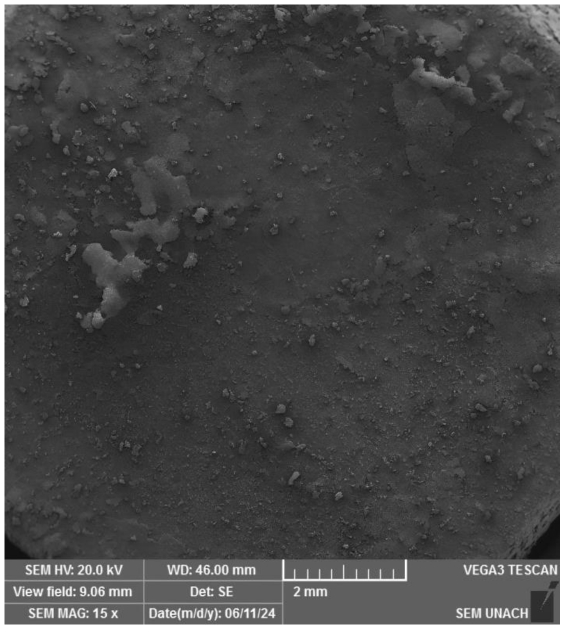
Det: SE
2 mm
SEM MAG: 16 x
Date(m/d/y): 06/11/24
SEM UNACH

(a)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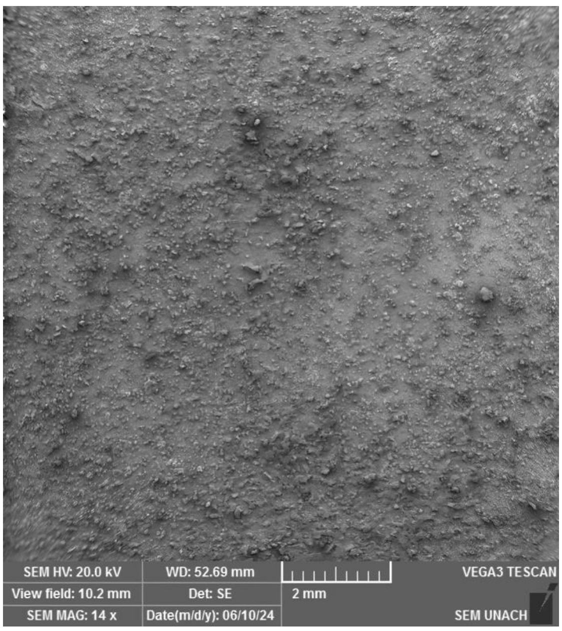
SEM UNACH

(b)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2 mm
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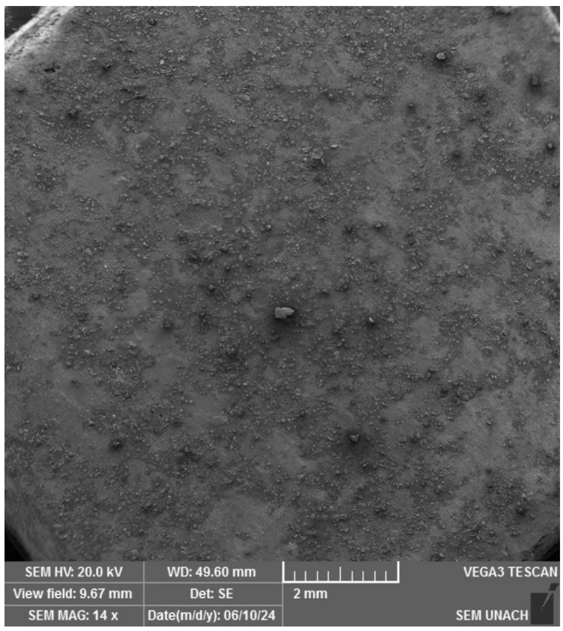
SEM UNACH

(c)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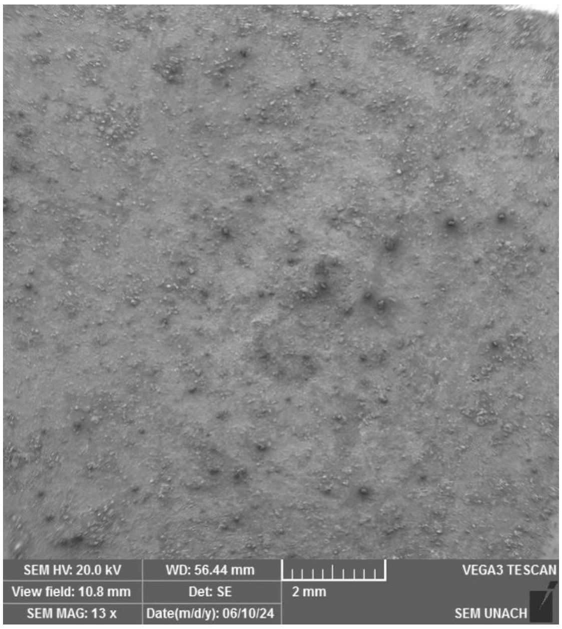
SEM UNACH

(d)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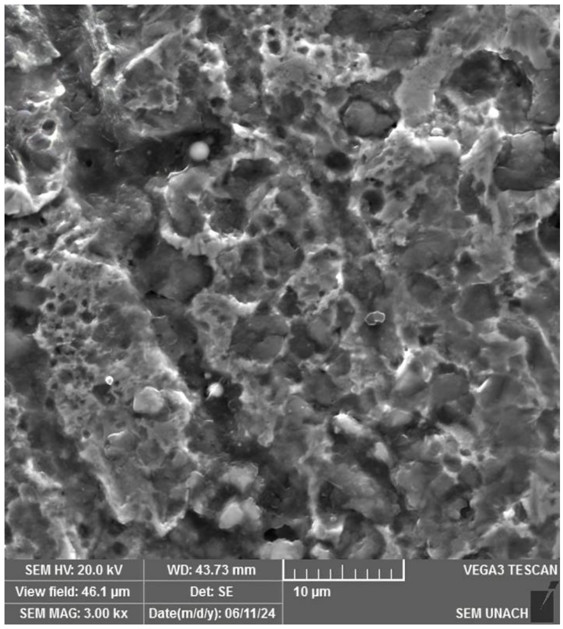
SEM UNACH

(e)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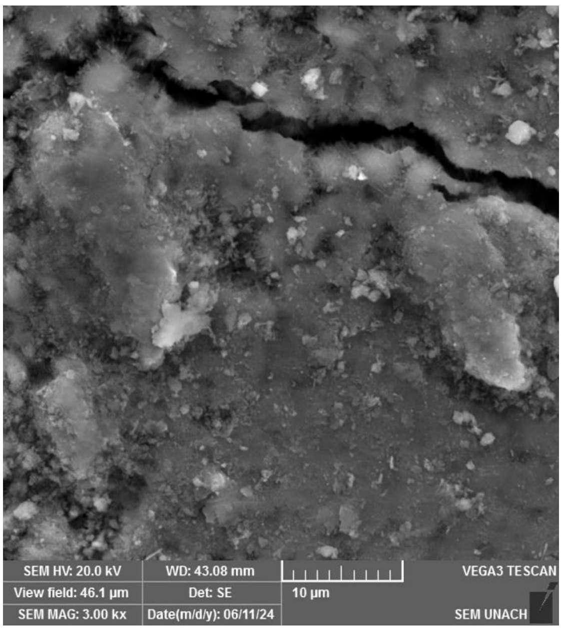
SEM UNACH

(f)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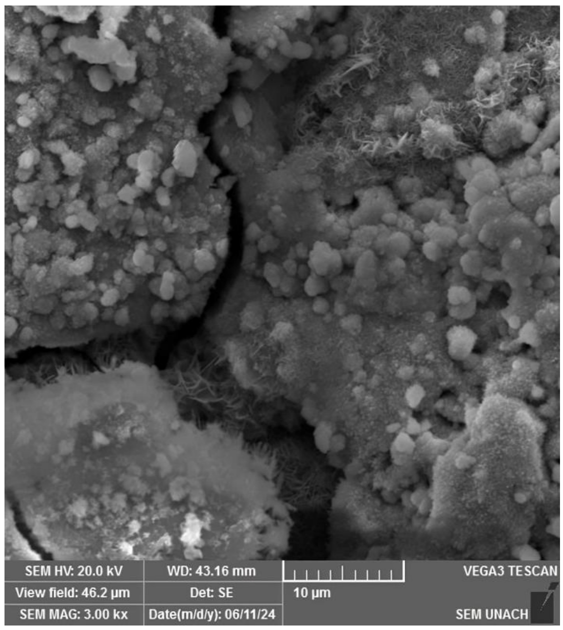
SEM UNACH

(g)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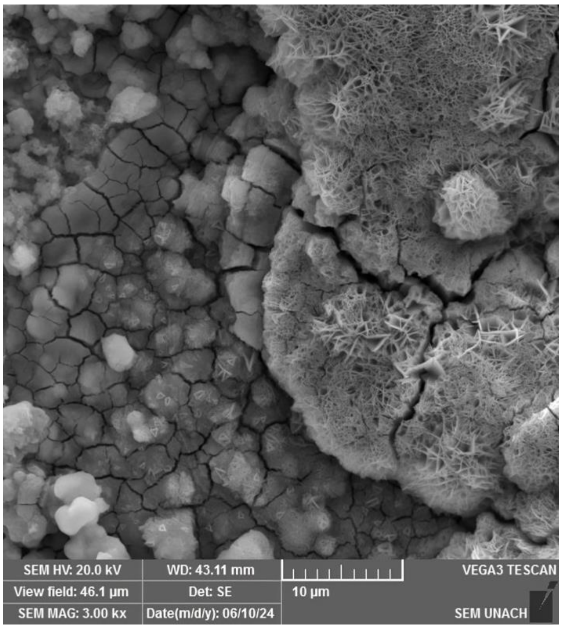
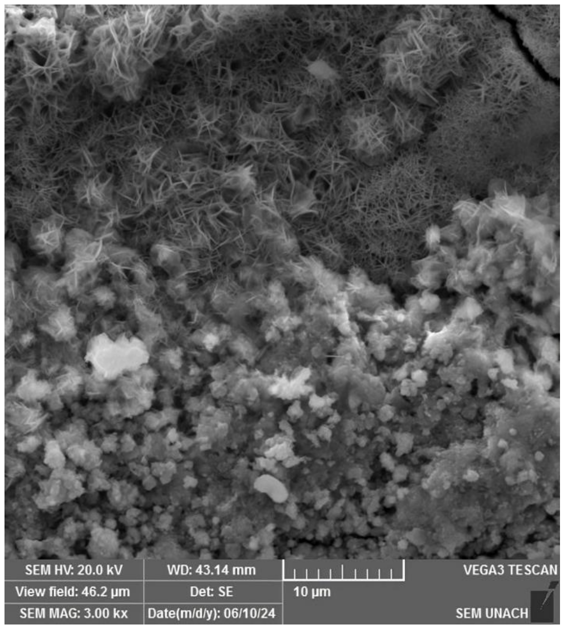
(h)



(i)



(j)

Figure 8. High magnification SEM results after 75 days immersion in 0.5M HCl. (a) CP 10x, (b) 0% 10x, (c) 5% 10x, (d) 10% 10x, (e) 15% 10x, (f) CP 3000x, , (g) 0% 3000x, , (h) 5% 3000x, , (i) 10% 3000x, , (j) 15% 3000x

4. Discussion

4.1. Morphological Characterization

The SEM images in Figure 8 reveal distinct morphological differences in the surfaces of A36 steel specimens treated with varying concentrations of banana peel extract, elucidating the corrosion inhibition process and the effectiveness of this natural extract in forming protective layers.

For the Control Plate (CP), the smooth surface without notable corrosion features establishes a baseline, indicating the natural state of the steel when uninhibited and highlighting its susceptibility to corrosion. In the 0% inhibitor plate, significant corrosion damage is evident, with the surface appearing heavily deteriorated and rough. This level of degradation confirms the steel's vulnerability in acidic environments without protection, as extensive reactions occur with the corrosive medium.

5% Inhibitor Plate: In the presence of 5% banana peel extract, the SEM images show a reduction in surface roughness compared to the 0% inhibitor plate. While the protective layer is not yet fully consistent, it suggests partial adsorption of inhibitor molecules onto the steel surface, providing moderate corrosion resistance.

10% Inhibitor Plate: The 10% inhibitor concentration results in a more uniform protective layer with a scaly texture, indicating enhanced chemisorption. This morphology reflects stronger interactions between the inhibitor compounds and the steel surface, reducing corrosive reactions and indicating an increase in corrosion inhibition effectiveness.

15% Inhibitor Plate: At the highest concentration of 15%, the SEM images reveal the most effective protection, with a dense and uniform protective layer. This scaly, well-adhered layer, resulting from strong chemical bonds between the inhibitor molecules and the steel surface, confirms the substantial corrosion inhibition effect at this concentration.

4.2. Optical Characterization

Optical Images in Figure 4 complement the SEM findings, showing visual differences in surface discoloration across treatments. The colorimetric analysis confirms these variations, with higher ΔE^* values corresponding to greater corrosion inhibition, as denser protective layers minimize oxidation and surface discoloration. This visual evidence strengthens the interpretation of the SEM data, showing that increasing the inhibitor concentration enhances the material's surface preservation.

Control Plate (CP):

The control plate exhibits the highest L^* value (55.47595), indicating the brightest surface among the samples. The a^* and b^* values are 5.212804 and 3.530164, respectively. This baseline measurement provides a reference for evaluating the effects of corrosion and inhibitor treatments.

0% Inhibitor Plate:

The 0% inhibitor plate shows a significant decrease in L^* value (37.02911), indicating a darker surface due to extensive corrosion. The a^* value (7.243639) shifts towards the red end, and the b* value (7.563207) shifts towards the yellow end, reflecting the presence of corrosion products. The ΔE* value of 18.99146 indicates a substantial color difference from the control, highlighting the severe impact of the acidic environment without any inhibitor protection.

5% Inhibitor Plate:

For the 5% inhibitor plate, the L* value further decreases to 30.45674, indicating continued corrosion, but the a* (4.36009) and b* (3.164386) values suggest a reduction in the formation of corrosion products compared to the 0% plate. The ΔE* value of 25.03641, although higher than the 0% plate, shows a different distribution of corrosion effects, possibly due to the formation of an initial protective layer.

10% Inhibitor Plate:

The 10% inhibitor plate shows a slight increase in L* value (31.68726) compared to the 5% plate, suggesting some improvement in surface brightness. The a* (4.973881) and b* (3.931917) values indicate a more balanced color profile, and the ΔE* value of 23.79328 demonstrates a closer resemblance to the control plate, indicating better corrosion inhibition.

15% Inhibitor Plate:

The 15% inhibitor plate shows the highest L* value among the treated samples (31.74258), indicating the least amount of darkening. The a* (4.602641) and b* (3.896529) values remain relatively stable, suggesting a consistent protective effect. The ΔE* value of 23.74404 supports the conclusion that the 15% concentration of banana peel extract provides the most effective corrosion protection, closely approaching the characteristics of the control plate.

4.3. Chemical Interactions with Passivating Elements

The corrosion inhibition effect of banana peel extract can be attributed to its interaction with the steel surface, particularly with elements susceptible to passivation. The active compounds in banana peel extract, such as phenolics and flavonoids, interact with iron to form a chemisorbed layer, which acts as a passivating barrier. This layer limits further interaction between the steel and the corrosive environment, thereby reducing the corrosion rate. Studies support that hydroxyl and carbonyl groups in these compounds contribute to this effect by bonding with iron atoms on the steel surface, forming stable complexes that prevent oxidation and protect the metal.

4.4. PH and Conductivity Analysis

The pH and conductivity measurements indicate that the banana peel extract does not significantly alter the acidity or ionic activity of the corrosive medium. This stability across inhibitor concentrations suggests that the inhibition effect primarily results from surface adsorption and chemical interaction with the steel surface, rather than modifying the solution's bulk properties. This finding enhances the reliability of the experimental conditions, ensuring consistent evaluations of the inhibitor's effects on corrosion resistance.

4.5. Gravimetric Characterization

As observed in Table 3, the treatment exhibiting the highest efficiency (24.44%) is the one with 15% plant inhibitor presence. This aligns with the findings of [21], demonstrating that increasing inhibitor concentration leads to a reduced corrosion rate in the material.

The corrosion rate also exhibits a decline with increasing plant inhibitor presence, as evident in Figure 5. The treatment with 15% inhibitor demonstrates the most favorable corrosion rate curve.

4.6. Mechanical Characterization

4.6.1. Stress-Strain Curves

Figure 6 shows the results indicate distinct differences in the mechanical properties of the steel specimens depending on the inhibitor concentration. The control plate and the 0% inhibitor group show the most significant reduction in mechanical performance, characterized by lower ultimate tensile strength and reduced ductility. In contrast, specimens treated with 5%, 10%, and 15% inhibitor concentrations exhibit improved mechanical properties, with the 15% concentration showing the most notable enhancement. These findings suggest that the banana peel extract effectively mitigates the detrimental effects of corrosion on the mechanical behavior of A36 steel.

4.6.2. Mechanical Properties

The Figure 7 is the graphical representation of the mechanical properties of A36 steel specimens treated with varying concentrations of banana peel extract inhibitor. It provides a comprehensive overview of the material's performance. The ultimate stress (σ_{max}) and yield stress (σ_y) demonstrate a noticeable increase in the control plate (CP), indicating the absence of corrosion effects compared to treated specimens. However, the presence of the inhibitor at 15% concentration also shows a significant improvement in these properties, suggesting effective mitigation of corrosion.

The modulus of elasticity (E) and the modulus of elasticity at failure (E_f) display variations that reflect the influence of the inhibitor on the material's stiffness. The 5% inhibitor concentration shows a peak in E, indicating a potential enhancement in material stiffness, while the E_f values suggest a better retention of elastic properties near failure.

Resilience (U_r) and toughness (U_t) illustrate the energy absorption capacity and resistance to fracture, respectively. The control plate (CP) exhibits the highest values, as expected for an uncorroded specimen. Among the treated samples, the 15% inhibitor concentration shows a notable increase in both U_r and U_t, indicating improved energy absorption and fracture resistance due to the protective layer formed by the inhibitor.

These findings collectively suggest that higher concentrations of banana peel extract provide significant protection against corrosion, thereby enhancing the mechanical properties of A36 steel. The scaly protective layer observed in SEM images supports the hypothesis of chemisorption as the primary inhibition mechanism, leading to improved structural integrity and durability of the steel. Further research is recommended to optimize inhibitor concentrations and explore long-term performance under varying environmental conditions.

4.7. Limitations and Long-term Stability of Banana Peel Extract as a Corrosion Inhibitor

The stability of banana peel extract as a corrosion inhibitor is inherently time-dependent due to the natural degradation of its organic components. Research indicates that active compounds in banana peel, including phenolic compounds, polyphenols, and flavonoids, are prone to gradual decomposition, impacting their long-term efficacy in corrosion inhibition. Lai Xuan Bach et al. [23] and further studies by Tambun et al. [24] found that these compounds can degrade over time, leading to a significant decline in corrosion prevention performance, thus indicating that banana peel extract may not be optimal for applications requiring long-term durability without periodic reapplication or reconstitution of the solution. The effectiveness of these compounds is primarily attributed to their ability to form a chemisorbed protective layer on the steel surface, supported by the presence of hydroxyl and carbonyl groups, which bolster the corrosion-inhibiting barrier. However, the integrity of this protective film diminishes as these organic compounds degrade. Consequently, additional research into enhancing the stability of these extracts could extend their longevity, making them more viable for industrial corrosion prevention applications and emphasizing the need for sustainable treatments that balance effectiveness with minimal environmental impact [25].

5. Conclusions

This study confirms the effectiveness of banana peel extract as a corrosion inhibitor for A36 steel, with concentration-dependent efficacy. The SEM analysis indicates that the inhibitor forms a chemisorbed, scaly protective layer on the steel surface, which acts as a robust barrier against corrosion. The 15% concentration demonstrated the most significant inhibition, reducing surface degradation and preserving the material's integrity.

Colorimetric results further support these findings; higher concentrations of banana peel extract showed increased surface lightness (L*) and minimal shifts in chromatic values (a* and b*), indicating superior protection against corrosion-induced discoloration. The ΔE^* values substantiate the reduced color change with increasing inhibitor concentration, highlighting 15% as the most effective dose for preserving steel’s visual and structural properties.

Mechanical characterization revealed that a 15% inhibitor concentration notably enhances key material properties, including ultimate stress, yield stress, and modulus of elasticity. This protective effect contributes to increased resilience and toughness, underscoring the potential of banana peel extract to not only prevent corrosion but also retain the mechanical integrity of A36 steel.

Overall, banana peel extract presents a promising, sustainable corrosion inhibition method for industrial applications, particularly at higher concentrations. Future research should aim to optimize its formulation and assess its long-term stability under diverse environmental conditions to further harness its potential in sustainable engineering practices.

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