Sustainable corrosion inhibition using *Aloe vera* extract and its nanocomposites for carbon steel (CS1137) in seawater

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Abstract

Two nanocomposite corrosion inhibitors were synthesized from *Aloe vera* extract: one incorporating sodium thiosulfate and the other silver nitrate. Both nanocomposites were subjected to structural characterization using atomic force microscopy (AFM), which revealed distinct morphological features. The sodium thiosulfate-based nanocomposite exhibited uniform and well-dispersed nanoparticles with an average size of 47.51 nm, suggesting a stable and homogeneous distribution. In contrast, the silver nitrate-based nanocomposite displayed slightly larger particles with an average diameter of 58.34 nm, indicating a tendency toward moderate aggregation. The corrosion inhibition performance of these nanocomposites for carbon steel (CS1137) was investigated in a 3.5% NaCl solution at room temperature using potentiodynamic polarization measurements. Results showed that increasing the concentration of *Aloe vera* extract significantly enhanced inhibition efficiency, with the maximum performance observed at 50 ppm. The inhibition effect is primarily attributed to the adsorption of bioactive phytochemicals naturally present in *Aloe vera*, including polyphenols, tannins, anthraquinones, and saponins. These compounds contain heteroatoms and π-electrons that facilitate strong adsorption onto the metal surface, thereby forming a compact protective film that impedes both anodic dissolution and cathodic reactions. A comparative evaluation revealed that the silver nitrate-based nanocomposite consistently outperformed plain *Aloe vera* extract and the sodium thiosulfate-modified system. At 50 ppm, the silver nitrate nanocomposite achieved the highest inhibition efficiency (~77%) and polarization resistance, highlighting its superior protective capability. Overall, these findings emphasize the promise of *Aloe vera*-derived nanocomposites as sustainable, cost-effective, and environmentally friendly corrosion inhibitors, particularly for safeguarding carbon steel in aggressive marine environments.

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1. Introduction

Rust is the common name for the natural process of corrosion specific to iron and its alloys. It transforms refined iron into more chemically stable forms such as oxides and hydroxides, while giving them a characteristic orange-red hue [1]. Corrosive environments include those with high temperatures, oxygen concentrations, high pressures, dampness, chlorides, and inorganic and organic acids, which can lead to chemical or electrochemical attacks that impair the structural integrity of metals and alloys. Strength, appearance, and permeability to liquids and gases are just a few of the important qualities that materials and structures lose to corrosion. Other than metals, materials like ceramics and polymers can also experience corrosion, however, the term "degradation" is more frequently used in this context [2]. When metals or alloys are extracted from minerals, energy must be expended to reduce them to their metallic state. The refined metals exist in a higher energy state than their ores and tend to spontaneously corrode to form more thermodynamically stable compounds such as carbonates, hydroxides, oxides, or salts. Inhibitors are chemicals that effectively block corrosion when present in low concentrations in corrosive environments. The activity of corrosion inhibitors is mediated by several mechanisms, including: the formation of an adsorbed layer on the metal surface; the creation of passivating species through the production of corrosion products; the formation of protective precipitates; the inactivation or elimination of aggressive components in the environment; and the modification of environmental properties through vapor phase inhibitors [3].

The use of inhibitors has repeatedly been demonstrated to be one of the finest methods for preventing corrosion in metals and alloys by studies conducted worldwide. As environmental issues have gained more attention, concern and pressure regarding these inhibitors' effectiveness as well as their environmental impact have grown [4]. Because the majority of synthetic compounds and organic inhibitors have good corrosion protection but are extremely toxic to the environment and humans, the safety of corrosion inhibitors and their impact on the environment is considered a global concern for industries [5]. These inhibitors could cause temporary or permanent harm to human organ systems, such as the liver or kidney. One of 400 species of succulent perennial plants, *Aloe vera* is the most physiologically active species and belongs to the *Liliaceae* family [6, 7]. The goal of the current work is to create two nano-inhibitors from *Aloe vera* using silver nitrate and sodium thiosulfate and to apply them to carbon steel 1137 to inhibit corrosion and enhance biological activity.

2. Materials and Methods

2.1. Materials

The materials used in this study included carbon steel (CS1137), with its chemical composition determined by X-ray fluorescence as shown in Table 1. Analytical grade sodium chloride (NaCl), sodium thiosulfate ($Na_2S_2O_3$), and silver nitrate ($AgNO_3$) were employed in the preparation of test solutions and nanocomposites. The precise composition of the CS1137 alloy tabulated in Table 1, highlighting its contents of chromium, nickel, phosphorus, sulfur, manganese, silicon, and carbon.

Table 1. Chemical composition of CS1137.

Cr (%)	Ni (%)	P (%)	S (%)	Mn (%)	Si (%)	C (%)	Fe (%)
0.16	0.11	<0.04	0.08–0.13	1.35–1.65	<0.40	0.32–0.39	Balance

2.2. Electrochemical testing

The experimental work employed an ultrasonic cleaner to remove surface contaminants from the steel specimens, an analytical balance for accurate mass determination, and a blender for preparing the *Aloe vera* extract. Electrochemical measurements were carried out using an M Lab Potentiostat connected to a computer for data acquisition and control. A three-electrode corrosion cell (1 L Pyrex) containing 3.5% NaCl was used as the electrolyte, with CS1137 as the working electrode, platinum as the counter electrode, and a saturated calomel electrode (SCE) as the reference. A magnetic stirrer was applied to maintain uniform mixing of the solutions, while a thermostatic water bath controlled the test temperature. Figure 1 illustrates the complete setup of the potentiostatic polarization system. The corrosion current density (i_{corr}) was determined using the Tafel extrapolation method. The linear regions of the anodic and cathodic branches of the polarization curves were extrapolated, and the point of intersection was taken as i_{corr}. All electrochemical tests were performed in a thermostatically controlled cell at room temperature (25±1°C). Inhibition efficiency (%*IE*) was calculated using equation (1). by the Tafel extrapolation method, fitting the linear regions of the anodic and cathodic branches of the polarization curves. The intersection of these lines was taken as i_{corr}.

Figure 1. Schematic representation of the complete setup for potentiostatic polarization measurement.

2.3. Sample preparation

CS1137 specimens were polished with emery papers (600, 800, 1200, 2000 grit), rinsed with distilled water, degreased with ethanol, and ultrasonically cleaned before testing.

2.4. Preparation of Aloe vera extract

Fresh *Aloe vera* leaves (3 kg) were collected from the College of Agriculture Garden, University of Baghdad. The outer rind was removed, and ~1.5 L of fresh gel was separated, cut into small pieces, and blended with 500 mL of distilled water to obtain a homogeneous stock extract. This corresponded to ~6 g/L. Working solutions of 10–50 ppm were prepared by further dilution.

2.5. Solution preparation

The solutions prepared for this study included a 3.5% w/v sodium chloride (NaCl) solution, obtained by dissolving 35 g of NaCl in 1 L of distilled water. A sodium thiosulfate ($Na_2S_2O_3$) solution with a concentration of 1×10^{-3} M was prepared by dissolving 0.079 g of $Na_2S_2O_3$ in 500 mL of deionized water. Similarly, a 1×10^{-3} M silver nitrate ($AgNO_3$) solution was prepared by dissolving 0.084 g of $AgNO_3$ in 500 mL of deionized water, with the solution stored in a dark container to prevent photodegradation.

2.6. Nanocomposite preparation

Aloe vera–$Na_2S_2O_3$ and *Aloe vera*–$AgNO_3$ nanocomposites were synthesized by mixing 25 mL of *Aloe vera* extract with 75 mL of $Na_2S_2O_3$ or $AgNO_3$ solution, respectively, followed by ultrasonic treatment for one hour. This 25:75 ratio was used only for synthesis. For electrochemical testing, the composites were diluted in 3.5% NaCl solution to yield a final *Aloe vera* concentration of 50 ppm. in this study. The first, *Aloe vera*–$Na_2S_2O_3$, was prepared by mixing 25 mL of *Aloe vera* extract with 75 mL of sodium thiosulfate ($Na_2S_2O_3$) solution, followed by ultrasonic treatment for one hour. The second, *Aloe vera*–$AgNO_3$, was obtained by combining 25 mL of *Aloe vera* extract with 75 mL of silver nitrate ($AgNO_3$) solution and subjecting the mixture to ultrasonic processing for one hour. It should be noted that the 25:75 (v/v) ratio was used solely for the synthesis of the composites. For electrochemical measurements, the resulting nanocomposites were subsequently diluted in 3.5% NaCl solution to yield a final *Aloe vera* concentration of 50 ppm.

3. Results and Discussion

3.1. Polarization studies

Figure 2 presents the potentiodynamic polarization curves of CS1137 in 3.5% NaCl containing different concentrations of *Aloe vera* extract. The inhibition performance of *Aloe vera* is mainly attributed to bioactive constituents such as polyphenols, tannins, anthraquinones, and saponins, which contain heteroatoms (O, N) and π-electrons that promote adsorption on the steel surface, forming a protective film. The corresponding electrochemical parameters, including corrosion potential (E_{corr}), corrosion current density (i_{corr}), and inhibition efficiency (%*IE*), penetration loss (*PL*), weight loss (*WL*), cathodic (b_c) and anodic (b_a) Tafel slopes and polarization resistance (R_p) are summarized in Table 2. An increase in *Aloe vera* concentration led to a decrease in i_{corr} and an improvement in %*IE*, reflecting enhanced surface coverage. Figure 3 and Table 3 compare the performance of 50 ppm *Aloe vera* extract with its nanocomposites. The *Aloe vera*–$AgNO_3$ nanocomposite exhibited the highest inhibition efficiency (77%), followed by *Aloe vera*–$Na_2S_2O_3$ (33%) and the plain extract (16%). The relatively small shifts in E_{corr} indicate that the inhibitors act as mixed type, affecting both anodic and cathodic processes.

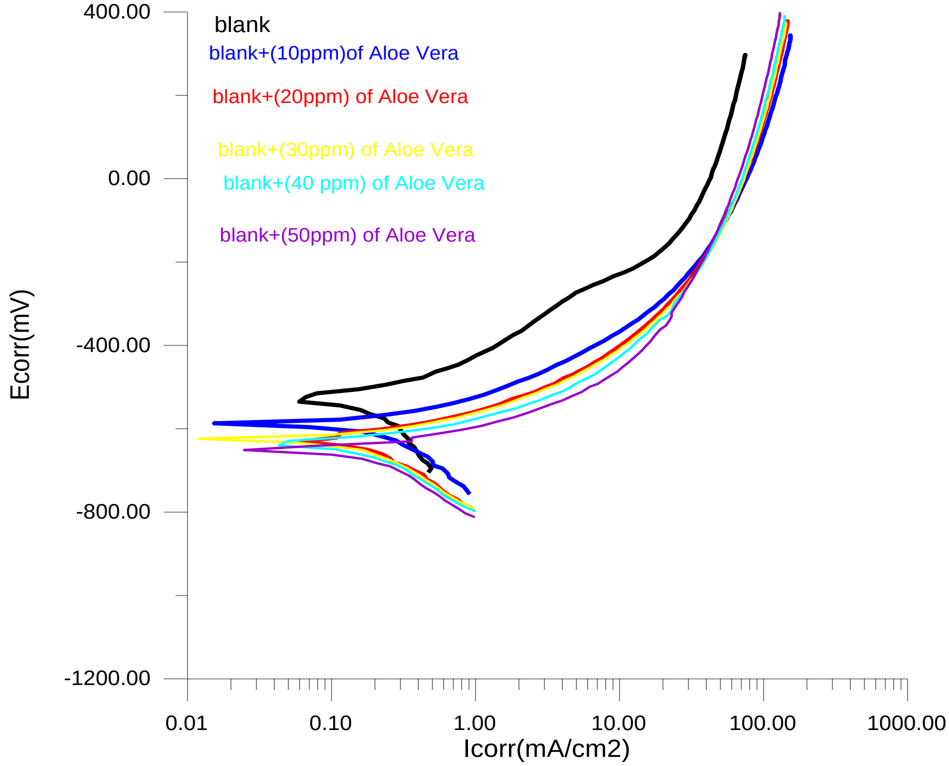

Figure 2. The polarization curves of carbon steel in seawater (3.5% NaCl) at different concentrations of *Aloe vera* solution.

Table 2. Corrosion parameters of carbon steel in seawater (3.5%NaCl) at different concentrations of *Aloe vera* solution.

Inhibitor conc. (ppm)	i_{corr} (mA/cm^2)	$-E_{corr}$ (mV)	*PL* (mm/a)	*WL* (g/m^2·dec)	b_a (mV/dec)	$-b_c$ (mV/dec)	%*IE*	R_p (Ω·cm^2)
0	153.73	573.8	1.78×10^1	3.83×10^1	84.4	203.2	–	168.43
10	152.88	663.3	1.77×10^1	3.82×10^1	78.7	164.3	0.32	151.13
20	148.47	664.7	1.72×10^1	3.71×10^1	82.1	167.3	3.20	161.07
30	147.24	628.4	1.71×10^1	3.68×10^1	82.7	185.5	3.99	168.68
40	130.39	639.8	1.51×10^1	3.26×10^1	70.8	153.1	14.98	161.22
50	128.32	630.4	1.49×10^1	3.21×10^1	73.5	157.4	16.33	169.54

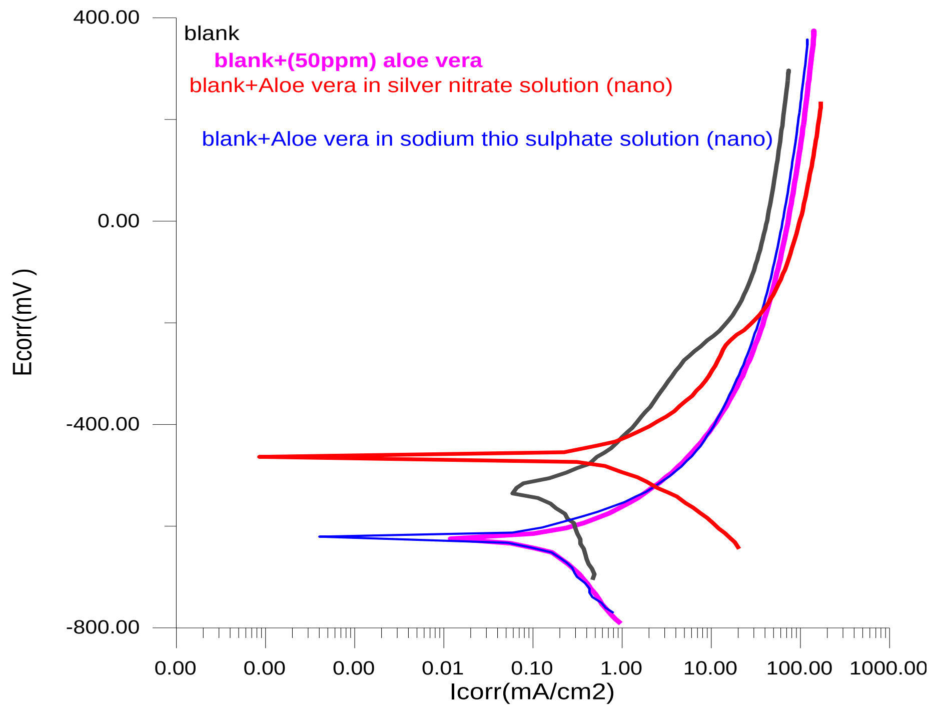

Figure 3. The polarization curves of carbon steel with the presence (50 ppm) *Aloe vera*, *Aloe vera* in nano sodium thiosulfate solution, and *Aloe vera* in nano silver nitrate solution in seawater (3.5% NaCl).

Table 3. Corrosion parameters of carbon steel with presence (50 ppm) *Aloe vera* (A.V.), *Aloe vera* in nano sodium thiosulfate solution, and *Aloe vera* in nano silver nitrate solution in seawater (3.5% NaCl).

Inhibitor conc. (ppm)	i_{corr} (mA/cm^2)	$-E_{corr}$ (mV)	*PL* (mm/a)	*WL* (g/m^2·dec)	b_a (mV/dec)	$-b_c$ (mV/dec)	%*IE*	R_p (Ω·cm^2)
0.00	153.73	573.8	1.78	3.83×10^1	84.4	203.2	–	168.43
50 (A.V.)	128.32	630.4	1.49	3.21×10^1	73.5	157.4	16.33	169.54
50 (A.V.)+ nano Na_2SO_3	102.23	619.4	1.19	2.56×10^1	68.1	137.8	33.34	193.58
50 (A.V.)+ nano $AgNO_3$	35.08	450.0	4.04	8.69×10^1	89.5	128.1	77.13	652.17

Table 2 lists the electrochemical corrosion characteristics including corrosion potential (E_{corr}), Tafel slopes (b_c and/or b_a), and corrosion current density (i_{corr}) as determined by the cathodic and anodic regions of Tafel lines. Figure 2 presents the potentiodynamic polarization curves for CS with and without different concentrations of *Aloe vera*, while Figure 3 shows the curves in the presence of various inhibitors. The inhibition efficiency (%*IE*) was calculated using equation (1) [8].

$$\%IE = \frac{i_{\text{corr (un)}} - i_{\text{corr (in)}}}{i_{\text{corr (un)}}} \times 100 \qquad (1)$$

where $i_{corr\ (in)}$ denotes inhibited corrosion current densities and $i_{corr\ (un)}$ denotes uninhibited current densities. Equation (2) can be used to determine the polarization resistance (R_p) values [9].

$$R_p = \frac{b_a \times b_c}{2.303(b_a + b_c) \times i_{corr}} \quad (2)$$

Figure 2 presents the Tafel plots of anodic and cathodic polarization curves for the corrosion of carbon steel in saline solution, both in the absence and presence of different concentrations of *Aloe vera* extract. Figure 3 compares the performance of various inhibitors. According to Table 2, the corrosion current density (i_{corr}) decreases as the inhibitor concentration increases. However, *Aloe vera* extract alone shows only modest inhibition efficiency (~16%), indicating limited practical applicability. This result highlights the need for modification with additives such as silver nitrate or sodium thiosulfate to significantly improve its effectiveness. The observed increase in inhibition efficiency (%*IE*) with concentration is attributed to adsorption of inhibitor molecules on the steel surface. Table 3 demonstrates the comparative performance of three inhibitors for corrosion protection of carbon steel in saline media: (i) *Aloe vera* (50 ppm), (ii) *Aloe vera* with nano-sodium thiosulfate, and (iii) *Aloe vera* with nano-silver nitrate. Among these, *Aloe vera* in nano-silver nitrate solution exhibited the highest inhibition efficiency and corrosion resistance [10].

An increase in polarization resistance further confirms that inhibition efficiency improves with *Aloe vera* concentration [11–12]. The addition of *Aloe vera* caused only a slight shift in corrosion potential (E_{corr}) toward more negative values, indicating adsorption on both anodic and cathodic sites. Thus, *Aloe vera* behaves as a mixed-type inhibitor. The reduction in i_{corr} values is a direct result of inhibitor adsorption, while fluctuations in anodic (b_a) and cathodic (b_c) Tafel slopes with increasing inhibitor concentration suggest that both anodic metal dissolution and cathodic reduction kinetics are affected. This behavior can be explained by the presence of multiple active sites in *Aloe vera* molecules (*e.g.*, heteroatoms such as O and N, and π-electron systems), which facilitate adsorption onto the steel surface [13]. Overall, the findings confirm that *Aloe vera* modified with nano-silver nitrate is the most effective formulation for mitigating carbon steel corrosion under saline conditions.

Aloe vera extract contains a variety of bioactive molecules such as polyphenols, tannins, anthraquinones, and saponins, which are rich in heteroatoms (O, N) and conjugated π-electrons. These functional groups facilitate adsorption onto the steel surface by forming coordination bonds or electrostatic interactions with vacant d-orbitals of Fe atoms, thereby reducing the number of active corrosion sites. In the presence of additives, further interactions may enhance inhibition. For instance, Ag^{+} ions from silver nitrate can coordinate with hydroxyl or carbonyl groups of polyphenols and anthraquinones, strengthening the stability of the adsorbed layer. Similarly, thiosulfate anions ($S_2O_3^{2-}$) may interact with hydroxyl and amine groups in saponins and tannins, providing additional anchoring sites and contributing to a more compact protective film. These synergistic effects explain the superior inhibition efficiency observed for *Aloe vera* nanocomposites compared to the plain extract. Figure 4 represented a proposed adsorption mechanism of *Aloe vera*-nanomaterials on steel surface.

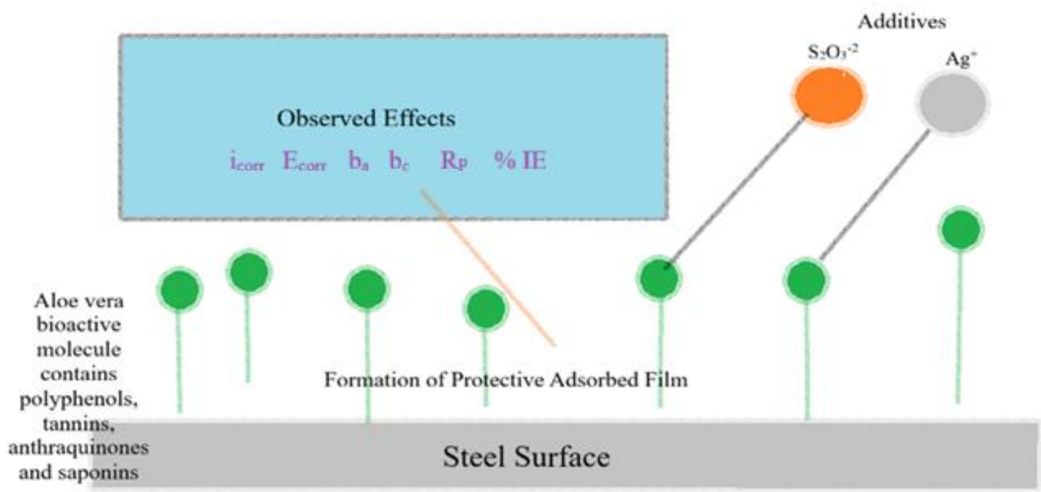

Figure 4. Proposed adsorption mechanism of *Aloe vera*-nanomaterials on steel surface.

3.2. Atomic force microscopy

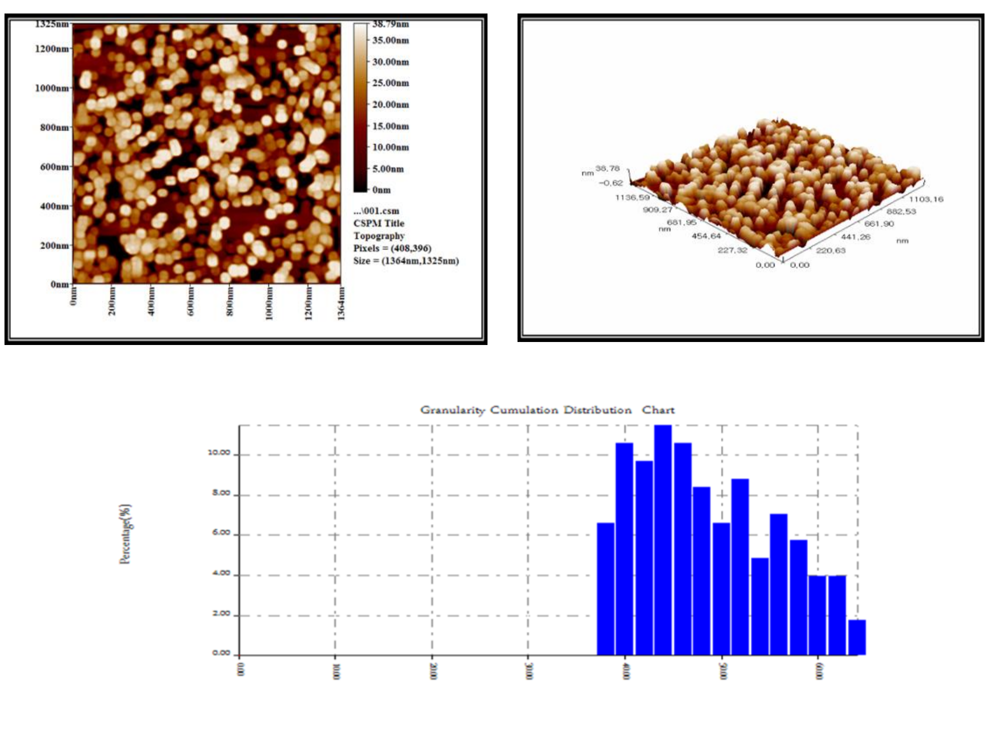

Figure 5. AFM for *Aloe vera* in silver nitrate nanoparticles.

AFM images (Figures 5 and 6) reveal that both nanocomposite coatings produced relatively smooth surfaces with low roughness (47.51 nm for $Na_2S_2O_3$-based, 58.34 nm for $AgNO_3$-based). The minimal color contrast in the photographs indicates a low degree of coating thickness variability. However, the images reveal substrate features and the presence of some larger particles, likely formed by the agglomeration of smaller particles on the surface [14–15].

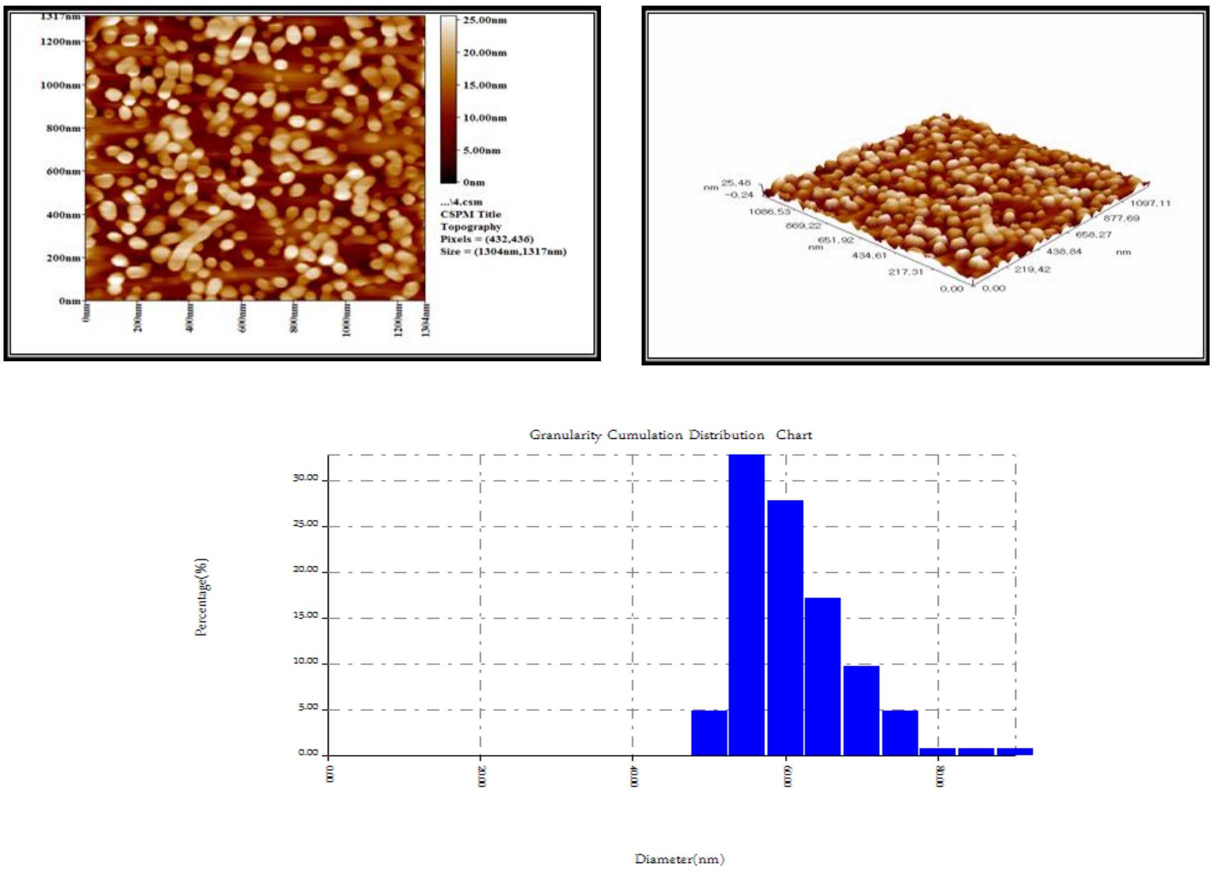

Figure 6. AFM for *Aloe vera* in sodium thio sulfate nanoparticles.

4. Conclusion

The results demonstrated that *Aloe vera* extract serves as an eco-friendly corrosion inhibitor for carbon steel in seawater, with inhibition efficiency increasing as the concentration rises, reaching its maximum at 50 ppm. Among the tested inhibitors, the $AgNO_3$-based nanocomposite exhibited the highest performance, achieving an inhibition efficiency of approximately 77%. Atomic force microscopy (AFM) analysis confirmed the formation of uniform nanoparticles and effective surface coverage, which contributed to enhanced protective properties.

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