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Original article

Effectiveness of Aloe Vera as a Natural Corrosion Inhibitor for Carbon Steel in Acidic Media

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Abstract
This study explores the performance of Aloe Vera extract as a sustainable corrosion inhibitor for carbon steel in sulfuric acid environments. Experimental evaluations were conducted under varying conditions, including inhibitor dosages (0, 12, 20, and 30 mL), acid concentrations (1, 1.5, and 2 M, H_2SO_4), and temperatures (25, 50, and 70 °C), over extended immersion periods. The results indicate that Aloe vera exhibits high inhibition efficiency exceeding 90% under mild conditions (12 mL in 1 M H_2SO_4 at 25 °C), while its performance diminishes progressively with increased acid strength and elevated temperatures. The inhibition mechanism is attributed to the adsorption of bioactive constituents from the extract onto the metal surface, forming a passive protective layer. Notably, increased inhibitor dosage partially counteracted the adverse effects of more aggressive environments. These findings highlight Aloe vera as a promising green alternative to synthetic inhibitors, with potential applications in acid pickling, oilfield operations, and other corrosive systems where environmental compatibility is critical.
Keywords. Corrosion Inhibition, Aloe Vera Extract, Carbon Steel, Acidic Media.

Introduction

Corrosion is a naturally occurring phenomenon that involves the degradation of materials when they interact with certain environmental conditions. In metallic substances, this oxidative deterioration can be accelerated by mechanical stress, influenced by their chemical and electrochemical nature [1]. Among the many sectors impacted by corrosion, the oil and gas industry is particularly vulnerable. Here, corrosion often leads to thinning of metal infrastructure, posing serious risks such as leaks that could escalate into explosions due to structural anomalies [2]. Although scholars offer varied definitions, corrosion is fundamentally understood as the material-environment interaction. From an engineering standpoint, metal corrosion continues to challenge industrial operations. It presents major complications in the petroleum industry, affecting both upstream and downstream processes. Key equipment, including pipelines, storage units, separators, and pumps, frequently suffers damage due to corrosive effects. The progressive deterioration of these systems, particularly in pipelines and cooling apparatus, contributes to operational inefficiencies and safety concerns [3]. Consequently, substantial losses in time, finances, materials, and workforce are incurred [4].
Mild steel stands out as a pivotal material in industrial operations due to its cost-effectiveness, ease of manufacturing, and notable tensile strength. Despite these advantages, its susceptibility to corrosion presents a major limitation across a broad spectrum of industries, ranging from automotive and aviation to agriculture, construction, energy, and particularly oil and gas. The corrosion of mild steel has emerged as a pressing issue, especially with its increasing deployment in aggressive, acidic environments such as pickling processes, acid cleaning, industrial descaling, and oil well acidizing [5-6].
Among industrial metals, mild steel alloys are the most extensively used, with corrosion losses estimated at approximately 4 tons per second globally [7]. This damage translates to an economic burden of 3–5% of the gross domestic product in many developed countries [8]. Given mild steel's widespread industrial relevance, identifying effective methods to slow down or inhibit corrosion is essential for preserving its structural integrity. One of the most effective countermeasures is the application of corrosion inhibitors, which function by either forming a protective surface film or altering the corrosion kinetics. Inorganic corrosion inhibitors—typically utilized in high-temperature and high-pressure systems where organic compounds may fall short play a critical role in this defense strategy [9]. These inhibitors, such as chromates, phosphates, molybdates, and silicates, are frequently employed in systems like boilers, pipelines, and cooling towers, where they act as surface-passivating agents to reduce corrosion [10]. However, many inorganic substances are toxic and pose risks to human health and the environment [11–12]. In oil production systems, for instance, these inhibitors mix with produced water and contribute to environmental degradation upon disposal—hence their usage is increasingly restricted [13]. Conversely, organic inhibitors—such as amines, imidazolines, and quaternary ammonium salts—work by adsorbing onto metal surfaces and blocking corrosive species from initiating damage. These compounds have gained wide acceptance in the oil and gas industry owing to their efficiency and relatively lower ecological impact [14].
The synergistic use of inorganic and organic inhibitors has been found to enhance corrosion resistance by combining their protective mechanisms. Despite this benefit, the release of such chemical agents into the

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environment—whether through industrial processes or natural phenomena—remains a serious concern for modern societies. The escalation of industrialization and economic growth, accompanied by the widespread synthesis of chemicals and compounds, has significantly heightened risks to both ecosystems and public health [15].

According to researchers, the dominant mode of corrosion inhibition involves chemical adsorption, wherein electron exchange occurs between inhibitor molecules and the mild steel surface. This mechanism is noted for its efficiency and cost-effectiveness, offering environmental advantages as well [16]. In recent studies, Aloe vera leaf extract has gained attention as a sustainable corrosion inhibitor. Its eco-friendly nature and abundance of adsorption-active sites make it a promising candidate for metal protection. The protective performance of Aloe vera has been evaluated against corrosion on various metals, including mild steel [17], zinc, aluminum, and copper in acidic conditions [18]. A study by [19] demonstrated the efficacy of aqueous Aloe vera extract in inhibiting aluminum corrosion in hydrochloric acid. Similarly, when tested on zinc in a 2 M HCl solution, the extract achieved an inhibition efficiency of 67% at a 10% v/v concentration [20]. Further investigations explored the inhibition behavior of Aloe vera on stainless steel immersed in 1 M sulfuric acid and on mild steel exposed to 1 M HCl, revealing its potential across multiple metallic substrates [21–22].

Aloe vera belongs to a group of shrubby, succulent plants within the Liliaceae (lily) family. It typically features a very short stem and grows to a height of approximately 80–100 cm. This species reproduces through basal shoots and root suckers. Its foliage is characterized by thick, fleshy, lance-shaped leaves that range from green to grey-green and are edged with small serrations [23]. Studies have revealed that Aloe vera contains a rich blend of bioactive constituents, including polysaccharides, steroids, polyols, organic acids, and critical trace elements such as nitrogen, allantoin, tannins, natural analgesics, and antibiotic-like compounds, along with nutritional components [24]. Among these, tannins have shown particular potential for corrosion mitigation due to their strong affinity for metallic surfaces, blocking active corrosion sites and thereby slowing the degradation process [25]. This work investigates Aloe vera's corrosion-inhibiting properties using mass loss techniques applied to mild steel specimens exposed to acidic environments. The corrosion resistance offered by plant-based extracts like Aloe vera is commonly attributed to surface-active species capable of forming a protective film over metallic surfaces. This film acts as a physical barrier, isolating the metal from corrosive media. Most of the inhibitory compounds identified in these extracts are long-chain hydrocarbons enriched with polar functional groups, which typically include heteroatoms such as nitrogen, oxygen, or sulfur [26]. This study aims to obtain a better understanding of the mode of inhibitory action of leaf extracts of Aloe vera on mild steel in sulphuric acid using the weight measurements method. The effects of different concentrations on the efficiency of aloe vera are also investigated.

Methods

Preparation of Aloe vera gel extract

For preparation of the aqueous extract of Aloe Vera gel, the Aloe Vera plant was brought from the plant nursery, located in Tobruk city and then the Aloe Vera roots were cut and washed with distill water, then cut the ends with a knife to get rid of the yellow pulp, which can reduce the quality of the extract by soaking these edges in distill water for two hours and then washing them again and drying them with a clean cloth. After obtaining the gel, a hand mixer was used to obtain the aqueous extract and make sure that there are no agglomerations during extraction, and leave it for a period until the foam settles at the top of the cup so that the extract does not contain any spaces of air, the extracted liquid gel is kept in a plastic container and kept it in a refrigerator at 4 °C until use [27].

Figure 1. The steps of the Preparation of Aloe vera gel extract

Preparation of acidic media

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The corrosive solution used in this work was sulphuric acid of concentration (typically 98% w/w), supplied by the chemical engineering laboratory of the Faculty of Engineering, which has a molecular weight of 98.08 g/mol and a density of 1.84 g/mL. The concentrated acid was diluted with distilled water to obtain the required concentrations of sulfuric acid (H_2SO_4)
To prepare a 1M sulfuric acid (H_2SO_4) solution, follow these precise experimental steps: pour approximately 800 mL of distilled water into a 1 L volumetric flask and carefully measure 53.2 mL of concentrated sulfuric acid using a graduated cylinder or pipette. After that, slowly add the acid to the water, stirring continuously to dissipate heat. After cooling, add distilled water to bring the final volume to 1 L. Mix thoroughly by gentle swirling to ensure homogeneous distribution.

Preparation of specimens
During the preparation stage, the carbon steel coupons were mechanically polished with a series of Emery papers of variable grades, starting with the coarsest and proceeding in steps to the finest (600) grade to remove impurities and surface irregularities. This step ensured uniformity of the surface prior to immersion, which is essential for obtaining accurate and consistent corrosion rate measurements. Also, these polished coupons were degreased with ethanol, rinsed with double-distilled water, dried with acetone, and weighed [28] as shown in Figure 2.

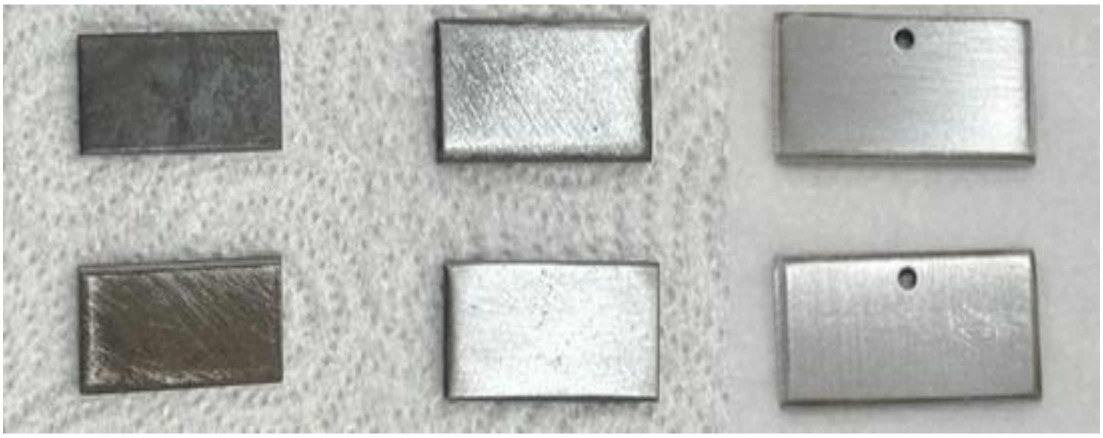

Figure 2. The steps of the Preparation of specimens

Procedures
The same surface area of 2 cm x 4 cm mild steel plates was thoroughly, distilled water and finally degreased with acetone. The samples were dried and stored in desiccators. They were weighed and the results were recorded before immersing in the test solution. The tested mild steel sheets were dipped into 200 mL, Aloe Vera gel and sulphuric acid in 400 mL beakers. Various concentration of turbid Aloe Vera extracts (3, 6, 9, 12, 20 and 30 ml) and the concentration of sulfuric acid is 1 M, 1.5 M and 2 M. Were added and left for 10 days at different temperatures (25 C, 50 C and 70 C) in water path The specimens were removed from the electrolyte, washed thoroughly with distilled water, dried and weighed.
The weight loss of the test specimens was calculated by using the equation in (1).

$$Weight\ loss = Wo - Wi \qquad Eq\ (1)$$

Where W_o is the initial weight of the mild steel specimen in grams, and W_i is the final weight of the mild steel specimen in grams after every 1-hour interval. The inhibitor efficiency (I_E%) can be measured and calculated by using the equation shown in equation (2). Where, IE % is the inhibitor efficiency, CR_0 and CR_1 (in g) are the values of the weight loss observed of mild steel in the absence and presence of inhibitor, respectively.

$$I_E = \frac{CR_0 - CR_1}{CR_0} \text{ X } 100 \qquad Eq\ (2)$$

Results and Discussion

Effect of Aloe Vera Concentration on the Corrosion Rate of Carbon Steel in Acidic Medium
A series of experiments was conducted to evaluate the performance of aloe vera extract as a natural corrosion inhibitor using different concentrations (0, 3, 6, 9, and 12 mL) in a 1 M sulfuric acid solution at room temperature (25°C) over a continuous period of 10 days. The weight loss corrosion rate was measured daily, as illustrated in Figure 3.

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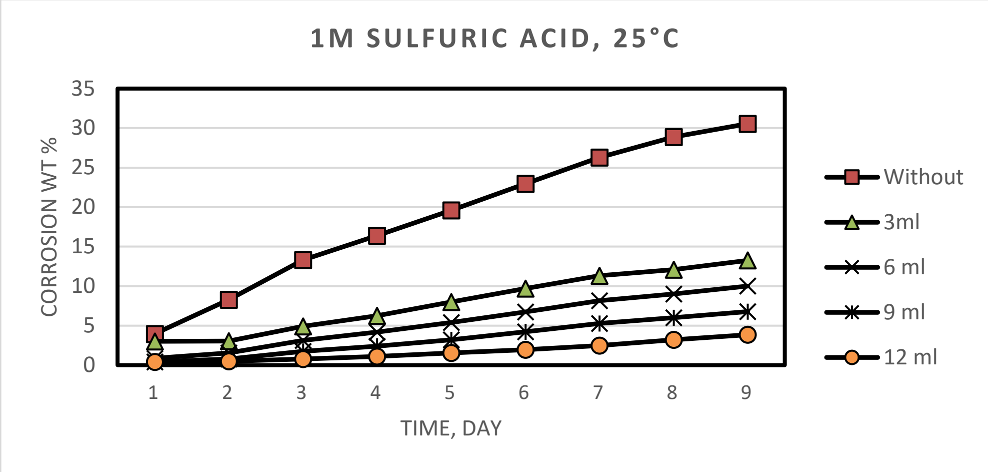

Figure 3. The weight percent of corrosion of carbon steel with 1M sulfuric acid in the presence of different concentrations of Aloe vera corrosion inhibitor.

The results showed that aloe vera extract is an effective corrosion inhibitor under these conditions, with a noticeable decrease in corrosion rate as the inhibitor concentration increased. At the highest concentration (12 mL), the corrosion rate dropped from 30.55 g to 3.8 g, over a 90% reduction in corrosion rate. These findings suggest aloe vera could be a promising natural and eco-friendly alternative to conventional chemical inhibitors in acidic environments.

As seen in Figure 3, the data shows a clear declining trend in corrosion rate with increasing aloe vera concentration, indicating that the inhibition mechanism likely involves physical or chemical adsorption onto the metal surface. It is probable that bioactive compounds in the extract, such as polyphenols, aldehydes, and polysaccharides, interact with the carbon steel surface to form a protective barrier layer that suppresses the acid-metal reaction. At a concentration of 12 mL, the corrosion rate decreased by over 90%, suggesting surface saturation with inhibitor molecules and nearing the system's maximum inhibition efficiency under the studied conditions (1 M H_2SO_4, 25 °C). This implies that further increases in inhibitor quantity may offer only marginal benefits unless environmental conditions change. Additionally, the daily corrosion rate exhibited a gradual decline over time, indicating that the protective layer became more stable and less susceptible to degradation by the acidic medium. This may also reflect the Aloe Vera's potential to regenerate the protective layer throughout the testing period.

Effect of Sulfuric Acid Concentration on Aloe Vera's Inhibitory Efficiency

Another experimental set was conducted to study the impact of varying sulfuric acid concentrations (1, 1.5, and 2 M) on the corrosion rate of carbon steel in the presence of aloe vera at concentrations of 12 and 20 mL. Tests were carried out at room temperature (25 °C) for a duration of 10 days. Results shown in Figures 4 and 5 revealed that increasing acid concentration leads to a marked reduction in inhibition efficiency. The corrosion rate increased from 3.8 g at 1 M H_2SO_4 to 14.9 g at 1.5 M using 12 mL of aloe vera. Increasing the inhibitor concentration to 20 mL reduced the corrosion rate to 14.4 g, achieving an efficiency of 68%.

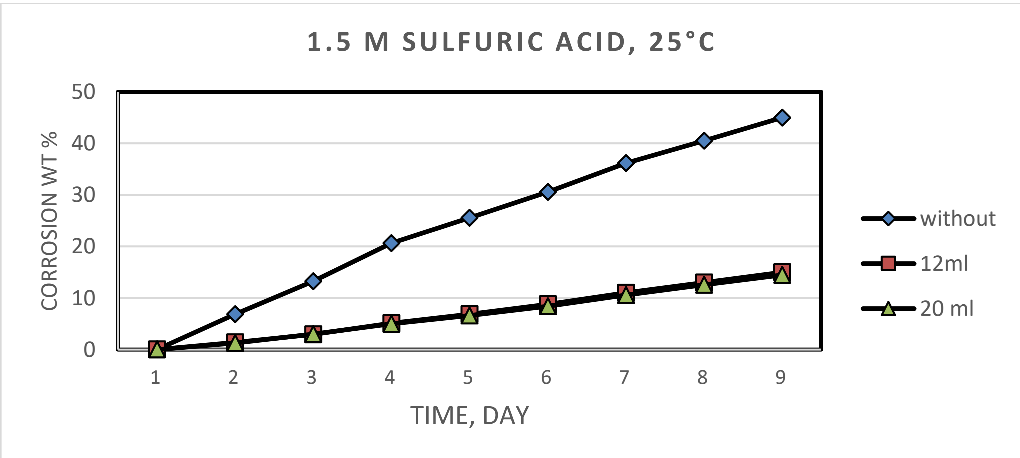

Figure 4. The weight percent of corrosion of carbon steel with 1.5 M sulfuric acid in presence of different concentration of Aloe Vera corrosion inhibitor.

At 2 M acid concentration, corrosion further intensified, with a rate of 19.5 g using 12 mL of aloe vera. However, increasing the inhibitor to 20 mL reduced the rate to 14.4 g, with an inhibition efficiency of 75%.

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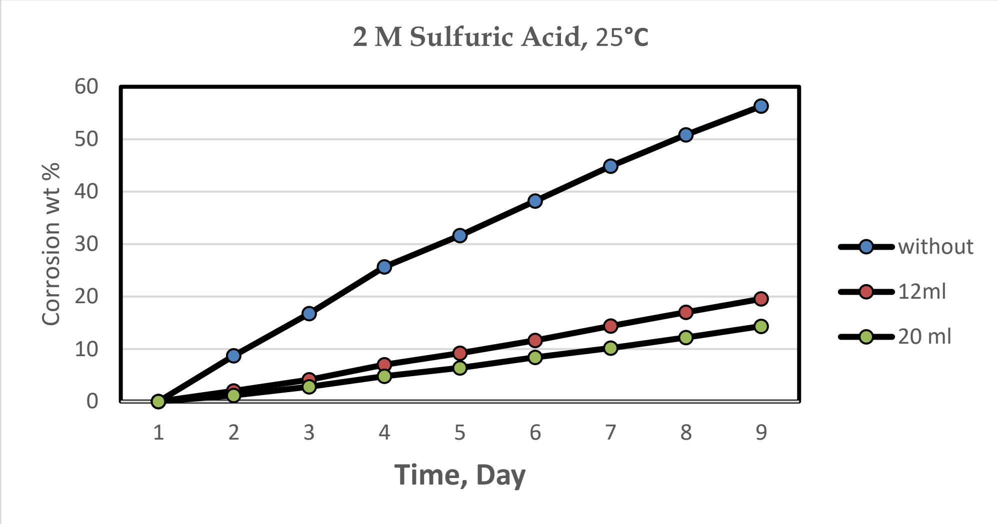

Figure 5. The weight percent of corrosion of carbon steel with 2M Sulfuric acid in the presence of different concentrations of Aloe Vera corrosion inhibitor.

These results indicate that the effectiveness of aloe vera as a corrosion inhibitor is significantly influenced by acid concentration, with its performance declining in harsher acidic conditions. Nevertheless, increasing the aloe vera concentration helps to some extent in mitigating this effect, demonstrating the inhibitor's relative adaptability in more aggressive environments.

Effect of Temperature on Inhibition Performance
The following Table 1 summarizes the effects of temperature and aloe vera concentration on corrosion rate in various sulfuric acid concentrations:
The results of influence of temperature (25 °C, 50 °C, and 70 °C) on the inhibition performance of aloe vera extract was studied in sulfuric acid environments with concentrations of 1, 1.5, and 2 M, over a period of 4 days and using varying volumes of the inhibitor (12, 20 and 30 mL).

Table 1. Effect of both temperature and acid concentration on the inhibition efficiency of the Aloe Vera at different concentrations.

Concentration of sulfuric acid, M	***Concentration of inhibitor, ml***	***Temperature, °C***		
		25°C	50 °C	70 °C
1 M of H_2SO_4	Without Aloe Vera	30	47	94.9
	20 ml of Aloe Vera	3.8	31	86
	30 ml of Aloe Vera	---	28.5	76.5
	Inhibition efficiency	90%	40%	19%
1.5 M of H_2SO_4	Without Aloe Vera	45	55	100
	20 ml of Aloe Vera	15	48	95
	30 ml of Aloe Vera	7.2	40	92
	Inhibition efficiency	84%	28%	8%
2 M of H_2SO_4	Without Aloe Vera	56	75	100
	20 ml of Aloe Vera	19.5	64	100
	30 ml of Aloe Vera	14.3	57	99
	Inhibition efficiency	74%	24%	0.5%

- **At 1 M of H_2SO_4:** increased temperature reduced inhibition efficiency: the corrosion rate rose from 3.8 g at 25 °C with 12 mL aloe vera to 28.5 g at 50 °C (30 mL), and reached 76.5 g at 70 °C with the same inhibitor volume.
- **At 1.5 M of H_2SO_4:** a similar trend was observed: the corrosion rate climbed from 14.5 g at 25 °C (20 mL) to 40.0 g at 50 °C (30 mL), and peaked at 91.7 g at 70 °C (30 mL).
- **At 2 M of H_2SO_4:** concentration, the trend continued: the corrosion rate increased from 14.3 g at 25 °C (20 mL) to 57.1 g at 50 °C, and reached 99.5 g at 70 °C with 30 mL of aloe vera.

Conclusion
This study demonstrated the effectiveness of Aloe vera extract as a sustainable and environmentally friendly corrosion inhibitor for carbon steel in acidic environments. The inhibition efficiency exceeded 90% at optimal

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conditions (12 mL inhibitor in 1 M H_2SO_4 at 25°C), indicating strong potential for practical applications in mild acid systems. However, the performance of Aloe vera diminished under more aggressive conditions, including elevated acid concentration and temperature. This sensitivity suggests a surface adsorption mechanism involving bioactive compounds in the extract, which may be disrupted at higher kinetic energy or acidic strength. The ability to restore inhibition efficiency by increasing the dosage, however, illustrates the adaptive nature of the inhibitor. These findings position Aloe vera as a promising green alternative to conventional chemical inhibitors, particularly for use in moderate-temperature systems and industrial processes where environmental considerations are prioritized. Further investigation into its adsorption isotherms, thermodynamic parameters, and surface morphology could enhance our understanding of its inhibition mechanisms and support broader implementation in corrosion control strategies.

Conflict of interest. Nil

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