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Corrosion Mitigation of Medium Carbon Steel in HCl Solution Using Ficus Carica Leaf Extract: Mass Loss Technique

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ABSTRACT

The corrosion of medium carbon steel in acidic environments poses significant industrial and economic challenges. In this study, the inhibitory performance of fig leaf (Ficus carica) extract as a eco-friendly corrosion inhibitor for medium carbon steel in 0.5 M HCl was investigated using the weight loss technique and DFT calculations. Weight loss methods were used to evaluate the inhibition performance over two time intervals (3-hours and 24-hours). The results showed that the inhibition efficiency increased with increasing extract concentration, with a maximum efficiency of 94.52% after 24-hours at 480 ppm. The enhanced performance over time is attributed to the gradual adsorption of phytochemicals, such as flavonoids and tannins, which form a stable, adherent barrier that limits the interaction between the metal and corrosive species. These findings support the potential use of fig leaf extract as a sustainable and green corrosion inhibitor compared to conventional corrosion inhibitors for medium steel protection in acidic environments.

الحد من تآكل الفولاذ الكربوني في محلول حمض الهيدروكلوريك باستخدام مستخلص أوراق نبات التين: تقنية فقدان الكتلة

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الملخص

يشكل تآكل الفولاذ الكربوني في البيئات الحمضية تحديات صناعية واقتصادية كبيرة. في هذه الدراسة، تم فحص الأداء التثبيطي لمستخلص أوراق التين (Ficus carica) كمثبط تآكل صديق للبيئة للصلب الكربوني في 0.5 مولاري من حمض الهيدروكلوريك باستخدام تقنية فقدان الكتلة وايضا المحاكاة الحوسبية. استُخدمت طرق فقدان الوزن لتقييم أداء التثبيط على فترتين زمنيتين (3 ساعات و24 ساعة). أظهرت النتائج أن كفاءة التثبيط زادت مع زيادة تركيز المستخلص، حيث بلغت الكفاءة القصوى 94.52% بعد 24 ساعة عند تركيز 480 جزء في المليون. ويُعزى الأداء المعزز بمرور الوقت إلى الامتزاز التدريجي للمواد الكيميائية النباتية، مثل الفلافونويدات والعفص، التي تشكل حاجزًا مستقرًا وملتصقًا يحد من التفاعل بين المعدن والأنواع المسببة للتآكل. تدعم هذه النتائج إمكانية استخدام مستخلص أوراق التين كمثبط مستدام وأخضر للتآكل.

الكلمات المفتاحية:
الكربون الصلب.
تثبيط التآكل.
حمض الهيدروكلوريك.
مستخلص أوراق التين.
طريقة فقدان الوزن.
كفاءة التثبيط.
مثبط أخضر.

1. Introduction

Corrosion is a natural electrochemical process that leads to the gradual degradation of metals when they react with their environment [1]. This process typically involves oxidation of the metal surface in the presence of moisture, oxygen, or acids, resulting in structural damage and material loss over time [1, 2]. In industrial contexts, corrosion

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represents a major challenge due to its impact on equipment durability, safety, and maintenance costs [3]. Steel, especially medium carbon steel, is one of the most widely used construction materials in industries due to its mechanical strength and low cost [4, 5]. However, it is particularly vulnerable to corrosion in acidic environments, such as those containing hydrochloric acid (HCl), commonly used in oil well acidizing, cleaning operations, pickling, and descaling processes [2]. Among the numerous strategies employed to mitigate metal deterioration, the use of **corrosion inhibitors** remains one of the most practical and cost-effective approaches [2]. Inhibitors function by adsorbing onto the metal surface and forming a protective film that blocks corrosive agents from interacting with the metal [5]. While synthetic inhibitors are effective, many of them are toxic, non-biodegradable, and environmentally hazardous [3, 4]. Consequently, there has been increasing interest in the development of **eco-friendly, biodegradable, and non-toxic corrosion inhibitors**, especially those derived from natural plant sources [6]. In recent years, the emphasis has shifted toward the use of green corrosion inhibitors derived from natural sources, particularly plant extracts [7, 8]. These substances are renewable, biodegradable, and often rich in organic molecules such as alkaloids, flavonoids, phenols, and tannins. These compounds possess functional groups (e.g., –OH, –COOH, –NH, –SH and aromatic rings) that can adsorb onto metal surfaces and form protective films that inhibit corrosion [9-14].

Ficus carica* (fig tree)** is a widely available plant known for its medicinal and antioxidant properties. The scientific name of the fig leaf is *Ficus carica*; it belongs to the family ***Moraceae and is widely known for its medicinal and antioxidant properties [7]. The leaves of the fig tree contain a variety of bioactive compounds that can potentially act as corrosion inhibitors. However, to date, limited work has been done to evaluate the effectiveness of **fig leaf extract** as a green inhibitor for medium carbon steel in acidic media. Recent studies have explored the use of *Ficus* species leaf extracts as eco-friendly corrosion inhibitors for medium carbon steel in acidic and saline media. These extracts have shown promising results, with inhibition efficiencies reaching up to 95.8% in HCl solutions [15] and 99% in saline environments [16]. The inhibition mechanism involves the formation of a protective film on the steel surface, with effectiveness increasing with concentration up to an optimal level [17]. The extracts generally act as mixed-type inhibitors, affecting both anodic and cathodic reactions [16, 18]. Adsorption of the extract components on the steel surface follows the Langmuir isotherm model [16, 18]. Quantum chemical calculations have been employed to understand the electrochemical mechanisms and identify the most effective components in the extracts, such as caffeoylmalic acid in *Ficus carica* [18].

1. With the continuation of our interest in studying corrosion inhibitors [19-28], this work aims to explore the effectiveness of fig leaf extract (*Ficus carica*) as a green and sustainable corrosion inhibitor for medium carbon steel in a 0.5 M HCl solution. The study employs weight loss measurements over different exposure times to assess the inhibition performance of this natural extract. The time-dependent behavior and mechanism of inhibition are also discussed in detail.

2. Experimental

2.1 Materials

Corrosion tests were carried out on a medium carbon steel bar obtained from the Libyan Steel Plant. The steel's composition by weight as included in Table 1.

Table 1: chemical composition of medium carbon steel

Element	Mn	C	S	P	Si	Fe
%	0.57	0.3	0.0004	0.011	0.23	98.8886

2.2 Solutions

A stock solution of the corrosive medium of 2.5 M HCl was prepared by diluting analytical grade 37% HCl with deionized water. The stock solution was used to prepare each test solution by diluting to obtain a 0.5 M HCl solution for all experiments.

2. Fresh fig leaves (*Ficus carica*) were washed with distilled water, air-dried at room temperature, and then ground into a fine powder. A known weight of the dried powder was soaked in boiled water overnight. The mixture was filtered and dried to obtain the powdered extract. The resulting extract was stored tightly covered bottle and kept in desiccators before use. A 1000 ppm aqueous extract solution was prepared as a stock solution. From this, a series of concentrations (50, 200, 400, 480, 600, and 800 ppm) was used in the corrosion experiments (Figure 1).

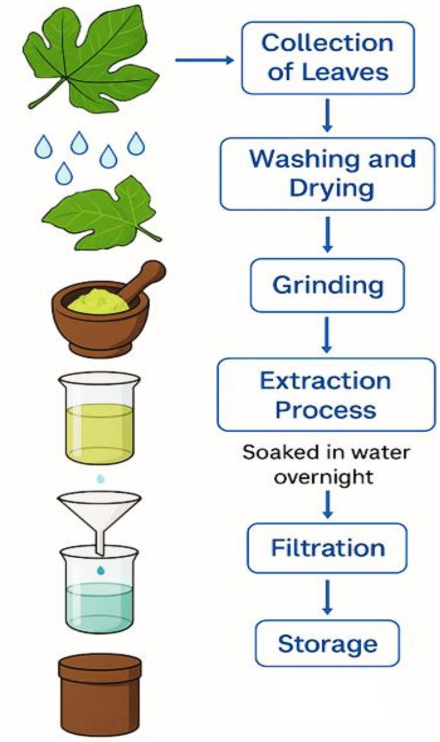

Fig. 1: Preparation of fig leaf extract

2.3 Weight Loss Measurements

For the weight loss tests, the steel specimens were cut into 4.0 cm long sections with a 1 cm diameter. Surface preparation involved grinding with silicon carbide abrasive papers of 400 to 1200 grit grades, followed by sequential cleaning in absolute ethanol and acetone. The samples were then left to dry at ambient temperature and preserved in desiccators to prevent moisture exposure before their use in corrosion testing. The specimens were weighed accurately and immersed in 100 mL of 0.5 M HCl solution with and without different concentrations of fig leaf extract (e.g., 50,100, 200, 400, 480 and 600 ppm) at room temperature (25°C). The immersion periods were 3-hours and 24-hours. After immersion, the specimens were removed, rinsed, dried, and reweighed. The corrosion rate (CR) and inhibition efficiency (IE%) were calculated using the standard weight loss formula:

$R\ (mg\ cm^{-2}\ min^{-1}) = (\Delta W / (A \times T))$

Where: R is corrosion rate with inhibitor, W is weight loss in grams, A is surface area in cm^{-2}, and T is time in hours

The inhibition efficiency (IE%) was calculated using:

$IE\% = [(R_0 - R) / R_0] \times 100$

Where: R_0 = corrosion rate without inhibitor.

3. Results and Discussion

3.1 Weight Loss Measurements

The data showed a clear trend of decreasing corrosion rate with increasing concentrations of fig leaf extract. Moreover, the inhibition efficiency (IE%) increased with increasing inhibitor concentration and immersion time. For a 3-hour exposure, the inhibition efficiency rose from 0% (no inhibitor) to a peak of 88.05% at 480 ppm. For 24-hour exposure, the efficiency peaked at 94.52% at the same concentration, as shown in Table 2 and Figures 2 &3.

Table 2: Corrosion rates and inhibition efficiencies at different concentrations and times (3h and 24h).

Conc. (ppm)	3-hour		24-hour	
	C.R×10^{-5} ($mg\ cm^{-2}\ min^{-1}$)	I E (%)	C.R×10^{-5} ($mg\ cm^{-2}\ min^{-1}$)	I E (%)
0	3.27	0.00	0.61	0.00
80	2.13	34.81	0.42	87.15
200	0.94	71.41	0.276	91.55
400	0.55	83.04	0.181	94.46
500	0.39	88.05	0.179	94.52

600	0.43	86.77	0.22	93.22
800	0.61	81.29	0.21	93.52

This suggests a strong interaction between the bioactive components of the extract and the metal surface. The inhibition efficiency increased sharply from low concentrations (50 ppm) up to 480 ppm, beyond which the efficiency plateaued or slightly declined (notably at 800 ppm). This may be attributed to saturation of the metal surface with inhibitor molecules or possible aggregation effects that limit adsorption. A longer exposure time (24-hour) significantly enhanced the inhibition performance compared to 3-hour, indicating progressive surface coverage and stronger interaction over time. This temporal improvement supports a chemisorption mechanism involving slow but stable bonding of active phytochemicals on the steel surface. The increase in inhibition efficiency over time can be explained by:

- **Progressive adsorption** of phytochemicals such as flavonoids, tannins, and phenolics.
- **Formation of a stable, dense organic film** on the steel surface.
- **Displacement of Cl^- ions** and water molecules by stronger organic inhibitors.
- **Antioxidant activity** of the extract reduces oxidative corrosion.

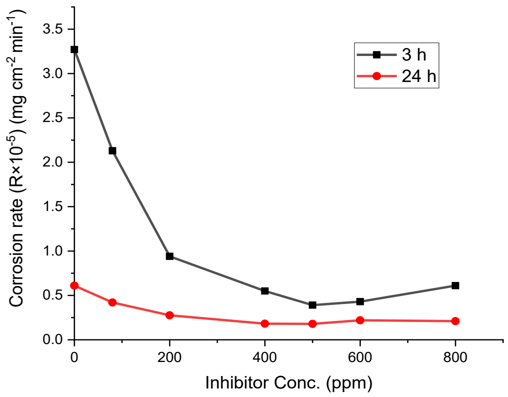

Fig. 2: The corrosion rate of fig leaf extract as a function of concentration at two exposure durations

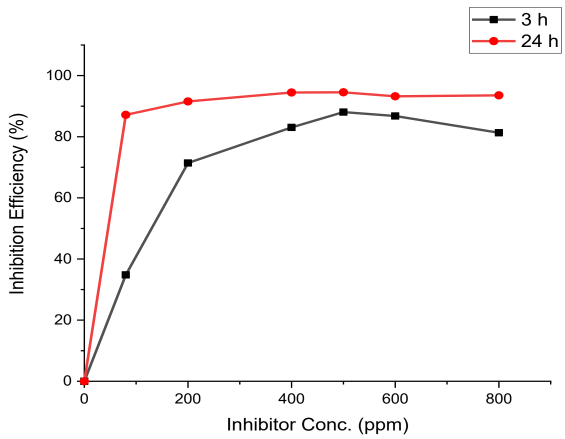

Fig. 3: The inhibition efficiency (%) of fig leaf extract as a function of concentration at 3-hour and 24-hour

3.2 Adsorption Isotherms

Langmuir and Al-awady isotherms were applied to understand the adsorption behaviour on the surface of the metal. The data obtained from the experiment were fitted to Langmuir and Al-awady isotherms (Table 3).

The adsorption behavior of the corrosion inhibitor on the metal surface was evaluated using the Langmuir adsorption isotherm model, with the linear plots of $\theta/(1-\theta)$ versus concentration (C) shown in Figure 1(a). The correlation coefficients (R^2) were 0.9809 and 0.921 for the 3-hour and 24-hour immersion times, respectively, indicating good linearity and applicability of the Langmuir model. The adsorption equilibrium constant K_{ads} was obtained from the slope of the linear plots, with values of 0.0145 for 3 hours and 0.0332 for 24 hours, suggesting stronger adsorption at longer immersion times.

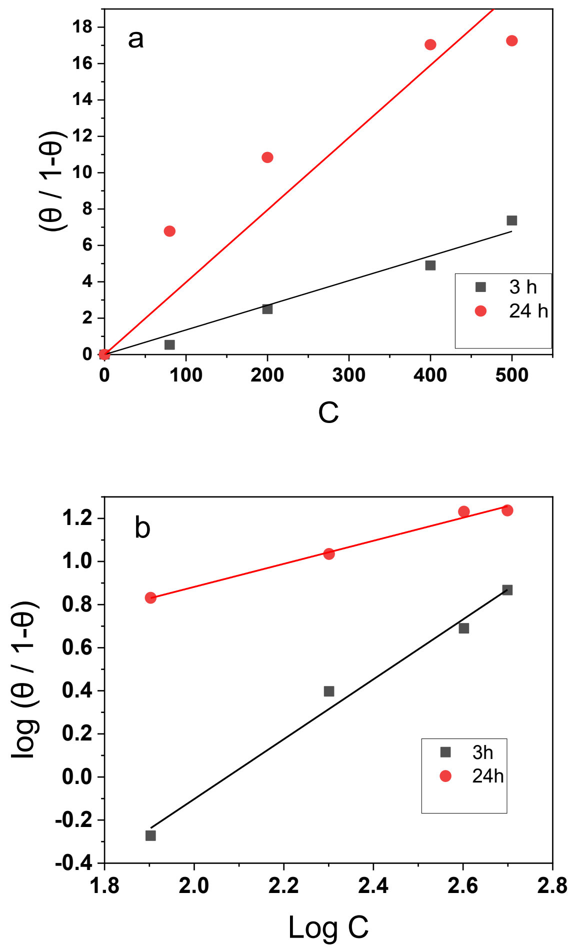

Figure 4: Adsorption parameters of a) Langmuir and b) Al-awady isotherms.

Using these values, the standard Gibbs free energy of adsorption ($\Delta G°_{ads}$) was calculated using the following equation $\Delta G°_{ads} = -RT \ln(55.5K_{ads})$. For the 3-hour immersion, $\Delta G°_{ads}$ was +0.5436 kJ/mol, indicating a weak and non-spontaneous adsorption process. In contrast, the 24-hour immersion yielded a $\Delta G°_{ads}$ of –1.513 kJ/mol, suggesting a weak but spontaneous physisorption interaction. These relatively low values of $\Delta G°_{ads}$ confirm that the inhibitor adsorbs primarily through physical interactions, with improved affinity and spontaneity over extended exposure times.

Table 3: Adsorption parameters of Langmuir and Al-awady isotherms

Adsorption model	Time	y	K_{ads}	$\Delta G_{ads}°$ kJ/mol
Langmuir	3-hour	/	0.0145	0.5436
	24-hour	/	0.0332	-1.513
Al-awady	3-hour	1.39	0.0013	6.517
	24-hour		0.6485	-8.882

The adsorption behavior of the corrosion inhibitor on the medium carbon steel surface was further analyzed using the Al-awady adsorption isotherm model, [29], Figure 4b, which accounts for the possibility of multiple inhibitor molecules occupying a single active site on the metal surface. The Al-awady adsorption isotherm is represented by the linear form $\log(\theta/(1-\theta)) = 1/y \log K' + y \log C$, where K′ is the modified adsorption equilibrium constant ($\log K_{Ads} = 1/y \log K'$) and y reflects the number of inhibitor molecules interacting with one adsorption site. For the 3-hour immersion period, the calculated slope (slope = y) was 1.39. The slope value $y > 1$ suggests that more than one inhibitor molecule is involved in occupying a single active site, possibly due to limited adsorption surface availability or early competitive interaction among molecules. K_{ads} values of 0.0013, indicating weak adsorption. The corresponding Gibbs free energy of adsorption ($\Delta G°_{ads}$) was +6.517 kJ/mol, a positive value suggesting a non-spontaneous adsorption process and negligible inhibitor-surface interaction at this early stage.

In contrast, the results after 24-hour of immersion showed improved adsorption characteristics. The slope, (= y), decreased to 0.53517 and being less than 1 suggests that a single inhibitor molecule may cover multiple active sites. Whth K_{ads} value of 0.6512. This translated to a more favorable ΔG°_{ads} of –8.882 kJ/mol, indicating a spontaneous but still relatively weak physical adsorption process. Overall, the Alawady model fits suggest that the adsorption mechanism evolves with immersion time, shifting from weak or negligible at 3-hour to a more favorable physisorption interaction at 24-hour.

3.3 Proposed Inhibition Mechanism

3.3.1 Important Chemicals in Fig Leaf Extract

Fig leaf extract is known to contain several bioactive compounds that can act as corrosion inhibitors for steel in acidic environments, such as hydrochloric acid. Here's a breakdown of the important chemicals and their protective mechanisms [10, 15, 17, 18]:

1. **Flavonoids**: Polyphenolic compounds with aromatic rings and OH^- groups.
2. **Tannins**: High molecular weight polyphenols with multiple hydroxyl groups.
3. **Saponins**: Glycosides with detergent-like properties.
4. **Alkaloids**: Nitrogen-containing compounds with heterocyclic rings.

3.3.2 Corrosion Inhibition Mechanism of Fig Leaf Extract on Steel in Acidic Environment

In essence, fig leaf extract works as a corrosion inhibitor by adsorbing its active phytochemicals onto the steel surface, forming a protective film that limits acid attack and slows down the electrochemical reactions responsible for corrosion.

Fig leaf extract contains a variety of bioactive compounds, primarily flavonoids, tannins, saponins, alkaloids, and phenolic acids, which contribute to its effectiveness as a corrosion inhibitor for medium carbon steel in acidic environments such as hydrochloric acid. These compounds possess functional groups like hydroxyl (–OH), carboxyl (–COOH), and aromatic rings with lone pair electrons and π-electrons, enabling them to adsorb strongly onto the steel surface. This adsorption results in the formation of a protective organic film that acts as a physical barrier, reducing direct contact between the aggressive acidic medium and the metal substrate. Furthermore, some phytochemicals can chelate iron ions at the metal interface, enhancing the stability of the protective layer. Additionally, the antioxidant properties of flavonoids and phenolics mitigate oxidative reactions that typically accelerate corrosion. Collectively, these mechanisms lead to a significant decrease in the corrosion rate of steel, demonstrating the potential of fig leaf extract as an eco-friendly and sustainable corrosion inhibitor in acid pickling and related industrial processes. A proposed mechanism is illustrated in Figure 5, where the fig leaf extract forms a protective film that blocks the access of corrosive agents. Phytochemicals present in fig leaf extract, such as flavonoids, tannins, and phenolic compounds, are known to contain heteroatoms (e.g., O, N) and π-electron systems. These can adsorb onto metal surfaces through physical and/or chemical interactions, forming a protective film that hinders metal dissolution and hydrogen evolution.

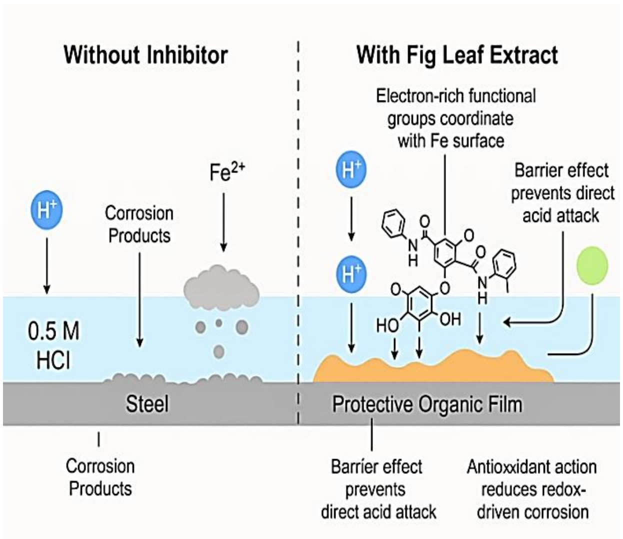

Fig. 5: Schematic Representation of the Corrosion Inhibition Mechanism of Fig Leaf Extract on Carbon Steel in HCl Solution

4. Conclusion

This study demonstrates the effectiveness of **fig leaf (*Ficus carica*) extract** as a green, eco-friendly corrosion inhibitor for medium carbon steel in **0.5 M hydrochloric acid**. The extract achieved an inhibition efficiency of up to 94.52% in 0.5 M HCl after 24-hour of exposure. Both **gravimetric and electrochemical methods** confirmed that the inhibition efficiency increases with an increase in extract concentration and immersion time.

The observed inhibition behavior is attributed to the **adsorption of phytochemicals**—such as flavonoids and tannins—on the metal surface, leading to the formation of a **protective barrier** that impedes both anodic and cathodic corrosion reactions. The time-dependent increase in efficiency suggests **gradual film stabilization** and enhanced surface coverage over prolonged exposure. These findings support the potential application of fig leaf extract as a sustainable alternative to toxic synthetic inhibitors for medium carbon steel protection in acidic environments. Additionally, competitive adsorption may occur, wherein inhibitor molecules displace previously adsorbed aggressive ions like Cl^-, enhancing chemisorption. The antioxidant properties of the extract further contribute to stabilizing the protective layer over time by neutralizing oxidative species.

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