Cucumber peel extract as an eco-friendly corrosion inhibitor for low-carbon steel in sulfuric acid

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Abstract

This study investigates the use of cucumber peel extract (CPE) as a sustainable and eco-friendly corrosion inhibitor for low-carbon steel in 0.5 M sulfuric acid (H_2SO_4). The research aims to address the environmental concerns associated with traditional corrosion inhibitors by exploring the potential of natural, biodegradable substances. The effects of temperature and inhibitor concentration on corrosion rates were examined using the weight loss method, providing a quantitative measure of the corrosion process. Results demonstrate that CPE significantly reduces the corrosion rate of low-carbon steel in acidic environments, making it a promising alternative to synthetic inhibitors. The inhibition efficiency of CPE was found to increase with higher inhibitor concentrations but decrease with rising temperatures. The highest inhibition efficiency recorded was 87.4% at 30°C with a CPE concentration of 10 mL/L, indicating substantial protection under optimal conditions. Adsorption studies revealed that CPE's behavior adheres to the Langmuir adsorption isotherm model, suggesting monolayer adsorption on the steel surface. This study highlights the potential of cucumber peel extract as an effective and environmentally friendly corrosion inhibitor, encouraging further exploration and application of natural extracts in corrosion prevention. The findings provide a basis for the development of green corrosion inhibitors that can contribute to sustainable industrial practices.

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1. Introduction

Steel and its alloys are extensively employed in various industrial applications and are often exposed to acidic environments. These acids can aggressively attack the metal surface, resulting in severe corrosion issues. One effective method to mitigate corrosion is the use of inhibitors. Many commonly used acid inhibitors in industry are organic compounds characterized by multiple bonds in their molecules. These compounds typically contain nitrogen, sulfur, and oxygen atoms, which facilitate their adsorption onto the metal surface [1]. Corrosion inhibitors typically manage corrosion by creating various types of protective films. These films can form through several mechanisms: adsorption, the creation of bulky precipitates, and/or the development of a passive layer on the metal surface. Most organic inhibitors slow down corrosion by adsorbing onto the surface, forming a thin, invisible film that is only a few molecules thick [2, 3]. Synthetic organic inhibitors used in industry can have significant detrimental effects on the environment. In contrast, organic inhibitors derived from plant and vegetable extracts are effective, economical, and environmentally friendly. These natural extracts offer a sustainable alternative to synthetic inhibitors, providing corrosion protection without harming the ecosystem [4, 5]. Most natural products are non-toxic, biodegradable, and widely available. Numerous studies have demonstrated the effectiveness of these naturally occurring substances as corrosion inhibitors for various metals in different environments [6–15].

The well-documented hazardous effects of many synthetic corrosion inhibitors have driven the search for natural alternatives [16, 17]. Most natural products are non-toxic, biodegradable, and widely available. Numerous studies have demonstrated the effectiveness of these naturally occurring substances as corrosion inhibitors for various metals in different environments [18–20]. Green inhibitors, derived from natural sources, have gained significant attention due to their eco-friendly properties and availability. These include extracts from fruits, leaves, seeds, and peels, which are rich in organic compounds capable of forming protective films on metal surfaces. This study introduces the use of cucumber peel extract (CPE) as an eco-friendly and sustainable corrosion inhibitor for low-carbon steel in sulfuric acid environments. While many studies have explored plant and vegetable extracts as corrosion inhibitors, the use of CPE, particularly in the context of Diyala governorate, Iraq, has not been previously reported. The novelty of this research lies in the identification and utilization of CPE, a readily available and cost-effective natural resource, as a potential alternative to synthetic inhibitors. This study also provides a comprehensive evaluation of the inhibition efficiency of CPE under varying temperatures and concentrations, contributing valuable insights to the field of green corrosion inhibitors. The aim of this study is to investigate the effectiveness of cucumber peel extract (CPE) as a sustainable and environmentally friendly corrosion inhibitor for low-carbon steel in 0.5 M sulfuric acid. The research seeks to determine the optimal conditions for CPE's inhibitory performance and to understand the underlying mechanisms of its action. The main objectives of the current study can be summarizing as follows:

1. **Extraction and preparation:** To extract cucumber peel extract (CPE) using appropriate methods and prepare it in various concentrations for testing.
2. **Evaluation of corrosion inhibition efficiency:** To assess the corrosion inhibition efficiency of CPE on low-carbon steel in 0.5 M sulfuric acid using the weight loss method.
3. **Effect of concentration:** To investigate the effect of different concentrations of CPE on the corrosion rate of low-carbon steel.
4. **Effect of temperature:** To examine the impact of varying temperatures on the inhibition efficiency of CPE and understand how temperature influences its protective capabilities.
5. **Adsorption studies:** To conduct adsorption studies and determine the adsorption isotherm model that best describes the interaction between CPE and the metal surface.
6. **Comparison with synthetic inhibitors:** To compare the effectiveness and environmental impact of CPE with commonly used synthetic corrosion inhibitors.
7. **Sustainability assessment:** To evaluate the potential of CPE as a sustainable alternative to synthetic inhibitors in industrial applications, considering its environmental benefits and availability.

2. Experimental work

2.1. Materials and chemicals

Low-carbon steel specimens, with dimensions of 3 cm×1 cm×0.1 cm, were utilized in weight loss tests. These specimens, cut from a larger sheet, had a chemical composition primarily consisting of 0.09% carbon, 0.4% manganese, and trace amounts of other elements, with the balance being iron. Prior to testing, the specimens underwent a thorough cleaning procedure, involving abrasion with emery paper of different grades, washing with tap and distilled water, drying, immersion in acetone and benzene, and storage in a desiccator over silica gel. During testing, the metal samples were completely immersed in 250 mL of 0.5 M H_2SO_4 corrosion solution contained in glass flasks. Exposure periods of 3 hours were carried out at specified temperatures, molarities of sulfuric acid solution, and inhibitor concentrations. After exposure, the specimens were cleaned, weighed, washed, dried, and subjected to weight loss measurements. These measurements were conducted at various temperatures (30, 40, 50, and 60°C) and inhibitor concentrations (2, 4, 6, 8, and 10 mL/L), with each test repeated twice for accuracy. Analytical reagent-grade H_2SO_4 with a purity of 98% and a molecular weight of 98.08 was utilized to prepare the acid electrolyte. The acid was meticulously diluted with double-distilled water to achieve a 0.5 M H_2SO_4 solution. To ensure the accuracy and reliability of the experiments, freshly prepared 0.5 M H_2SO_4 solutions were used for each set of experiments to minimize the influence of any potential contamination.

2.2. Preparation of cucumber peel extract

Cucumber peel extract (CPE) was obtained from readily available cucumber plants in Diyala governorate, Iraq. The peels were collected, dried in the shade, ground into a powder, and then converted to powdered form. The extract was prepared by refluxing 100 g of powdered dry peels in 1000 mL of distilled water for 3 hours. After cooling and overnight soaking, the mixture was filtered, and the volume of the filtrate was adjusted to 50 mL using 0.5 M H_2SO_4. This resulting solution was considered as the stock solution and was partitioned into smaller volumes (2, 4, 6, 8, and 10 mL) for each liter of 0.5 M H_2SO_4. The extract was subjected to analysis using Fourier transform infrared spectroscopy (FTIR-600, Biotech Engineering Management, UK).

3. Results and Discussion

3.1. FTIR studies

FTIR measurements were performed to provide some insight into the potential interactions between the adsorbed inhibitor and the mild steel surface in an acidic environment. The inhibitor's chemical structure determines its inhibitory strength. Figure 1 depicts the FTIR spectrum of mild steel immersed in an inhibited solution containing CPE.

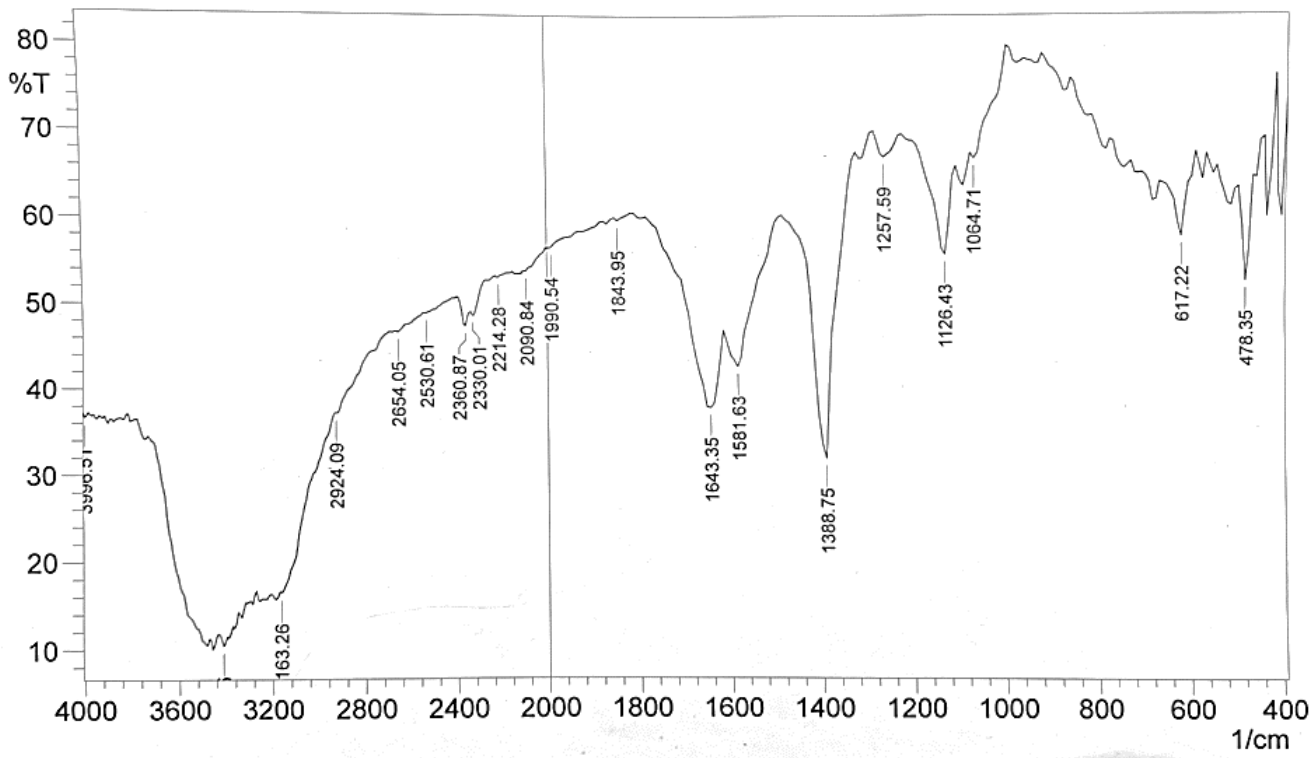

Figure 1. FTIR spectrum of cucumber peel extract.

Cucumber peel extract (CPE) was studied to determine the primary functional group. The signal at 3385 cm^{-1} represented O–H vibration. Peaks at 3163.26 cm^{-1} and 2924.09 cm^{-1}

may imply N–H and C–H stretching vibrations. The peaks at 1643.35 cm^{-1} and 1388.75 cm^{-1} corresponded to C=O and N=N stretching vibrations. The peaks at 1388.75 cm^{-1} and 1257.59 cm^{-1} may be associated with C–H bending and C–N stretching vibrations. Peaks at 1064.71 cm^{-1} and 1126.43 cm^{-1} were detected due to C–O and C–O–C vibrations. Peaks at 617.22 cm^{-1} and 478.35 cm^{-1} were found due to the vibrations of the presence of aromatic compounds such as flavonoids and tannins in the sample. As a result, CPE included a high concentration of bioorganic compounds [21].

3.2. Weight loss studies

Weight loss rate (M_{LR}) and inhibition efficiency (%*IE*) were evaluated using Equation 1 and Equation 2, respectively [22, 23].

$$M_{\mathrm{LR}} = \frac{\text{mass loss (g)}}{\text{surface area (m}^2\text{)}\times\text{time (day)}} \tag{1}$$

$$\%IE = \frac{M_{\mathrm{LR}}^{\mathrm{un}} - M_{\mathrm{LR}}^{\mathrm{in}}}{M_{\mathrm{LR}}^{\mathrm{un}}} \tag{2}$$

$M_{\mathrm{LR}}^{\mathrm{un}}$ and $M_{\mathrm{LR}}^{\mathrm{in}}$ are the weight loss rates in the uninhibited and inhibited corrosive solution, respectively. The weight loss rate outcomes were collected in Table 1 at different temperatures and inhibitor concentrations. The table shows that the weight loss rate increased with temperature and decreased with CPE concentration. The reduction in the weight loss rate may be attributed to the formation of a protective inhibitory layer on the metal surface. The maximum inhibition efficiency was 87.4% at 10 mL/L CPE and 30°C. The %*IE* decreased with a rise in temperature, which may be attributed to the desorption of the adsorbed layer at elevated temperatures.

Table 1. The variation of corrosion rate of low-carbon steel in 0.5 M H_2SO_4 and inhibition efficiency (%*IE*) of cucumber peel extract as a function of temperature and inhibitor concentration.

No.	***C*, mL/L**	***T*, °C**	**Weight loss rate**	***IE*, %**
1	0	30	717.1	–
2		40	1347.3	–
3		50	3379.2	–
4		60	6000.5	–
5	2	30	250.5	65.1
6		40	515.4	61.8
7		50	1376	59.3
8		60	3350.5	44.2

No.	*C*, mL/L	*T*, °C	Weight loss rate	*IE*, %
9	4	30	202.2	71.8
10		40	420.4	68.8
11		50	1108.1	67.2
12		60	2111.5	64.8
13	6	30	172.2	76.0
14		40	364.3	73.0
15		50	998.6	70.4
16		60	1850.6	69.2
17	8	30	153.7	78.7
18		40	275.2	79.6
19		50	764.2	77.4
20		60	1444.5	75.9
21	10	30	90.2	87.4
22		40	200.5	85.1
23		50	690.5	79.6
24		60	1280.6	78.7

3.3. Effect of inhibitor concentration and adsorption studies

In the search of a deeper understanding of the adsorption of CPE on the low-carbon surface, the experimental findings were analyzed using several isotherms, including models such as Langmuir, kinetics-thermodynamic, Freundlich, and Temkin. The mathematical formulas of these models are given by Equation 3 through Equation 6 [24, 25], while graphical illustrations are given by Figure 2.

$$\frac{c}{\theta}=\frac{1}{K}+C \tag{3}$$

$$\ln\frac{\theta}{1-\theta}=\ln K'+y\ln C \tag{4}$$

$$\ln\theta=\ln K+n\ln C \tag{5}$$

$$\theta=-\frac{1}{2a}\ln K-\frac{1}{2a}\ln C \tag{6}$$

C represents the CPE concentration is the adsorption constant, *K′* in Equation 4 is a constant equal to $K^{1/y}$. In addition, *y*, *n*, and *a* are constants related to the adsorption models.

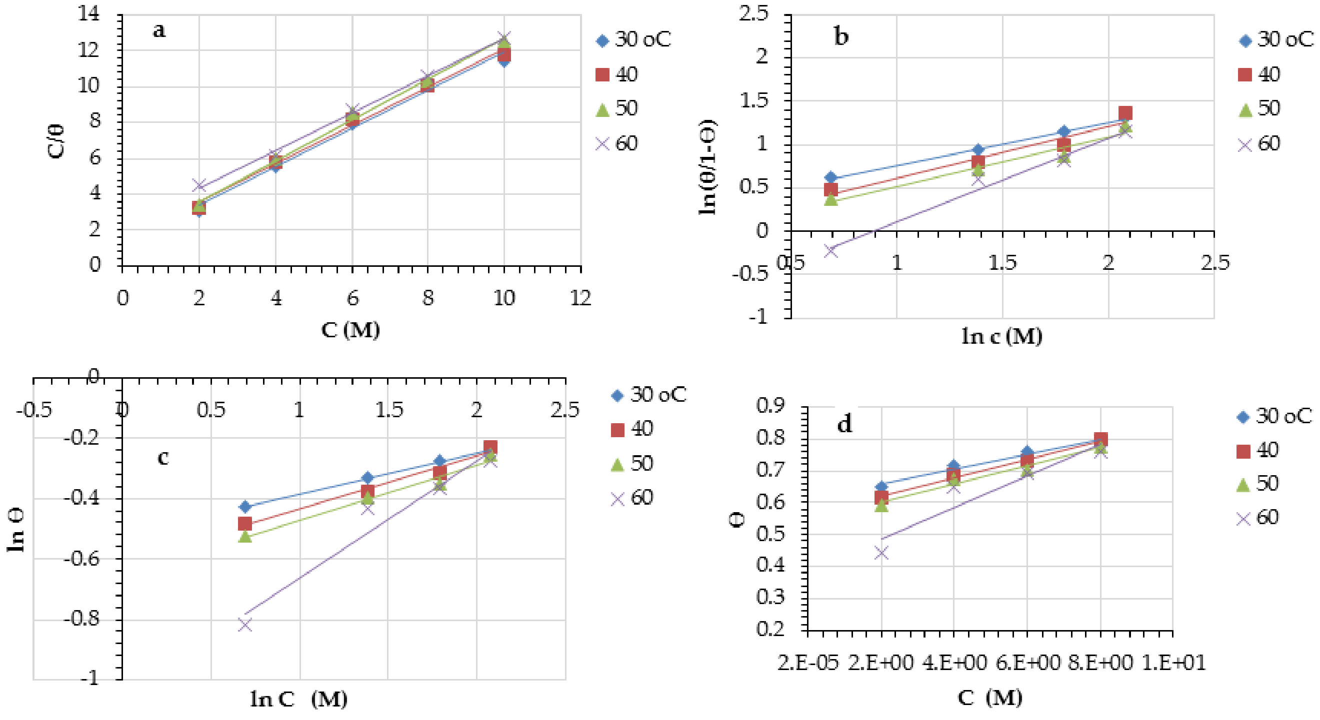

Figure 2. (a) Langmuir; (b) kinetic-thermodynamic model; (c) Freundlich; and (d) Temkin adsorption isotherms of CPE on the low-carbon steel.

According to the correlation coefficients (R^2) values, the Langmuir adsorption model was the best fit for the adsorption data. The values of R^2 were more than 0.99, as shown in Table 2.

Table 2. Langmuir adsorption isotherm parameters.

***T*, K**	***K*ads, L/mL**	***R*²**
303	0.81	0.9942
313	0.70	0.9956
323	0.76	0.9979
333	0.43	0.9985

3.4. Effect of temperature and thermodynamic studies

To perform a methodical examination of how temperature affects the inhibitory efficacy of CPE, a series of weight loss experiments were undertaken activation parameters, such as activation energy E_a, entropy ΔS_a and enthalpy ΔH_a were calculated using Arrhenius equation (Equation 7) and transition state theory (Equation 8) [26, 27]:

$$M_{\mathrm{LR}} = A\exp\left(-\frac{E_{\mathrm{a}}}{RT}\right) \qquad (7)$$

$$M_{\mathrm{LR}} = \left(\frac{RT}{Nh}\right)\exp\left(\frac{\Delta S_{\mathrm{a}}}{R}\right)\exp\left(-\frac{\Delta H_{\mathrm{a}}}{RT}\right) \tag{8}$$

In the equations above, A is the Arrhenius constant, h is Plank's constant, and N is Avogadro's number. Plotting the natural logarithm of the weight loss rate ($\ln M_{\mathrm{LR}}$) against the reciprocal of absolute temperature ($1/T$), as shown in Figure 4, yields lines with slopes ($-E_{\mathrm{a}}/R$) and intercepts ($\ln A$), which can be used to calculate activation energy and the Arrhenius constant. To calculate ΔH_{a} and ΔS_{a}, utilize the natural logarithm of the corrosion rate by absolute temperature ($\ln M_{\mathrm{LR}}/T$) against the reciprocal of absolute temperature ($1/T$), as seen in Figure 4.

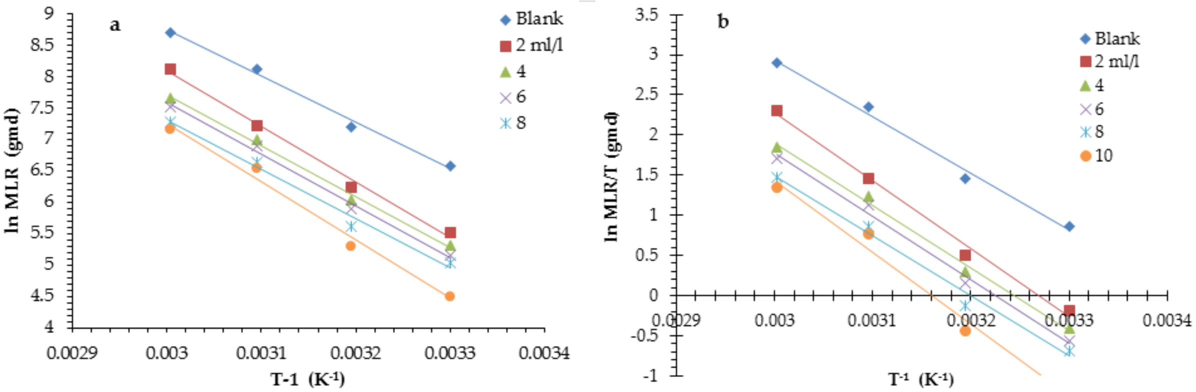

Figure 4. (a) Arrhenius and (b) Transition-state plots of low-carbon steel in uninhibited and inhibited 0.5 M H_2SO_4.

Table 3 and Figure 4 provide a comprehensive depiction of the activation energies in response to changes in the concentrations of the inhibitor at 303, 313, 323, and 333 K. Certainly, the E_{a} increases as the CPE concentration rises.

Table 3. Activation parameters for the corrosion of low-carbon steel in inhibited 0.5 M H_2SO_4 by CPE.

C mL/L	**E_{a}** kJ/mol	**ΔH_{a}** kJ/mol	**ΔS_{a}** J/mol×K	**$E_{\mathrm{a}}-\Delta H_{\mathrm{a}}$** kJ/mol
2	61.17	58.53	2.46	2.64
4	73.38	70.74	33.63	2.64
6	67.20	64.56	11.91	2.64
8	68.28	65.64	14.18	2.64
10	65.01	62.36	1.96	2.65

This increase in energy at elevated concentrations can be attributed to the formation of a CPE layer on the metal surface; in turn, more energy is needed to achieve the corrosion reaction. Under these specific conditions, the interaction between CPE molecules and the low-carbon steel surface might be characterized as physical adsorption. This agreed with the adsorption findings. All of the usual entropy of activation values in the absence and presence of CPE were positive. This can be read to signify that the activated complex in the rate-determining stage represents dissociation rather than association, implying that the degree of orderliness increases during the adsorption process as the reactants move to the activated complex. The positive values of entropy also suggest that the process is spontaneous [28]. The enthalpy of activation values is all positive, both in the presence and absence of inhibitor. The positive sign corresponds to the endothermic character of the corrosion process. The higher values in the presence of the inhibitor indicate that more energy must be given to the system to drive the corrosion process; this is consistent with the idea that a protective barrier has formed on the mild steel surface [28].

The values of activation energy (E_a) and the enthalpy of activation (ΔH_a) are positive, indicating that the corrosion process of low-carbon steel in sulfuric acid is endothermic. This endothermic nature means that energy is absorbed during the corrosion reaction. The higher values of E_a and ΔH_a in the presence of the cucumber peel extract (CPE) inhibitor suggest that more energy is required to drive the corrosion process. This is consistent with the formation of a protective barrier on the steel surface, which hinders the corrosive attack by the acidic medium. In the context of the relationship $E_a-\Delta H_a=RT$, where R is the universal gas constant (8.314 J/mol×K) and T is the temperature in Kelvin, this difference can be interpreted in terms of the kinetic theory of gases. For a monoatomic gas, the kinetic energy is primarily translational, and the relationship between activation energy and enthalpy of activation can be understood through the principles of thermodynamics and kinetic theory. Given that $E_a-\Delta H_a$ represents the difference between the total energy required to initiate the corrosion process and the change in enthalpy, it can be approximated by the term RT for monoatomic gases. This approximation holds because the internal energy change for a monoatomic gas is primarily due to translational motion, and at constant pressure, the enthalpy change includes a term related to the work done by the system. For the temperatures considered in this study, let’s assume an average temperature around room temperature, which is approximately 298 K (25°C). We can use this temperature to validate the relationship:

$$RT=\frac{8.314\ \text{J}}{\text{mol}\times\text{K}}\cdot 298\ \text{K}=2477.372\ \text{J/mol}=2.477\ \text{kJ/mol}$$

This value of RT (approximately 2.477 kJ/mol) is close to the differences $E_a-\Delta H_a$ observed in the table, which are around 2.64 kJ/mol. This consistency suggests that the corrosion process, in the presence of the inhibitor, involves an activation energy that includes contributions from the thermal energy of the system. The positive difference between E_a and ΔH_a further supports the notion that the inhibitor forms a barrier, raising the energy threshold for the corrosion reaction. The slight deviation from the exact RT value could be attributed to the complexities of the corrosion process and the interactions at the metal surface, which may not be perfectly modeled by the simple kinetic theory of monoatomic gases. However, the close agreement reinforces the endothermic nature of the corrosion process and the effectiveness of CPE as a corrosion inhibitor.

3.5. Comparative analysis of inhibition efficiency

To contextualize the effectiveness of cucumber peel extract (CPE) as a corrosion inhibitor, it is beneficial to compare its performance with other natural inhibitors as in Table 4. Various plant extracts have been explored for their potential as environmentally friendly corrosion inhibitors, and several studies have reported promising results. Neem (*Azadirachta indica*) extract has been widely studied for its corrosion inhibition properties. Research indicates that neem extract can achieve an inhibition efficiency of up to 93% in acidic environments. The active compounds in neem, such as azadirachtin and nimbin, contribute to its effectiveness by forming a protective film on the metal surface [30]. Henna (*Lawsonia inermis*) extract is another plant-based inhibitor that has shown significant corrosion inhibition capabilities. Studies have reported an inhibition efficiency of approximately 85% when henna extract is used in sulfuric acid environments. The primary active component, lawsone, facilitates adsorption onto the metal surface, thereby reducing the corrosion rate [31]. Pomegranate (*Punica granatum*) peel extract has also been identified as a potent green inhibitor. Research demonstrates that pomegranate peel extract can achieve an inhibition efficiency of about 83%. The high content of phenolic compounds, such as punicalagin and ellagic acid, in pomegranate peel contributes to its corrosion inhibition properties [32]. In this study, CPE has shown to be an effective corrosion inhibitor for low-carbon steel in 0.5 M H_2SO_4. The highest inhibition efficiency recorded for CPE was 87.4% at 30°C with a concentration of 10 mL/L. The main components in cucumber peel, such as flavonoids and tannins, are responsible for forming a protective barrier on the steel surface, reducing the corrosion rate significantly. The comparative analysis reveals that CPE demonstrates superior inhibition efficiency compared to other natural inhibitors. The 87.4% inhibition efficiency observed for CPE surpasses that of neem, henna, and pomegranate peel extracts, indicating its potential as a highly effective and environmentally friendly corrosion inhibitor.

Table 4. Comparative inhibition efficiency of various natural inhibitors.

Inhibitor	**Medium**	**Temperature**	***IE* %**	**Active Compounds**	**Mechanism of Inhibition**	**Ref.**
Neem Extract	Acidic	Not specified	80	Azadirachtin, Nimbin	Forms a protective film on the metal surface	[33]
Henna Extract	Acid	Not specified	85	Lawsone	Facilitates adsorption onto the metal surface	[34]

Inhibitor	**Medium**	**Temperature**	***IE* %**	**Active Compounds**	**Mechanism of Inhibition**	**Ref.**
Pomegranate Peel Extract	Acidic	Not specified	83	Punicalagin, Ellagic Acid (phenolic compounds)	Not specified	[35]
Cucumber Peel Extract (CPE)	Acidic	30°C	87.4	Flavonoids, Tannins	Forms a protective barrier on the steel surface	This Study

3.6. Synergistic intermolecular effects of biocompounds in cucumber peel extract (CPE)

3.6.1. Synergistic intermolecular effects

Cucumber peel extract (CPE) contains various bioactive compounds that interact synergistically to enhance its corrosion inhibition efficiency. The main constituents identified in CPE include flavonoids, tannins, alkaloids, and saponins. These compounds collectively contribute to the formation of a protective film on the steel surface, which obstructs the corrosion process. The synergistic effect occurs due to the combined action of these compounds, which enhances the overall inhibitory performance more than any single compound could achieve alone. For instance, flavonoids and tannins are known to adsorb strongly onto the metal surface, forming a dense protective layer [8–12]. Alkaloids and saponins contribute to the inhibition mechanism by interacting with the corrosive agents in the environment, reducing their aggressiveness. This combined effect creates a robust barrier that significantly reduces the corrosion rate of low-carbon steel in acidic environments.

3.6.2. Comparison with other natural inhibitors

The effectiveness of CPE as a corrosion inhibitor can be compared to other natural inhibitors like neem extract, henna extract, and pomegranate peel extract.

Neem Extract: Neem (*Azadirachta indica*) extract has been widely studied for its corrosion inhibition properties. It contains active compounds like azadirachtin, nimbin, and nimbidin, which adsorb onto the metal surface and form a protective layer. Studies have shown neem extract to achieve inhibition efficiencies of up to 90% in acidic environments [34].

Henna Extract: Henna (*Lawsonia inermis*) extract contains lawsone, gallic acid, and tannic acid, which are effective in reducing the corrosion rate of metals. Henna extract has demonstrated inhibition efficiencies of around 85% in various studies [35].

Pomegranate Peel Extract: Pomegranate (*Punica granatum*) peel extract is rich in polyphenols, tannins, and flavonoids. It has been reported to exhibit inhibition efficiencies of approximately 80% due to its strong adsorptive properties and ability to form a protective film on the metal surface.

A recent study by Feng *et al*. (2022) explored the use of cucumber leaf extract as a green corrosion inhibitor for carbon steel in acidic solutions. The study highlighted the presence of bioactive compounds in the extract, which interacted synergistically to inhibit corrosion effectively [8]. The findings demonstrated that the cucumber leaf extract could achieve significant inhibition efficiency, supporting the potential of cucumber-derived extracts as effective corrosion inhibitors.

4. Conclusion

The CPE is a good and efficient corrosion inhibitor for low-carbon steel in a sulfuric acid medium. Inhibition efficiency increases with inhibitor concentration, and the extract had a maximum inhibition efficiency of 87.4% at the optimal concentration of 10 mL/L at 30°C. The adsorption of various amounts of plant extract onto the surface of the Langmuir adsorption isotherm. The negative sign of the free energy of adsorption suggests that the adsorption of the CPE on the low-carbon steel surface was a spontaneous process that was discovered to be a physical adsorption process.

Data Availability

All data generated and calculated are completely included in this article.

Conflict of Interest

There are no competing interests.

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