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Evaluation of plant-based crude extract as environmentally friendly corrosion inhibitor

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Abstract

Corrosion is a persistent industrial problem, undermining metal integrity and leading to substantial economic and environmental losses. Conventional synthetic inhibitors, while effective, are often toxic, creating demand for environmentally friendly alternatives. This study evaluates the corrosion inhibition potential of *Datura stramonium* leaf extract on mild steel in 1 M HCl. The extract demonstrated significant efficiency, which increased with concentration, achieving optimal performance at 300 ppm across all tested temperatures (303, 313, and 323 K). The extract reached an inhibition efficiency of 96.7% at 500 ppm at 303 K. At the optimal concentration, the inhibition reached 91.8, 73.2, and 53.9% at 303, 313, and 323 K respectively. Thermodynamic analyses revealed spontaneous adsorption onto the steel surface, with efficiency decreasing moderately at higher temperatures, a characteristic of physisorption. The extract maintained appreciable inhibition at elevated temperatures (up to 58% at 323 K and 500 ppm), suggesting its ability to inhibit corrosion under harsh conditions. Adsorption studies revealed that the Langmuir isotherm most accurately described the inhibitor's behavior ($R^2 = 0.993$—0.999), indicating monolayer adsorption on a homogeneous metal surface. Electrochemical measurements indicate that the leaf extract acts as an effective mixed-type corrosion inhibitor for mild steel in 1 M HCl. The inhibition performance is attributed to phytochemicals containing oxygen and nitrogen donor atoms and aromatic rings, which facilitate effective surface coverage and the formation of a stable protective film on the metal surface, as confirmed by morphological studies of the formed film. These findings establish *Datura stramonium* leaf extract as a plant-based, cost-effective, and environmentally friendly alternative to conventional synthetic inhibitors, consistent with green chemistry and sustainable industrial practice.

Keywords *Datura stramonium* L., Phytochemicals, Anticorrosion property, Biodegradability, Environmental concerns

1 Introduction

Corrosion remains a critical challenge across diverse industrial sectors, threatening the integrity and longevity of metal infrastructures while incurring significant economic and environmental costs [1–5]. Traditional synthetic corrosion inhibitors, though effective, often pose health and ecological risks due to their toxicity and poor biodegradability, prompting the urgent search for environmentally benign alternatives [6–10]. Among various green inhibitors, plant-derived crude alkaloids and flavonoids have attracted substantial attention for their abundance, renewability, and remarkable efficacy in mitigating metal degradation in aggressive environments [8].

These natural compounds, characterized by the presence of heteroatoms such as nitrogen, oxygen, and sulfur in their molecular structures, facilitate the adsorption onto metal surfaces, forming protective films that hinder electrochemical reactions responsible for corrosion [11, 12]. Studies on alkaloid-rich extracts from plants like *Artemisia vulgaris*, *Solanum tuberosum*, and *Rauvolfia macrophylla* have demonstrated inhibition efficiencies exceeding 90%, underscoring the potential of these phytochemicals as reliable green alternatives [11–13]. Similarly, crude flavonoid extracts, particularly those featuring strong antioxidant and chelating properties, act

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by forming robust surface barriers, thereby substantially reducing corrosion rates on metals such as mild steel and copper [14]. The efficacy of these plant extracts is further enhanced by synergistic actions among diverse phytoconstituents, with notable increases in inhibition observed when alkaloids and flavonoids are co-present [15].

Recent reviews have reiterated the key roles of alkaloids and flavonoids in eco-friendly corrosion mitigation, highlighting the adsorption mechanism's alignment with the Langmuir isotherm and the predominance of physical or mixed-type adsorption as the underlying process [16, 17]. The mechanistic insights gained from electrochemical and spectroscopic studies reveal that these compounds can act as mixed-type inhibitors, offering comprehensive protection under acidic, neutral, and saline environments [18, 19]. Flavonoids, with their polyphenolic scaffolds, not only serve as corrosion inhibitors but also impart significant antioxidant potential, further protecting metal surfaces from oxidative attack [20].

Beyond their corrosion-inhibiting capabilities, plant-derived alkaloids and flavonoids hold promise for sustainable industrial applications due to their low cost, non-toxicity, and biodegradability [21]. The transition toward green inhibitors is thus supported by mounting evidence of comparable or superior efficacy to synthetic counterparts, as well as by alignment with emerging regulatory and environmental standards [22].

Datura stramonium, commonly known as thorn apple, is an abundant weed widely distributed in many regions, offering a readily available source of alkaloids and flavonoids with potential industrial applications [1, 2, 23]. Previous studies have predominantly focused on the corrosion-inhibiting properties of its seed extracts, demonstrating notable inhibition efficiencies at low concentrations [2, 24]. However, there is a paucity of research examining the efficacy of leaf extracts, which may contain distinct phytochemical compositions that could influence corrosion inhibition. Therefore, investigating the anticorrosion efficacy of *Datura stramonium* leaf extract in 1 M HCl is essential to determine its potential as an effective and sustainable plant-based corrosion inhibitor. This study provides a detailed evaluation of the leaf extract's phytochemicals, elucidating their mechanistic roles and prospective applicability across diverse metallurgical systems for sustainable corrosion mitigation.

2 Experimental methods

2.1 Materials

Fresh leaves of *Datura stramonium* L. were used as the primary plant material for this study. Analytical grade reagents, including methanol, hydrochloric acid, and acetone, were procured and used without further purification. All solvents and chemicals were of analytical grade to ensure the reliability and reproducibility of experimental results. Mild carbon steel specimens, measuring 24.0 mm × 6.0 mm × 1.0 mm, were also employed for corrosion testing.

2.2 Sample collection

Leaves of *Datura stramonium* L. (jimsonweed or thorn apple), a toxic annual herb of the Solanaceae family, were collected from the Old Airport area in Mbeya Region, Tanzania. Four sampling points were selected: Point A (Latitude −8.91918, Longitude 33.46257), Point B (Latitude −8.91904, Longitude 33.46211), Point C (Latitude −8.91915, Longitude 33.46264), and Point D (Latitude −8.91986, Longitude 33.46332). Fresh leaves were harvested by hand from healthy plants, thoroughly cleaned to remove dust and debris, and air-dried under shade to minimize loss of bioactive constituents. The dried leaves were then oven-dried at a controlled temperature to constant weight, ground into fine powder using a mechanical grinder, sealed in airtight containers, and stored under dry conditions until required for further experimental analysis.

2.3 Extraction of crude leaf extract

The crude leaf extract was prepared following established procedures reported in the literature [24, 25]. In summary, dried and powdered *Datura stramonium* L. leaves (200 g) were soaked in 1000 mL of methanol at room temperature for 72 h with occasional shaking. The mixture was filtered through Whatman No. 1 filter paper, and the solvent was removed under reduced pressure using a rotary evaporator at 40 °C. The resulting crude extract was oven-dried at 40 °C for 48 h to a constant weight. This crude extract, containing both alkaloids and flavonoids, was used directly for corrosion analysis without further separation. The dried crude extract was stored in airtight amber bottles at 4 °C until required for experimental use.

2.4 Characterization of the crude leaf extract

The plant extract was screened for phytochemical constituents and characterized using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy, Thermogravimetric Analysis (TGA), and solubility analysis.

2.4.1 Qualitative phytochemical analysis

Phytochemical screening of the *Datura stramonium* L. leaf extract was conducted to qualitatively identify the presence of bioactive compounds using standard procedures reported in the literature [26]. This analysis is

essential as these phytochemicals are known to contribute significantly to corrosion inhibition by adsorbing onto metal surfaces and forming protective barriers [10, 27].

2.4.2 Solubility analysis

The solubility of the *Datura stramonium* leaf extract was assessed using the conductivity method. A known quantity of the dried crude extract was dissolved in deionized water, and the electrical conductivity of the resulting solution was measured using a calibrated conductivity meter at room temperature [28]. This analysis provides an indication of the extract's ionic and polar constituents, which are relevant to its interaction with metal surfaces and its potential efficiency as a corrosion inhibitor.

2.4.3 ATR-FTIR analysis

The spectra of the *Datura stramonium* fruit extract were recorded using a Bruker spectrophotometer over a wavelength range of 4000—400 cm^{-1}.

2.4.4 Degradability assessment

The degradability of the leaf extract corrosion inhibitor was evaluated using standard Chemical Oxygen Demand (COD) and five-day Biochemical Oxygen Demand (BOD_5) tests. COD was determined by the closed reflux dichromate method to quantify the total oxygen demand of the organic constituents, while BOD_5 was measured after incubating samples at 20 °C for five days to assess the biodegradable fraction. All analyses were conducted following standard procedures, and results were reported in mg O_2/L [29].

2.4.5 Thermal stability analysis

The thermal stability of the leaf extract was evaluated using simultaneous thermogravimetric analysis (TGA) coupled with high-resolution differential scanning calorimetry (HDSC). A known mass of the dried extract was heated under a nitrogen atmosphere from room temperature to 700 °C. TGA provided measurements of mass loss across temperature ranges, while HDSC recorded thermal transitions, enabling assessment of moisture loss, decomposition of organic constituents, and overall thermal stability relevant to corrosion inhibition [30].

2.5 Anticorrosion analysis

2.5.1 Weight loss measurements

The corrosion inhibition efficiency of the leaf extract was assessed using the weight loss method, which provides a direct and reliable measure of overall corrosion behavior over time by accounting for both uniform and localized metal dissolution. This technique is simple, cost-effective, and widely recognized for evaluating the performance of green corrosion inhibitors, particularly those derived from plant extracts, as the observed mass loss offers an accurate indication of inhibition efficiency under realistic exposure conditions [31].

The experiments were conducted following procedures described in the literature [24, 28]. In summary, mild steel specimens were cleaned, degreased with acetone, air-dried, and pre-weighed prior to experimentation. The specimens were immersed for 24 h at 303 K to 323 K in hydrochloric acid solutions containing varying concentrations of *Datura stramonium* leaf extract (100, 200, 300, 400, and 500 ppm) and in blank solutions without the extract. After exposure, they were re-cleaned and air-dried. All experiments were carried out in triplicate to ensure reproducibility. The corrosion rate (CR), inhibition efficiency (IE), and surface coverage (θ) were calculated using Eqs. (1) - (3), with mean values reported. The CR (mm/yr) indicates the rate of metal deterioration in a given environment, IE (%) represents the percentage reduction in corrosion due to the inhibitor, and θ (dimensionless) denotes the fraction of the metal surface covered by the inhibitor [24, 27, 32].

$$CR = 87.6 \times \frac{\Delta w}{D.A.t} \tag{1}$$

$$IE = \frac{w_{uninh.} - w_{inh.}}{w_{uninh.}} \times 100 \tag{2}$$

$$\theta = \frac{w_{uninh.} - w_{inh.}}{w_{uninh.}} \tag{3}$$

where Δw = weight loss (mg), A = density of mild steel (7.86 g/cm^3), A = surface area of specimen (cm^2), t = immersion time (h), the constant 87.6 converts the rate into mm/yr, $w_{uninh.}$ = weight loss without inhibitor, and $w_{uninh.}$ = weight loss with inhibitor.

2.5.2 Electrochemical measurements

Electrochemical experiments were carried out using a conventional three-electrode system comprising mild steel as the working electrode, a platinum counter electrode, and an Ag/AgCl reference electrode. Measurements were performed in 1.0 M HCl with and without various concentrations of the leaf extract at 303 K under unstirred conditions. Prior to testing, the working electrode was mechanically polished, degreased, rinsed with distilled water, and dried. The electrode was immersed in the test solution for 8 h to stabilise the open-circuit potential (OCP). All experiments were conducted in triplicate to ensure reproducibility.

Potentiodynamic polarization (PDP) curves were recorded by scanning the potential from −250 to + 250 mV relative to the OCP at a scan rate of 1 mV s^{-1}.

The corrosion potential (E_{corr}), corrosion current density (i_{corr}), and anodic (β_a) and cathodic (β_c) Tafel slopes were obtained by extrapolation of the linear Tafel regions of the OCP. The inhibition efficiency from PDP measurements, IE_{PDP} (%), was calculated using Eq. (4): [33]

$$IE_{PDP}(\%) = \frac{CR_o - CR_i}{CR_o} \times 100 \quad (4)$$

where CR_o and CR_i denote the corrosion rates in the absence and presence of the inhibitor, respectively.

Electrochemical impedance spectroscopy (EIS) measurements were performed at the OCP over a frequency range of 10 kHz to 0.1 Hz using a 10 mV AC perturbation. The impedance spectra were analyzed by fitting to an equivalent electrical circuit consisting of solution resistance (R_s), polarization resistance (R_p), and a constant phase element (CPE) to account for surface heterogeneity. The inhibition efficiency derived from EIS, IE_{EIS} (%), was calculated using Eq. (5): [28]

$$IE_{EIS}(\%) = \frac{R_p - R_p^o}{R_o} \times 100 \quad (5)$$

where R_p and R_p^o are the polarization resistance values in the absence and presence of the inhibitor, respectively.

2.5.3 Protective layer formation analysis

To confirm the formation of a protective film on mild steel due to inhibitor adsorption, specimens immersed in 1 M HCl for 24 h in the absence and presence of the leaf extract were analyzed. The adsorbed films were characterized using ATR-FTIR spectroscopy over a scanning range of 4000–400 cm^{-1}. Complementary surface analysis was performed using scanning electron microscopy (SEM) to evaluate the effect of the inhibitor on corrosion protection. SEM images were captured at appropriate magnifications to compare uninhibited and inhibited surfaces, and surface features such as roughness, pits, and protective film formation were qualitatively assessed to determine the effectiveness of the inhibitor.

3 Results and discussion

3.1 Characterization of leaf extract

Characterization was conducted to elucidate the chemically active constituents, their functional groups, solubility, and thermal stability, all of which affect adsorption onto metal surfaces and support the extract's effectiveness as a corrosion inhibitor.

3.1.1 Phytochemical screening

Qualitative analysis of the leaf extract revealed the presence of alkaloids, flavonoids, glycosides, phytosterols, steroids, and triterpenes, as confirmed by characteristic color reactions (Table 1). The detection of alkaloids, flavonoids, phytosterols, steroids, and triterpenes suggests that the extract possesses compounds with strong potential for corrosion inhibition. These phytochemicals are known to act through adsorption on metal surfaces, electron donation from heteroatoms or π-bonds, and the formation of protective hydrophobic films, thereby reducing metal dissolution. Similar findings have been reported where plant-derived alkaloids, flavonoids, and terpenoids significantly enhanced anticorrosion efficiency in aqueous systems [34, 35].

3.1.2 Functional groups analysis

The functional groups present in the leaf extract were elucidated using FTIR spectroscopy. This technique provides rapid, non-destructive identification of functional groups, offering complementary validation of the preliminary phytochemical screening results and valuable insight into the chemical structures responsible for corrosion inhibition. The FTIR spectrum (Fig. 1) of the leaf extract reveals the presence of key functional groups,

Table 1 Phytochemical screening of Datura stramonium leaf extract

Phytochemical group	Observed characteristics	Presence (±)*
Alkaloids	Reddish-brown color observed	+
Glycosides	Reddish-brown ring at liquid interface	+
Phytosterols	Golden-green fluorescence at interface	+
Steroids	Reddish-brown to green coloration	+
Tannins	No color change observed	-
Anthraquinones	No change after addition of ammonia solution	-
Triterpenes	Reddish-brown color at interface	+
Amino acids	No reaction after addition of NaOH	-
Flavonoids	Intense yellow color, disappearing after acid addition	+
Saponins	No froth formation	-

* '+' denotes a positive test result, while '-' denotes a negative test result

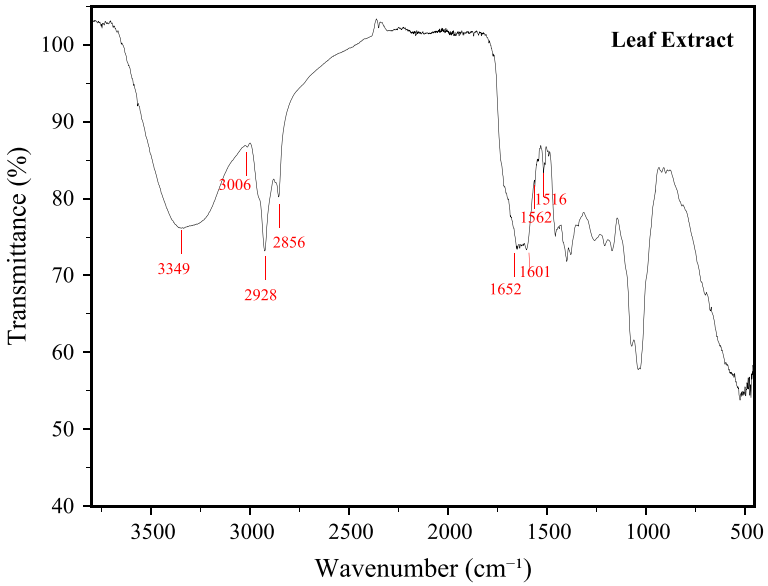


Fig. 1 FTIR spectrum of Datura stramonium leaf extract showing characteristic functional groups

including hydroxyl (-OH), carbonyl (C=O), amine (-NH, -N<), ether (C–O–C), and conjugated carbon–carbon double bonds (C=C), which correspond to the phytochemicals identified, namely flavonoids, alkaloids, triterpenes, steroids, phytosterols, and glycosides (Table 2). The presence of these groups confirms the availability of active sites capable of interacting with metal surfaces through adsorption, chelation, electron donation, and hydrophobic barrier formation, collectively supporting the extract's potential as an effective corrosion inhibitor [5, 10].

3.1.3 Solubility property

The solubility of the leaf extract, tested in deionized water, was evaluated through both conductivity and pH measurements. Conductivity reflects the extent of ionic species released into solution, whereas pH indicates the influence of acidity on dissolution equilibria. These dual measurements provide a comprehensive understanding of inhibitor solubility across pH conditions, consistent with findings that the solubility and efficiency of organic inhibitors vary with pH and ionic release [34, 36]. As illustrated in Fig. 2, the conductivity of the leaf extract in aqueous media increased, while the pH decreased, with a plateau suggesting the presence of weak acidic compounds. The simultaneous increase in conductivity and decrease in pH demonstrates the ability of the leaf extract to dissociate in aqueous media, thereby forming ionic species. This dissolution process is important, since the extent to which a scale inhibitor dissolves directly governs its effectiveness in preventing corrosion; poorly soluble inhibitors often exhibit reduced efficiency due to limited interaction with the metal surface [34, 35].

3.1.4 Degradability of leaf extract

The degradability of the leaf extract corrosion inhibitor was evaluated using COD and BOD_5, yielding values of 440 mg O_2/L and 360 mg O_2/L, respectively. The resulting BOD_5/COD ratio of 0.82 indicates high biodegradability, as ratios above 0.5 are characteristic of readily biodegradable organic materials [29]. This suggests that the extract is composed predominantly of naturally occurring, oxygen-rich compounds that are easily metabolized by microorganisms. From an environmental standpoint, the pronounced biodegradability of the extract enhances its suitability as a green corrosion inhibitor, as it minimizes the potential for long-term environmental persistence and associated ecological risks. In contrast to many conventional synthetic inhibitors, which often contain toxic or poorly degradable constituents, the studied leaf extract demonstrates improved environmental compatibility and conforms to the principles of sustainable and eco-friendly corrosion control [37].

3.1.5 Thermal stability

The TGA thermogram of the leaf extract exhibits a distinct multi-stage thermal degradation profile, reflecting its compositional complexity and adsorption-relevant functionality (Fig. 3). The curve originates at 100% mass at ambient temperature, followed by an initial 7.3% mass loss up to 115 °C, attributed to the desorption of

Table 2 Identified functional groups in the leaf extract and their corresponding phytochemical classes with anticipated corrosion inhibition mechanisms

Phytochemical group	Characteristics of identified absorption bands				Anticipated inhibition mechanism
	Band	Wavenumber (cm^{-1})	Intensity	Assignment	
Alkaloids	C-N–H	1516	Medium	δ(C-N–H)—amine	Adsorption via N lone pairs
	C-N	1166	Medium	ν(C-N)—amine	
	C-N	1075	Medium	ν(C-N)—amine	
	C-N	1042	Medium	ν(C-N)—amine	
Flavonoids	O–H	3349	Strong, Broad	ν(O–H)—phenols	Electron donation, antioxidant, surface adsorption
	C = C	1601	Medium	ν(C = C)—aromatic	
	C = C	1562	Medium	ν(C = C)—aromatic	
	C–OH	1375	Strong	ν(C–OH)—phenols	
	C–OH	1342	Strong	ν(C–OH)—phenols	
Phytosterols/Steroids	C = O	1652	Strong	ν(C = O)—Carboxylic acid	Adsorption, hydrophobic barrier formation
	C-H	1453	Medium	δ(C-H)—alkyl	
	C-H	904	Medium	δ(= C-H)—alkyl	
Triterpenes	O–H	2928	Strong, Broad	ν(O–H)—Carboxylic acid; ν(C-H)—alkyl	Electron donation, hydrophobic barrier formation
	O–H	2856	Strong, Broad	ν(O–H)—Carboxylic acid; ν(C-H)—alkyl	
	C = O	1652	Strong	ν(C = O)—Carboxylic acid	
	O–H	1398	Medium	δ(O–H)—Carboxylic acid	
	C–OH	1264	Medium	ν(C–OH)—Carboxylic acid	
	C–OH	1212	Medium	ν(C–OH)—Carboxylic acid	
	O–H	923	Medium	δ(O–H)—Carboxylic acid	
	C-H	904	Medium	δ(= C-H)—alkyl	
Glycosides	Overlaps with -OH bands above	3349, 2928, 2856	Strong	ν(O–H)/ν(C–OH)	Chelation via -OH groups

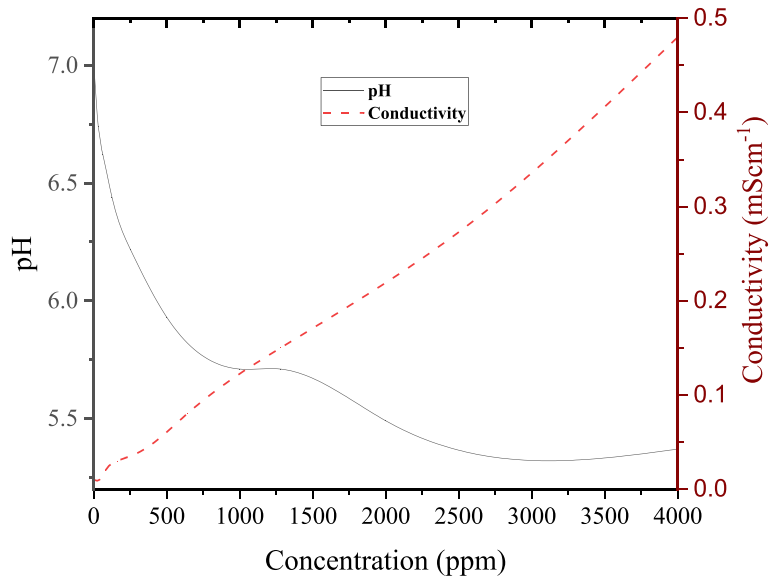


Fig. 2 Variation of pH and electrical conductivity of Datura stramonium leaf extract as a function of concentration

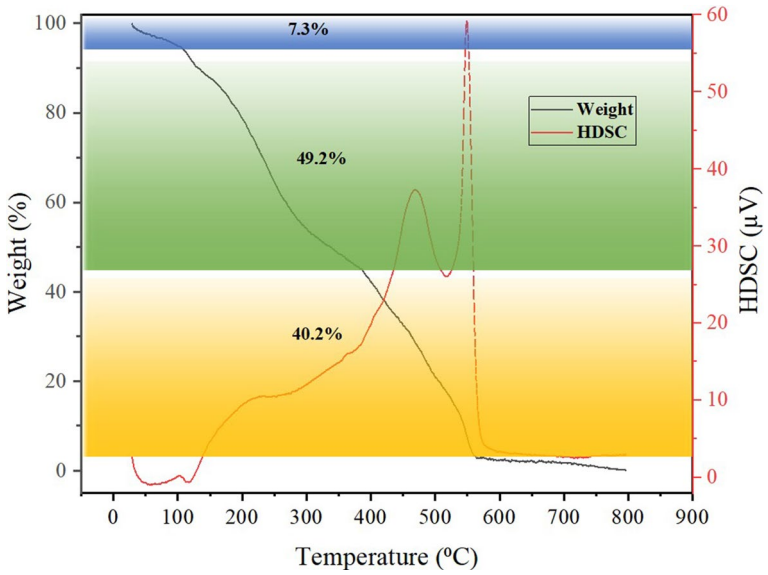


Fig. 3 TGA and HDSC thermograms for Datura stramonium leaf

physically adsorbed moisture and volatile components [30]. This behavior is consistent with the presence of hydrophilic functional groups that promote adsorption onto metal surfaces in corrosion inhibition systems. A pronounced 49.2% mass loss between 115 and 390 °C corresponds to the progressive decomposition of organic constituents, while a further 40.2% loss from 390 to 560 °C is associated with the breakdown of thermally stable compounds, including aliphatic phenolic structures. Beyond 560 °C, the mass stabilizes, indicating the depletion of volatile and decomposable components. The HDSC thermogram (Fig. 3) confirms these observations, showing endothermic events at lower temperatures related to moisture removal and volatilization, followed by broader thermal transitions at elevated temperatures associated with the decomposition of phytochemical constituents [30]. The absence of sharp exothermic degradation peaks indicates controlled thermal behavior, favorable for sustained adsorption and effective corrosion inhibition characteristic of green inhibitors. Collectively, these results confirm the thermal stability of the leaf extract and support its suitability as an eco-friendly corrosion inhibitor.

3.2 Anticorrosion property

The *Datura stramonium* leaf extract exhibits significant anticorrosion properties, as demonstrated through the assessment of inhibition efficiency, the effect of temperature on corrosion inhibition, activation parameters, adsorption studies, and thermodynamic analyses. Its effectiveness increases with concentration, indicating strong adsorption onto the mild steel surface and effective inhibition of the corrosion process.

3.2.1 Effect of concentration on corrosion inhibition

The results presented in Fig. 4 show the variation in corrosion inhibition efficiency of *Datura stramonium* leaf extract on mild steel in 1 M HCl at different extract concentrations. As observed, inhibition efficiency increased progressively with increasing extract concentration, from 76.6% at 100 ppm to 96.7% at 500 ppm at 303 K, indicating enhanced surface coverage of the metal by the inhibitor molecules [1, 2]. This improvement demonstrates that a higher concentration of the extract provides more phytochemical constituents capable of adsorbing onto the mild steel surface and forming a stable, protective film that effectively impedes corrosion [2, 23, 38].

The optimal inhibition performance was attained at 300 ppm across all temperatures (303, 313, and 323 K), suggesting that at this concentration, the metal surface approaches saturation with adsorbed inhibitor molecules. Beyond this point, additional increases in concentration yield minimal improvement, as most active adsorption sites on the steel surface are already occupied [1, 28].

3.2.2 Potentiodynamic polarization

The PDP curves for mild steel in 1.0 M HCl, recorded in the absence and presence of the leaf extract (Fig. 5), display systematic shifts of both anodic and cathodic directions relative to the blank solution. This simultaneous displacement indicates that the extract effectively suppresses both anodic metal dissolution and cathodic hydrogen evolution reactions. The E_{corr} exhibits only

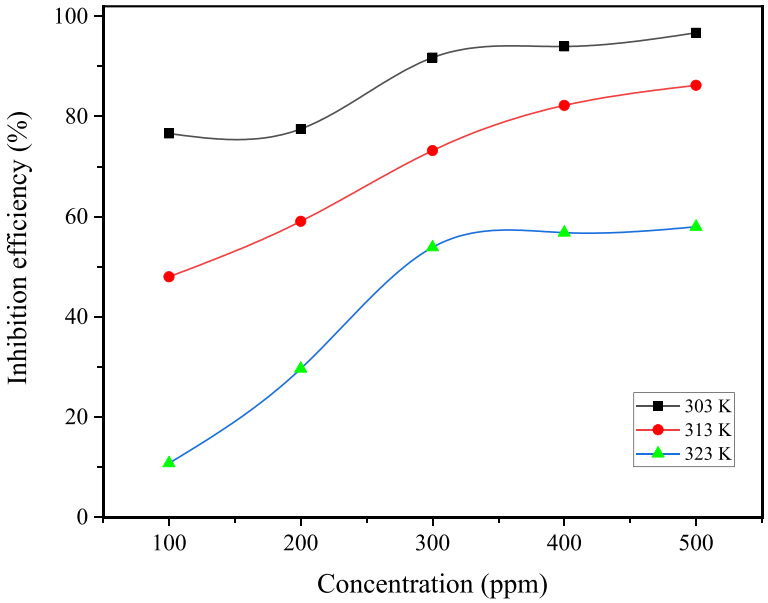


Fig. 4 linhibition efficiency as a function of Datura stramonium leaf extract concentration

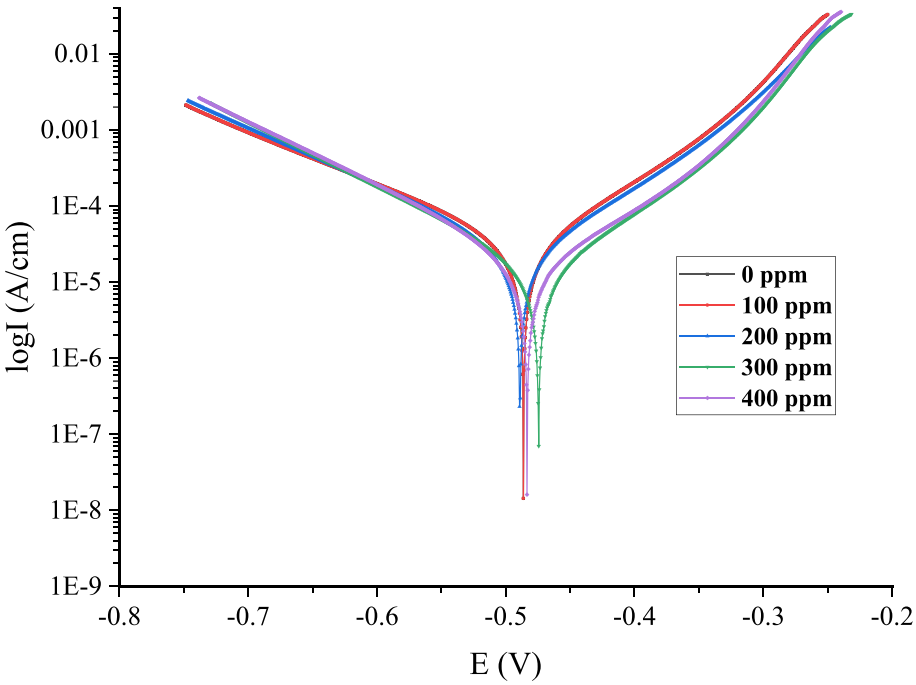


Fig. 5 Potentiodynamic polarization curves for the corrosion of mild steel in 1 M HCl solution in the absence and presence of leaf extract at 303 K

minor concentration-dependent shifts (≤ 28 mV; Table 3), confirming that the extract functions as a mixed-type corrosion inhibitor rather than preferentially influencing a single electrochemical process. Such behaviour is typical of plant-based inhibitors composed of multiple adsorption-active constituents [30, 37].

A pronounced decrease in i_{corr} from 150.39 µA cm^{-2} for the uninhibited system to 12.42 µA cm^{-2} at 300 ppm demonstrates highly effective inhibition through adsorption-controlled surface coverage, leading to a proportional reduction in corrosion rate in accordance with Faraday's law. The moderate, concurrent changes observed in both

Table 3 Potentiodynamic polarization parameters for the corrosion of mild steel in 1 M HCl solution at 303 K

C_{inh}**(ppm)**	$-E_{corr}$ **(mV vs. Ag/AgCl)**	i_{corr} **(μA/cm²)**	β_a **(mV/dec)**	β_c **(mV/dec)**	**CR (mm/yr)**	IE_{PDP}**(%)**
0	502.47	150.39	130.07	123.60	1.764	0.00
100	486.27	28.80	93.13	138.38	0.338	80.85
200	488.97	22.88	94.62	123.49	0.268	84.79
300	474.48	12.42	85.12	109.03	0.146	91.74
400	483.44	14.02	93.31	105.53	0.165	90.68

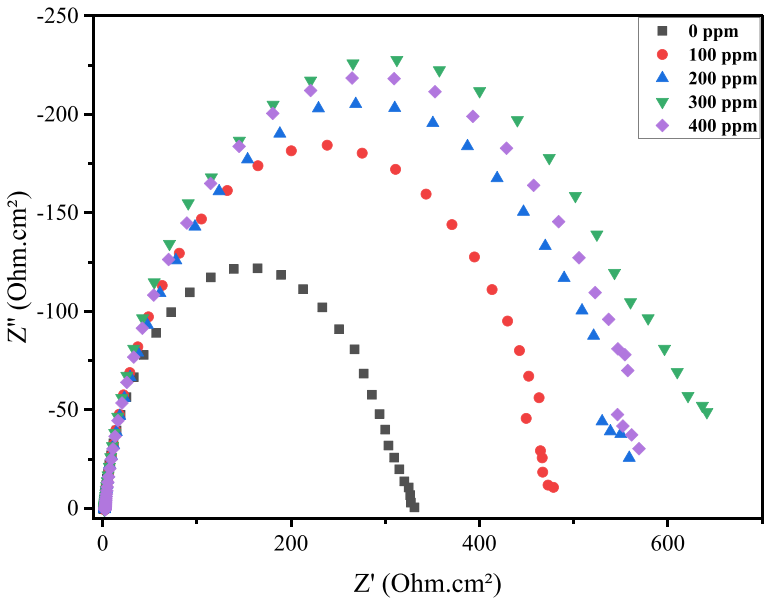


Fig. 6 Nyquist plot for the mild steel in 1 M HCl solution in the absence and presence of different concentrations of the inhibitor at 303 K

anodic and cathodic Tafel slopes, without significant distortion, indicate that the inhibitor retards charge-transfer kinetics without altering the underlying corrosion mechanism. Consequently, the bidirectional shift of the polarization curves is attributed to the formation of a compact, protective adsorbed film composed of heteroatom-rich phytochemicals that block active sites and stabilize the metal-solution interface.

Consistent with this interpretation, the inhibition efficiency increases from 80.85% at 100 ppm to a maximum of 91.74% at 300 ppm, followed by a slight decline at higher concentration, likely due to surface saturation effects. Notably, the inhibition efficiencies derived from potentiodynamic polarization closely agree with those obtained from the weight-loss method, confirming the reliability of the electrochemical measurements and underscoring the proposed adsorption-driven inhibition mechanism.

Table 4 Electrochemical impedance parameters for the corrosion of mild steel in 1 M HCl solution at 303 K

C_{inh}**(ppm)**	C_{dl}**(μFcm^{-2})**	R_s**(Ωcm²)**	R_p**(Ωcm²)**	IE_{EIS}**(%)**
0	31.92	3.5159	82.64	0.00
100	16.73	2.9208	478.83	82.74
200	15.38	2.2009	766.83	89.22
300	18.95	2.0919	960.95	91.40
400	19.73	1.7067	890.66	90.72

3.2.3 Electrochemical impedance spectroscopy

The EIS results, as illustrated in the Nyquist plot (Fig. 6), show that the plots are characterized by depressed semicircles with a single capacitive loop, reflecting the inherent roughness and inhomogeneity of the mild steel surface due to corrosion [28]. In the absence of inhibitor, the small semicircle (R_p = 82.64 Ω cm^2; C_{dl} = 31.92 μF

cm^{-2}) indicates rapid charge transfer on the unprotected steel surface. With increasing concentrations of the leaf extract, the semicircle diameters increase substantially up to 300 ppm, corresponding to a rise in R_p (960.95 Ω cm^2) and a decrease in C_{dl} (Table 4). This behaviour is attributed to the formation of a protective adsorbed inhibitor film that suppresses charge-transfer kinetics by displacing water molecules and improving surface smoothness [28, 33]. Above the optimal concentration, the semicircle diameter decreases marginally, suggesting surface saturation or partial desorption. The imperfections of the semicircles decrease with higher inhibitor concentrations, reflecting a reduction in surface roughness. Overall, the Nyquist plots confirm that corrosion inhibition is adsorption-controlled, enhancing polarization resistance and aligning with potentiodynamic polarization and weight-loss results.

3.2.4 Effect of temperature on corrosion inhibition

The results presented in Fig. 7 show that the corrosion inhibition efficiency of Datura stramonium leaf extract decreases with increasing temperature. At 100 ppm, inhibition efficiency decreases from 76.6% at 303 K to 47.9% at 313 K and 10.8% at 323 K, while at 500 ppm it falls from 96.7% to 86.2% and 58.0% at the respective temperatures. This decline can be attributed to the desorption of inhibitor molecules from the mild steel surface as temperature increases. Elevated temperatures enhance molecular kinetic energy, weakening the physical interactions between the adsorbed phytochemicals and the metal surface, which in turn exposes more active corrosion sites. Such behavior is characteristic of a physisorption mechanism, where weak van der Waals or electrostatic forces dominate the adsorption process [1, 2, 4, 23, 38].

Despite the reduction in inhibition efficiency at higher temperatures, the extract remains effective, achieving 58.0% inhibition at 323 K and 500 ppm. This persistence indicates that some of the active constituents may also participate in stronger adsorption or partial chemisorption, forming a more stable protective film. This mixed adsorption behavior enhances film integrity and provides reasonable corrosion protection even under thermal stress [4, 23].

3.2.5 Activation and thermodynamic parameters

Thermodynamic parameters were evaluated to elucidate the corrosion inhibition mechanism of *Datura stramonium* leaf extract on mild steel in 1 M HCl. The temperature dependence of the corrosion rate (CR) was analyzed using the Arrhenius equation in logarithmic form (6): [28]

$$\log CR = -\frac{E_a}{2.303\,R}\frac{1}{T} + \log A \tag{6}$$

where CR is the corrosion rate, A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. A plot of $logCR$ versus $1/T$ yielded a straight line (Fig. 8), from which E_a was obtained from the slope. The enthalpy (ΔH^*_{sol}) and entropy (ΔS^*_{sol}) of activation were

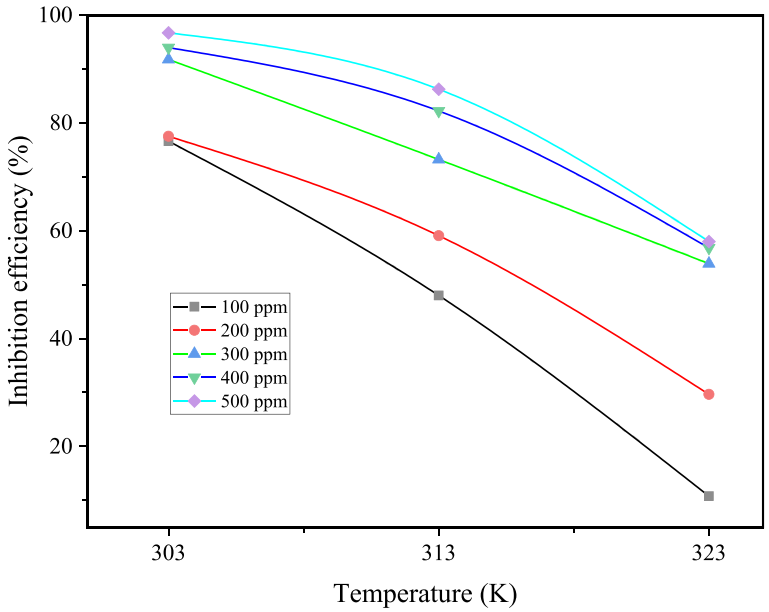


Fig. 7 Effect of temperature on inhibition efficiency of leaf extract in 1 M HCl solution at various concentration of Datura stramonium leaf extract

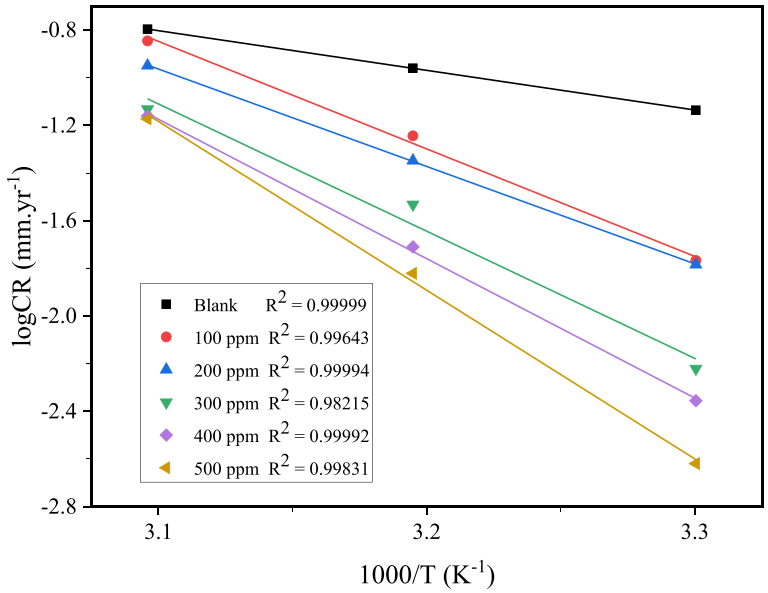


Fig. 8 Arrhenius plots of *logCR* versus 1000/*T* for mild steel corrosion in 1 M HCl containing different concentrations of Datura stramonium leaf extract

determined using the transition-state equation in logarithmic form (7): [38]

$$\log\left(\frac{\mathrm{CR}}{\mathrm{T}}\right) = -\frac{\Delta \mathrm{H}^{*}_{\mathrm{sol}}}{2.303\,\mathrm{R\,T}} + \left[\log\left(\frac{\mathrm{R}}{\mathrm{N.h}}\right) + \frac{\Delta \mathrm{S}^{*}_{\mathrm{sol}}}{2.303\,\mathrm{R}}\right] \tag{7}$$

where h is Planck's constant, N is the Avogadro's number, R is the universal gas constant (8.314 J.mol^{-1}.K^{-1}), ΔS^{*}_{sol} is the entropy of activation, and ΔH^{*}_{sol} is the enthalpy of activation. From the slope and intercept of a plot of *logCR* versus $1/T$ (Fig. 9), ΔH^{*}_{sol} and ΔS^{*}_{sol} were deduced, providing insight into the thermodynamic behavior of the corrosion process.

As shown in Table 5, the blank solution exhibited a low E_a of 31.87 kJ/mol, indicating that corrosion of mild steel in 1 M HCl is kinetically favourable. In the presence of

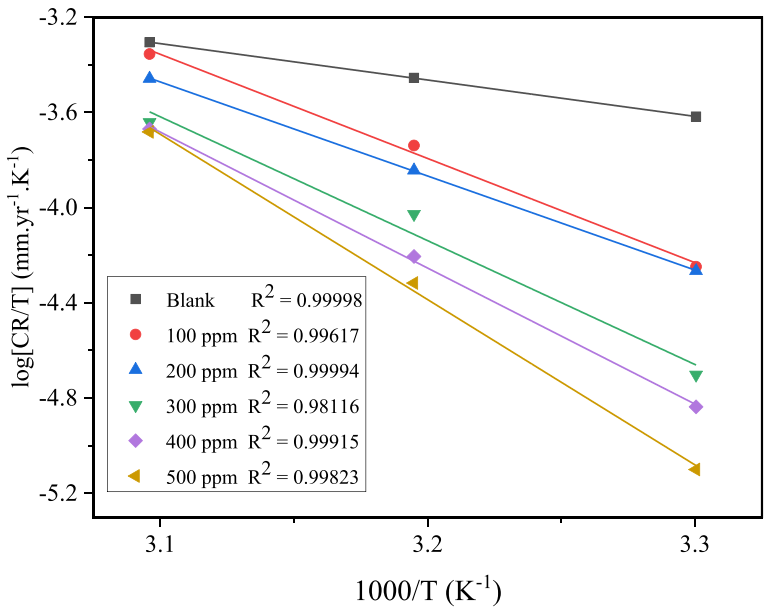


Fig. 9 Transition-state plots of mild steel corrosion in 1 M HCl with different concentrations of Datura stramonium leaf extract

Table 5 Activation parameters for mild steel in 1 M HCl solution in the presence of various concentrations of Datura stramonium leaf extract

System	$E_a\left(kJ.mol^{-1}\right)$	$\Delta H^*_{sol}\left(kJ.mol^{-1}\right)$	$\Delta S^*_{sol}\left(J.mol^{-1}.K^{-1}\right)$
Blank	31.87	29.27	−13.73
100 ppm	86.42	83.82	6.51
200 ppm	78.28	75.68	3.21
300 ppm	102.26	99.66	11.81
400 ppm	112.02	109.42	15.30
500 ppm	135.61	133.01	24.08

the leaf extract, E_a increased with concentration, reaching 135.61 $kJ.mol^{-1}$ at 500 ppm, demonstrating that the leaf extract raises the energy barrier for corrosion and thus slows the reaction. Similarly, ΔH^*_{sol} increased from 29.27 $kJ.mol^{-1}$ in the blank to 133.01 $kJ.mol^{-1}$ at 500 ppm, indicating that adsorption of the extract is endothermic and consistent with physical adsorption. The entropy of activation, ΔS^*_{sol}, shifted from a negative value (–13.73 $J.mol^{-1}.K^{-1}$) in the blank to positive values with increasing inhibitor concentration, reaching 24.08 $J.mol^{-1}.K^{-1}$ at 500 ppm. This reflects increased disorder at the metal–solution interface, consistent with the displacement of water molecules by inhibitor molecules and formation of a protective layer [3].

An interesting anomaly was observed at 200 ppm, where E_a and ΔH^*_{sol} slightly decreased to 78.28 $kJ.mol^{-1}$ and 75.68 $kJ.mol^{-1}$, respectively, compared to the 100 ppm sample. This may be attributed to incomplete or uneven surface coverage at this intermediate concentration, highlighting that optimum adsorption and uniform surface coverage are critical for maximum inhibition efficiency [1, 2]. Overall, the thermodynamic parameters confirm that *Datura stramonium* leaf extract effectively inhibits mild steel corrosion via a physisorption mechanism, with increasing efficiency at higher concentrations.

3.2.6 Adsorption isotherms

Understanding adsorption isotherms is essential for elucidating the mechanism of corrosion inhibition, as they provide insight into the interaction between inhibitor molecules and the metal surface, the nature of adsorption (physisorption or chemisorption), and the surface coverage behavior [3, 4, 31]. The adsorption data of *Datura stramonium* leaf extract on mild steel in 1 M HCl were fitted to the Langmuir, Freundlich, and Temkin isotherm models, and their respective

Table 6 R^2 comparison of Langmuir, Freundlich, and Temkin isotherms for Datura stramonium adsorption on mild steel in 1 M HCl

Adsorption model	Correlation coefficient (R^2)		
	303 K	313 K	323 K
Langmuir	0.99308	0.98824	0.99958
Freundlich	0.85801	0.98724	0.92744
Temkin	0.85936	0.97627	0.94573

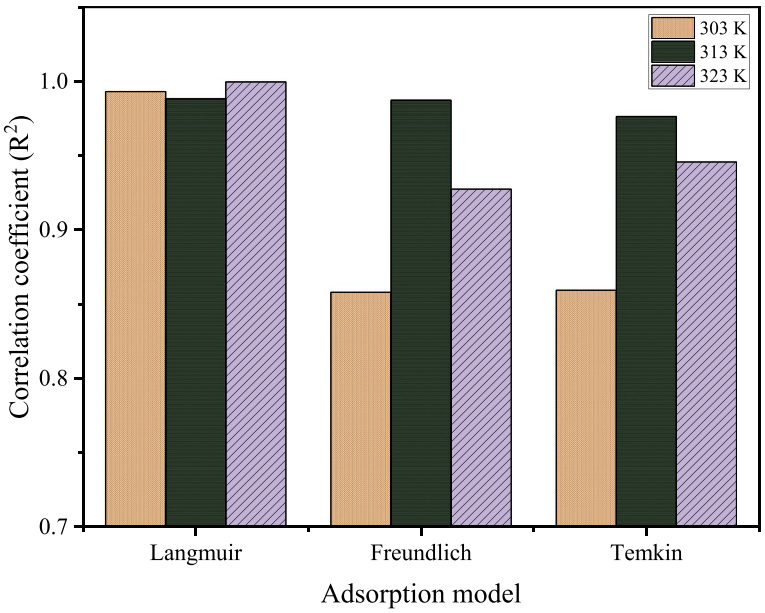


Fig. 10 Comparison of correlation coefficients (R^2) for Langmuir, Freundlich, and Temkin adsorption isotherms for the adsorption of Datura stramonium extract on mild steel in 1 M HCl

correlation coefficients (R^2) are presented in Fig. 10 and Table 6. The R^2 values serve as the primary criterion for assessing the best-fitting model, where values closer to unity indicate a better correlation between experimental and theoretical data.

Among the tested models, the Langmuir isotherm (Fig. 11) exhibited the highest R^2 values (0.99308—0.99958) across all temperatures, compared with the Freundlich (0.85801—0.98724) and Temkin (0.85936—0.97627) models. This strong linearity confirms that the adsorption of the inhibitor molecules follows Langmuir behavior, implying monolayer adsorption on a homogeneous metal surface with uniform active sites and negligible lateral interactions among adsorbed molecules [1, 38]. This trend signifies that the *Datura stramonium* extract forms a stable and compact protective film on the steel surface, effectively isolating it from the corrosive environment. The slight variation in R^2 with temperature suggests consistent adsorption behavior over the studied range, indicating that the extract maintains strong surface affinity even at elevated temperatures. Such behavior supports its potential as a reliable green corrosion inhibitor [23, 38].

Following the establishment of the adsorption isotherm model, the linear form of the Langmuir equation was employed to determine the adsorption equilibrium constant (K_{ads}) for each inhibitor concentration at the corresponding temperature. These K_{ads} values served as the basis for evaluating the adsorption thermodynamic parameters discussed in the subsequent section. The linearised Langmuir Eq. (8) is expressed as: [38]

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \tag{8}$$

where C represents the inhibitor concentration and θ denotes the surface coverage of the metal surface by the inhibitor molecules.

The obtained K_{ads} values were further used to calculate the Gibbs free energy, enthalpy, and entropy of adsorption, which provide insight into the spontaneity, energy changes, and degree of order associated with the adsorption process [3, 4, 38].

3.2.7 Adsorption thermodynamic parameters

The thermodynamic parameters of adsorption were evaluated to elucidate the nature and strength of interaction between the *Datura stramonium* leaf extract and the mild steel surface. These thermodynamic parameters are essential for understanding the adsorption mechanism and the stability of the inhibitor–metal interface under varying environmental conditions. The apparent enthalpy (ΔH^*_{ads}) and entropy (ΔS^*_{ads}) of adsorption were derived from the Van't Hoff Eq. (9) [4]

$$\log K_{ads} = -\frac{\Delta H^*_{ads}}{2.303R}\frac{1}{T} + \frac{\Delta S^*_{ads}}{2.303R} \tag{9}$$

where ΔH^*_{ads} is the apparent enthalpy of adsorption ($J{\cdot}mol^{-1}$), ΔS^*_{ads} entropy of adsorption ($J.mol^{-1}.K^{-1}$), and R is the universal gas constant (8.314 $J.mol^{-1}.K^{-1}$). The values of ΔH^*_{ads} and ΔS^*_{ads} were obtained from the slope and intercept of the linear plot of $logK_{ads}$ versus $1/T$ as: $\Delta H^*_{ads} = -2.303R \times \text{slope}$ and $\Delta S^*_{ads} = 2.303R \times \text{intercept}$.

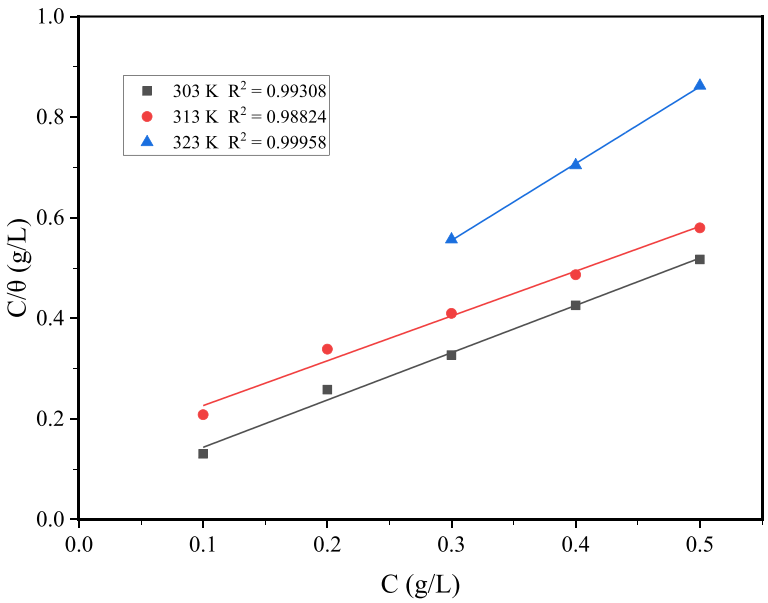


Fig. 11 Langmuir adsorption isotherms of Datura stramonium leaf extract for mild steel corrosion in 1 M HCl at 303, 313, 323, and 333 K

The Gibbs free energy of adsorption (ΔG^*_{ads}) was subsequently calculated using (10): [4, 38]

$$\Delta G^*_{ads} = \Delta H^*_{ads} - T\Delta S^*_{ads} \quad (10)$$

Since the molecular weight of the plant extract was undetermined, the standard 55.5 mol.L^{-1} correction factor was omitted, and the derived ΔG^*_{ads} values are considered approximate, reflecting adsorption spontaneity rather than absolute standard-state quantities.

Table 7 and Figs. 12 and 13 provide a summary of the thermodynamic parameters for the adsorption of *Datura stramonium* leaf extract on mild steel in 1 M HCl over the temperature range 303–323 K and concentrations from 100 to 500 ppm. The ΔG^*_{ads} values are negative across all conditions (from approximately –9.14 to –0.91 $kJ.mol^{-1}$ at 100 ppm and –10.29 to –2.76 kJ.mol^{-1} at 500 ppm), confirming that the adsorption process is spontaneous. As temperature increases, the magnitude of ΔG^*_{ads} decreases, indicating that adsorption becomes slightly less favourable at elevated temperatures, a behaviour characteristic of physisorption [4, 38]. Meanwhile, the ΔH^*_{ads} values show a clear maximum at lower concentrations (–133.9 kJ.mol^{-1} at 100 ppm) and then decrease in magnitude to around –85.4 kJ.mol^{-1} at 200 ppm, before stabilizing between –92.0 kJ.mol^{-1} and –124.4 kJ.mol^{-1} at higher concentrations. This trend suggests that initially, inhibitor molecules undergo stronger binding to the metal surface (requiring greater heat release), but as surface coverage increases beyond about 200 ppm, site saturation and intermolecular interactions reduce the incremental binding energy. The ΔS^*_{ads} values become increasingly negative (from –257.3 to –411.7 J.mol^{-1}.K^{-1}), indicating that the adsorption leads to a more ordered inhibitor film on the metal interface, consistent with the displacement of solvent molecules and the formation of a compact barrier layer [3]. Collectively, these thermodynamic trends suggest that the inhibitor–metal interaction evolves from an energetically strong, high-entropy initial adsorption to

Table 7 Thermodynamic parameters for the adsorption of Datura stramonium leaf extract on mild steel in 1 M HCl

Concentration (ppm)	Slope (L.g^{-1}.K)	Intercept (L.g^{-1})	R^2	ΔG^*_{ads} (kJ.mol^{-1})			ΔH^*_{ads} (kJ.mol^{-1})	ΔS^*_{ads} (J.mol^{-1}.K^{-1})
				303 K	313 K	323 K		
100	6.99	–21.50	0.977	–9.14	–5.03	–0.91	–133.9	–411.7
200	4.46	–13.44	0.986	–7.39	–4.82	–2.25	–85.4	–257.3
300	4.81	–14.32	0.985	–8.91	–6.17	–3.43	–92.0	–274.3
400	5.25	–15.73	0.999	–9.28	–6.26	–3.25	–100.5	–301.1
500	6.50	–19.68	0.999	–10.29	–6.52	–2.76	–124.4	–376.7

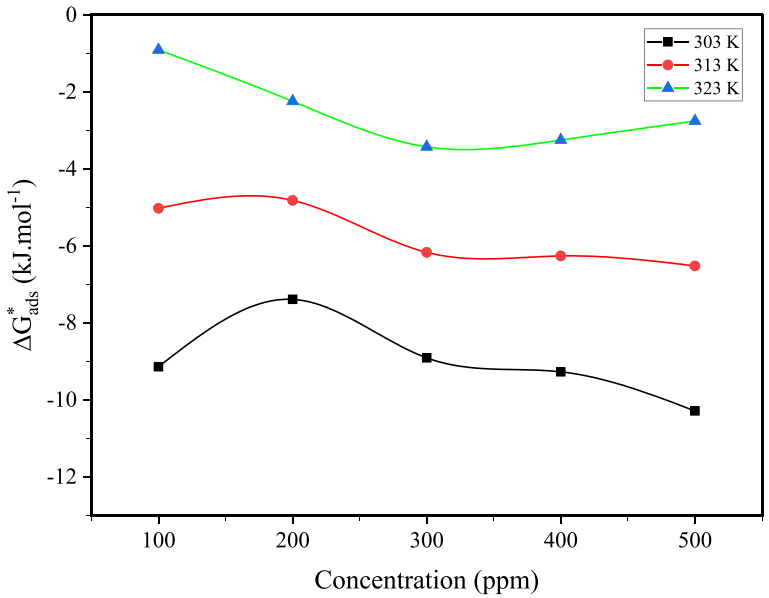


Fig. 12 Variation of ΔG^*_{ads} with inhibitor concentration at different temperatures on mild steel in 1 M HCl

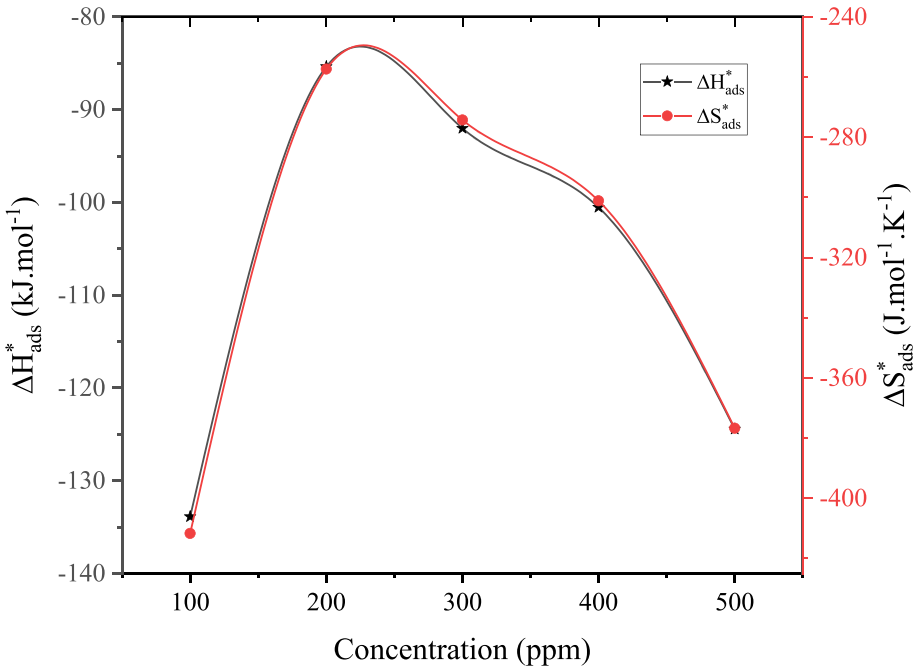


Fig. 13 Variation of ΔH^*_{ads} and ΔS^*_{ads} with inhibitor concentration on mild steel in 1 M HCl

a more stabilized, organized film at higher concentrations, thereby enhancing corrosion inhibition efficiency under the tested conditions.

3.2.8 Protective layer analysis

The ATR-FTIR spectra of the leaf extract and inhibited carbon steel (Fig. 14) reveal that the inhibited steel surface exhibits characteristic peaks corresponding to the functional groups present in the extract. This confirms the formation of an adsorbed inhibitor film on the metal surface, indicating that the phytochemicals in the extract interact with and cover active sites on the steel. Complementary SEM analysis (Fig. 15) further supports these observations: the uninhibited carbon steel

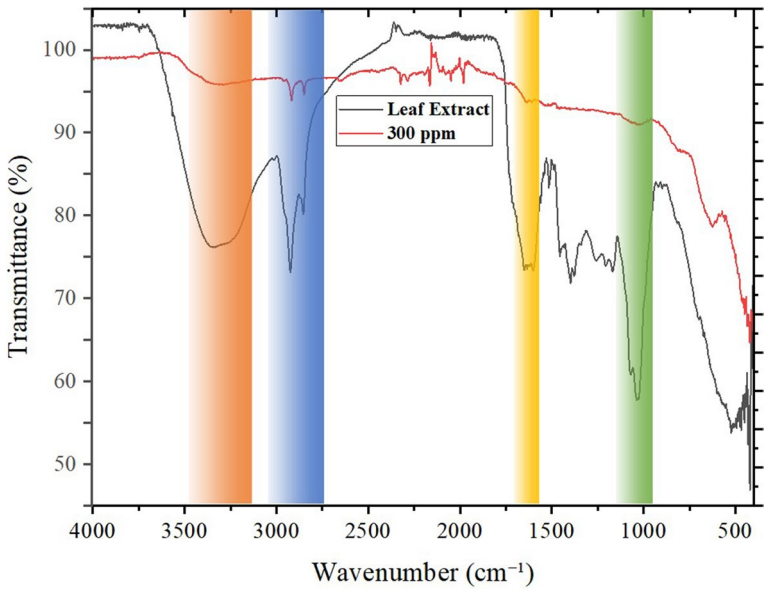


Fig. 14 ATR-FTIR spectra of the leaf extract and the protective film formed on mild steel in 1 M HCl solution with 300 ppm inhibitor at 303 K

exhibits a rough, corroded surface, while the inhibited sample displays a smooth and uniform morphology, indicating effective surface protection. Together with the ATR-FTIR results, which show characteristic adsorption peaks of the leaf extract on the steel surface, these findings confirm the formation of a stable adsorbed film. This film effectively blocks reactive sites and reduces surface roughness, in agreement with the enhanced polarization resistance and inhibition efficiency observed in the electrochemical measurements.

4 Conclusion and recommendations

The present study demonstrates that *Datura stramonium* leaf extract is an effective, environmentally benign corrosion inhibitor for mild steel in 1 M HCl. The extract exhibited high inhibition efficiency, which increased with concentration, and formed a stable protective film on the metal surface through predominantly physisorption, while retaining appreciable activity at elevated temperatures. Electrochemical analysis indicates that the leaf extract acts as a mixed-type corrosion inhibitor for mild steel, shifting both anodic and cathodic reactions. Adsorption studies indicated Langmuir-type behavior, confirming monolayer coverage and strong surface interaction facilitated by phytochemicals containing oxygen and nitrogen donor atoms and aromatic rings. These findings highlight the potential of *Datura stramonium* leaf extract as a cost-effective, biodegradable, and sustainable alternative to conventional synthetic inhibitors, in alignment with green chemistry principles and

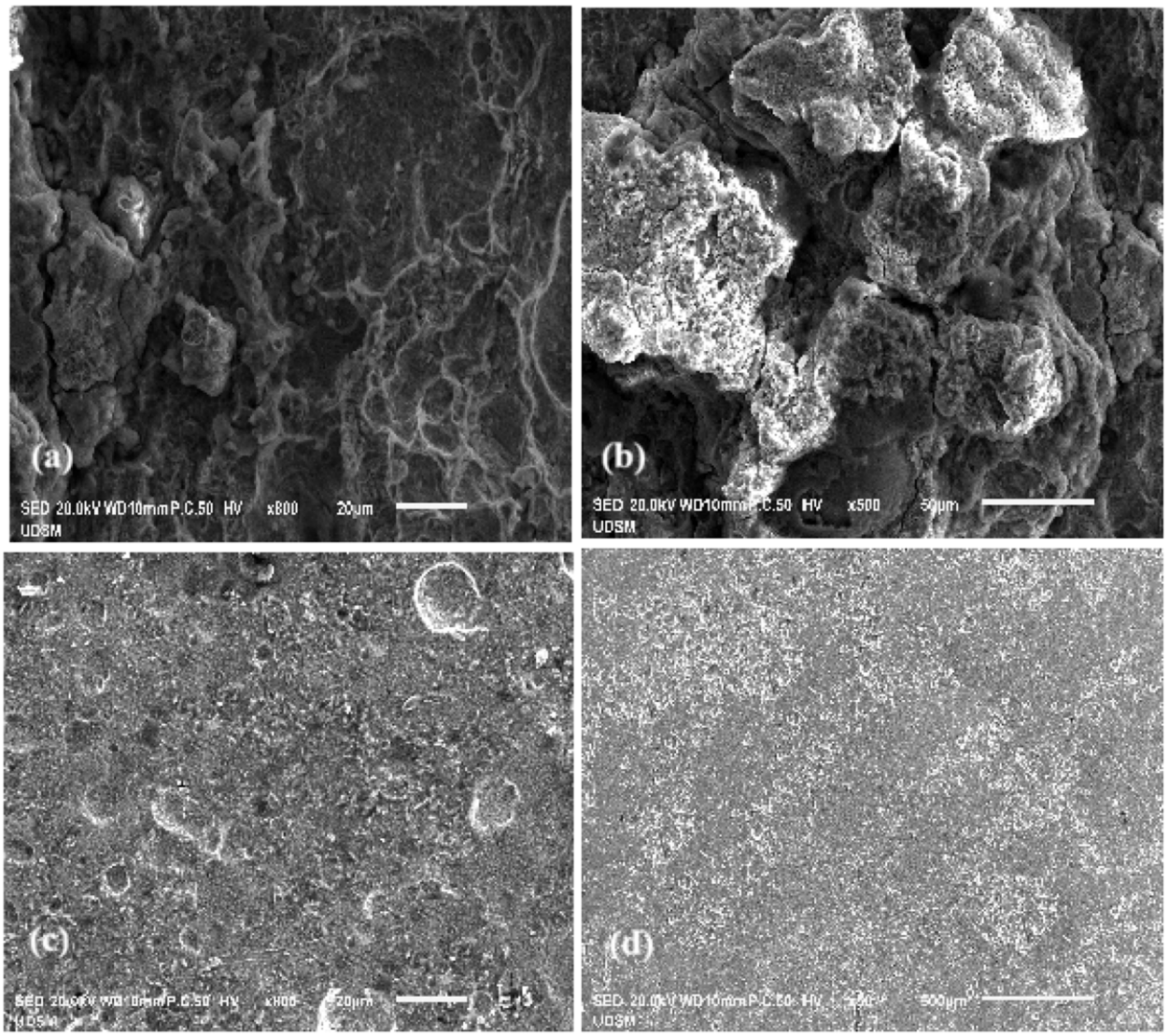


Fig. 15 SEM micrographs of carbon steel surfaces in 1 M HCl at various magnifications: (**a**-**b**) without inhibitor, showing a rough, corroded surface; and (**c**-**d**) with 300 ppm inhibitor

environmentally responsible industrial practices. For future studies, it is recommended that the bioactive constituents of the extract be isolated and investigated individually. Evaluating these compounds separately may elucidate the specific mechanisms of inhibition, quantify their relative contributions to adsorption and protective film formation, and facilitate the development of more targeted and efficient green corrosion inhibitors suitable for industrial applications.

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Authors' contributions
Musa Mpelwa: Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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Data availability
Data is available from the corresponding author upon request.

Declarations

Competing interests
The authors declare no competing interests.

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