CORROSION SCIENCE AND TECHNOLOGY, Vol.24, No.2(2025), pp.63~75 pISSN 1598-6462 / eISSN 2288-6524
[Research Paper] DOI: https://doi.org/10.14773/cst.2025.24.2.63

Effect of Combining *Moringa oleifera* and *Datura stramonium* Extracts as a Green Corrosion Inhibitor for Mild Steel

Hadjer Didouh[1,†], Mohammed Sadou[2], Rami K. Suleiman[3], and Mohammed Hadj Meliani[1]

[1]*Department of Process Engineering, Laboratory of Theoretical Physics and Materials Physics (LPTPM), Faculty of Technology, Hassiba Benbouali University of Chlef, Hay Salem, 02000, Algeria*
[2]*Materials Chemistry, Catalysis and Reactivity Laboratory, Hassiba Ben Bouali University Chlef, Algeria*
[3]*Interdisciplinary Research Center for Advanced Materials, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia*

(Received August 05, 2024; Revised February 15, 2025; Accepted February 18, 2025)

The present investigation explores the effect of combining extracts from Moringa oleifera and Datura stramonium as an eco-friendly corrosion inhibitor for carbon steel in acidic media. The corrosion inhibition efficacy was systematically evaluated through gravimetric analysis and electrochemical techniques. The results reveal that Moringa oleifera exhibits the highest corrosion inhibition efficiency of 93.48%, followed by the combination of both plant extracts, which demonstrates superior protective performance compared to Datura stramonium alone consisting of 250 ppm Moringa oleifera leaf extract (MOLE) + 250 ppm Datura stramonium leaf extract (DSLE) at 60 °C, achieved an inhibition efficiency of 84.71%. Although slightly lower than the performance of MOLE alone, this result highlights the dominant contribution of MOLE within the blend and underscores its ability to enhance the protective effect of DSLE. This formulation enables the valorization of the otherwise toxic Datura stramonium by integrating it into a functional, eco-friendly corrosion inhibitor system. Surface characterization techniques corroborated the formation of a protective adsorbed film on the carbon steel substrate. The enhanced performance is postulated to arise from the combination effect between the diverse phytochemical constituents present in Moringa oleifera and Datura stramonium, which augment the adsorption kinetics and film-forming capabilities.

Keywords: *Corrosion, Moringa oleifera, Datura stramonium, Green Inhibitors, Carbon Steel*

1. Introduction

Corrosion, a ubiquitous phenomenon characterized by the progressive deterioration of materials predominantly metals through chemical or electrochemical interactions with their environment, presents a formidable challenge to global economic stability and structural integrity [1]. This process, initiated by exposure to moisture, atmospheric gases, acids, or other corrosive agents, frequently manifests as rust or analogous corrosion products [2,3]. The inherent susceptibility of metals and their alloys to corrosive degradation necessitates continuous maintenance and remediation efforts to preserve safety standards, cost-effectiveness, and operational functionality throughout the lifespan of critical infrastructure [4].

The economic ramifications of corrosion are profound and far-reaching. According to the world corrosion organization, the annual global expenditure attributable to corrosion-related issues is estimated at 2.4 trillion US dollars, approximately 3% of the world's gross domestic product (GDP). In numerous developed nations, the financial burden of corrosion damage represents between 3.5% and 4.5% of the gross national product (GNP) [6]. The combined economic impact of all natural disasters, including seismic events, floods, and severe storms. It is crucial to note that these costs encompass not only direct expenses associated with repairs and maintenance but also indirect consequences such as production losses, environmental degradation, and compromised safety conditions [7].

The environmental implications of corrosion are equally profound, particularly in industries such as oil and gas extraction, transportation, and marine operations [8,9]. Corrosion-induced failures lead to catastrophic events such as leaks, spills, and other environmental disasters

†Corresponding author: h.didouh@univ-chlef.dz

with long-lasting effects on ecosystems and human health. For instance, corroded pipelines or storage facilities may release toxic substances into soil and water systems, resulting in contamination and pollution. Similarly, the corrosion of marine structures, including offshore drilling platforms and vessels, leads to the discharge of oil and other pollutants into oceanic environments, causing significant harm to marine ecosystems and coastal communities [10].

Moreover, corrosion poses substantial health risks to both industrial workers and the public. degraded infrastructure presents safety hazards, while the release of toxic chemicals due to corrosion can pose health risks to workers and nearby residents. In high-risk industries such as oil and gas extraction, corroded equipment significantly elevates the likelihood of workplace accidents and injuries [11-13]. While corrosion poses significant challenges across various industries, the development of inhibitors has emerged as a promising approach to mitigate its destructive effects, offering tailored solutions for specific corrosive environments and materials.

Corrosion inhibitors are defined as chemical entities that, when present in minute concentrations within corrosive environments, significantly retard the rate of metallic deterioration without compromising the mechanical properties of the substrate [14-17]. The efficacy of an ideal corrosion inhibitor is predicated on its stability in the presence of other medium components at operational temperatures, its effectiveness at low concentrations, its compliance with non-toxicity standards, and its economic viability [16].

The deleterious effects associated with conventional synthetic inorganic and organic inhibitors, including environmental toxicity, carcinogenicity, high costs, and stringent environmental safety regulations, have catalyzed a paradigm shift in research focus toward the exploration of plant-based natural compounds as alternative corrosion inhibitors [13,18,19]. These natural, plant-derived extract corrosion inhibitors are increasingly viewed as a panacea for the multifaceted challenges posed by traditional synthetic inhibitors.

Extensive research has demonstrated the successful application of plant-based extracts for corrosion mitigation in acidic media [15,16,20-28].

Recent research in corrosion has highlighted Moringa oleifera as a promising eco-friendly corrosion inhibitor. Multiple studies have demonstrated its efficacy across various metallic substrates and corrosive environments. Fouda et al. reported a 91.7% inhibition efficiency on mild steel in 1M HCl at 600 ppm concentration [29]. Anadebe et al. found inhibition efficiencies of 91.2% and 86.9% for carbon steel in acidic and alkaline media, respectively, at 1.5 g/L concentration [30]. Additionally, an 89% inhibition efficiency was observed for copper in a nitric and phosphoric acid mixture [31].

Recent studies have made significant strides in developing green corrosion inhibitors, demonstrating high efficacy at ambient temperatures. Notably, research by Gbenga Olabode et al. investigated the corrosion inhibition properties of Datura stramonium leaf extract (DSLE) on carbon steel in 1M HCl solution. Their findings revealed an impressive maximum inhibition efficiency of 98.69% at a concentration of 0.5 g/L under room temperature conditions. Potentiodynamic polarization analysis indicated that DSLE functions as a mixed-type inhibitor [32]. Mohanasundaram et al. studied the corrosion inhibition properties of Datura extract on mild steel in sulphuric acid. the research demonstrates an inhibition efficiency of 85.73% [33]. However, these advances are limited in their application to extreme environments. Didouh et al. demonstrated an exceptional inhibition efficiency of 99% at a concentration of 0.5 g/L under elevated at 60 °C. This finding is significant as it extends the potential applications of Moringa oleifera extract to high-temperature industrial environments, where many organic inhibitors typically lose effectiveness. The study highlights the thermal stability of the extract's active compounds and opens new avenues for eco-friendly corrosion protection in challenging thermal conditions [5].

The unique challenge presented by the south Algerian sahara’s oil and gas operations, where temperatures frequently exceed 60 ºC, remains unaddressed. Furthermore, the most effective plant-derived inhibitors discovered thus far, such as the compound isolated, often come from species with significant medicinal value. This dual demand creates a conflict between industrial and healthcare applications, potentially limiting the availability of these inhibitors for corrosion prevention. Our study aims to bridge this critical gap by exploring a novel approach: combining a high-efficiency, medicinal plant-derived inhibitor with a complementary species of limited medicinal value. This research seeks to develop an inhibitor formulation that maintains high efficiency at temperatures above 60 ºC evaluate the potential of combining multiple plant-derived compounds for enhanced corrosion inhibition.

By addressing these specific limitations of current research, our study aims to provide a more sustainable and effective solution for corrosion inhibition in the extreme conditions of saharan oil and gas operations.

The combination of Moringa oleifera and Datura stramonium extracts as a corrosion inhibitor represents an innovative approach with potential effects. This mixture enhances overall inhibition efficiency and broadens the spectrum of protection across different metallic substrates and corrosive environments at high temperatures. However, this area remains largely unexplored, presenting several research gaps that warrant further investigation.

2. Material and methods

2.1 Materials

2.1.1 Metal preparation

API 5L X52 carbon steel, with a composition of 0.22% C, 1.22% Mn, 0.24% Si, 0.16% Cr, 0.14% Ni, 0.06% Mo, 0.04% S, 0.19% Cu, 0.04% Ti, <0.05% Nb, 0.32% Al, and balance Fe, was used as the substrate material. "%" in the chemical composition refers to weight percent (wt%). For electrochemical testing, specimens were prepared by embedding steel coupons in epoxy resin, exposing a 1 cm^2 working surface. The exposed surfaces were mechanically polished using a series of silicon carbide (SiC) abrasive papers (80-1200 grit), followed by ultrasonic cleaning in acetone, rinsing with deionized water, and drying under nitrogen.

2.1.2 Moringa oliefera & Datura stramonium extract preparation

Moringa oleifera leaves used in this study were gathered from Mohammadia-Mascara in Algeria. The leaves were washed and air-dried in a laboratory at room temperature for a week. They were then crumbled into pieces smaller than 2 mm, soaked in 70% ethanol for 36 hours, and heated at 70 ºC. After cooling, the mixture was filtered through a qualitative filter paper, and the solvent was allowed to dry in a vacuum oven at 40 ºC for 48 hours until it turned into a fine powder. The solution for the experiments was prepared freshly before each experiment.

Datura stramonium leaves were gathered from Ain Defla, Algeria. The leaves were washed, air-dried for 7 days, and pulverized. 150 g of powder underwent reflux extraction with 10% HCl for 6 hours. The resulting acidic solution was neutralized to pH 8 with sodium hydroxide (NaOH) and then extracted with chloroform. The organic layer was dried and concentrated, yielding a gummy residue that was further dried and powdered. This extract was used to prepare various concentrations for corrosion inhibition studies.

2.1.3 Corrosive media preparation

1 M HCl, prepared by diluting analytical-grade 37% HCl in bi-distilled water. Solutions of 1 M HCl with various Moringa Oleifera Leaves Extract (MOLE) and Datura Stramonium Leaves Extract (DSLE) concentrations were prepared by adding the desired amount of HCl and MOLE and DSLE to the bi-deionized water. The MOLE and DSLE were weighed out using a high-precision balance and all weighing operations were performed with this equipment. The solutions were stirred.

2.2 Methods

2.2.1 Phytochemical screening of Moringa-Datura mixture

A comprehensive phytochemical analysis was conducted on a composite extract derived from Moringa oleifera and Datura stramonium leaves. The screening aimed to elucidate the presence of key secondary metabolites in this novel botanical mixture. Established protocols, adapted from [32], were employed to detect tannins, cardiac glycosides, saponins, terpenoids, and flavonoids. The following essays were performed:

Tannin detection: Braymer's test was utilized for tannin identification. A 2 mL aliquot of the Moringa-Datura extract mixture was treated with a 10% alcoholic ferric chloride solution. The development of blue or green coloration was interpreted as a positive indication of tannin presence, with the intensity potentially reflecting contributions from both plant species.

Saponin analysis: saponins were evaluated using the foam test. A 2 mL sample of the composite extract was vigorously agitated with 6 mL of distilled water. The formation and persistence of foam were assessed, with particular attention paid to foam stability, as this could indicate potential mixture effects between saponins from Moringa and Datura.

Cardiac Glycoside identification: the Keller-Killiani test was employed for cardiac glycoside detection. A 5 mL volume of the mixed extract was treated with 2 mL of glacial acetic acid and a drop of ferric chloride solution. This mixture was carefully underlaid with 1 mL of concentrated sulfuric acid. The formation of a brown ring at the interface indicated the presence of deoxysugars characteristic of cardenolides. Additional observations included potential violet ring formation below the brown ring and a greenish ring in the acetic acid layer. The intensity and clarity of these indicators were noted, as they might reflect the combined cardiac glycoside profiles of both plants.

Flavonoid assessment: the alkaline reagent test was used to evaluate flavonoids. A 2 mL sample of the Moringa-Datura extract was treated with several drops of 20% sodium hydroxide solution. The development of an intense yellow color, which became colorless upon the addition of dilute hydrochloric acid, signified flavonoid presence. The color intensity was carefully observed, as it could provide insights into the relative flavonoid contributions from each plant species.

Terpenoid Detection: terpenoids were identified using the Salkowski test. 2 mL of the composite extract, 1 mL of chloroform was added, followed by a few drops of concentrated sulfuric acid. The immediate formation of a reddish-brown precipitate was considered a positive result for terpenoids. The precipitate's characteristics, including color intensity and quantity, were noted as potential indicators of the combined terpenoid profiles of Moringa and Datura.

2.2.2 Weight loss

The inhibitor's efficacy was evaluated using gravimetric analysis. Pre-weighed carbon steel coupons were immersed in corrosive solutions with and without inhibitor at various concentrations at 60 ºC simulating the conditions of south Algeria. Post-exposure, coupons were cleaned with clarke's solution (ASTM G1-03) [34] to remove corrosion products, then rinsed, dried, and reweighed. Four replicate coupons per condition were analyzed to ensure statistical robustness. Corrosion rates were calculated using the standard weight loss formula, enabling quantitative assessment of the inhibitor's performance under the specified experimental conditions [35]:

$$CR = \frac{\Delta m}{S \times t \times \rho} \quad (1)$$

CR: corrosion rate ($g/cm^2 \cdot h$).
S: surface area of the sample (cm^2).
t: time of the experiment (h).
Δm: mass difference (g).
ρ: density of the carbon steel (g/cm^3).

$$\Delta m = m_i - m_f \quad (2)$$

m_i: the sample mass before immersion.
m_f: the sample mass after immersion.

The inhibitory effect is given by the following relationship:

$$IE\ (\%) = \frac{(V_{HCl} - V_{inh})}{V_{HCl}} \times 100 \quad (3)$$

V_{HCl}: corrosion rate in acidic environment without inhibitor.

V_{inh}: corrosion rate in acidic environment with inhibitor.

2.2.3 Electrochemical test

The electrochemical setup utilized in this study. The system comprises a potentiostat/galvanostat (EG&G Princeton Applied Research, model 273A), capable of imposing and measuring stable potentials and currents in both cathodic and anodic regions. Additionally, the setup includes a frequency analyzer (Solatron model SI 1255) for electrochemical impedance spectroscopy (EIS) measurements. A nitrogen source equipped with a pressure regulator, allowing for an inlet pressure of 300 bars and adjustable outlet pressure between 1 and 12 bars, was employed. The potentiostat/galvanostat was connected to a computer system for data acquisition and analysis using software (SoftCorrIII for stationary methods, and Z plot, Z view for EIS). The electrochemical cell, composed of 1000 mL Pyrex glass, featured five orifices to accommodate various components: a working electrode, a saturated calomel reference electrode (SCE), a glass gas bubbler, and two counter-electrodes made of graphite (6 mm in diameter and 30 cm in length). The carbon steel working electrode (X52), polished and rinsed with acetone, was immersed in the solution. Various concentrations of individual and combined green inhibitors were then introduced to assess their corrosion mitigation properties. Open circuit potential (OCP) ± 30 mV for potential region, potential scan rate of 0.166 mV/s and EIS sinusoidal voltage of 10 mV applied with frequency domain from 100 KHz to 10 mHz were used. Values of polarization resistance (RP), corrosion current density i_{corr}, corrosion rate (CR) and inhibition efficiency IE were calculated by using the Linear of polarization resistance (LPR) technique. Values of the ohmic resistance of solution Re, charge transfer resistance (R_{ct}), and inhibition efficiency (IE) were determined using EIS diagrams as Nyquist plot [36]. The inhibition efficiency of the extract was calculated using the following equation: IE (%) = $\frac{R_{Po} - R_P}{R_{Po}} \times 100$, where: R_{Po}, R_P are the charge transfer resistance in the absence and presence of inhibitor extract, respectively.

2.2.4 Surface analysis

X52 steel specimens were prepared for scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM-EDX) analysis using standard metallographic techniques, including sequential grinding with SiC papers (80-2000 grit) and ultrasonic cleaning. The prepared electrodes were immersed in two deaerated solutions: (a) 1 M HCl and (b) 1 M HCl + 250 ppm Moringa oleifera + 250 ppm Datura stramonium (this concentration was selected to investigate the effects of combining Moringa oleifera extract with other components, as the individual inhibitory properties of Moringa have already been extensively studied, particularly in combination with potassium iodide (KI). The focus of this study is to assess the enhanced corrosion inhibition resulting from this interaction). Samples were incubated at 60 °C for 168 hours in sealed vessels. Post-exposure, specimens were rinsed, dried under nitrogen, and analyzed using a field emission SEM (Quanta 650).

2.2.5 Adsorption isotherm

The adsorption isotherms are generally used to describe the mathematical relationship between the adsorb concentration present in the liquid phase and that present in the solid phase, at equilibrium and at a constant temperature. There are different profiles of isotherms. The shape of the adsorption isotherm curve varies according to the adsorb-adsorbent torque.

3. Results

3.1 Extract characterization

Flavonoids (++++): both Moringa oleifera and Datura stramonium are rich sources of alkaloids and flavonoids. Alkaloid, particularly abundant in Datura stramonium, are known for their ability to form complexes with metal ions and adsorb on metal surfaces [19]. Flavonoids, prevalent in both plants, possess strong antioxidant properties and form protective films on metal surfaces. The high concentration of these compounds suggests they play a primary role in the inhibition mechanism.

Tannins (+++): the presence of tannin contributes to the extract's corrosion inhibition efficacy. These compounds form complexes with metal ions, creating a protective layer on the metal surface [37]. Their antioxidant properties also help neutralize aggressive ions in the corrosive medium.

Terpenes/Terpenoids (+++): terpenes, present in high amounts, are known to adsorb on metal surfaces, forming a barrier against corrosive media. Their hydrophobic nature may contribute to displacing water molecules from the metal surface, reducing the corrosion rate.

Saponins (++) and Cardiac Glycosides (++): while present in moderate amounts, saponins contribute to the inhibition process through their surfactant-like properties, potentially enhancing the formation of protective films [29]. Cardiac glycosides, though not typically associated with corrosion inhibition, may contribute to the overall

Table 1. Phytochemical analysis of Moringa-Datura extract

Phytochemical class	Tannin	Flavonoid	Cardiac Glycoside	Terpenes/ Terpenoid	Saponin
Absence/Presence	+++	++++	++	+++	++

protective effect.

The use of this Moringa oleifera and Datura stramonium mixture as a green corrosion inhibitor offers several advantages as a plant-based solution, it presents a biodegradable alternative to conventional synthetic inhibitors [35]. The combination of two plants with different phytochemical profiles leads to enhanced inhibition efficiency of Datura stramonium at 60 ℃ [38]. Both plants are widely available and easily cultivated, making the inhibitor potentially economical for large-scale applications. diverse phytochemical composition suggests multiple inhibition mechanisms, including physical adsorption, chemisorption, and film formation [39].

Analysis reveals that MOLE contains abundant polyphenols, flavonoids, and protein-based compounds with multiple functional groups (-OH, $-NH_2$, and C=O), while DSLE primarily features alkaloids with specific nitrogen-containing heterocyclic structures. The molecular size comparison indicates that MOLE compounds exhibit larger molecular structures (molecular weight range: 500-1500 g/mol) compared to DSLE's primary active compounds (molecular weight range: 250-350 g/mol). This structural difference significantly influences their surface coverage and adsorption behavior on mild steel. The larger MOLE molecules, coupled with their multiple functional groups, enable stronger multi-site adsorption and more effective surface protection. In contrast, DSLE's smaller molecules and fewer active sites result in less comprehensive surface coverage, which better explains its lower inhibition efficiency.

3.2 Corrosion inhibition effect

3.2.1 Weight loss

Table 2 presents corrosion rate and inhibitor efficiency in the presence and absence of individual and mixture of inhibitor. The corrosion rate for the blank sample (without any inhibitor) was 0.00077 g/cm^2 at 6 hours, and 0.0001125 g/cm^2 at 24 hours, showing a decrease in corrosion rate over time because of the development of a protective oxide layer on the surface.

MOLE exhibited excellent corrosion inhibition, achieving an inhibition efficiency of 93.48% and 92.22% at 6 and 24 hours, respectively. This suggests that MOLE forms a strong protective layer on the carbon steel surface. This high inhibition efficiency is attributed to the presence of bioactive compounds in MOLE, such as phenolic acids and flavonoids, known for their antioxidant properties [40].

DSLE showed moderate inhibition efficiency, with 68.26% at 6 hours. The lower efficiency compared to MOLE is due to the different active compounds in DSLE, which may not form as robust a protective layer. DSLE contains alkaloids and other compounds that contribute to its inhibitory action, but its lower effectiveness at higher temperatures might be due to the decomposition of these compounds.

The mixture of 250 ppm MOLE and 250 ppm DSLE showed moderate inhibition efficiency compared to the extracts alone, with 84.78% at 6 hours and 82.59% at 24 hours. This is due to the combined action of different bioactive compounds forming a more stable protective layer on the steel surface, enhancing Datura's effectiveness with Moringa oleifera.

Mixtures of 150 ppm MOLE + 350 ppm DSLE and 350 ppm MOLE + 150 ppm DSLE also demonstrated significant inhibition efficiencies. This suggests that optimizing the mixture ratios could achieve high inhibition efficiency, which may be a cost-effective solution. This is particularly relevant for industrial

Table 2. Weight loss at different exposure durations

Concentration (ppm)	6 h		24 h	
	CR (g/cm^2·h)	IE (%)	CR (g/cm^2·h)	IE (%)
Blank	0.00077	-	0.0001125	-
500 ppm MOLE	0.00005	93.48	0.00000875	92.22
500 ppm DSLE	0.00024	68.26	0.0000375	66.67
150 ppm MOLE + 350 ppm DSLE	0.00018	76.09	0.0000325	71.11
350 ppm MOLE + 150 ppm DSLE	0.00023	70.43	0.000035	68.89
250 ppm MOLE + 250 ppm DSLE	0.00012	84.78	0.000018	82.59

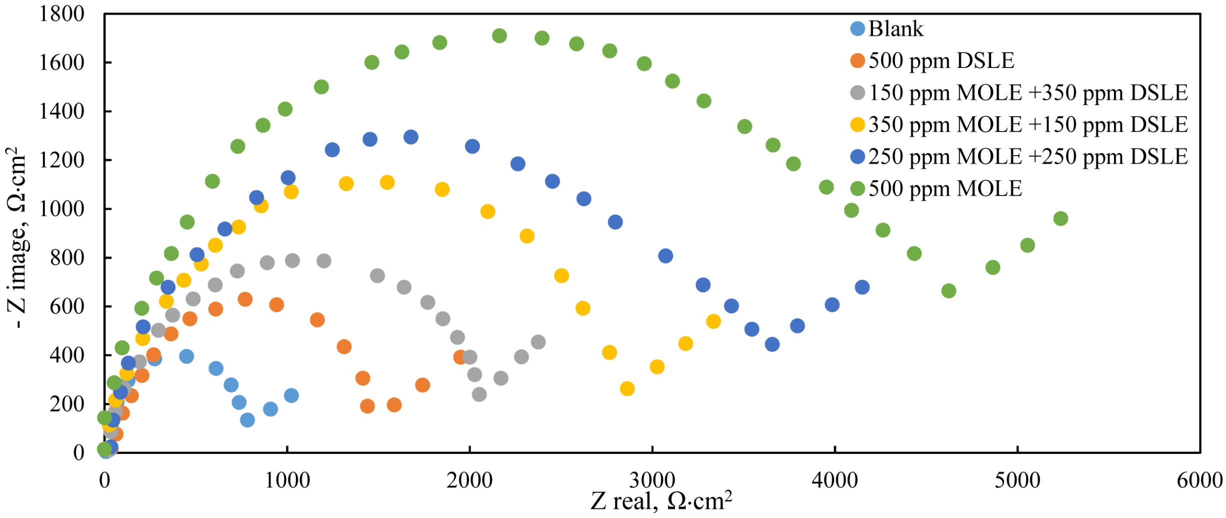

Fig. 1. Nyquist plot at 60 °C in 1 M HCl in the presence and absence of individual and mixture of the two inhibitor plant extracts

applications where the cost and availability of inhibitors are crucial factors [41].

The results indicate that Moringa oleifera extract is an effective green corrosion inhibitor for carbon steel in acidic environments, with significant inhibition efficiency even at high temperatures. Datura stramonium extract demonstrates moderate inhibition efficiency, especially when combined with MOLE.

3.2.2 Electrochemical analysis

The electrochemical impedance spectroscopy (EIS) presented in the Nyquist plot (Fig. 1) and summarized in provides valuable insights into the corrosion inhibition mechanisms of MOLE and DSLE on carbon steel in 1 M HCl.

The blank solution exhibits the lowest Rct, indicating the highest corrosion rate. The individual inhibitors, 500 ppm DSLE, and 500 ppm MOLE show Rct values of 1500 Ω·cm^2 and 5000 Ω·cm^2, respectively. This substantial difference (a factor of 3.33) demonstrates the superior inhibition efficiency of MOLE compared to DSLE at the same concentration.

The mixed inhibitor systems show intermediate Rct values, ranging from 2200 to 3200 Ω·cm^2. Notably, the 250 ppm MOLE + 250 ppm DSLE mixture achieves an Rct of 3200 Ω·cm^2, which is 64% of the Rct value for 500 ppm MOLE alone, while using only half the MOLE concentration. This confirms a combination effect between MOLE and DSLE molecules in the adsorption process.

Table 3. Electrochemical parameters derived from EIS measurements for carbon steel in 1 M HCl with various inhibitor concentrations

Inhibitor concentration	R_{ct} (Ω·cm^2)	IE (%)
Blank	600	-
500 ppm MOLE	5000	88.0
250 ppm MOLE + 250 ppm DSLE	3200	81.3
350 ppm MOLE + 150 ppm DSLE	2800	78.6
150 ppm MOLE + 350 ppm DSLE	2200	72.7
500 ppm DSLE	1500	60.0

The inhibitive efficiency values clearly demonstrate the effectiveness of both individual and mixed inhibitors. MOLE at 500 ppm shows the highest IE of 88%, more effective functional groups for adsorption on the steel surface.

The mixed inhibitor systems all show higher inhibition efficiency values than DSLE alone, indicating that MOLE enhances the inhibition efficiency of DSLE. The 250 ppm MOLE + 250 ppm DSLE mixture achieves an IE of 81.3%, which is 92.4% of the IE of 500 ppm MOLE while using only half the MOLE concentration. This enhancement is due to complementary adsorption sites MOLE molecules may adsorb on surface sites not covered by DSLE.

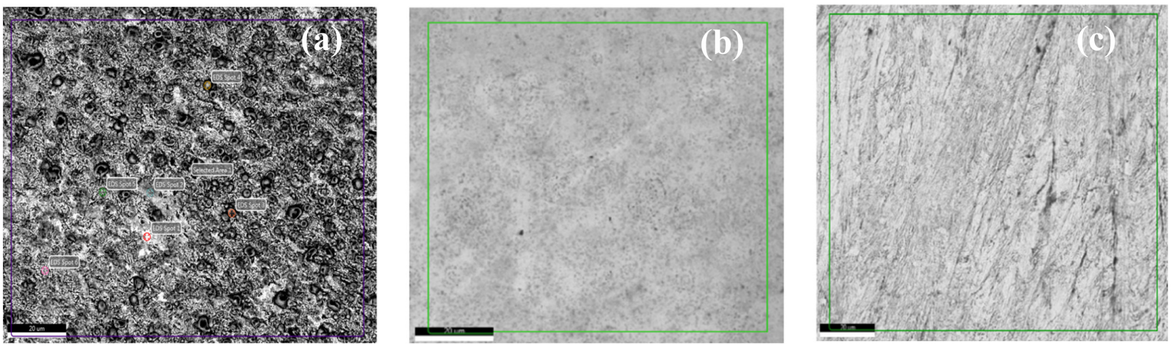

Fig. 2. Surface analysis in (a) 1 M HCl, (b) 1M HCl+ MOLE and (c)1M HCl+ 250 ppm MOLE+250 ppm DSLE

3.2.3 Surface analysis

The SEM images (Fig. 2a) reveal substantial corrosion damage on the carbon steel surface. The morphology is dominated by deep pits and rough, uneven areas, characteristic of an aggressive acid attack. The presence of large pits and cracks indicates severe material degradation, confirming the high corrosivity of the 1 M HCl environment at elevated temperatures. This extensive damage is attributed to the unprotected exposure of the metal surface to the corrosive medium, leading to accelerated anodic and cathodic reactions. The surface appears significantly roughened, with visible pitting and corrosion products. The aggressive nature of hydrochloric acid at 60 ºC has caused considerable damage to the metal surface. The pits are irregularly shaped and distributed across the surface, indicating localized corrosion.

SEM images of carbon steel treated with Moringa oleifera extract (Fig. 2b) show a more uniform surface compared to treatments with mixture extract. Moringa forms a protective film that helps mitigate corrosion in 1 M HCl at 60 ºC.

SEM images of carbon steel treated with the mixture of Moringa oleifera and Datura stramonium extract (Fig. 2c) reveal minimal surface damage, characterized by fewer pits and a less uniform surface compared to treatments with individual Moringa extract. The mixture forms a comprehensive protective film, effectively mitigating corrosion in 1 M HCl at 60 ºC. This effect is likely due to the combined adsorption of active compounds from both extracts, creating a robust and impermeable barrier that shields the metal surface from corrosive agents. Moringa oleifera is known to contain various phytochemicals such as flavonoids, phenolic acids, and alkaloids. Datura stramonium also contains alkaloids, particularly tropane alkaloids. These compounds often have heteroatoms (N, O, S) and π-electrons, which facilitate adsorption on metal surfaces. The SEM analysis shows a substantial reduction in surface damage, with the protective film inhibiting acid attack and resulting in a smoother surface with fewer pits and cracks. The inhibition efficiency is evidenced by the reduced surface deterioration. This effectiveness is attributed to the adsorption of molecules onto the metal surface, forming a barrier that limits interaction between the metal and corrosive species.

3.3 Adsorption isotherm

Table 4 and Fig. 3 show the isotherm adsorption of the mixture inhibitor in 1 M HCl at 60 ºC. The superior fit of the Frumkin isotherm (R^2 = 0.9477) confirmed that lateral interactions between adsorbed mixture inhibitor molecules play a crucial role in the adsorption process, which is consistent with the complex nature of plant-based corrosion inhibitors. This behavior is because of the diverse phytochemical constituents in the Moringa oleifera and Datura stramonium extracts, which exhibit mixture interactions on the metal surface [42]. The moderate fit of the Freundlich (R^2 = 0.7582) and Temkin (R^2 = 0.7443) isotherms indicate a degree of surface heterogeneity and non-uniform distribution of adsorption energies, aligning with previous studies on mixed-plant extract inhibitors [43]. Conversely, the poor fit of the Langmuir isotherm (R^2 = 0.2401) implies significant deviations from ideal monolayer adsorption, possibly due to the formation of multilayers or the presence of multiple types of adsorption sites.

Table 4. Correlation coefficient for each isothermal model at 60 °C

Isotherm model	Correlation coefficients			
	Langmuir	Temkin	Frumkin	Freundlich
R^2	0.2401	0.7443	0.9477	0.7582

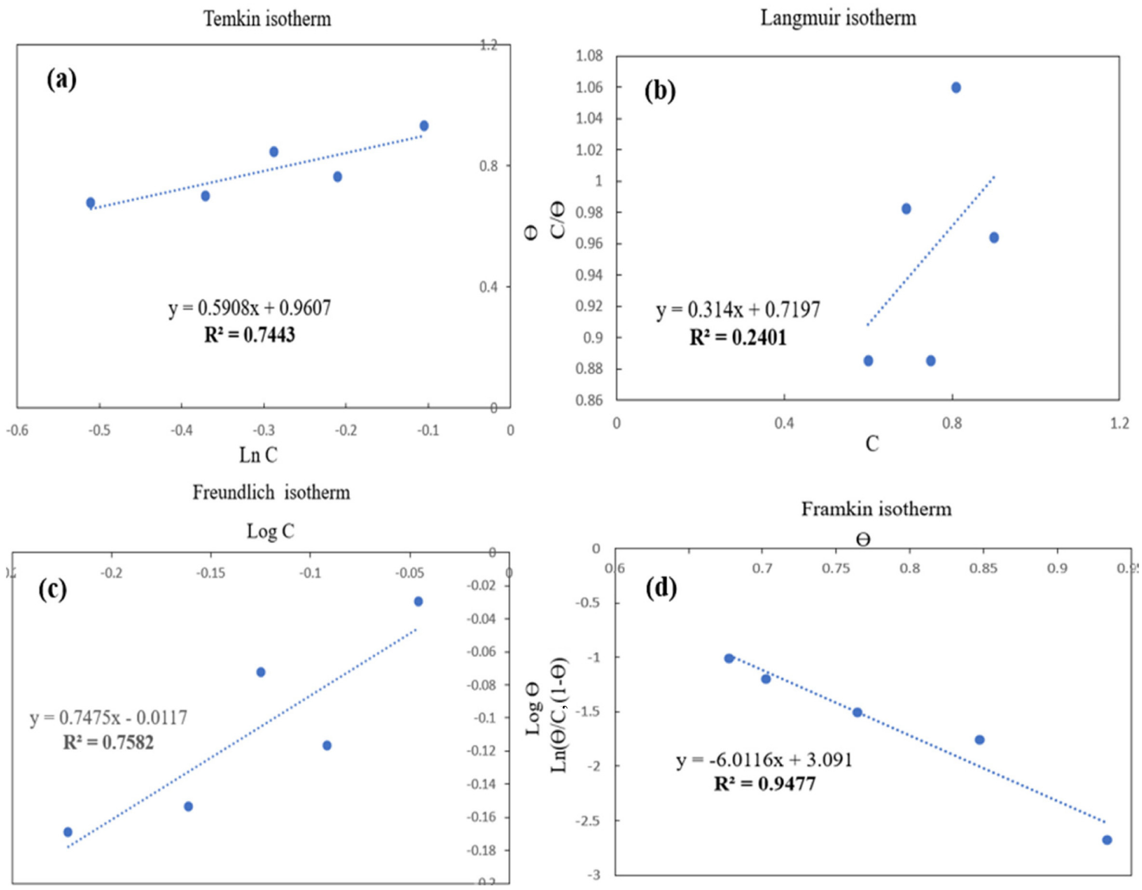

Fig. 3. Adsorption isotherm: (a) Temkin isotherm, (b) Langmuir isotherm, (c) Freundlich isotherm and (d) Framkin isotherm
· θ: Surface coverage or fractional of adsorption sites
· C : The inhibitor concentration
· R^2 : Coefficient of determination, indicating goodness of fit

Temkin and Pyzhev consider the effect of adsorbent/ adsorbate interactions on the adsorption isotherm and suggest that, because of these interactions, the adsorption heat decreases linearly with the growth of the adsorbent surface overlap rate.

This is in good agreement with the results found by Hackerman [44] and Feng [45]. This result can be attributed to the difference in the degree of adsorption of anions to the metal surface by creating oriented dipoles and consequently increasing the adsorption of organic cations on these dipoles [46].

Corrosion inhibitors that increase the ohmic resistance of the electrolyte are considered, in some cases, as film inhibitors (anodic and cathodic). The resistance of the solution increases following the formation of a film on the surface of the metal. When the film is selectively deposited on the anodic surface, the corrosion potential moves to positive values. In the case where the film is deposited on the cathodic surface, the corrosion potential balances towards negative values [47,48]. In the case of the formation of a film on anodic and cathode surfaces, the displacement of the corrosion potential is on the side of the predominant trend. Mixed inhibitors decrease the speed of the two partial reactions but have little effect on the corrosion potential [49].

3. Conclusion

This study demonstrates the mixture effects of combining Moringa oleifera leaf extract (MOLE) and Datura stramonium leaf extract (DSLE) for corrosion inhibition of carbon steel. While MOLE at 500 ppm achieved the highest individual inhibition efficiency of 93.48%, the 250 ppm MOLE + 250 ppm DSLE mixture showed a moderate 84.78% efficiency, indicating significant enhancement due to MOLE. This combination allows the valorization of the toxic Datura plant. These findings suggest that plant-based mixtures can provide effective and sustainable corrosion protection in industrial applications.

Acknowledgements

The support provided by the Research Center and Development of Boumerdes, Algeria is gratefully acknowledged.

References

1. M. Komary, S. Komarizadehasl, N. Tošić, I. Segura, J. A. Lozano-Galant, and J. Turmo, Low-cost technologies used in corrosion monitoring, *Sensors*, **23**, 1309 (2023). Doi: https://doi.org/10.3390/lubricants9120122
2. A. Alamiery, Short report of mild steel corrosion in 0.5 M H_2SO_4 by 4-ethyl-1-(4-oxo-4-phenylbutanoyl) thiosemicarbazide, *Jurnal Tribologi*, **30**, 90 (2021). https://jurnaltribologi.mytribos.org/v30/JT-30-90-99.pdf
3. I. A. Alkadir Aziz, I. Adnan Annon, M. H. Abdulkareem, M. M. Hanoon, Mohammed H. Alkaabi, Lina M. Shaker, Ahmed A. Alamiery, W. N. R. Wan Isahak, Mohd S.Takriff, Insights into corrosion inhibition behavior of a 5-mercapto-1, 2, 4-triazole derivative for mild steel in hydrochloric acid solution: experimental and DFT studies, *Lubricants*, **9**, 122 (2021). Doi: https://doi.org/10.3390/lubricants9120122
4. B. Zajec, M. Bajt Leban, T. Kosec, V. Kuhar, A. Legat, S. Lenart, K. Fifer Bizjak, K. Gavin, Corrosion monitoring of steel structure coating degradation, *Tehnički vjesnik*, **25**, 1348 (2018). Doi: https://doi.org/10.17559/TV-20170206004112
5. H. Didouh, A. Buyuksagis, M. Hadj Meliani, M. Dilek, Y. Kayali, R. K. Suleiman, T. A. Saleh, Investigating the use of Moringa Oleifera leaf extract as an environment-friendly corrosion inhibitor for API 5L X52 steel in 1 M HCl, *Journal of Molecular Liquids*, **390**, 122910 (2023). Doi: https://doi.org/10.1016/j.molliq.2023.122910
6. H. Ding, J. Lan, S. Yao, D. Zhang, B. Han, G. Pan, X Li, Evolution of polycyclic aromatic hydrocarbons in the surface sediment of southern Jiaozhou Bay in northern China after an accident of oil pipeline explosion, *Marine pollution bulletin*, **183**, 114039 (2022). Doi: https://doi.org/10.1016/j.marpolbul.2022.114039
7. E. E. Ebenso, C. Verma, L. O. Olasunkanmi, E. D. Akpan, D. K. Verma, H. Lgaz, L. Guo, S. Kaya, M.A. Quraishi, Molecular modelling of compounds used for corrosion inhibition studies: a review, *Physical Chemistry Chemical Physics*, **23**, 19987 (2021). Doi: https://doi.org/10.1039/D1CP00244A
8. A. Alamiery, E. Mahmoudi, and T. Allami, Corrosion inhibition of low-carbon steel in hydrochloric acid environment using a Schiff base derived from pyrrole: gravimetric and computational studies, *International Journal of Corrosion and Scale Inhibition*, **10**, 749 (2021). Doi: https://doi.org/10.17675/2305-6894-2021-10-2-17
9. A. A. Al-Amiery, A. B. Mohamad, A. A. H. Kadhum, L. M. Shaker, W. N. R. W. Isahak, and M. S. Takriff, Experimental and theoretical study on the corrosion inhibition of mild steel by nonanedioic acid derivative in hydrochloric acid solution, *Scientific Reports*, **12**, 4705 (2022). Doi: https://doi.org/10.1038/s41598-022-08146-8
10. P. Sirajudheen, V. R. Kasim, C. P. Nabeena, M. C. Basheer, and S. Meenakshi, Tunable photocatalytic oxidation response of ZnS tethered chitosan-polyaniline composite for the removal of organic pollutants: A mechanistic perspective, *Materials Today: Proceedings*, **47**, 2553 (2021). Doi: https://doi.org/10.1016/j.matpr.2021.05.054
11. M. M. Hanoon, A. M. Resen, L. M. Shaker, A. A. H. Kadhum, and A. A. Al-Amiery, Corrosion investigation of mild steel in aqueous hydrochloric acid environment using n-(Naphthalen-1yl)-1-(4-pyridinyl) methanimine complemented with antibacterial studies, *Biointerface Research in Applied Chemistry*, **11**, 9735 (2021). Doi: https://doi.org/10.33263/BRIAC112.97359743
12. S. Al-Baghdadi, T. S. Gaaz, A. Al-Adili, A. A. Al-Amiery, and M. S. Takriff, Experimental studies on cor-

rosion inhibition performance of acetylthiophene thiosemicarbazone for mild steel in HCl complemented with DFT investigation, *International Journal of Low-Carbon Technologies*, **16**, 181 (2021). Doi: https://doi.org/10.1093/ijlct/ctaa050

13. S. B. Al-Baghdadi, A. A. Al-Amiery, T. S. Gaaz, and A. A. H. Kadhum, Terephthalohydrazide and isophthalo-hydrazide as new corrosion inhibitors for mild steel in hydrochloric acid: Experimental and theoretical approaches, *Koroze a ochrana materialu*, **65**, 12 (2021). Doi: https://doi.org/10.2478/kom-2021-0002
14. A. Okewale and F. Omoruwuo, Neem leaf extract as a corrosion inhibitor on mild steel in acidic solution, *International Journal of Engineering Research in Africa*, **35**, 208 (2018). Doi: https://doi.org/10.4028/www.scientific.net/JERA.35.208
15. A. Dehghani, G. Bahlakeh, B. Ramezanzadeh, and M. Ramezanzadeh, Potential role of a novel green eco-friendly inhibitor in corrosion inhibition of mild steel in HCl solution: Detailed macro/micro-scale experimental and computational explorations, *Construction and Building Materials*, **245**, 118464 (2020). Doi: https://doi.org/10.1016/j.conbuildmat.2020.118464
16. S. Abdelaziz, M. Benamira, L. Messaadia, Y. Boughoues, H. Lahmar, and A. Boudjerda, Green corrosion inhibition of mild steel in HCl medium using leaves extract of Arbutus unedo L. plant: An experimental and computational approach, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **619**, 126496 (2021). Doi: https://doi.org/10.1016/j.colsurfa.2021.126496
17. K. A. Abdelshafeek and A. M. El-Shamy, Review on glucosinolates: Unveiling their potential applications as drug discovery leads in extraction, isolation, biosynthesis, biological activity, and corrosion protection, *Food Bioscience*, 103071 (2023). Doi: https://doi.org/10.1016/j.fbio.2023.103071
18. G. Gece, Drugs: A review of promising novel corrosion inhibitors, *Corrosion Science*, **53**, 3873 (2011). Doi: https://doi.org/10.1016/j.corsci.2011.08.006
19. C. Verma, E. E. Ebenso, and M. A. Quraishi, Ionic liquids as green and sustainable corrosion inhibitors for metals and alloys: an overview, *Journal of Molecular Liquids*, **233**, 403 (2017). Doi: https://doi.org/10.1016/j.molliq.2017.02.111
20. D. Prabhu and P. Rao, Coriandrum sativum L. A novel green inhibitor for the corrosion inhibition of aluminium in 1.0 M phosphoric acid solution, *Journal of environmental chemical engineering*, **1**, 676 (2013). Doi: https://doi.org/10.1016/j.jece.2013.07.004
21. N. Ammouchi, H. Allal, E. Zouaoui, K. Dob, D. Zouied, and M. Bououdina, Extracts of ruta chalepensis as green corrosion inhibitor for copper CDA 110 in 3% NaCl medium: experimental and theoretical studies, *Analytical and Bioanalytical Electrochemistry*, **11**, 830 (2019). http://dspace.univ-skikda.dz:4000/handle/123456789/1833
22. A. Oulabbas, Natural extract of Opuntia ficus indica as green inhibitor for corrosion of XC52 steel in 1M H_3PO_4, *Materials research express*, **6**, 1 (2019). Doi: https://doi.org/10.1088/2053-1591/aae8b9
23. R. Boulmerka, S. Abderrahmane, and F. Benachour, Grated Agave Americana–Green corrosion inhibitor for stainless steel in 0.5 M H_2SO_4, *International Journal of Chemical and Biochemical Sciences*, **19**, 126 (2021). https://www.iscientific.org/wp-content/uploads/2021/09/17-IJCBS-21-19-17.pdf
24. M. Allaoui, O. Rahim, B. Labed, I. Bellaoueur, and D. Abdessettar, Green inhibitors aqueous extract of Rumex vesicarius on the corrosion of carbon steel in acid media 1M HCl., *Fresenius Environmental Bulletin*, **31**, 11529 (2022). https://www.researchgate.net/publication/374700659_GREEN_INHIBITORS_AQUEOUS_EXTRACT_OF_Rumex_vesicarius_ON_THE_CORROSION_OF_CARBON_STEEL_IN_ACID_MEDIA_1M_HCl
25. G. Belkis, H. S. Abdelkader, and R. Oumelkheir, Evaluation of the Inhibitive Performance of Cyperus Conglomeratus Leaves Extract as a Green Corrosion Inhibitor on Mild Steel XC70 in Acid Medium, *Corrosion Science and Technology*, **21**, 171 (2022). Doi: https://doi.org/10.14773/cst.2022.21.3.171
26. N. K. Brixi, R. Cherif, A. Bezzar, L. Sail, and A. Aït-Mokhtar, Effectiveness of henna leaves extract and its derivatives as green corrosion inhibitors of reinforcement steel exposed to chlorides, *European Journal of Environmental and Civil Engineering*, **26**, 5912 (2022). Doi: https://doi.org/10.1080/19648189.2021.1925159
27. W. Boukhedena, S. Deghboudj, M. Benahmed, and H. Laouer, Experimental and Statistical Investigation of a Novel Green Inhibitor Ferula Lutea as Potential Corrosion Inhibiting Carbon Steel in an Acidic Medium, *Journal of the Mexican Chemical Society*, **68**, 344 (2024). Doi: https://doi.org/10.29356/jmcs.v68i3.1891
28. L. Allam, C. OULMAS, D. Boughrara, A. KADRI, and N. BENBRAHIM, Eugenia Caryophyllata extract as

green inhibitor for steel corrosion in 1 M HCl solution, *Journal of Materials, Processes and Environment*, **5**, 18 (2017). https://asjp.cerist.dz/en/article/25820

29. A. S. Fouda, A. M. Ahmed, S. M. El-Darier, and I. M. Ibrahim, Moringa oleifera as an eco-friendly corrosion inhibitor for carbon steel in hydrochloric acid solution, *International Journal of Corrosion and Scale Inhibition*, **9**, 1630 (2020). Doi: https://doi.org/10.17675/2305-6894-2020-9-4-27
30. V. C. Anadebe, C. S. Okafor, and O. D. Onukwuli, Electrochemical, molecular dynamics, adsorption studies and anti-corrosion activities of Moringa leaf biomolecules on carbon steel surface in alkaline and acid environment," *Chemical Data Collections*, **28**, 100437 (2020). Doi: https://doi.org/10.1016/j.cdc.2020.100437
31. H. A. El and D. F. I. El, Moringa oleifera plant extract as a copper corrosion inhibitor in binary acid mixture (HNO_3+ H_3PO_4), *Zastita materijala*, **59**, 422 (2018). Doi: https://doi.org/10.5937/zasmat1803422F
32. O. K. E. Gbenga Olabode, A. O. ALUKO, and O. T. SANYA, Inhibitive potential of Datura strmonium leaf extract on the corrosion behavior of mild steel in 1M HCl acidic solution, *Leonardo Journal of Sciences*, **32**, 76 (2018). http://ljs.academicdirect.org/A32/076_092.pdf
33. S. Mohanasundaram, S. Geetha, R. Nagajothi, V. P. Sundramurthy, J. Vijayakumar, N. S. Alharbi, M. Thiruvengadam, Evaluation of anti-corrosion potential of *Datura Metel* plant extract on mild steel upon sulphuric acid exposure, *Canadian Metallurgical Quarterly*, **64**, 196 (2024). Doi: https://doi.org/10.1080/00084433.2024.2310352
34. ASTM G1-03, Standard practice for preparing, cleaning, and evaluating corrosion test specimens, American Society for Testing and Materials, ASTM Standard (2011).
35. M. Abdallah, H. M. Altass, B. A. Al Jahdaly, and M. M. Salem, Some natural aqueous extracts of plants as green inhibitor for carbon steel corrosion in 0.5 M sulfuric acid, *Green Chemistry Letters and Reviews*, **11**, 189 (2018). Doi: https://doi.org/10.1080/17518253.2018.1458161
36. F. Khoukhi, S. Kebbouche-Gana, N. E. Djelali, M. L. Gana, R. BOUKHALFA, T. A. HAMOUDA, and A. LOUFAR, Efficiency Evaluation of Anti-corrosion Treatment of Carbon Steel by Extracts of Red Algae Collected from Mediterranean Coast, *Revista de Chimie*, **72**, 59 (2021). Doi: https://doi.org/10.37358/Rev.Chim.1949
37. A. Ostovari, S. M. Hoseinieh, M. Peikari, S. R. Shadizadeh, and S. J. Hashemi, Corrosion inhibition of mild steel in 1 M HCl solution by henna extract: A comparative study of the inhibition by henna and its constituents (Lawsone, Gallic acid, α-d-Glucose and Tannic acid), *Corrosion Science*, **51**, 1935 (2009). Doi: https://doi.org/10.1016/j.corsci.2009.05.024
38. I. B. Obot, S. A. Umoren, and N. K. Ankah, Pyrazine derivatives as green oil field corrosion inhibitors for steel, *Journal of Molecular Liquids*, **277**, 749 (2019). Doi: https://doi.org/10.1016/j.molliq.2018.12.108
39. R. Kumar, O. S. Yadav, and G. Singh, Electrochemical and surface characterization of a new eco-friendly corrosion inhibitor for mild steel in acidic media: a cumulative study, *Journal of Molecular Liquids*, **237**, 413 (2017). Doi: https://doi.org/10.1016/j.molliq.2017.04.103
40. A. M. Abdel-Gaber, B. A. Abd-El-Nabey, I. M. Sidahmed, A. M. El-Zayady, and M. Saadawy, Inhibitive action of some plant extracts on the corrosion of steel in acidic media, *Corrosion science*, **48**, 2765 (2006). Doi: https://doi.org/10.1016/j.corsci.2005.09.017
41. E. E. Oguzie, Evaluation of the inhibitive effect of some plant extracts on the acid corrosion of mild steel, *Corrosion Science*, **50**, 2993 (2010). Doi: https://doi.org/10.1016/j.corsci.2008.08.004
42. M. Benahmed, I. Selatnia, N. Djeddi, S. Akkal, and H. Laouer, Adsorption and Corrosion Inhibition Properties of Butanolic Extract of Elaeoselinum thapsioides and Its Synergistic Effect with Reutera lutea (Desf.) Maires (Apiaceae) on A283 carbon Steel in Hydrochloric Acid Solution, *Chemistry Africa*, **3**, 251 (2020). Doi: https://doi.org/10.1007/s42250-019-00093-8
43. C. Verma, E. E. Ebenso, I. Bahadur, and M. A. Quraishi, An overview on plant extracts as environmental sustainable and green corrosion inhibitors for metals and alloys in aggressive corrosive media, *Journal of molecular liquids*, **266**, 577 (2018). Doi: https://doi.org/10.1016/j.molliq.2018.06.110
44. N. Hackerman, Recent advances in understanding of organic inhibitors, *Corrosion*, **18**, 332t (1962). Doi: https://doi.org/10.5006/0010-9312-18.9.332
45. Y. Feng, K. S. Siow, W. K. Teo, and A. K. Hsieh, The synergistic effects of propargyl alcohol and potassium iodide on the inhibition of mild steel in 0.5 M sulfuric acid solution, *Corrosion Science*, **41**, 829 (1999). Doi: https://doi.org/10.1016/S0010-938X(98)00144-9
46. M. Lagrenee, B. Mernari, M. Bouanis, M. Traisnel, and F. Bentiss, Study of the mechanism and inhibiting efficiency of 3, 5-bis (4-methylthiophenyl)-4H-1, 2, 4-triazole on mild steel corrosion in acidic media, *Corrosion*

Science, **44**, 573 (2002). Doi: https://doi.org/10.1016/S0010-938X(01)00075-0
47. B. E. Conway, Electrochemical surface science: The study of monolayers of ad-atoms and solvent molecules at charged metal interfaces, *Progress in surface science*, **16**, 1 (1984). Doi: https://doi.org/10.1016/0079-6816(84)90008-X
48. R. T. Loto, Evaluation of the corrosion inhibition effect of the combined admixture of rosemary and cinnamon cassia oil on mild steel in weak acid electrolyte, *Sustainable Chemistry and Pharmacy*, **17**, 100298 (2020). Doi: https://doi.org/10.1016/j.scp.2020.100298
49. D. Landolt, Traité des matériaux, *Presses polytechniques et universitaires romandes, Lausanne* (1993).