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The Inhibitive Properties of Avocado (*Persea Americana*) Leaves Extract on the Corrosion of Mild Steel in 1M HCl

Monica Chikodinaka Nkwocha, Lebe Agwu Nnanna and Onyinyechi Chinanuekpere Nwadiuko

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Abstract: *The corrosion inhibition activity of avocado (Persea americana) leaves extract (AV), on mild steel in 1 M HCl was studied employing gravimetric analysis and electrochemical techniques, including Potentiodynamic Polarization (PDP) and Electrochemical Impedance Spectroscopy (EIS). The results show that AV significantly inhibited the corrosion of mild steel, with the highest inhibition efficiency recorded at 1500 mg/L, getting to 93.8%. Electrochemical impedance spectroscopy reflected an increase in charge transfer resistance (Rct) and a lowering in double layer capacitance (Cdl), meaning the adsorption of AV molecules on the steel surface. Potentiodynamic polarization curves implied that AV works as a mixed-type inhibitor, effectively bringing down both cathodic and anodic reactions. The findings show that Avocado leaf, AV, offers good potential as a green corrosion inhibitor for mild steel in acidic environments.*

Keywords: *Avocado leaves, corrosion inhibition, mild steel, hydrochloric acid, electrochemical techniques*

Monica Chikodinaka Nkwocha
Department of Physics, Michael Okpara University of Agriculture, Umudike
Email: monicachikodinaka@gmail.com

Onyinyechi Chinanuekpere Nwadiuko
Address: Department of Physics, Michael Okpara University of Agriculture, Umudike
Email: onwadiuko@yahoo.com
Orcid id: 0009-0004-7311-2799

Lebe Agwu Nnanna
Address: Department of Physics, Michael Okpara University of Agriculture, Umudike
Email: lebennanna@yahoo.com
Orcid id: 0000-0001-9451-9310

1.0 Introduction

Corrosion of metals in acidic environments remains a persistent challenge across numerous industries, resulting in significant economic losses and environmental hazards (Elsayed *et* al., 2024; Mazumder, 2020). Mild steel, due to its versatility and widespread use in construction, manufacturing, and the oil and gas sector, is particularly susceptible to corrosion when exposed to aggressive media such as hydrochloric acid (HCl) (Udensi et al., 2020). This degradation compromises structural integrity, increases maintenance costs, and reduces service life.

Traditional corrosion inhibitors, although effective, often contain toxic and non-biodegradable chemicals that pose risks to both human health and the environment. As a result, there is a growing interest in the development of green, eco-friendly alternatives (Singaravelu et al., 2024). In recent years, plant-based inhibitors have attracted considerable attention due to their availability, biodegradability, and presence of phytochemicals such as tannins, alkaloids, flavonoids, and saponins—compounds known to inhibit corrosion through adsorption onto metal surfaces (Nwosu et al., 2018; Muthukrishnan et al., 2017).

A wide range of plant materials have been explored for their corrosion inhibitive properties. For example, *Garcinia kola* and *Kola nitida* seed extracts was reported to display inhibition efficiencies above 83% in acidic media (Eddy, 2010), while Musa species peel extracts exhibited efficiency above 85% (Eddy et al., 2009). Other plant parts have also been found to be good corrosion inhibitors, such as plant gums (Kumar et al., 2024), roots, stems, vegetables, and fruits (Eddy et al., 2022; Oyewole et al., 2021). These plant extracts typically contain functional groups with heteroatoms, π-bonds, aromatic rings, and conjugated systems that enhance their effectiveness as corrosion inhibitors (Eddy et al., 2010a-b; El Nemr *et al*., 2024).

Despite the abundance of research on plant-based inhibitors, studies on avocado (Persea americana) leaf extract remain limited. Previous investigations by Deyab and Mohsen (2025) reported an average inhibition efficiency above 94% on carbon steel in saline environments using electrochemical and gravimetric techniques. Similarly, Mu'azu et al. (2022) observed nearly 100% inhibition using weight loss measurements; however, the study lacked electrochemical analysis and did not evaluate long-term exposure, limiting its applicability in real-world conditions. These findings, though promising, underscore the need for a more comprehensive and methodologically robust assessment of avocado leaf extract in strongly acidic environments.

Avocado leaves are rich in phytochemicals such as phenolic compounds, flavonoids, terpenoids, tannins, and alkaloids, which exhibit antioxidant and antimicrobial properties that may contribute to corrosion inhibition (Saxena et al., 2018). Comparatively, extracts from other plants—such as *Dryopteris cochleata* (Nathiya & Raj, 2017), *Psidium guajava* seeds (Sharma & Sharma, 2016), and papaya peel (Chaubey et al., 2018)—have demonstrated significant corrosion resistance in acidic media, further validating the potential of plant-based inhibitors. However, the application of avocado leaf extract in 1 M HCl, particularly on mild steel, remains underexplored. There is a critical need to bridge this gap using both gravimetric and electrochemical methods to obtain a comprehensive understanding of the inhibition mechanism and performance.

This study therefore aims to evaluate the corrosion inhibitive properties of avocado (Persea americana) leaf extract on mild steel in 1 M HCl using weight loss (gravimetric) analysis, Potentiodynamic Polarization (PDP), and Electrochemical Impedance Spectroscopy (EIS). The outcome of this research is expected to contribute valuable data on the development of sustainable, green corrosion inhibitors, offering an environmentally friendly solution for protecting mild steel in acidic industrial processes.

2.0 Materials and Methods

2.1 Materials

2.1.1 Mild Steel Specimens

The metal used for this investigation was mild steel, which had a chemical composition comprising 0.15% carbon, 0.25% manganese, 0.035% phosphorus, 0.04% silicon, and the remainder being iron. The mild steel was cut into rectangular coupons with dimensions of 2 cm by 2 cm by 0.1 cm. These specimens were mechanically polished using emery papers of progressively finer grades to achieve a smooth surface finish. After polishing, the specimens were rinsed thoroughly with distilled water, degreased using acetone to remove any traces of grease or oil, and then air-dried. The polished and cleaned coupons served as the working electrodes in the electrochemical experiments.

2.1.2 Chemical Reagents

The chemical reagents employed in this study included hydrochloric acid (HCl) with a concentration of 37% and acetone. Both reagents were of analytical grade and were obtained from commercial suppliers. A 1 M HCl solution, which served as the corrosive medium, was prepared by diluting concentrated hydrochloric acid with distilled water. All experimental procedures were carried out at ambient room temperature, which averaged 28 ± 2°C.

2.2 Preparation of Avocado Leaf Extract (AV)

Fresh leaves of avocado (Persea americana) were harvested from trees located in Imerienwe, Ngor Okpala Local Government Area, Imo State, Nigeria. The leaves were carefully washed with distilled water to eliminate dust and other surface impurities. They were then spread out in a well-ventilated room and allowed to air-dry at room temperature until completely dehydrated. After drying, the leaves were ground into a fine powder using a hand-operated grinding machine.

To prepare the extract, 40 grams of the powdered avocado leaves were introduced into 400 milliliters of 1 M HCl solution. This mixture was subjected to heating for a duration of three hours. Upon completion of heating, the mixture was allowed to stand undisturbed for twenty-four hours at room temperature. The extract was subsequently filtered using a fine sieve to obtain a clear solution, which served as the stock solution. This stock solution was diluted with distilled water to prepare working concentrations of 200 mg/L and 1500 mg/L, which were used for all electrochemical tests. The preparation procedure followed established methods as described by Chaubey et al. (2018) and Saxena et al. (2018).

2.3 Electrochemical Measurements

All electrochemical experiments were carried out using a Gamry Reference 600 Potentiostat equipped with a standard three-electrode electrochemical cell. In this setup, the mild steel coupon functioned as the working electrode, a platinum rod served as the counter electrode, and a saturated calomel electrode (SCE) was employed as the reference electrode.

2.3.1 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) was performed at the open circuit potential (OCP) within a frequency range of 100 kHz to 10 mHz. The measurements were carried out using a sinusoidal perturbation of ±10 mV. From the Nyquist plots obtained, the charge transfer resistance (R*ct*) was determined, and the inhibition efficiency (IE%) was calculated using equation 1

$$IE\% = \frac{Rct_{inhibited} - Rct_{blank}}{Rct_{blank}} \times 100 \qquad (1)$$

where Rct_{blank} is the charge transfer resistance of mild steel in 1 M HCl without the inhibitor, and $Rct_{inhibited}$ is the charge transfer resistance in the presence of the avocado leaf extract.

2.3.2 Potentiodynamic Polarization (PDP)

Potentiodynamic polarization measurements were carried out following the stabilization of the open circuit potential. The electrode potential was scanned within a range of −250 mV to +250 mV relative to the corrosion potential, at a scan rate of 1 mV/s. From the polarization curves generated, values for corrosion current density (Icorr), corrosion potential (Ecorr), and Tafel slopes for both anodic and cathodic reactions were extracted.

The inhibition efficiency (IE%) for the polarization studies was calculated using equation 2

$$IE\% \frac{Icorr_{blank} - Icorr_{inhibited}}{Icorr_{blank}} \times 100 \qquad (2)$$

where $Icorr_{blank}$ is the corrosion current density in the absence of the inhibitor, and $Icorr_{inhibited}$ is the corrosion current density in the presence of avocado leaf extract.

3.0 Results and Discussion

3.1 Electrochemical Impedance Spectroscopy (EIS)

Fig. 1a displays the Nyquist plots for mild steel immersed in 1 M HCl in the absence and presence of avocado leaf extract (AV) at concentrations of 200 mg/L and 1500 mg/L. In all the cases, the Nyquist plots exhibit a single capacitive loop, which indicates that the corrosion process is predominantly charge-transfer controlled. The diameter of the semicircle increases with the addition of the inhibitor, suggesting an increase in charge transfer resistance (Rct), which is directly related to corrosion inhibition efficiency.

According to Table 1, the Rct for the uninhibited system (blank) is 48.5 Ω·cm². In contrast, the Rct increases significantly to 301.2 Ω·cm² at 200 mg/L AV and 652.5 Ω·cm² at 1500 mg/L AV, corresponding to inhibition efficiencies of 83.9% and 92.6%, respectively. This enhancement in Rct indicates the formation of a protective film on the mild steel surface due to the adsorption of phytochemicals present in the avocado leaf extract, which impedes charge transfer between the metal and the corrosive environment.

This trend is in agreement with earlier findings by Chaubey et al. (2018) and Saxena et al. (2018), who observed similar increases in Rct values for mild steel in acidic media using plant extracts as inhibitors. The data suggest that AV acts as an effective barrier against aggressive chloride and hydrogen ions in the acid.

3.2 Bode and Phase Angle Plots

Figs. 1b and 1c present the Bode magnitude and Bode phase angle plots, respectively. The Bode magnitude plot (Fig. 1b) shows an increase in impedance modulus at low frequencies with increasing inhibitor concentration, reaffirming the enhanced corrosion resistance in the presence of AV. The phase angle plot (Fig. 1c) exhibits a single peak, which is higher and broader for the inhibited systems, particularly at 1500 mg/L. This indicates an increase in surface coverage and improved protective behavior of the adsorbed film formed by AV.

The increase in phase angle is characteristic of capacitive behavior due to the formation of a more homogeneous and adherent inhibitor layer, which has been reported by other authors using green inhibitors derived from *Lawsonia inermis* and *Azadirachta indica* (Muthukumarasamy et al., 2021).

3.3 Potentiodynamic Polarization Studies

Fig. 1d presents the Tafel polarization curves for mild steel in 1 M HCl in the absence and presence of AV. The presence of the extract results in a marked reduction in corrosion current density (Icorr), with only minor shifts in corrosion potential (Ecorr), indicating that the avocado leaf extract acts as a mixed-type inhibitor with predominant cathodic inhibition.

From Table 1, the corrosion current density decreases from 171.5 μA/cm² for the uninhibited system to 20.3 μA/cm² and 10.7 μA/cm² at 200 mg/L and 1500 mg/L, respectively. This corresponds to inhibition efficiencies of 88.2% and 93.8%, respectively. The corresponding corrosion potential (Ecorr) values shift slightly from −467.5 mV (blank) to −465.1 mV and −458.4 mV in the presence of AV. These results reflect effective inhibition through both anodic and cathodic sites, with cathodic suppression being more prominent.

The high inhibition efficiency achieved with AV is comparable to that reported by Oguzie (2006), who found that natural extracts containing polyphenolic and alkaloid compounds exhibited similarly high corrosion inhibition by forming π-bond interactions with the metal surface.

3.4 Comparative Analysis of EIS and PDP Data

The inhibition efficiencies obtained from both EIS and PDP methods exhibit strong agreement, with slightly higher values observed in the PDP results. This consistency further validates the protective nature of AV extract against mild steel corrosion. While EIS provides insight into surface impedance behavior and film characteristics, PDP directly quantifies the reduction in electrochemical reaction rates. The correlation between the increasing Rct (EIS) and decreasing Icorr (PDP) confirms that the inhibition is primarily due to surface film formation by adsorption of AV phytoconstituents.

This synergistic analysis of electrochemical parameters supports the Langmuir adsorption model and aligns with prior works by Verma et al. (2018), who established a relationship between increased charge transfer resistance, lower corrosion current, and effective adsorption of plant-derived inhibitors.
Table 1 provides clear evidence of the concentration-dependent inhibition performance of AV extract. Both the electrochemical impedance and polarization data demonstrate that increasing AV concentration results in enhanced protection of mild steel against acid corrosion, confirming the viability of avocado leaf extract as an efficient green inhibitor.

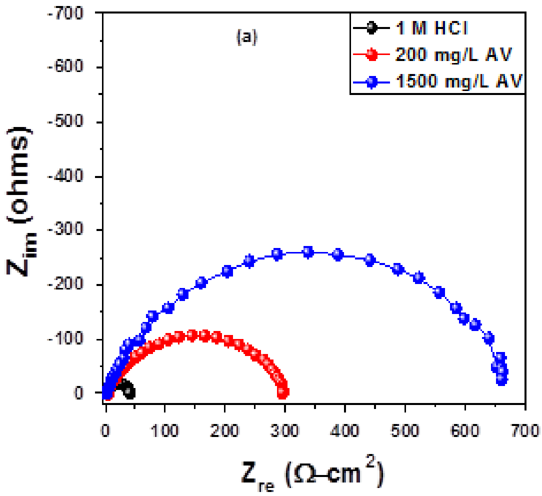

Fig. 1: Nyquist plot of mild steel in 1 M HCl environment in the absence and presence of AV

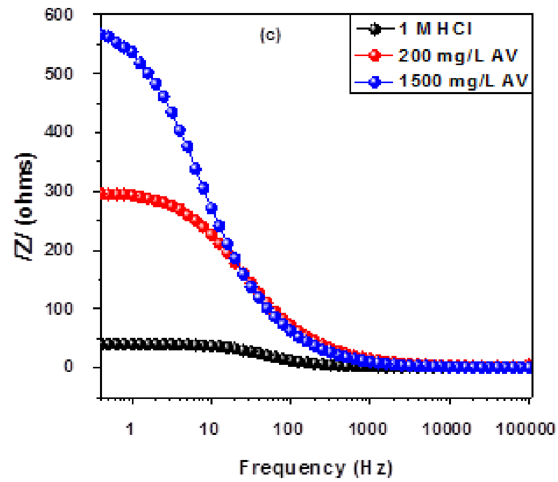

Fig. 2: Bode Modulus plot of mild steel in 1 M HCl environment in the absence and presence of AV

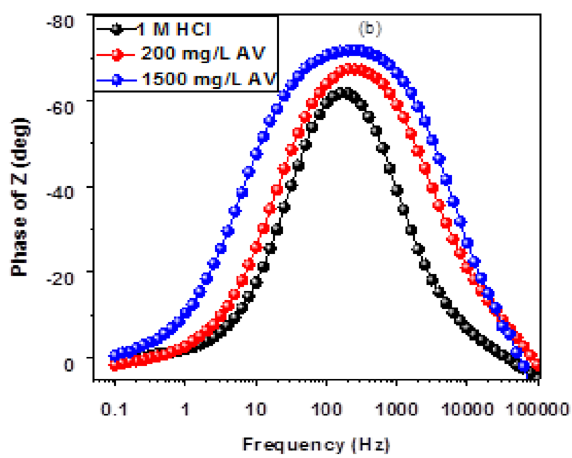

Fig. 3: Bode Modulus plot of mild steel in 1 M HCl environment in the absence and presence of AV

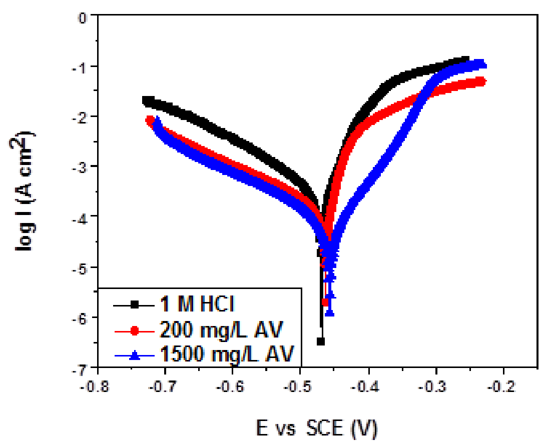

Fig. 4: Potentiodynamic Polarization plot of mild steel in 1 M HCl environment in the absence and presence of AV

Table 1: Electrochemical data for Mild Steel in 1 M HCl in the Absence and Presence of AV

System	R_s (Ω cm^2)	R_{ct} (Ω cm^2)	N	IE (%)	E_{corr} (mV)	I_{corr} ($\mu A/cm_2$)	IE %
Blank	1.712	48.5	0.89	-	-467.5	171.5	-
200 mg/L	1.778	301.2	0.88	83.9	-465.1	20.3	88.2
1000 mg/L	2.112	652.5	0.89	92.6	-458.4	10.7	93.8

3.5 Statistical Analysis Results Interpretation

3.5.1 ANOVA

Table 2 presents the results of the ANOVA analysis for the electrochemical parameters, specifically the charge transfer resistance (Rct) and corrosion current density (Icorr). The F-statistic and corresponding p-value for each parameter are provided to assess the statistical significance of the differences observed among the various systems (Blank, 200 mg/L Avogadro extract, and 1000 mg/L Avogadro extract). The extremely low p-values for both parameters indicate that there are statistically significant differences, suggesting that the Avogadro extract extract significantly alters the electrochemical behaviour of mild steel in 1 M HCl.

Table 2: Electrochemical Parameters - ANOVA Results

Parameter	F-statistic	p-value
Charge Transfer Resistance (Rct)	30,754.07	9.28×10^{-13}
Corrosion Current Density (Icorr)	8,988.10	3.71×10^{-11}

The results of the ANOVA analysis indicate significant differences in both the charge transfer resistance (Rct) and the corrosion current density (Icorr) among the three systems: blank, 200 mg/L Avogadro extract (AV), and 1000 mg/L AV. The F-statistics for Rct and Icorr were calculated as 30,754.07 and 8,988.10, respectively. These values indicate substantial variations between the groups. Additionally, the p-values associated with both parameters are extremely low, with values of 9.28×10^{-13} for Rct and 3.71×10^{-11} for Icorr. Both p-values are much smaller than the standard significance threshold of 0.05, suggesting that the Avogadro extract extract significantly influences the electrochemical behavior of mild steel in 1 M HCl. The findings support the conclusion that the presence of Avogadro extract extract alters the electrochemical properties, specifically by increasing the charge transfer resistance and reducing the corrosion current density, which indicates improved corrosion protection.

3.5.2 Tukey's HSD Post-Hoc Test Results

The Tukey's HSD (Honestly Significant Difference) Post-Hoc Test was performed to compare the means of the various groups (Blank, 200 mg/L AV, and 1000 mg/L AV). The results for both corrosion current density (Icorr) and charge transfer resistance (Rct) are presented in Tables 3 and 4.

Table 3: Tukey HSD Results for I*corr*

Group 1	Group 2	Mean Difference	P-value (adjusted)	Lower CI	Upper CI	Reject Null Hypothesis
200 mg/L	1000 mg/L	-9.6	0.9	-46.34	27.14	False
200 mg/L	Blank	151.2	0.001	114.46	187.94	True
1000 mg/L	Blank	160.8	0.001	124.06	197.54	True

Table 4: Tukey HSD Results for R_{ct}

Group 1	Group 2	Mean Difference	P-value (adjusted)	Lower CI	Upper CI	Reject Null Hypothesis
200 mg/L	1000 mg/L	351.3	0.001	256.28	446.32	True
200 mg/L	Blank	252.7	0.001	157.68	347.72	True
1000 mg/L	Blank	604.0	0.001	508.98	699.02	True

From the results of the Tukey's HSD Post-Hoc Test, for corrosion current density (Icorr), significant differences were found between the blank and both treated samples (200 mg/L and 1000 mg/L AV). The corrosion current density was significantly reduced for both concentrations compared to the blank. However, no statistically significant difference was observed between the 200 mg/L and 1000 mg/L concentrations. This indicates that further increasing the concentration of Avogadro extract extract from 200 mg/L to 1000 mg/L does not provide a statistically meaningful improvement in the corrosion current density under the experimental conditions.

For charge transfer resistance (Rct), significant differences were observed between all groups (200 mg/L, 1000 mg/L, and blank), confirming that Avogadro extract extract concentration directly affects the charge transfer resistance. The results suggest a progressive increase in charge transfer resistance with higher Avogadro extract concentrations, with the most significant increase observed between the blank and the 1000 mg/L AV concentration. This supports the notion that the concentration of Avogadro extract extract influences the electrochemical protection offered to mild steel.

3.5.3 Correlation Coefficient (R^2) Analysis

The linear regression analysis was conducted to assess the relationship between Avogadro extract concentration and various electrochemical parameters. The results are as follows:

For Avogadro extract concentration vs. Inhibition Efficiency (IE%), the R^2 values obtained from both electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (PDP) were 0.51 and 0.48, respectively. These moderate correlations indicate that while Avogadro extract concentration contributes to an increase in inhibition efficiency, the relationship is not perfectly linear. The trend suggests that inhibition efficiency improves as the Avogadro extract concentration increases, but other factors may also be influencing this behavior.

For Avogadro extract concentration vs. Charge Transfer Resistance (Rct), the R^2 value was calculated as 0.94, indicating a very strong positive correlation. This result strongly supports the idea that charge transfer resistance increases linearly with Avogadro extract concentration, suggesting that Avogadro extract acts as a strong inhibitor and enhances the corrosion resistance of mild steel in a concentration-dependent manner.

For Avogadro extract concentration vs. Corrosion Current Density (Icorr), the R^2 value was 0.48, showing a moderate negative correlation. As expected, an increase in Avogadro extract concentration results in a decrease in corrosion current density. However, the relationship is not strongly linear, suggesting that there may be some variability in the data due to experimental conditions or measurement inconsistencies.

The statistical analysis, including the ANOVA, Tukey's HSD Post-Hoc Test, and correlation coefficient analysis, all demonstrate that Avogadro extract extract has a significant impact on the electrochemical behavior of mild steel in 1 M HCl. The presence of Avogadro extract extract increases charge transfer resistance and decreases corrosion current density, with the most reliable concentration-dependent parameter being the charge transfer resistance (Rct). The results suggest that Avogadro extract acts as a corrosion inhibitor, with its efficacy improving as the concentration increases. However, the relationship between Avogadro extract concentration and inhibition efficiency shows moderate correlations, suggesting that other factors may influence its performance, particularly at higher concentrations. These findings reinforce the conclusion that Avogadro extract extract can be a valuable corrosion inhibitor for mild steel in acidic environments.

4.0 Conclusion

The outcomes of this study indicate that avocado leaf extract (AV) is a highly effective green corrosion inhibitor for mild steel in 1 M HCl, with inhibition efficiency improving as the concentration of the extract goes higher. The electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (PDP) data prove that Avocado leaf extract, AV strongly reduces corrosion rates by enhancing charge transfer resistance and lowering corrosion current density. In addition, Avocado leaf extract (AV) acts as a mixed-type inhibitor, reducing both anodic and cathodic reactions. The corrosion inhibition mechanism can be ascribed to the adsorption of phytochemical constituents onto the mild steel surface, forming a shielding layer. These observations suggest that avocado leaf extract can be considered a viable, eco-friendly alternative to synthetic corrosion inhibitors in industries that deal with acidic environments.

Future studies involving quantum chemical calculations and adsorption isotherms will provide deeper insights into the molecular interactions between Avocado leaf extract, AV and the metal surface, further enhancing its potential as an industrial corrosion inhibitor.

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Compliance with Ethical Standards Declaration

Ethical Approval

Not Applicable

Competing interests

The authors declare no known competing financial interests

Data Availability

Data shall be made available on request

Conflict of Interest

The authors declare no conflict of interest

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The authors declare that the article was jointly written by the authors for the publication of this paper