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Performance of Acetone Extract of *Anthocleista grandiflora* as a Potential Bioinhibitor on Corrosion Behavior of Carbon Steel in Seawater Environment

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Abstract

In this study, we evaluated the potential of *Anthocleista grandiflora* leaf (AGL) plant extract as an environmentally friendly and cost-effective corrosion inhibitor for carbon steel in seawater. We employed various experimental methods, including gravimetric analysis, potentiodynamic polarization, electrochemical impedance spectroscopy, scanning electron microscopy (SEM) and Fourier transform infrared spectrophotometry (FTIR). Our findings indicate that increasing the concentrations of the AGL extract results in higher charge transfer resistance (R_{ct}) and reduced double-layer capacitance (C_{dl}), suggesting the effective adsorption of AGL extract on the surface of carbon steel. The inhibition efficiencies were notably high, 98.7%, 92.40%, and 90.7% determined with gravimetric analysis, potentiodynamic polarization, and electrochemical impedance spectroscopy, respectively. Polarization analysis revealed that the AGL extract acted as a mixed-type inhibitor. Moreover, the results obtained from different techniques exhibited a consistent agreement. The SEM images revealed that the surface layer formed by the AGL extract on the mild steel surface further devoids the surface from pitting as the extract concentration increases. Comparative analysis with similar bio-based inhibitors suggested that the tested AGL extract holds a significant promise as a corrosion inhibitor for carbon steel in seawater. Therefore, our findings support the recommendation of utilizing this AGL extract as an effective anti-corrosion agent in marine industries, owing to its green, low-cost, and efficient characteristics.

Keywords

carbon steel, *Anthocleista grandiflora*, phytochemical, mixed-type inhibitor, anti-corrosion, seawater

1 Introduction

The corrosion of carbon steel poses a significant challenge in various industrial processes due to exposure to corrosive substances like acids, alkalis, and salt solutions. This issue has spurred considerable research interest aimed at mitigating the detrimental effects of corrosion on metals and their alloys [1–7]. Corrosion, defined as the degradation of metallic materials through physico-chemical interaction with the environment, adversely affects their properties, applications, and leads to significant safety and economic losses [8–11]. The economic impact of corrosion is substantial, estimated to range from 1% to 5% of the gross national product of an industrialized country, particularly evident in countries like China, USA, Japan, and Germany [12–15]. Carbon steel, widely used in civil construction, agriculture, maritime, and industrial applications, is particularly susceptible to corrosion despite its advantages such as good mechanical resistance, cost-effectiveness, availability, and high ductility [16–18]. Addressing the corrosion of carbon steel is a paramount concern for both the scientific and industrial communities. Improper handling can significantly diminish its functional properties and visual appeal. Various corrosion protection techniques have been employed, including the

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application of inhibitors to minimize corrosion's detrimental effects [1–5]. often prioritize natural or organic-based inhibitors due to their high availability, non-toxicity, and ease of obtaining from abundant natural sources [6–9].

A range of natural ingredients, such as *Syzygium cumini* leaves [19], *Ecuadorian citrus* peels [20], human hair [21], *Eruca sativa* seeds [22], and *Acanthopanax senticosus* [23], have been extensively studied as corrosion inhibitors to mitigate corrosion effects on various metals. Additionally, waste materials like waste *Biebersteinia multifida* root, [24] and eggshell agro-industrial wastes, [25] have shown promising corrosion inhibition efficiency. However, prudent utilization of natural resources is imperative. Presenting scientific, logical, and economical information is crucial in utilizing plant extracts as green materials for corrosion inhibitors, ensuring a systematic and strategic approach to their use for enhanced effectiveness and efficiency. Despite the availability of numerous corrosion-resistant materials, many rely on synthetic, engineered items that are harmful to the environment. Hence, plant extracts emerge as an excellent and preferable choice for environmentally friendly, readily available, low-cost, biodegradable, and non-toxic corrosion inhibitors [16, 23]. *Anthocleista grandiflora*, also known as the "forest fever" tree, is a large tree found in the moist forests of the eastern, western, and southeastern African tropics, as well as on the Comoros. The flowers of this tree appear in cymes, often grouped into thyrses, and can sometimes be umbel-like, scorpioid, or reduced to single flower bracts, which are typically small. These flowers are usually bisexual and cream-colored. While the tree is not edible, its roots, stems, bark, leaves, and flowers have been used for several medicinal purposes [26, 27]. Notably, few or no studies have explored the use of *Anthocleista grandiflora* leave (AGL) extract for corrosion inhibition on carbon steel in seawater. Therefore, the present study aims to contribute to the growing interest in eco-friendly, readily available, biodegradable, and non-toxic corrosion inhibitors by examining the ability of the AGL acetone extract to act as a green inhibitor against the corrosive effects of aggressive environments like seawater. AGL has been previously studied for its medicinal purposes [28–30], adding further value to its potential application as corrosion inhibitor is our main focus.

2 Materials and method

2.1 Preparation of the metal probes

Corrosion investigations were conducted on carbon steel with the following compositions: C (0.13%), Mn (0.82%), P (0.47%), Cr (0.08%), and Fe (99.50%). Before subjecting the carbon steel to corrosion, it underwent mechanical cutting. The size is 2 cm × 2 cm with a thickness of 0.5 cm. Subsequently, the surface of each coupon was meticulously polished using 400, 800, and 1200 grit emery papers to achieve a smooth surface. Following this, the coupons underwent degreasing with acetone, followed by rinsing with distilled water to eliminate debris, and finally dried with warm air, adhering to the methodology outlined in a prior study [31].

2.2 Preparation of the AGL extract

The identified AGLs were gathered from mature plants at Nigeria Maritime University premises, totalling 1.5 kg. Upon collection, they were carefully transported to the laboratory in a sealed plastic bag, where they underwent washing with distilled water and ethanol. Subsequently, the leaves were air-dried for four days in a controlled environment before being ground into powder and stored in sample bottles for the extraction process. A cold extraction method was employed, utilizing a powder-to-solvent volume ratio of 1:10, with soaking lasting for 72 h [32]. Following the extraction, the residue was filtered through Whitman filter paper and air-dried until a constant mass was achieved, allowing the comparison of the masses of the pre- and post-extraction particle and to determine the relative amounts of plant material extracted [33]. The collected crude extract (filtrate) was then diluted in a 1000 mL of seawater to obtain the required working concentrations (200, 400, 600, and 800 ppm). The ethanol and acetone utilized in the experiment were of analytical grade.

2.3 Gravimetric technique

Gravimetric measurements were conducted over a span of 75 days at various temperatures ranging from 303 K to 318 K, utilizing a thermostated bath. Pre-weighed steel specimens, having been washed, were immersed in beakers containing seawater, both without and with varying concentrations of the acetone extract derived from AGL, under static conditions within the thermostated bath. At intervals of 15 days, the corroded steel specimens were retrieved. Following the retrieval, the specimens underwent thorough washing with distilled water, acetone rinsing, drying via a stream of warm air, and subsequent reweighing to determine the mass loss.

The experiments were conducted in duplicate, with only the average values of the mass losses being reported. The collected mass loss data were then utilized to calculate the corrosion rate (CR) and inhibition efficiency (IE%) using Eqs (1–4), as per established methodologies outlined in the literature [34–36].

$$\Delta W = W_i - W_a, \quad (1)$$

$$CR \frac{W_{bl} - W_{\text{inh}}}{A \times T}, \quad (2)$$

$$\text{IE\%} = \frac{W_{\text{blank}} - W_{\text{inh}}}{W_{\text{blank}}} \times 100, \quad (3)$$

$$\theta = \frac{W_{\text{blank}} - W_{\text{inh}}}{W_{\text{blank}}}, \quad (4)$$

where W_i and W_a are initial and after treatment mass of the specimens. W_{blank} and W_{inh} are the mass loss values obtained in the uninhibited and inhibited environments, respectively; A is the total surface area of the specimen (m^2) and T denotes period of exposure (day). θ is the corrosion inhibition parameter.

2.4 Potentiodynamic polarization measurements

The Potentiostat/Galvanostat 263 (Princeton Applied Research, USA) electrochemical system workstation was utilized to perform the potentiodynamic polarization (PDP) measurements. The carbon steel specimen with a working electrode area of 0.5 cm^2 was exposed to the seawater, while a platinum foil measuring 2 cm × 2 cm served as the counter electrode. Saturated calomel electrode (SCE) were employed as reference electrode. All electrochemical measurements were conducted at 298 K, utilizing 100 mL of electrolyte (seawater) under stationary conditions. Prior to the PDP (Tafel) measurement, the electrode was immersed into the test solution at open circuit potential (OCP) for 300 s to ensure its stability. PDP curves were recorded within the range of –300 mV to +300 mV around the OCP, employing a scan rate of 0.16 mV/s [37]. Additionally, electrochemical impedance spectroscopy (EIS) measurements were performed within the frequency range of 0.1 Hz to 0.5 MHz, with 10 points per decade. The objective of these tests was to analyze the influence of the concentrations of AGL extract on the electrochemical behavior of carbon steel in a seawater solution, employing inhibitor concentrations of 200, 400, 600, and 800 ppm, respectively. Each test was conducted in triplicate to ensure the reproducibility of the average values obtained. All reported potentials were referenced to SCE. The values of the pertinent electrochemical corrosion kinetic parameters, including corrosion current density (I_{corr}), corrosion potential (E_{corr}), and the cathodic and anodic Tafel slopes (β_c and β_a), were derived by extrapolating the polarization curves. The percentage of inhibition efficiency (%IE) and η for PDP and EIS were calculated from I_{corr} and R_{ct} values, respectively, using the following equations:

$$\text{\%IE} = \frac{I_{corr(\text{blank})} - I_{corr(\text{inh})}}{I_{corr(\text{blank})}} \times 100, \quad (5)$$

$$\eta = \frac{R_{ct1} - R_{ct0}}{R_{ct1}} \times 100, \quad (6)$$

where $I_{corr(\text{blank})}$ and $I_{corr(\text{inh})}$ are the corrosion current density values in the absence and presence of inhibitor. R_{ct0} and R_{ct1} are the charge transfer resistances without and with inhibitors, respectively.

2.5 Characterization of the AGL extract

The titrimetric technique was employed to ascertain the phytochemical composition of the extract. Before conducting the experiment, Fourier transform infrared spectrophotometry (FTIR) analysis was conducted to characterize the AGL with a Nicolet iS50 FTIR spectrometer, (Thermo Fisher Scientific, USA). FTIR is a powerful analytical tool that provides information about the molecular structure and functional groups present in a sample by measuring the absorption of infrared radiation. By analyzing the FTIR spectra, the active functional groups present in the AGL sample can be identified, aiding in understanding its chemical composition and potential inhibitive characteristics.

2.6 Scanning electron microscopy

To assess the corrosion level of the mild steel surfaces exposed to seawater, we submerged mild steel samples in seawater solutions, both with and without AGL extract, for 12 h. Subsequently, we examined the morphology of the mild steel surfaces using a JSM-7800 (JEOL Ltd., Japan) scanning electron microscope (SEM).

3 Results and discussion

3.1 Phytochemical screening

Table 1 presents the outcomes of the phytochemical analysis of the acetone extract derived from AGL. These results reveal the presence of various phytochemical compounds, including flavonoids, saponins, tannins, among others, all of which play pivotal roles in corrosion inhibition [38]. The phytochemical constituents identified in the extract are primarily accountable for its inhibitory effects, as they contain heteroatoms capable of forming intricate chemical bonds with the carbon steel [39]. Organic compounds employed as corrosion inhibitors often incorporate heteroatoms such as nitrogen, oxygen, phosphorus, and sulfur,

Table 1 Phytochemical analysis chart

Phytochemical constituents	Confirmation
Flavonoids	+++
Saponins	++
Tannins	+
Steroids	+
Cardiac glycosides	++
Phenols	+
Teroenoids	+

+ + + : Highly present, + + : Moderately present, + : Trace amount

also in polar functional groups, like CHO, COOH, and OH, which are prevalent in aromatic and heterocyclic compounds [40, 41]. The presence of lone pairs of electrons associated with these heteroatoms facilitates the formation of protective shields, effectively reducing the corrosion rate [42, 43]. Given that corrosion is an electrochemical phenomenon involving electron loss, heteroatoms function as corrosion inhibitors through an adsorption process at the metal/corrosive agent interface, thereby compensating for electron loss and impeding the further corrosive degradation of the carbon steel surface [43]. Similar conclusions have been drawn in previous studies [44, 45]. These findings emphasize the significant inhibitory potential of AGL extract, attributed to the presence of phytochemicals containing heteroatoms, thus rendering it highly effective in corrosion inhibition.

3.2 FTIR analysis of the AGL extract

A Fourier transform infrared spectrophotometer was used to determine the molecular structure and functional groups present in the AGL extract at room temperature, dried sample. Each peak observed in the spectrum, as depicted in Fig. 1, corresponds to specific functional groups, identifying the chemical composition of the extract. According to the data presented in Table 2, the peak at 3191.28 cm^{-1} signifies the presence of O-H stretching, indicative of alcohol compounds. Additionally, a prominent peak observed at 2111.72 cm^{-1} indicates C=C stretching, characteristic of alkene compounds. Furthermore, medium peaks observed at 1593.85 cm^{-1} and 1239.05 cm^{-1} correspond to N-H bending and C-O stretching vibrations, respectively, suggesting the presence of amine and carbohydrate compounds within the extract. The anticorrosion efficacy of AGL extract can be attributed to the nature and characteristics of the heterocyclic compounds present. The protective mechanism against corrosion of carbon steel in seawater with AGL extract can be understood from the perspective of molecular adsorption. This phenomenon occurs as the heteroatoms within the phytochemical constituents of the AGL extract establish coordinate bonds with the vacant *d*-orbitals of iron and adhere to the steel surface, forming a stable thin film layer that impedes electrochemical reactions [46, 47]. Therefore, the diverse functional groups present in the AGL extract, including O-H, C=C, N-H, C-O and O-N bonds, facilitate the adsorption process and effectively reduce the corrosion rate [48].

3.3 Gravimetric analysis

The experiment involved measuring the mass loss of carbon steel samples immersed in seawater over various time intervals, both without and with different concentrations of AGL extract. The relationship between mass reduction and time is graphically depicted in Fig. 2. It was observed that the corrosion inhibition efficiency is influenced by the concentration of the extract.

The curves representing different extract concentrations consistently exhibited lower mass reductions compared to those without extract concentration. This indicates that increasing the concentration of the AGL extract led to a reduction in mass loss and an increase in the protection against metal corrosion. Experimental data strongly support the notion that the AGL extract serves as an effective inhibitory substance against carbon steel corrosion in a seawater environment. Moreover, θ and %IE, attributed to the formation of a protective thin layer as described by Eq. (4), exhibited an upward trend with increasing extract concentration [49]. Detailed experimental results are provided in Table 3, highlighting the inhibitory effects of the AGL extract on carbon steel corrosion in seawater, and the corresponding increase in protection with higher extract concentrations.

Fig. 3 illustrates the plots depicting the inhibition efficiency at various concentrations of AGL extract concerning carbon steel dissolution in seawater at 303 K. The plots demonstrate an initial rise in inhibition efficiency with increasing exposure time as the extract concentration increases. This is visible in the 600 ppm and 800 ppm but as the extract concentration decreases, there was a sudden decline, visible at days 45 to 75. It is widely recognized that the effectiveness of inhibitors diminishes with prolonged immersion time. This observation suggests that over an extended exposure period there may be a partial desorption of inhibitor molecules previously adsorbed on the metal surface [49]. The decrease in inhibition efficiency over time could also result from the development of corrosion products or an insoluble film on the surface of the carbon steel. This film acts as a barrier, impeding the penetration of aggressive ions from the corrosive environment and the diffusion of oxygen inward, consequently reducing the corrosion rate on the surface of the carbon steel.

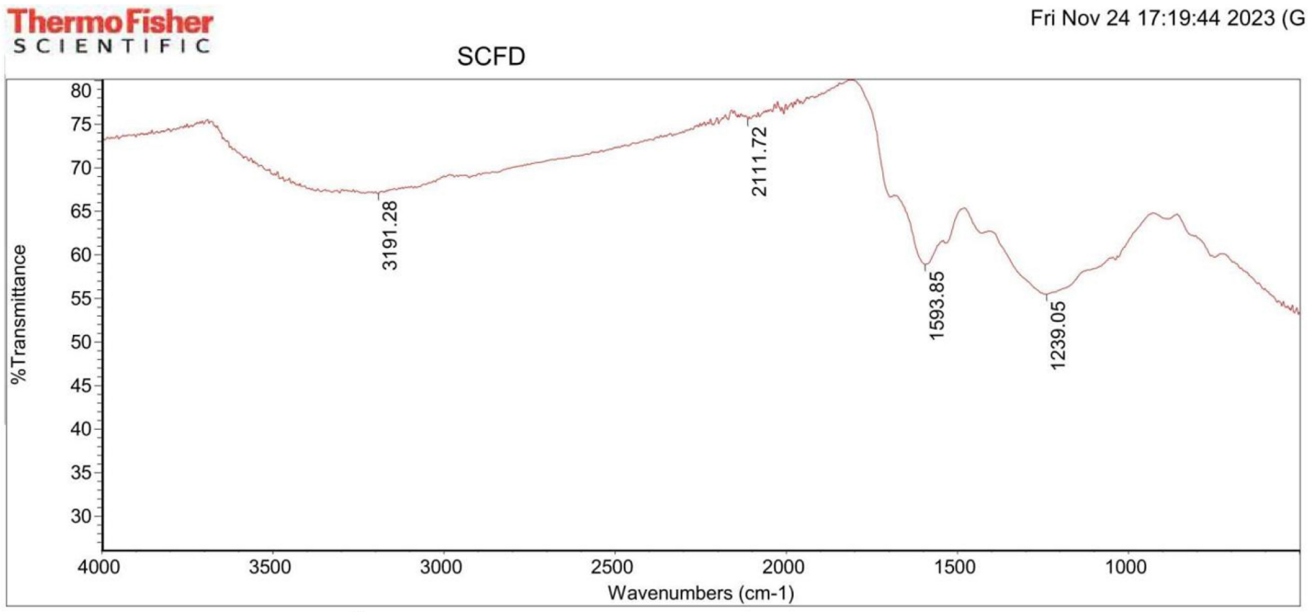

Fig. 1 Fourier transform infrared transmittance spectrum for AGL extract

Table 2 Interpretation of the FTIR spectrum of AGL extract

Wave number (cm^{-1})	Functional groups	Compounds
3191.28	O-H	Alcohol
2111.72	C=C	Alkene
1593.85	N-H	Amine
1239.05	C-O	Carbohydrate

Table 3 %IE and θ of the carbon steel dissolution in seawater from mass loss data at various AGL extract concentrations at 313 K

AGL extract concentration (ppm)	%IE	θ
200	64.3	0.643
400	78.6	0.786
600	88.6	0.886
800	98.7	0.987

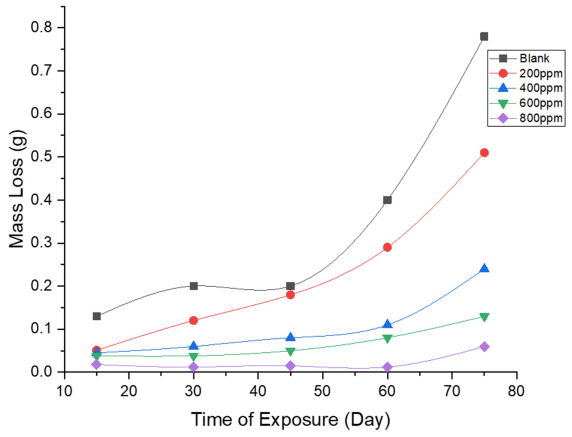

Fig. 2 Plots of mass loss versus time of exposure for the corroded carbon steel in seawater without and with various AGL extract concentrations at 318 K

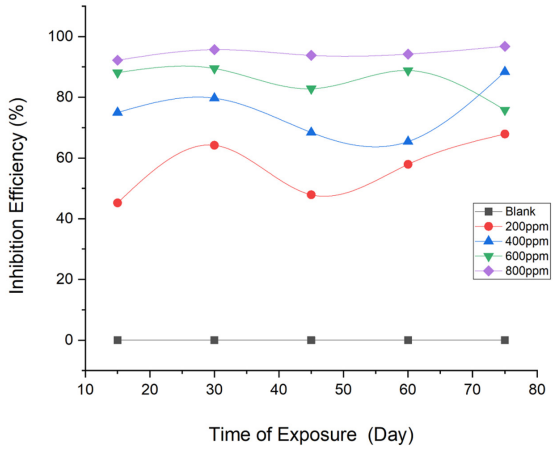

Fig. 3 Inhibition efficiency of AGL extract in various concentration for carbon steel protection in sea water at 303 K

Fig. 4 illustrates that as the concentration of AGL extract decreases over time, the corrosion rate of the AGL extract increases. This trend strongly suggests that as the concentration of the inhibitor decreases, the rate of corrosion penetration also increases. The significant reduction in the corrosion rate of carbon steel observed with the presence of AGL extract can be attributed to the adsorption of AGL extract molecules onto the surface of the carbon steel. As a result, the polar groups of the molecules attach directly to the metal surface, while the non-polar ends extend

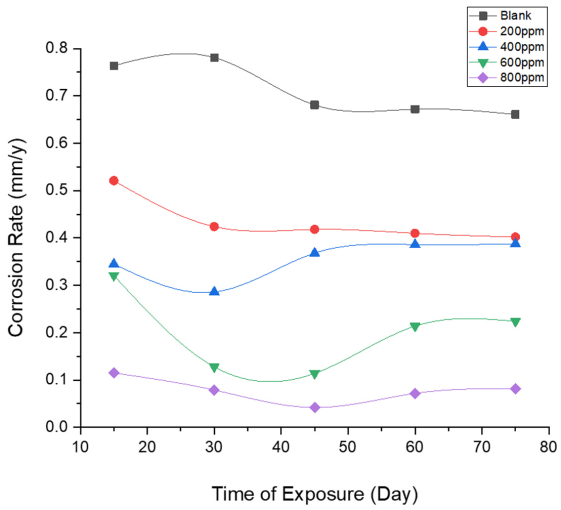

Fig. 4 Corrosion rate of carbon steel in seawater containing different concentrations of AGL acetone extract at 313 K

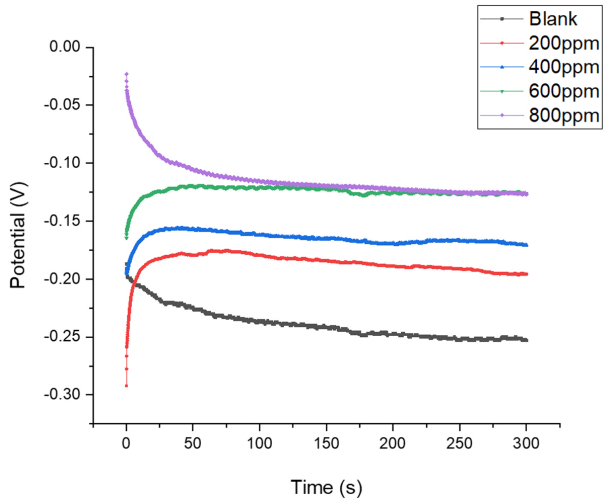

Fig. 5 OCP curves of carbon steel with and without acetone extract of AGL in seawater environment

vertically away from the surface of the carbon steel. This arrangement effectively repels corrosive species, creating a barrier against both chemical and electrochemical attacks from the surrounding environment [50].

Moreover, the inhibitor molecules act as physical impediments, restricting the diffusion of ions to and from the surface of the carbon steel. This restriction prevents the carbon steel atoms (ions) from participating in further anodic or cathodic reactions (redox reactions), consequently leading to a decrease in the corrosion rate. Overall, the adsorption of inhibitor molecules onto the surface of carbon steel effectively blocks or reduces the corrosion rate in aggressive environments, corroborating the findings of Ayeni et al. [49] and Bouklah et al. [50].

3.4 Electrochemical measurement

3.4.1 Open circuit potential

The OCP evaluation of the carbon steel substrate was conducted during a 300-second immersion period in seawater, both in the presence and absence of the AGL extract. The data portrayed in Fig. 5 revealed that the OCP reached a state of equilibrium within the initial 50 s of immersion, as evidenced by the absence of significant deviations from the OCP values thereafter. The trend of OCP for both conditions exhibited a similar trajectory, commencing at a lower potential and gradually increasing over time. This observed phenomenon can be attributed to the gradual formation of an oxide layer on the surface of the carbon steel, a natural response to the attack of corrosive species, untila stable state is achieved [51–53]. Notably, it was observed that the initial OCP value in the solution containing the AGL extract was higher compared to the blank solution. This discrepancy may indicate the adsorption of inhibitors onto the surface of the carbon steel [54]. Furthermore, a clear examination of the data illustrated in Fig. 5 showed that AGL primarily exerts its inhibition effects by impeding anodic reactions. This assertion is supported by the positive shift observed in the OCP upon the addition of the AGL extract [55]. In essence, the findings suggest that the AGL extract serves to modulate the electrochemical processes occurring at the surface of the carbon steel, thereby mitigating its corrosion in seawater environment.

3.4.2 Potentiodynamic polarization

Fig. 6 illustrates the PDP curve, accompanied by the corrosion current density and corrosion potential (E_{corr}) data presented in Table 4. The curve exhibits a mixed pattern, manifesting a downward shift in response to the current corrosion density. Tafel bends were meticulously calculated within a potential range of –300 to +300 mV against SCE at a scan

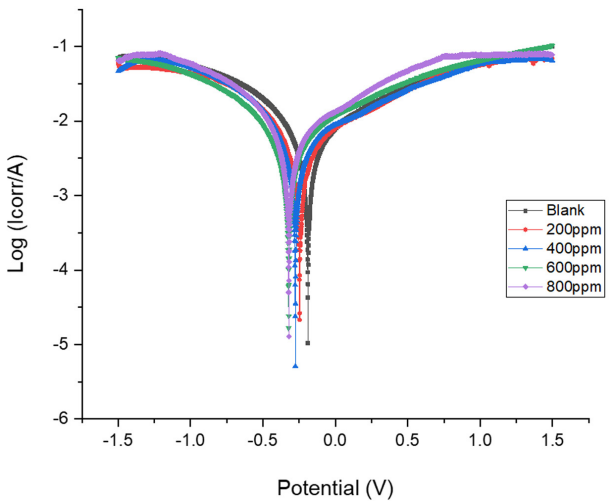

Fig. 6 Potentiodynamic polarization curves of carbon steel with and without acetone AGL extracts in saline environments.

Table 4 Polarization parameters of carbon steel in seawater without and with various concentration of AGL extract

Inhibitor concentration (ppm)	$-\beta_c$ (mV dec^{-1})*	β_a (V dec^{-1})*	E_{corr} *vs.* SCE (mV)	I_{corr} (mA cm^{-2})	*IE* (%)
0	102.1	75.6	–188.4	238.4	
200	106.4	103.4	–234.8	68.8	71.14
400	96.2	85.3	–368.4	48.5	79.66
600	101.2	82.9	–462.3	25.4	89.35
800	91.8	85.2	–485.5	18.2	92.40

*decade

rate of 0.16 mV/s. The results derived from this measurement divulge that the corrosion of carbon steel demonstrates a reduction with increasing extract concentration. The curves were subjected to fitting procedures, yielding E_{corr} and I_{corr} values. Notably, E_{corr} of the carbon steel specimens exhibits variation in both the positive (anodic) and negative (cathodic) directions, albeit with a magnitude of less than 85 mV. This observation suggests that the substance extracted from AGL acts as a mixed-type inhibitor. These are inhibitors that can inhibit both anodic and cathodic reaction, a finding consistent with the study by Khayatkashani et al. [24]. I_{corr} is widely acknowledged as a direct indicator of the corrosion rate. As depicted in Fig. 6, I_{corr} diminishes with increasing extract concentration. This PDP curve indicates that the AGL extract effectively inhibits steel corrosion in seawater. One plausible explanation for this phenomenon could be linked to the hindrance of the active corrosion sites on the carbon steel surface by the adsorption of the biomolecules through their heteroatoms [56]. This impediment serves to shield the carbon steel surface from corrosive attack, thereby attenuating the corrosion rate in seawater environment.

3.4.3 Electrochemical impedance spectroscopy

EIS experiments serve as a valuable tool for analyzing and interpreting corrosion reactions occurring on diverse metal surfaces. In Fig. 7, EIS curves of carbon steel in a seawater solution are presented both with and without the presence of AGL extract. These measurements were conducted at a controlled temperature of approximately 298 K, encompassing a frequency range from 100 kHz to 0.1 Hz, with a perturbation of 5 mV to facilitate the analysis of EIS parameters. The Nyquist curve exhibits a distinct depressed semicircle pattern, wherein the diameter of this semicircle exhibits a positive correlation with the concentration of the extract utilized. The obtained values indicate that an increase in AGL extract concentration results in elevated charge transfer resistance (R_{ct}) values and diminished double-layer capacitance (C_{dl}). The augmentation of R_{ct} with escalating inhibitor concentration is likely attributable to

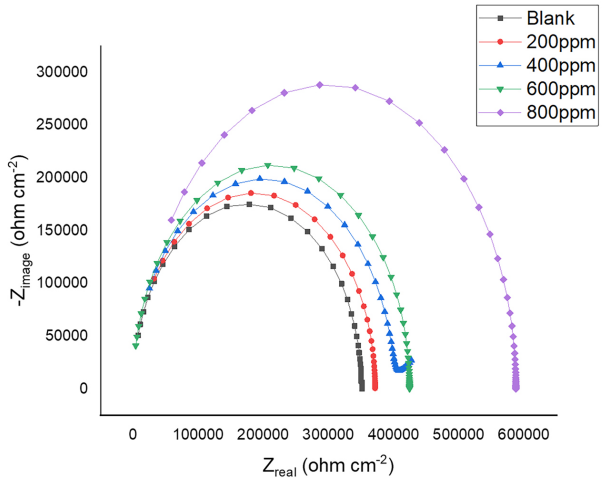

Fig. 7 EIS plots for carbon steel in seawater without and with various concentration of AGL extract

the gradual adsorption of AGL extract onto the metal surface. Conversely, the decrease in C_{dl} values with increasing AGL extract concentration can be attributed to the reduction in the local dielectric constant and the thickening of the electrical double layer. This phenomenon serves as a clear indication of the adsorption of inhibitor molecules onto the metal/solution boundary [57–60].

These findings are consistent with and corroborate the results of numerous preceding studies [61–64]. The EIS parameters of carbon steel in seawater are presented in Table 5, with the data obtained through EIS fitting utilizing the circuit model depicted in Fig. 8. This comprehensive analysis provides valuable insights into the interaction between AGL extract and carbon steel in a corrosive environment, shedding light on the inhibitory effects of the extract on corrosion processes.

3.5 SEM analysis

To better understand the inhibitory effects of the AGL extract the surface morphology of the mild steel was examined. SEM images of the mild steel surface after 120 days of immersion in seawater environment, with varying concentrations of AGL (200 ppm, 400 ppm and 800 ppm), are depicted in Figs. 9 (b–d). Without AGL extract as presented in Fig. (9a),

Table 5 EIS parameters of carbon steel in seawater without and with various concentration of AGL extract*

Inhibitor concentration (ppm)	R_s (Ω cm^{-2})	n	R_{ct} (Ω cm^{-2})	C_{dl} (μFcm^2)	η (%)
0	1.81	0.9	94.07	57.8	-
200	1.62	0.89	263.64	18.71	64.3
400	1.43	0.89	695.42	10.6	86.5
600	1.52	0.91	891.14	8.21	89.7
800	2.112	0.92	1001.58	6.91	90.7

*R_s: solution resistance; R_p: charge transfer resistance, n: surface heterogeneity; C_{dl}: double-layer capacitance

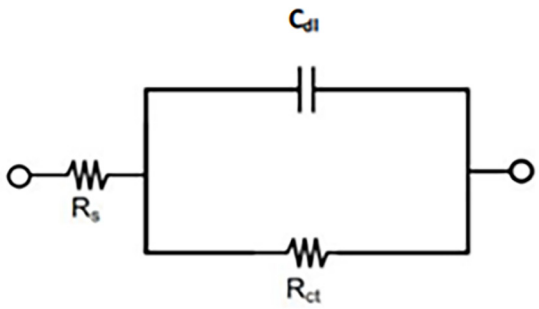

Fig. 8 Equivalent circuit for EIS data

deep pitting was observed on the carbon steel surface, indicating significant corrosion in the seawater environment. However, surfaces treated with AGL extract, especially at 800 ppm, exhibited smoother morphologies. This suggests that the molecules of the AGL extract adsorbed onto the carbon steel surface, forming a protective film that mitigated corrosion induced by the aggressive medium. Consequently, carbon steel experienced enhanced protection in the seawater environment when treated with AGL extract.

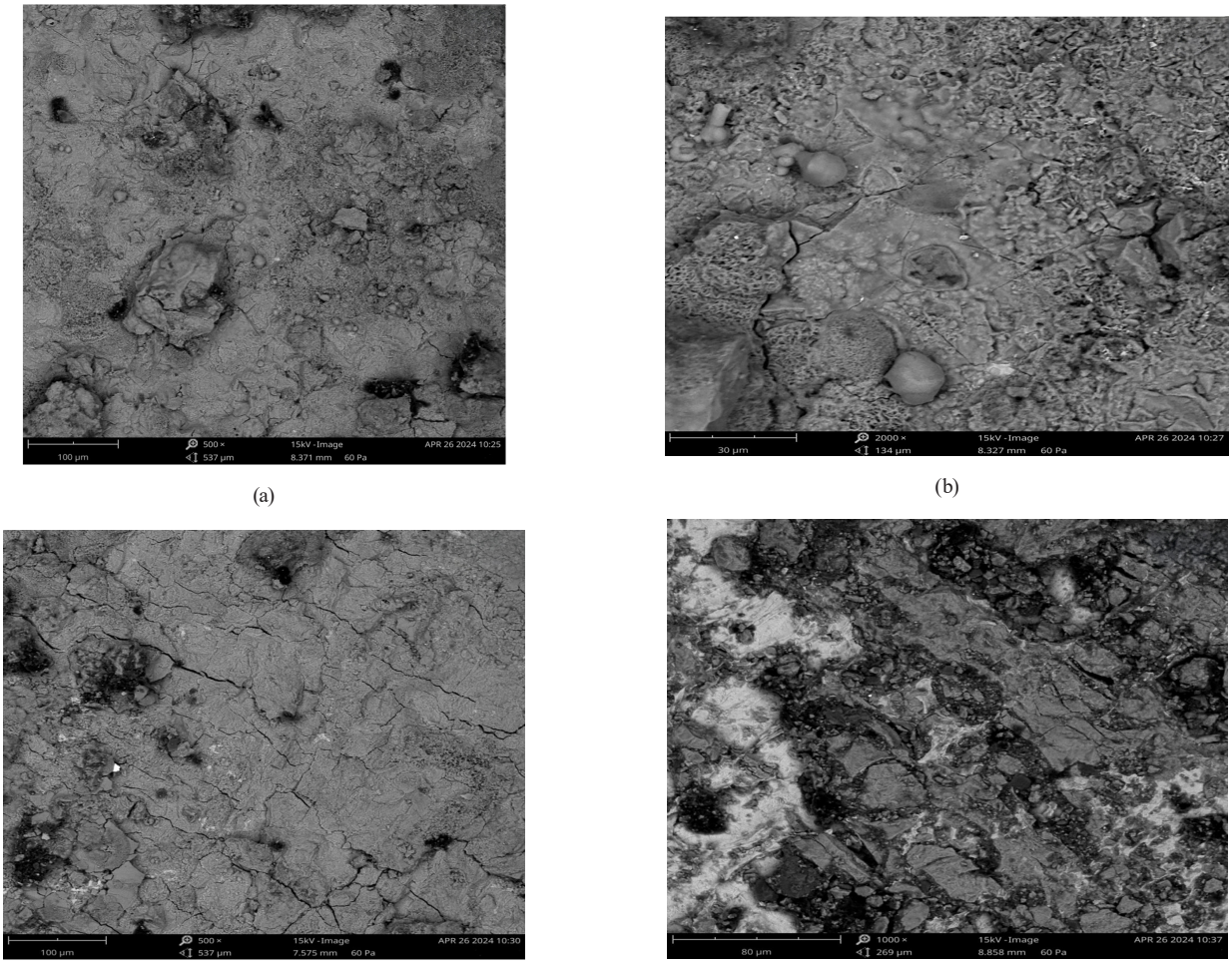

Fig. 9 SEM micrographs of mild steel after immersion to AGL extract free seawater (a); to seawater containing 200 ppm (b), 400 ppm (c) and 800 ppm (d) AGL extract in seawater

3.6 Comparative study

Table 6 provides a comparative analysis of the inhibitory effectiveness of the AGL acetone extract utilized in this study with several other inhibitory agents investigated earlier. The table illustrates that the extract derived from AGL exhibits favorable inhibitory performance when compared to existing inhibitors, and in fact, surpasses the performance of many inhibitors already available on the market. Notably, the acetone extract of AGL demonstrates competitive inhibition efficiency, achieving maximum efficiencies at minimal optimum concentrations when juxtaposed with some of the established inhibitors. This suggests that the extract investigated in this study holds promising potential as a corrosion inhibitor for carbon steel.

Table 6 revealed the significance of the AGL extract as a viable alternative to other green corrosion inhibitors, highlighting its efficacy and potential for practical application in corrosion protection strategies.

4 Conclusions

The following conclusions were deduced from the analysis of the results:

1. Inhibition efficiencies of 98.70%, 92.40%, and 90.7% were achieved through experimental studies employing gravimetric, potentiodynamic polarization, and electrochemical impedance spectroscopic techniques, respectively.
2. Phytochemical screening and FTIR analysis unveiled the presence of several phytochemical compounds in the extract, characterized by functional groups containing heteroatoms that facilitate inhibition activities. Notably, the inhibition efficiency percentage of the extract exhibited an increase with rising extract concentrations.
3. The AGL extract functioned as a mixed-type inhibitor, as evidenced by the potentiodynamic polarization and electrochemical impedance spectroscopy results, which indicated a consistent increase in charge transfer resistance and a concurrent decrease in double-layer capacitance in the presence of the AGL extract.
4. The SEM images revealed that as a result of AGL extract forming a surface layer on the mild steel surface further devoid the surface from pitting as the extract concentration increases.
5. A comparative analysis with similar bio-based inhibitors demonstrated that the tested AGL extract holds significant promise as a corrosion inhibitor for carbon steel in seawater. Consequently, this research presents the AGL extract as a viable anti-corrosion agent suitable for application in marine industries.

5 Competing interest

The authors declare that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

6 Availability of data and materials

The datasets used and/or analyzed during the current paper are available from the corresponding author on reasonable request.

7 Authors' contributions

S.O.O and E.O.O: conceived and designed the analysis, S.O.O, E.O.O, V.E.A and J.E.E; performed the experiment and analysis; S.O.O and V.E.A analyzed data and prepared the manuscript: All Authors offered vital intellectual support, assessed, reviewed and appraised the manuscript.

Table 6 Comparative table of inhibition efficiency of some bio-based extract

Inhibitor Extract	Metal form	Medium	Inhibitor concentration	Weight loss method, IE(%)	PDP IE(%)	EIS IE(%)	Reference
Solanum macrocarpon L	Mild steel	0.5 M H_2SO_4	0.5%w/v	95.00	-	-	[64]
Falcaria vulgaris L	Mild steel	1 M HCl	800 ppm	-	92.20	91.30	[63]
Arlemisia L	Mild steel	0.6 M NaCl	10 mL/L	87.50	-	-	[17]
Pigeon pea L	Mild steel	1.2 M HCl	0.9 g/L	85.71	92.10	90.10	[34]
Prosopia juliflora L	Low carbon steel	1 M HCl	300 ppm	87.70	90.70	91.50	[62]
Anthcleista grandiflora L	Low carbon steel	Seawater	800 ppm	98.70	92.40	90.70	Present study

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