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Benevolent Behavior of Arecanut Husk Extracts as Potential Corrosion Inhibitor for Aluminum in both 0.5 M HCl and 0.1 M NaOH Environments

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Abstract

The purpose of present study is to incite the effectiveness of green color arecanut husk extract as an inhibiting agent for aluminum metal in both 0.5 M HCl and 0.1 M NaOH systems. The protection efficiency of green inhibitor was assessed through gravimetric, and Tafel plot (potentiodynamic polarization) techniques. The weight loss experiment was performed in unstirred and stirred test solutions in order to study the stability of the inhibitory protective film on the surface of the aluminum. The influence of temperature and time on adsorption of arecanut husk extracts constituents on the surface of aluminum has been studied. Both Tafel and Nyquist curves measurement after the stabilization period of the aluminum metal in 0.5 M HCl/0.1 M NaOH solution confirmed that the introduction of arecanut husk extract appreciably decreased the rate of aluminum corrosion. The powder X-ray diffraction tool was used to study the nature of green inhibitor and its protective film created on aluminum metal in 0.5 M HCl and 0.1 M NaOH medium. The scanning electron microscopy and atomic force microscopy images confirm that the inhibited aluminum surface is superior compared to uninhibited aluminum surface.

Keywords Aluminum · Arecanut husk · Gravimetric · Tafel plot · Powder X-ray diffraction

1 Introduction

Aluminum metal possesses exceptional thermal, electrical, and mechanical properties. Because of high mechanical and corrosion resistance, specific weight (2.7 g/cm^3), low cost, and high stiffness, aluminum metal was widely applied in building material, transportation, aerospace, electrical engineering, household, and technological applications [1–4]. Aluminum metal oxidizes easily due to its high electronegative property. Hence, aluminum metal reacts with oxygen and produce aluminum oxide layer (Al_2O_3) [thickness 0.01 mm]. This impenetrable layer further ceases the reaction on aluminum metal.

$$2Al + 3/2O_2 \rightarrow Al_2O_3 \quad G^\circ = -1675\ kJmol^{-1}$$

The natural oxide layer formed on the surface of the aluminum is stable in between the pH range 3–8 and hence protects the metal from corrosion in such existing conditions. The hydrochloric acid and sodium hydroxide solutions are needed for several industrial applications. The natural oxide layer loses its strength when it is exposed to high concentration of acid and base solutions [5, 6]. Therefore, acid and base solutions attack on the free aluminum surface and deteriorate the metal structure.

The aluminum surface layer undergoes a subsequent series of reactions when in contact with an acid solution,

$$Al_2O_3 + 3H_2O \rightarrow 2Al(OH)_3 + 3H^+$$

$$Al(OH)_3 + H^+ \rightarrow Al(OH)_2{}^+ + H_2O$$

$$Al(OH)_2{}^+ + 2H^+ \rightarrow Al^{3+} + 2H_2O$$

Overall reaction:

$$Al_2O_3 + 6H^+ \rightarrow 2Al^{3+} + 3H_2O$$

Al^{3+}exists as $Al\left[\left(H_2O\right)_6\right]^{3+}$in acid solution.

Aluminum dissolution in alkaline systems involves following reactions:

$$Al_2O_3 + 3H_2O \rightarrow 2Al(OH)_3$$

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$$Al(OH)_3 + OH^- \rightarrow Al(OH)_4^-(aq)$$

$$Al_{(S)} \rightarrow Al^+ + e^-$$

$$H_2O + e^- \rightarrow OH^- + H^+$$

$$H + H \rightarrow H_2$$

$$Al + OH^- \rightarrow Al(OH)_{ads}$$

$$Al_{(S)} + H_2O \rightarrow Al(OH)_{ads} + \tfrac{1}{2}H_2$$

$$Al(OH)_{ads} + OH^- \rightarrow Al(OH)_{2,ads} + e^-$$

$$Al(OH)_{ads}{}^2 + OH^- \rightarrow Al(OH)_{3,ads} + e^-$$

$$Al(OH)_{3,ads} + OH^- \rightarrow Al(OH)_4^-$$

H_2 gas is produced due to reduction of H_2O molecules in the main cathodic process,

$$H_2O(surface) + e^- \rightarrow H + OH^-$$

$$H + H_2O(surface) + e^- \rightarrow H_2 + OH^-$$

Due to aluminum corrosion, huge losses occur in each year in all countries. The losses due to corrosion are categorized into two types: one is direct losses (includes corroded metal cost and labor charge of replacement) and the other one is indirect losses (includes losses in efficiency losses, product loss due to leakage, product contamination).

The indirect losses cannot be anticipated in terms of currency. So it is so particularly vital to recognize the mechanism of aluminum corrosion [7].

Corrosion inhibitors are the one of the best methods for aluminum metal degradation in both acid and base systems due to its low cost and high adsorption efficiency. Because of strict environmental regulations, industries consider the following points for the selection of inhibitors for various applications:

(i) Cost and availability of the inhibitor,
(ii) Stability of the inhibitor,
(iii) Affinity with corroding solution,
(iv) Eco-friendly nature,
(v) Biodegradable, and
(vi) High adsorption ability.

Majority organic compounds possessing sulfur, oxygen, nitrogen, and phosphorous atoms were greatly employed as effective corrosion inhibitors. But, great number of organic species are pricey and harmful to the environment. Therefore, more attention is paid on non-toxic and cheap corrosion inhibitors. Plant products are the richest sources of natural organic species which can be employed as ecological corrosion inhibitors [8–13].

Green arecanut husk is one of the waste natural products and employed as a fuel during arecanut processing. In epoxy composites, it is used as a reinforcing material. Arecanut husk possessing special elements in their lignin (amorphous in nature), hemicelluloses (amorphous in nature), cellulose (crystalline in nature), furfuraldehyde, propectin, and pectin groups [14–18]. Results of literature analysis revealed that special elements (nitrogen, phosphorus, oxygen, and sulfur) in organic species participate in the corrosion inhibition process through the adsorption mechanism (Fig. 1).

No specific information exists on the arecanut husk extract as a potential corrosion inhibitor for aluminum in both 0.5 M HCl and 0.1 M NaOH solution. Therefore, the present investigation is focused on finding the inhibiting property of arecanut husk extract at the electrode (aluminum)–electrolyte (0.5 M HCl/0.1 M NaOH solution) interface by weight loss (both stirred and unstirred conditions), Tafel plot, impedance, scanning electron microscopy (SEM) and atomic force microscopy (AFM) techniques. Further, crystalline or amorphous nature of the arecanut husk extract and its protective film on the surface of the metal was confirmed by powder X-ray diffraction technique.

2 Experimental Sections

2.1 Metal and Corrosive Media Under Study

The chemical composition of aluminum metal in percentage employed in the studies of corrosion is given in Table 1 [19]. 0.5 M HCl and 0.1 M NaOH solution are the media

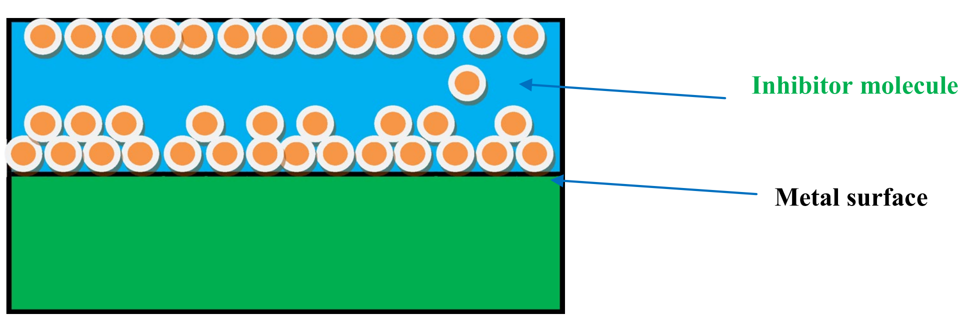

Fig. 1 Schematic demonstration of plant extract adsorption on the surface of the metal molecules on metal surface

Table 1 Al specimen composition

Element	Si	Fe	Zn	Tl	Cr	Mn	Cu	Mg	Al
Weight percentage	0.3–0.7	0.6	0.2	0.1	0.2	0.3	0.1	0.4–0.9	Remainder (96.9–97.8%)

employed in the aluminum corrosion inhibition study. Standard procedure is followed for the preparation of test solutions.

2.2 Inhibitor Used

The 100 g of small pieces of arecanut husk (submerged in 450 ml of 1% HCl solution for 1 day) was refluxed in a Soxhlet apparatus with 450 ml of 1% HCl solution for effective 5-h duration. Different concentrations (3, 6, 12, and 18 g/L) were prepared from the filtered solution.

2.3 Chemical Method

The polished (with different grades of sand papers) and cleaned aluminum metal was submerged in 100 ml of 0.5 M HCl/0.1 M NaOH solutions without and with the arecanut husk extract for predetermined temperature and time.

The removed aluminum metal was washed with running tap water and acetone to eliminate the corrosion products and differences in the weight of the aluminum metal were noted.

The protection efficiency of the arecanut husk extract was calculated by using the following formula:

$$\text{Protection efficiency of arecanut husk extract} = \frac{\left(W_1 - W_2\right)}{W_1} \times 100 \quad (1)$$

where W_2 is the aluminum weight loss by inhibiting corroding system (0.5 M HCl/0.1 M NaOH) and W_1 is the aluminum weight loss in uninhibited corroding system (0.5 M HCl/0.1 M NaOH).

Equation 2 was used to calculate the aluminum corrosion rate in protected and unprotected systems [20],

$$\text{Corrosion rate in mils penetration per year} = \frac{534W}{ATD}, \quad (2)$$

where W is weight loss (milligrams); A is the surface area (square inches); T is the immersion time (hours), and D is the density (gram per cubic centimeter).

2.4 Electrochemical Method

The electrochemical results (both potentiodynamic polarization and AC impedance spectroscopy) were obtained by CHI660C workstation, which consists three electrode systems, namely aluminum (working) electrode, platinum (counter) electrode, and calomel (reference) electrode. The 1 cm^2 area of aluminum electrode was immersed in 0.5 M HCl/0.1 M NaOH solution without and with different concentrations of the arecanut husk extract. Tafel curves are recorded potentiodynamically with a scan rate of 0.01 V/s in between the potential range ± 200 mV. Nyquist plots were obtained in the frequency range of 100,000 to 1 Hz with an amplitude of 0.01 V.

2.5 Powder X-ray Diffraction Technique

Powder X-ray diffraction technique (Rigaku miniflex 600 W) was used to investigate the amorphous/crystalline nature of the arecanut husk extract and its protective film on the surface of the aluminum in 0.5 M HCl/0.1 NaOH solution after the 2-h immersion time.

2.6 Surface Examination

The aluminum surface condition in inhibiting and uninhibited systems after 2-h duration (simple immersion) was analyzed through scanning electron microscopy and atomic force microscopy techniques at 303 K.

3 Results and Discussion

3.1 Gravimetric Experiment

Mass loss (weight loss) experiment was carried out with four different concentrations of arecanut husk extract, to study the effect of the arecanut husk extract on aluminum surface in both 0.5 M HCl and 0.1 NaOH environments, gravimetric study was performed with different immersion times and temperatures. The parameters obtained from this method are listed in Tables 2, 3, 4. It is observed that the rise in the arecanut husk extract concentration from 3 to 18 g/L decreases the aluminum corrosion rate from higher to lower value. This indicated that increased concentration of arecanut husk extract increases the adsorption of plant extract constituents on aluminum surface, which strongly defend the aluminum metal surface in 0.5 M HCl and 0.1 M NaOH environments by creating a barrier for charge and mass transfer. Hence, the aluminum metal surface was strongly protected in 0.5 M HCl and 0.1 M NaOH solution by arecanut husk extract constituents.

The effect of contact time on protection efficiency of the arecanut husk extract was also studied by submerging aluminum metal in 0.5 M HCl/0.1 M NaOH solution from 1

Table 2 Weight loss results at laboratory temperature (303 K)

T	C (g/L)	Aluminum			
		0.5 M HCl		0.1 M NaOH	
		$\upsilon_{corr}\times10^{-4}$ (mpy)	η_w (%)	$\upsilon_{corr}\times10^{-4}$ (mpy)	η_w (%)
1	Blank	8.699		61.86	
	3	1.933	77.778	19.33	68.75
	6	1.449	83.333	16.91	72.656
	12	0.966	88.889	12.08	80.468
	18	0.483	94.444	5.79	90.625
2	Blank	11.116		62.83	
	3	2.658	76.087	20.54	67.307
	6	1.933	82.609	18.84	70.000
	12	1.449	86.957	12.32	80.388
	18	0.966	91.304	7.24	88.461
3	Blank	16.110		64.44	
	3	4.027	75.000	22.55	65.000
	6	3.222	80.000	19.33	70.000
	12	2.738	83.000	12.88	80.000
	18	1.611	90.000	80.5	87.500
4	Blank	18.124		78.54	
	3	4.833	73.333	27.79	64.615
	6	3.987	78.000	24.16	69.230
	12	3.383	81.333	18.12	76.923
	18	2.174	88.000	12.08	84.615
5	Blank	24.166		82.16	
	3	6.766	72.000	29.96	63.529
	6	6.283	74.000	27.06	67.058
	12	5.799	76.000	19.33	76.470
	18	4.833	80.000	14.49	82.352
10	Blank	42.291		86.99	
	3	12.083	71.429	36.24	58.333
	6	11.116	73.714	33.83	61.111
	12	9.666	77.143	31.41	63.888
	18	8.699	79.429	25.61	70.555
24	Blank	50.346		90.623	
	3	24.166	54.022	40.277	55.555
	6	23.763	55.172	39.874	56.000
	12	23.36	53.600	39.27	56.666
	18	22.958	54.400	38.263	57.777
48	Blank	52.380		95.658	
	3	25.173	51.941	45.311	52.631
	6	24.971	52.326	45.110	52.842
	12	24.166	52.019	44.808	53.157
	18	23.964	54.248	44.304	53.684
72	Blank	53.736		100.69	
	3	26.851	50.031	50.346	50.000
	6	26.717	50.281	50.212	50.133
	12	26.582	50.530	49.675	50.666
	18	26.180	51.280	49.541	50.800

Table 3 Effect of 0.5 M HCl/0.1 M NaOH solution temperature on corrosion inhibition efficiency

T (K)	C (g/L)	Inhibition efficiency in percentage	
		Aluminum	
		0.5 M HCl	0.1 M NaOH
303	3	77.778	68.750
	6	83.333	72.656
	12	88.889	80.468
	18	94.444	90.625
308	3	80.000	66.666
	6	80.000	70.000
	12	85.000	76.666
	18	90.000	86.666
313	3	77.272	63.888
	6	81.818	67.777
	12	86.363	75.000
	18	0.909	83.333
318	3	76.000	63.636
	6	80.000	65.909
	12	84.000	72.727
	18	88.000	81.818
323	3	74.074	60.606
	6	77.777	63.636
	12	81.481	69.696
	18	85.185	80.303

to 72 h. It is noticed that protection efficiency of arecanut husk extract decreases in both 0.5 M HCl and 0.1 M NaOH environments by increasing the exposure time from 1 to 72 h. This is due to the fact that solubility of protective film increases with immersion time. Hence, the more free area is available for corrosion process. As a result, protection efficiency decreases with increasing immersion time from 1 to 72 h. Similar observation has been reported by previous authors [21–23]. The weight loss experiment was also carried out in stirred condition without and with inhibitor (with an expose time of 1 h). It is concluded that protection efficiency obtained in stirred condition is higher than the unstirred condition, which indicates that stable, compact, uniform, and persistence protective film formed on the surface of the aluminum in stirred condition.

3.2 Reason for Lower Protection Efficiency at Low Inhibitor Concentrations

Results in the table have also shown that lower aluminum protection is achieved at lower arecanut husk extract constituents; this is due to soluble protective film on aluminum surface in both corrosive conditions, as the amount of arecanut

Table 4 Effect of 0.5 M HCl/0.1 M NaOH stirring solution on corrosion inhibition efficiency with an immersion period of one hour at 303 K

Concentration (g/L)	0.5 M HCl		0.1 M NaOH	
	Corrosion rate $\times 10^{-4}$ (mpy)	Protection efficiency in percentage	Corrosion rate $\times 10^{-4}$ (mpy)	Protection efficiency in percentage
Bare	8.699		61.86	
3	1.449	83.333	16.916	72.656
6	0.966	88.888	14.499	76.562
12	0.048	94.444	7.249	88.281
18	0.048	94.444	2.416	96.093

husk extract increases the soluble protective film changes to the insoluble complex which responsible for high protection efficiency values.

3.3 Effect of Inhibitor Storage Time on Protection Efficiency

The protection efficiency of the inhibitor was also investigated after its storage in room temperature for 2 years. During the storage time, it is found that the arecanut husk extract is free from bacterial and fungal attack. The protection efficiency of the inhibitor after its storage time 2 years was well agreement with an inhibition efficiency of freshly prepared inhibitor. Thus, arecanut husk extract molecules inhibit the aluminum corrosion in both 0.5 M HCl and 0.1 M HCl solutions effectively with a shelf life of at least 2 years. Therefore, arecanut husk extract has significant shelf period.

It is also observed that protection efficiency of arecanut husk extract decreases with enhancing the solution temperature from 303 to 323 K. This is due to the enhanced aluminum dissolution rate and partial desorption of plant extract constituents from the electrode surface. By increasing the 0.5 M HCl/0.1 M NaOH solution temperature from 303 to 323 K, the equilibrium shifts to higher desorption side than adsorption side and hence the stability of protective film weakness.

As a result lower protection efficiency at higher solution temperature, which indicates the physical adsorption nature of arecanut husk extract molecules on aluminum surface in 0.5 M HCl/0.1 M NaOH environments.

The activation parameters of the aluminum corrosion process in free and arecanut husk extract containing 0.5 M HCl/0.1 M NaOH solution were determined by Arrhenius and transition state equations (Figs. 2a, b, 3a, b; Table 5). The activation energy (E_a) values in free 0.5 M HCl/0.1 M NaOH solution were lower than inhibited systems, which confirms that electrode (aluminum) dissolution rate is very slow with the introduction of arecanut husk extract constituents and also supports the physical nature of protective film. The endothermic nature of the aluminum corrosion

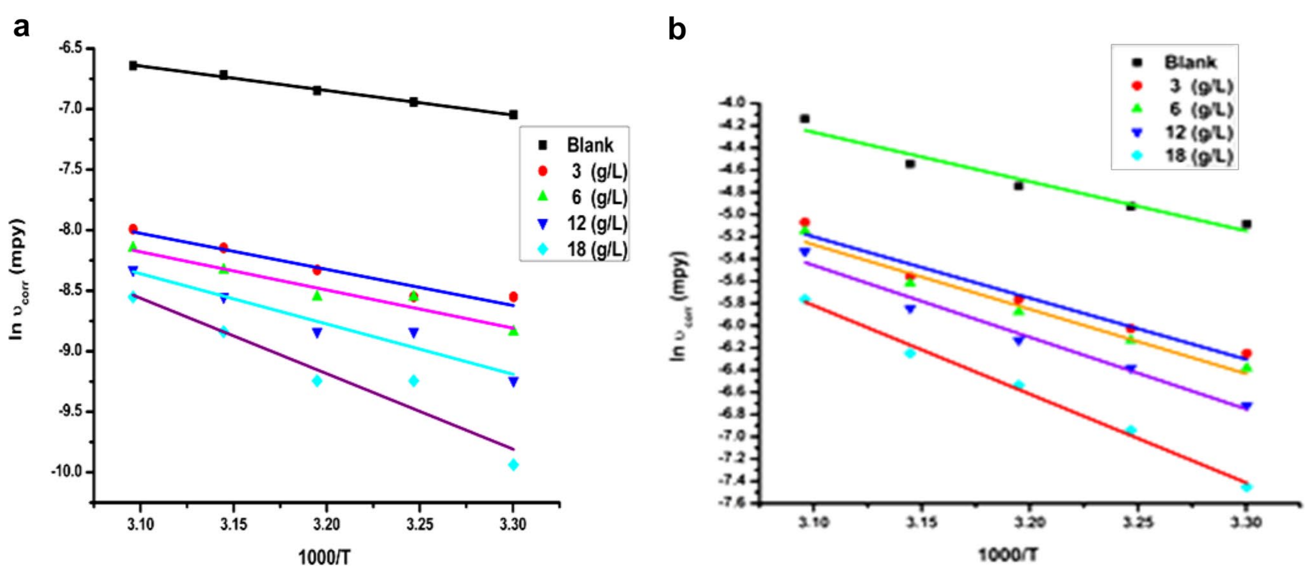

Fig. 2 Arrhenius plot, **a** aluminum in 0.5 M HCl solution without and with inhibitor, **b** aluminum in 0.1 M NaOH solution without and with inhibitor

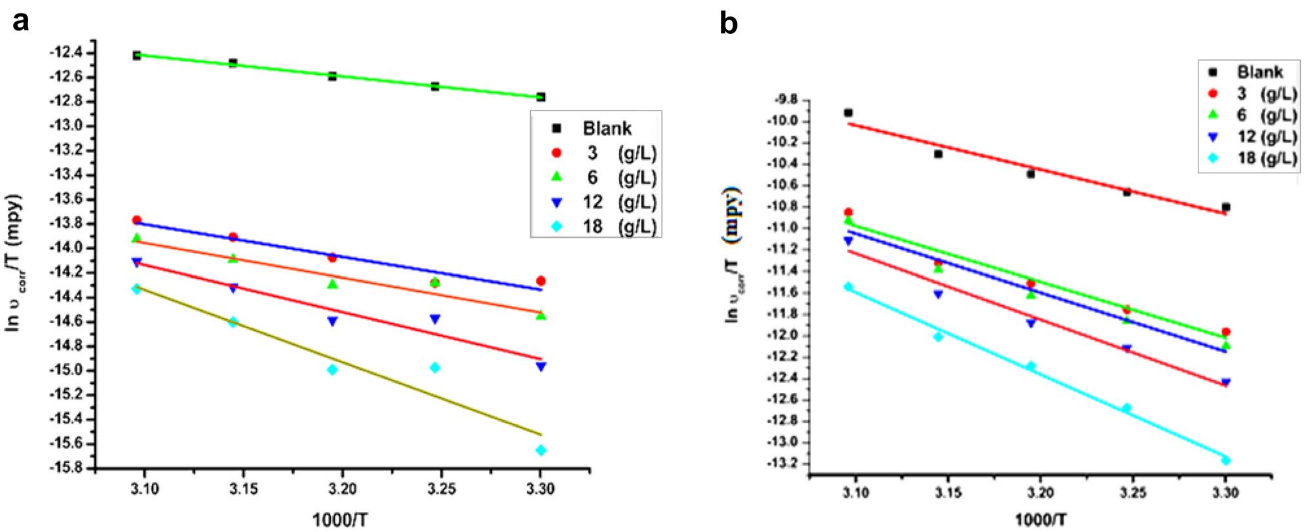

Fig. 3 Transition state plot, **a** aluminum in 0.5 M HCl without and with inhibitor, **b** aluminum in 0.1 M NaOH without and with inhibitor

Table 5 Activation parameters

Electrode	Medium	C (g L^{-1})	*Ea** (kJ mol^{-1})	ΔH* (kJ mol^{-1})	ΔS* (J mol^{-1} K^{-1})
Aluminum	0.5 M HCl	Blank	16.830	14.230	−313.901
		3	24.736	22.136	−300.888
		6	26.184	23.583	−297.670
		12	34.519	31.918	−273.332
		18	51.812	49.212	−221.404
	0.1M NaOH	Blank	36.917	34.316	−231.808
		3	45.880	43.280	−211.843
		6	48.292	45.692	−204.959
		12	53.782	51.181	−189.486
		18	66.299	63.699	−153.688

process in both 0.5 M HCl/0.1 M NaOH solutions was confirmed by positive activation enthalpy (ΔH) values, which indicates the adsorption plant extract constituents on the surface of aluminum. The decrease in the entropy of the system was confirmed by negative entropy of activation (ΔS) values.

It is generally assumed that, during aluminum corrosion process, plant extract molecules adsorbed on the surface of the metal (aluminum). The adsorbed plant species strongly interact with active aluminum sites and inactive the metal (aluminum) corrosion process. Basic information regarding the interaction between plant extract molecules and aluminum surface was obtained from adsorption isotherm models. The values of inhibitor concentration and surface coverage (Θ) were applied to different adsorption isotherm models and best R^2 value was obtained in the Langmuir isotherm model. The thermodynamic parameters obtained from the Langmuir adsorption model are listed in Table 6.

Table 6 Thermodynamic parameters

Electrode	Medium	Temperature (K)	K_{ads} (L g^{-1})	$\Delta G°_{ads}$ (kJ mol^{-1})
Aluminum	0.5 M HCl	303	980.411	−34.759
		308	1226.918	−35.907
		313	1138.329	−36.295
		318	1227.445	−37.074
		323	1248.938	−37.704
	0.1 M NaOH	303	559.456	−33.346
		308	557.544	−33.887
		313	549.169	−34.393
		318	535.704	−34.882
		323	470.285	−35.080

The large equilibrium constant of adsorption (K_{ads}) values supports the high protection efficiency of arecanut husk extract molecules and strong interaction between the arecanut husk extract molecules and electrode (aluminum) surface. Hence, aluminum metal is protected in both 0.5 M HCl/0.1 M NaOH solutions in the presence of four different concentrations of plant extract. The free energy of adsorption (ΔG°_{ads}) values was in negative side, which indicates that adsorption of arecanut husk extract molecules on the surface of the aluminum obeys spontaneous process. On present investigation, the obtained ΔG° values are in between the literature values which confirm that the aluminum corrosion inhibition process occurs through comprehensive adsorption (both physical and chemical adsorption) mode.

Heat of adsorption (Q) (obtained from plot of log (Θ/1 − Θ) vs 1/T, Fig. 4a, b and Table 7) is an evidence of release of more quantity of heat.

4 Electrochemical Studies

4.1 Potentiodynamic Polarization Studies (Tafel Plot Studies)

The Tafel curve parameters for aluminum metal in both 0.5 M HCl and 0.1 M NaOH solution containing four different concentrations of the arecanut husk extract are listed in Table 8. The Tafel curve (potentiodynamic polarization plot) is shown in Fig. 5a, b.

Table 7 Heat of aluminum corrosion reaction in both 0.5 M HCl and 0.1 M NaOH solutions

Concentration (g/L)	Q in (KJ/mol)	
	0.5 M HCl	0.1 M NaOH
3	−10.306	−13.826
6	−11.595	−16.637
12	−20.712	−22. 404
18	−38.712	−34.279

The protection efficiency (corrosion inhibition efficiency) of the arecanut husk extract for the aluminum metal in 0.5 M HCl/0.1 M NaOH solution was calculated by using below mathematical relation,

$$\text{Protection efficiency} = \left[1 - \frac{i'_{corr}}{i_{corr}}\right] \times 100$$

where i'_{corr} is the value of electrode (aluminum) corrosion current density in protected 0.5 M HCl/0.1 M NaOH solution and i_{corr} the value of electrode (aluminum) corrosion current density value in free 0.5 M HCl/0.1 M NaOH solution.

It is observed that the values of corrosion potential (E_{corr}) and Tafel slopes (βa and βc) did not show any regular trend in the presence of arecanut husk extract molecules indicating that arecanut husk extract molecule blocks the both anodic and cathodic reactions of aluminum surface in both 0.5 M HCl and 0.1 M NaOH solution through mixed mechanism.

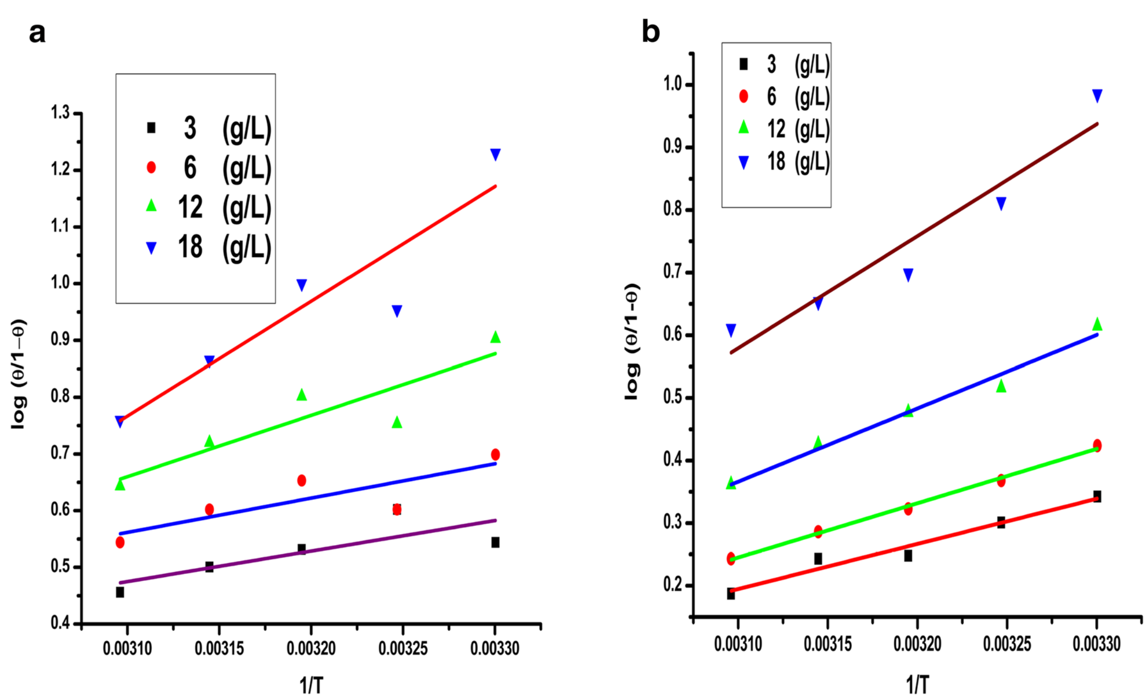

Fig. 4 Plot of log (Θ/1 − Θ) vs 1/T, **a** aluminum metal in 0.5 M HCl solution, **b** aluminum metal in 0.1 M NaOH solution

Table 8 Tafel parameters

Electrode	Medium	Concentration (g L^{-1})	E_{corr} (mV)	$i_{corr} \times 10^{-3}$ (A)	βc (V dec^{-1})	βa (V dec^{-1})	η_p
Aluminum	0.5 M HCl	Blank	−770	8.916	6.679	6.031	
		3	−752	2.530	5.664	5.830	71.624
		6	−742	1.747	5.773	5.653	80.406
		12	−765	1.740	6.378	7.184	80.484
		18	−753	1.715	3.283	6.801	80.764
	0.1 M NaOH	Blank	−1579	17.00	5.307	4.364	
		3	−1579	2.010	5.102	4.873	88.176
		6	−1537	1.940	5.061	4.863	88.588
		12	−1559	1.818	5.109	4.621	89.305
		18	−1527	1.774	5.048	4.818	89.564

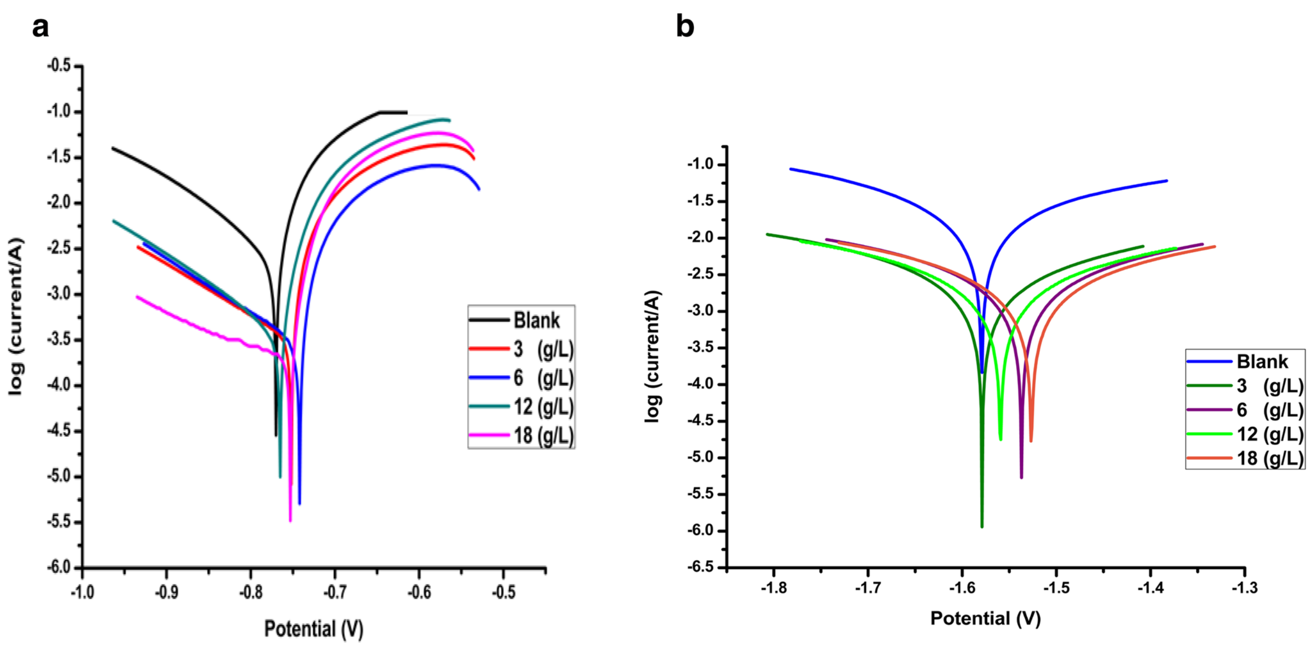

Fig. 5 Tafel plot, **a** aluminum in 0.5 M HCl without and with inhibitor, **b** aluminum in 0.1 M NaOH without and with inhibitor

The aluminum corrosion inhibition process occurs through the adsorption mechanism. The corrosion current (i_{corr}) values decrease with increase in arecanut husk extract concentrations from 3 to 18 g/L, which shows that the aluminum corrosion reaction was controlled by arecanut husk extract constituents. The enhancement in the protection efficiency values with the rise in arecanut husk extract concentration is due to the formation of a thick barrier layer which effectively isolates the electrode surface from 0.5 M HCl/0.1 M NaOH solution [24–26].

4.2 Impedance Spectroscopy Technique

Impedance studies were carried out in order to support the weight loss and Tafel plot results. The increased depressed semi-circle with natural extract concentration is clearly is an indication of corrosion inhibition property of plant extract on metal surface in corrosive media (Nyquist plots, Fig. 6a, b).

4.3 Powder X-ray Diffraction Technique

Figure 7 represents that, sharp, intense peak in arecanut husk extract. The protective film formed (after 2-h immersion period) on the aluminum surface in 0.5 M HCl solution also contains sharp peak with less intensity (compared to arecanut husk extract). The less intensity of peak is may be due to the adsorption of extract constituents on the aluminum metal surface in 0.5 M HCl solution. But, during aluminum corrosion inhibition process in 0.1 M NaOH

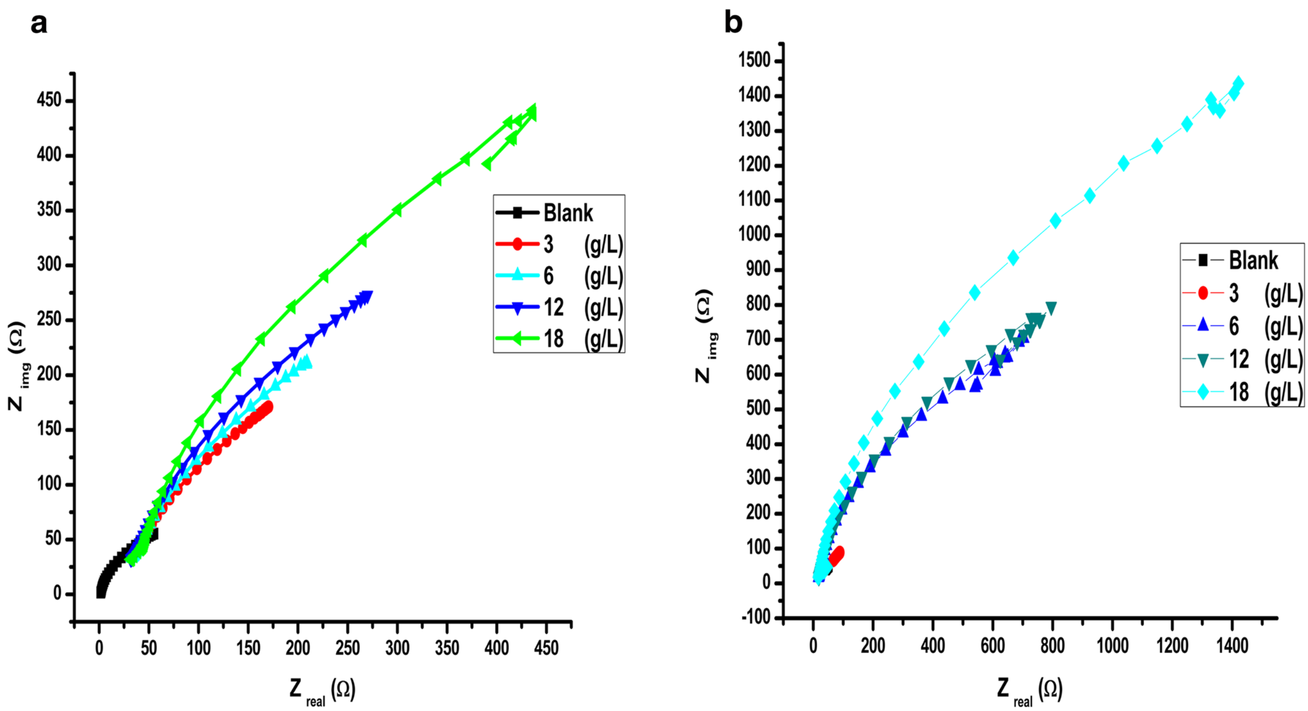

Fig. 6 Nyquist plots, **a** aluminum in 0.5 M HCl without and with inhibitor, **b** aluminum in 0.1 M NaOH without and with inhibitor

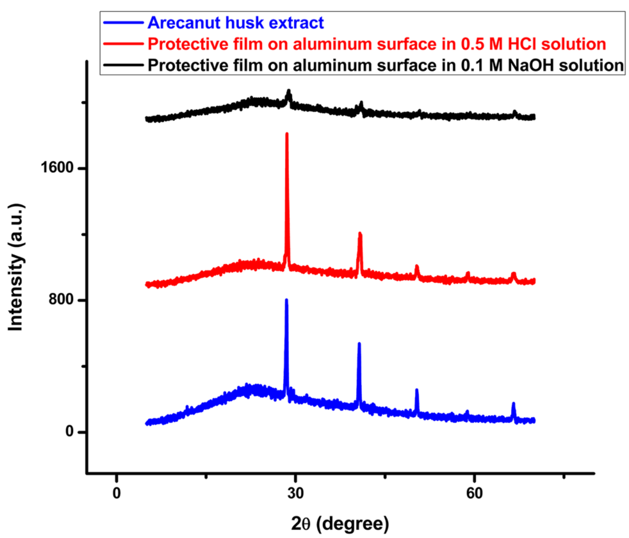

Fig. 7 Powder XRD pattern of arecanut husk extract and its protective film on aluminum surface in both 0.5 M HCl and 0.1 NaOH media

medium, the protective film formed by arecanut husk extract constituents (after 2-h immersion period) on aluminum surface in 0.1 M NaOH solution lost its crystalline nature that was evidenced by the absence of sharp peaks as shown in the figure.

4.4 Surface Inspection

4.4.1 Scanning Electron Microscopy (SEM) Technique

The changes in the aluminum surface topography due to corrosion reaction without and with the arecanut husk extract were analyzed using scanning electron microscopy technique. The resulted image are shown in Fig. 8a, b.

When the aluminum metal immersed in 0.5 M HCl/0.1 M NaOH solution, the much variation in the surface morphology was observed with many numbers of lines and cracks, which is an indication of higher dissolution rate of aluminum metal in 0.5 M HCl/0.1 M NaOH solution. When arecanut husk extract was introduced into the 0.5 M HCl/0.1 M NaOH solution, the surfaces are in good condition with the least number of lines and cracks. This change is due to the adsorption of arecanut husk extract molecules on the surface of the electrode (aluminum) in 0.5 M HCl/0.1 M NaOH solution.

4.4.2 Atomic Force Microscopy Technique (AFM) Technique

The decrease in average roughness (S_a) values (Fig. 9a, b; Table 9) with the introduction of arecanut husk extract to the 0.5 M HCl/0.1 M NaOH solution highly favors the SEM results.

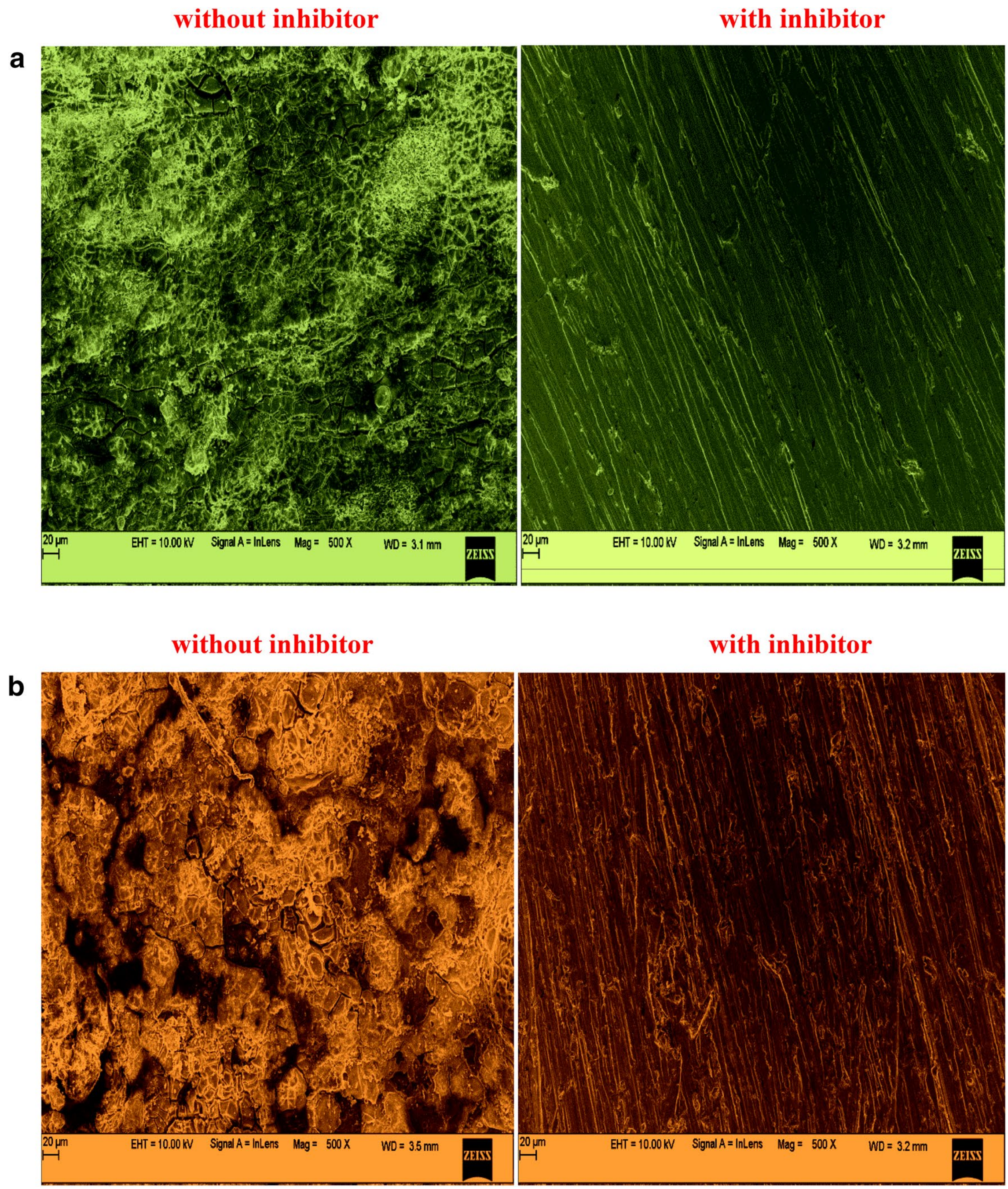

Fig. 8 **a** Aluminum metal in 0.5 M HCl solution. **b** Aluminum metal in 0.1 M NaOH solution

5 Conclusions

Arecanut husk extract showed the good inhibitory action over the electrode (aluminum) surface in both acid (0.5 M HCl) and alkali (0.1 M NaOH) media. Arecanut husk extract controls the aluminum corrosion inhibition process by mixed mechanism. The endothermic aluminum corrosion process in both 0.5 M HCl and 0.1 NaOH solutions was confirmed by weight loss parameters. The adsorption process follows the Langmuir model in the studied temperature range 303–323 K. Both Tafel and impedance studies showed the adsorption of arecanut husk extract constituents on aluminum surface in 0.5 M HCl and 0.1 M NaOH environments. The SEM and AFM images confirmed the inhibitory action of arecanut husk extract molecules in both 0.5 M HCl and 0.1 M NaOH solutions.

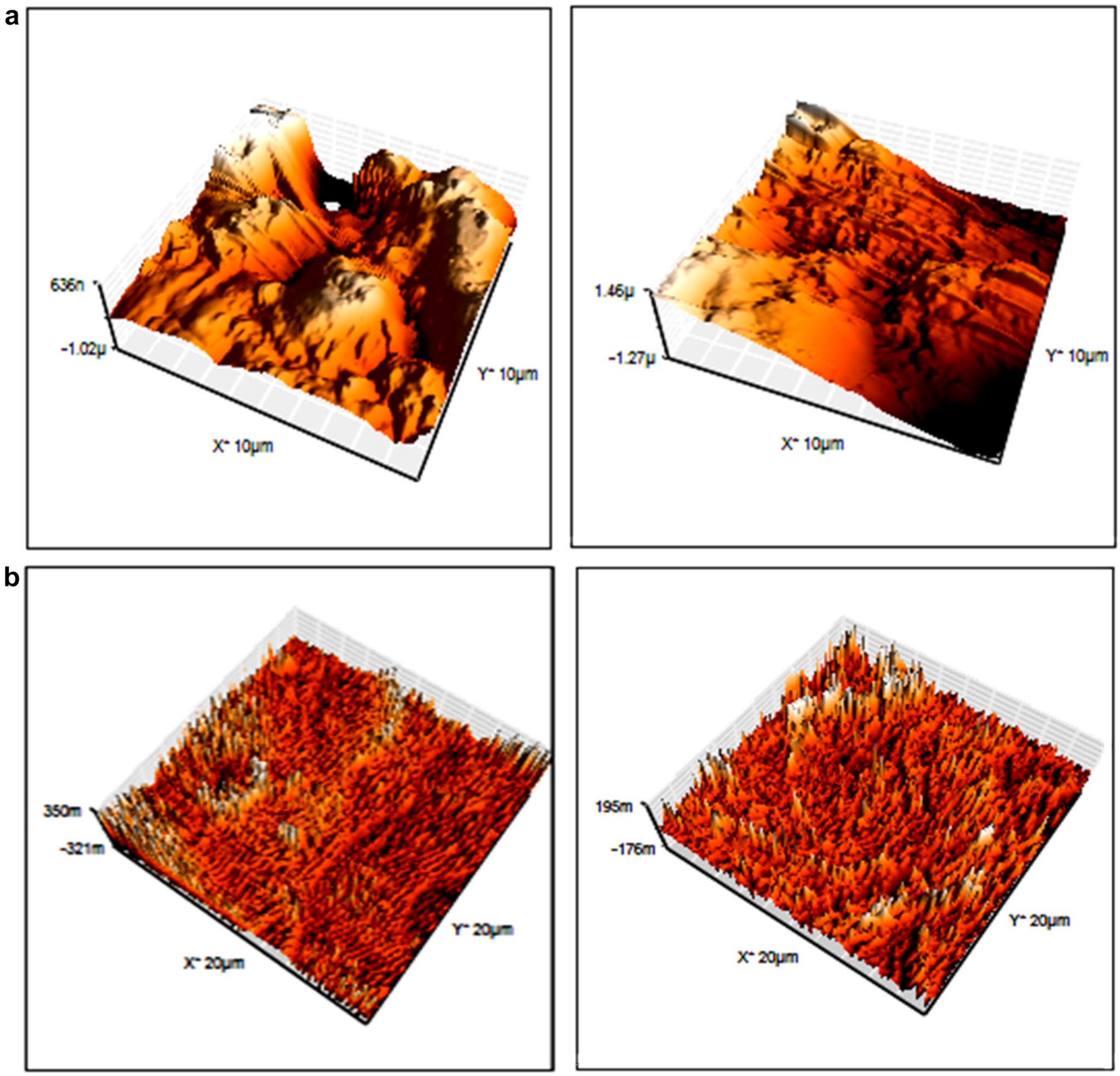

Fig. 9 **a** Aluminum surface in 0.5 M HCl solution without and with inhibitor, respectively. **b** Aluminum surface in 0.1 M NaOH solution without and with inhibitor, respectively

Table 9 Average roughness values obtained by AFM technique

Concentration	Medium	Average roughness (S_a)
Bare 18 (g/L)	0.5 M HCl	206.49 nm 127.19 nm
Bare 18 (g/L)	0.1 M NaOH	277.93 nm 121.2 nm

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Compliance with Ethical Standards

Conflict of interest Both authors declare no conflict of interest.

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