The brown algae *Cystoseira Baccata* extract as a friendly corrosion inhibitor on carbon steel in acidic media

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Abstract

The inhibition properties of the isopropanol extract of brown seaweed *Cystoseira baccata* (CBE), against corrosion of carbon steel in HCl 1M medium, was evaluated using the weight-loss method and electrochemical measurements. It was shown that the extract exhibit excellent performance as inhibitors and the inhibition efficiency increased with the concentration. The maximal value of inhibition efficiency is 86.5% obtained by the Tafel method at 700 mg/l at 298 K. The polarization curves indicate that the CBE acts as a mixed-type inhibitor. The results obtained by electrochemical impedance spectroscopy shows that the inhibitory action of this extract is based on the increase in the charge transfer resistance and the decrease in the double layer capacity. The temperature influence studied in the temperature range 298–328 K by weight-loss method shows that the inhibition efficiency decreases with increasing temperature for all concentrations of CBE. The adsorption and activation parameters allow us to suggest the physical adsorption of this inhibitor on the metal. The adsorption of the extract on the carbon steel follows Langmuir adsorption isotherm.

Keywords Corrosion inhibitor · Carbon steel · Acid media · Seaweed · *Cystoseira baccata* · Extract

1 Introduction

Corrosion inhibitors are chemical compounds added at low concentrations in a corrosive environment to slow down or stop the corrosion process of metal [1, 2]. Most of these substances are organic compounds that mainly contain heteroatoms such as oxygen, sulphur and nitrogen and are capable of adsorbing multiple bonds on the metal surface [3, 4]. Although synthetic inhibitors have shown good anticorrosive activity, most of them are highly toxic to humans and the environment [5]. The toxicity can be manifested either during the synthesis of the compound or during its applications. Current research is increasingly focused on the use of inhibitors called green inhibitors. The non-toxic and biodegradable nature of natural products has led to their use as ecological inhibitors [6–9].

Since 1930, plant and algae extract has been used as a corrosion inhibitor. Studies on natural products extract as a corrosion inhibitor has become more extensive [10–17]. *Cystoseira baccata* brown algae from the Sargassaceae family considered as a natural source of several active compounds. It is already known as such antibacterial, antifouling, antioxidant, Antileishmanial activities [18–21].

In the continuation of our study on the corrosion inhibition potential of marine algae. We have evaluated the corrosion inhibition power of the isopropanol extract of *Cystoseira baccata* (CBE) on carbon steel in 1M HCl, using three methods of weight loss, potentiodynamic polarization and (EIS), thus understanding the mechanism of inhibition of this extract.

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2 Experimental details

2.1 Preparation of *Cystoseira baccata* extract

Cystoseira baccata (Sargassaceae) harvested at *El-Jadida* beach (Atlantic sea, Morocco), was extensively washed with distilled water and dried in the shade at room temperature. The seaweed powder was delipidated by hexane for 8 h after the extract was prepared by soxhlet extraction of powder in isopropanol 70% for 8 h. After evaporation and freeze-drying, the extract was kept in a desiccator. The CBE was dissolved in 1M HCl, appropriately diluted to get solutions of desired concentrations.

2.2 Specimen preparation

The carbon steel (CS) specimens with dimensions of 40 mm × 10 mm × 1 mm in size, with a mass composition of C = 0.38%, Si = 0.21%, P = 0.09%, S = 0.05%, Mn = 0.05%, Al = 0.01% and the remainder iron. The pretreatment of the surfaces of the specimens was carried out by polishing with 500, 1000, 1500 and 2000 grit emery paper, followed by washing with double-distilled water. The surface was finally degreased with ethanol and acetone and then dried at room temperature.

2.3 Weight loss measurement

For the determination of the corrosion rate of carbon steel (CS), gravimetric tests were performed in a thermostatically controlled water bath with a temperature regulator, in the temperature of the range (298–328 K). The CS samples were immersed in 30 ml of 1M HCl with different extract concentrations ranging from 0 to 700 mg/l for 6 h of immersion. After the end of the time period prescribed for the test, the sample was taken out, washed thoroughly with distilled water, dried, and accurately weighed using a digital balance (accuracy: ± 0.1 mg). Each measurement was repeated three times, and the average values were recorded.

The corrosion rate (W), inhibition efficiency (IE%), and surface coverage (θ), were calculated according to the following equations: [22]:

$$w \text{ (mmpy)} = 87600 \cdot \Delta m / d \cdot S \cdot t \quad (1)$$

$$IE\% = 100 * \theta = 100 * (w_0 - w) / w_0 \quad (2)$$

where Δm (g) is the weight loss, d is the density of coupon in (g cm^{-3}), S is the area of the specimen (cm^2), and t is the immersion time in hours, w_0 and w are the corrosion rates

(mmpy) of the sample in the absence and presence of the inhibitor, respectively.

2.4 Electrochemical measurements

Electrochemical testing is the method most commonly used for research into corrosion. It can analyze the corrosion of mild steel under transient conditions and can also describe the whole corrosion process of mild steel in a corrosive medium.

Electrochemical measurements were carried out in three-electrode Pyrex glass cell. The CS as a working electrode (WE) in the square form with the geometric area of 1 cm^2 embedded in PVC carrier using epoxy resin. So that the flat surface was the only surface in the electrode, a platinum counter electrode (CE) and a saturated calomel electrode (SCE) was used as the reference. The equipment used is EC-Lab SP 200 Research Grad model potentiostat/galvanostat/FRA, and the experimental data analyzed by EC-Lab software. Open-circuit potential (E_{ocp}) was obtained by immersing the working electrode in the test solution for 30 min. The impedance measurements were performed in the frequency range from 100 kHz to 10 mHz, with 8 points per decade, by applying 10 mV alternating current (AC) voltage peak-to-peak. The potentiodynamic curves were realized polarization from −1 V to 1 V relative to the E_{ocp} with a scan rate of 1 mV/s in the potential.

2.5 Fourier-transform infrared spectroscopy (FTIR)

FTIR spectra of *Cystoseira baccata* extract and the scraped product from CS after 6 h of immersion in 1M HCl containing 700 mg/l of CBE were recorded on a SHIMADZU FT-IR 8400S spectrometer with a Smart iTR Attachment and diamond attenuated Total Reflectance (ATR) crystal in range 500–4000 cm^{-1} .

3 Results and discussion

3.1 Potentiodynamic Polarization

Figure 1 shows polarization curves for steel in 1M HCl media, without and with the addition of various concentrations of CBE. The values of different polarization parameters such as corrosion current density (i_{corr}), corrosion potential (E_{corr}), Tafel coefficients cathodic (β_c) and anodic (β_a) and inhibition efficiency IE% were listed in Table 1.

The inhibition efficiency of IE% was calculated as follows [23]:

Fig. 1 Potentiodynamic polarization plots for steel in 1M HCl media, without and with the addition of various concentrations of CBE

Table 1 Potentiodynamic polarization data for carbon steel in 1M HCl in the absence and presence of various concentrations of CBE

Concentration (mg/l)	E_{corr} (mV/SCE)	b_a (mV/dec)	b_c (mV/dec)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	IE (%)
Blank	-449.3	133	189.1	320.8	–
200	-487.7	92.8	108.7	107.2	66.5
300	-481.9	91.5	96.4	100.8	68.5
400	-481.5	98.2	108.3	87.7	72.6
500	-481	107.5	96.6	83.8	73.8
700	-475	110.4	114.6	44.2	86.2

$$IE\% = \frac{(I_{corr}^{\circ} - I_{corr})}{I_{corr}^{\circ}} \times 100 \quad (3)$$

I_{corr}° and I_{corr} are the values of corrosion current density in the absence and presence of inhibitors, respectively.

From Fig. 1, it can be observed that the cathode curves are a linear part, in the form of Tafel lines, indicating that the hydrogen reduction reaction on the steel surface is carried out according to a precise activation mechanism [15].

Table 1 shows that the values of the corrosion current density I_{corr} decrease with the addition of different concentrations of CBE. Also, the corrosion potential (E_{corr}) moves slightly (-39 mV) with the concentration of extract towards the less noble values, and according to [24], if the displacement of the potential exceeds ± 85 mV, the inhibitor acts as a cathodic or anodic type. If the displacement of the E_{corr} values does not exceed ± 85 mV, the inhibitor can be considered as a mixed type. Additionally, this extract causes no remarkable change

in the anodic and cathodic Tafel slopes (β_a , β_c). And both the cathodic and anodic reactions were affected by a reduction of the anodic dissolution of steel and also retarded the cathodic hydrogen evolution reaction. These results suggest that the *C. baccata* extract functioned as a mixed type inhibitor [25, 26].

3.2 Electrochemical impedance spectroscopy

The *Cystoseira baccata* extract Nyquist curves on CS in hydrochloric acid medium 1M shown in Fig. 2, reveal that the diameter of the semicircles of the Nyquist diagram increases with increasing extract concentration. Those semi-circles are not perfect; this result attributed to the frequency dispersion, due to the heterogeneity of the surface of the electrode. The impedance spectra have a single capacitive loop indicating that the corrosion of the steel is mainly controlled by a charge transfer process on an inhomogeneous surface electrode [27]. Indeed, only one time constant is detected on the Bode diagram presented in Fig. 3. The equivalent circuit used is well described in [28] and shown in Fig. 4.

The electrochemical impedance parameters, the charge transfer resistance R_{ct} , the solution resistance R_s , the double layer capacitance C_{dl} , slope (S), phase angle (Φ), and inhibition efficiency $IE\%$ are given in Table 2.

The inhibition efficiency $IE\%$ is calculated from the following formula [29]:

$$IE\% = \left(\frac{R_{ct} - R_{ct}^{\circ}}{R_{ct}} \right) \times 100 \quad (4)$$

with R_{ct}° and R_{ct} are the charge transfer resistance without and with inhibitor, respectively.

The impedance of the CPE represented by the following expression [30]:

Fig. 2 Nyquist plots for CS in 1M HCl without and with various concentrations of CBE

Fig. 3 Bode diagram for CS in 1M HCl with different concentrations of CBE

Fig. 4 Equivalent circuit model used

$$Z_{CPE} = A^{-1}(i\omega)^{-n} \quad (5)$$

where A is the amplitude comparable to a capacitance, $i^2 = -1$, ω the angular frequency and n the phase shift ($-1 < n < 1$) when $n = 0$ the CPE represents pure resistor, if $n = 1$, the CPE is reduced to a pure capacitor (C), and if $n = -1$ the CPE represents inductor and When $n = 0.5$, it is the Warburg impedance (W) [31].

The double-layer capacitance (C_{dl}) calculated from the constant phase element (CPE) is presented by [32]:

$$C_{dl} = (A * R_{ct}^{1-n})^{1/n} \quad (6)$$

It is quite clear from Table 2 that, the R_{ct} increase with the increase in inhibitor dosage, Therefore, the C_{dl} and A decrease in double-layer capacitance would signify the increase in the thickness of the capacitive surface layer

which is an indication of gradual replacement of surface water molecules with inhibitor adsorption.

The C_{dl} connected with the organic deposition thickness by the Helmotz relation (7) [33]:

$$C_{dl} = \frac{\epsilon \cdot \epsilon_0}{d} S \quad (7)$$

where d is the thickness of the protective layer, ϵ dielectric constant of the medium, ϵ_0 the vacuum permittivity and S is the effective surface area of the electrode.

The least value of C_{dl} and highest inhibition efficiency were obtained with 700 mg l⁻¹ inhibitor dosage indicate the optimum surface coverage. At the optimum inhibitor concentration, the obvious effect of the hydrophobic backbone of the inhibitor can be elucidated by the increase in cohesive energy of absorbed mono-layer on the CS surface [34]. Nevertheless, an overall inhibition effect was remained intact may be due to the compaction of mono-layer upon achieving CBE of inhibitor which is evident with an increase in R_{ct} and capacitance of film.

The phase shift values n increase with the addition of the seaweed extract (0.8401–0.9007) relative to the uninhibited solution (0.818), which indicates, according to Popova et al. [35], the decrease in the heterogeneity of the steel surface with the adsorption of inhibiting molecules. But they did not vary significantly, confirming that the dissolution mechanism of the steel in the absence and

Table 2 Electrochemical impedance parameters and inhibition efficiency of CS in 1M HCl in the absence and presence of different concentrations of CBE

Concentration (mg/l)	R_s	A	n	C_{dl}	R_{ct}	S	$-\Phi$	IE%
Blank	5.404	0.714	0.818	325.4	44.81	-0.564	32.17	–
200	0.724	0.333	0.8657	202.6	120.4	-0.805	48.16	62.7
300	0.65	0.262	0.9007	185.3	163.4	-0.868	56.55	72.5
500	0.719	0.207	0.8683	128.2	205	-0.828	54.63	78.1
700	0.873	0.12	0.8401	62.48	265.9	-0.796	47.22	83.1

presence of the extract is controlled by a charge transfer process [36].

Always with Table 2, it is clear that the slope S of the linear part of the bode plots ($\log(f)$ vs. $\log(|Z|)$) decreases with the addition of *CBE* concentration and that the values of the phase angle (Φ) in the presence of the extract higher than that of the blank. Generally, for an ideal capacitor, it is necessary that S of -1 and a phase shift ($-\Phi$) of 90° [37, 38]. From these results, it is deduced that the system tends to behave as a pure capacity.

3.3 Effect of temperature

Temperature is a critical factor in corrosion inhibitor evaluation studies. The effect of temperature makes it possible to determine the nature of adsorption of the inhibitor on the surface of the metal. Figure 5 shows the effect of temperature on the inhibition efficiency of CS in acid media, using the weight-loss method at various concentrations of *CBE* in the temperature range (298–328 K) during 6 h of immersion. Table 3 presents the values of corrosion rate and inhibition efficiency (*IE*%) for CS in 1M HCl in the absence and presence of a different concentration of the inhibitor. Figure 5 and Table 4 show an increase in

Fig. 5 Effect of temperature on *IE*% for CS with different concentrations of *C. baccata* extract in 1M HCl

Table 3 Influence of temperature on the corrosion parameters for CS in the absence and presence of a various concentrations of *CBE* in the temperature range (298–328 K) during 6 h

Concentration (mg/l)	298 K		308 K		318 K		328 K	
	w (mmpy)	IE (%)	w (mmpy)	IE (%)	w (mmpy)	IE (%)	w (mmpy)	IE (%)
Blank	2.75	–	7.15	–	16.52	–	27.43	–
100	1.57	42.8	4.23	40.80	12.53	24.14	22.90	16.53
200	1.37	50	3.77	47.19	10.44	36.81	20.19	26.40
300	1.19	56.8	3.45	51.71	9.48	42.61	18.94	30.95
400	1.07	61.2	3.03	57.63	8.64	47.67	17.68	35.54
500	0.98	64.2	2.84	60.28	8.45	48.81	16.58	39.56
600	0.77	71.96	2.48	65.26	7.90	52.19	15.65	42.93
700	0.55	80	1.96	72.58	7.08	57.11	15.28	44.31

Table 4 Adsorption parameters of *CBE* on the steel surface at different temperatures

	Temperature (K)	R ²	K _{ads}	Constant of isotherm	ΔG _{ads}
Langmuir	298	0.9631	5.5096	slope 1.0869	– 21.34
	308	0.9746	5.0505	1.1860	– 21.83
	318	0.8661	1.1394	1.1623	– 18.60
	328	0.9114	0.6564	1.0212	– 17.68
Temkin	298	0.9186	2.0871	a – 0.4593	– 18.93
	308	0.9545	2.0263	– 0.4772	– 19.49
	318	0.9904	1.8229	– 0.4952	– 19.85
	328	0.9947	1.6386	– 0.4973	– 20.18
Freundlich	298	0.964	0.8321	f 0.30	– 16.65
	308	0.9837	0.7762	0.32	– 16.48
	318	0.9844	0.6529	0.38	– 16.05
	328	0.984	0.5596	0.50	– 15.67

corrosion rates and a decrease in the values of inhibition efficiency with increasing temperature for the different *CBE* concentrations. The rise in temperature adversely affects the corrosion inhibiting action of *CBE*; this can be explained by the breakdown of the physical interactions between the molecules of the extract and the metal surface. This type of interaction is usually temperature sensitive and also is easily removed from the surface [39, 40].

3.4 Adsorption isotherms and thermodynamic parameters

The adsorption isotherm is a characteristic for studying solid/liquid equilibria. It is a curve linking the quantity of adsorbate adsorbed by material, as a function of the equilibrium pressure (or concentration) of the adsorbate at a constant temperature. In our case, the relationship

between the surface coverage θ and the level C_{inh} of the inhibitor. Several theoretical models have been tested to describe the behaviour of inhibitors in the corrosion process, such as Langmuir, Temkin, and Freundlich [41–43]:

$$\text{Langmuir : } \frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh} \quad (8)$$

$$\text{Temkin : } \exp(-2a\theta) = KC_{inh} \quad (9)$$

$$\text{Freundlich : } \ln\theta = \ln K_{ads} + f \cdot \ln C_{inh} \quad (10)$$

where C_{inh} is the concentration of the inhibitor, θ is the surface coverage, and K_{ads} is the adsorptive equilibrium constant, a is interaction constant between adsorbed particles and f is Freundlich isotherm interaction constant.

Figure 6 shows the graphical representations of the relationship between θ and C_{inh} at different temperatures for different models of isotherms. Table 4 presents the values of the correlation coefficient (R^2), slopes, intercepts, K_{ads} , a , f and those the free adsorption standard energy ΔG_{ads}° . The K_{ads} values obtained made it possible to evaluate the ΔG_{ads}° (Table 4), by using the following equation [44]:

$$\Delta G_{ads}^\circ = -RT \ln(C_{H_2O} K_{ads}) \quad (11)$$

where $C_{H_2O} = 10^3$ g/l. R is the universal gas constant, T is the absolute temperature.

The values of the correlation coefficient R^2 for the three isotherms are close to 1. The values of the Freundlich isothermal coefficient f , which describes the ease with which active species adsorb to the metal surface, which indicates that adsorption of the molecules is feasible ($0 < f < 1$) [45], but they disagree with an ideal value of $n = 0.6$ [46]. The means that the process of adsorption of this extract does not follow this isotherm. Negative signs of Temkin isotherm interaction parameters a indicate molecular repulsion in the adsorbed layer of the adsorbate, demonstrating that Temkin isotherm is not suitable for our inhibitor [47]. For Langmuir, isotherm plots have a linear behaviour with equal slopes roughly unity. This suggests that the adsorption of CBE on the steel surface obeyed to the Langmuir's adsorption isotherm.

Generally, negative values of ΔG_{ads}° indicate spontaneous adsorption of CBE and values less than or equal to -20 kJ.mol $^{-1}$ are related to physical interactions between charged molecules and metallic charges. In contrast,

Fig. 6 Adsorption isotherms of CBE, **a** Langmuir isotherm, **b** Temkin isotherm, **c** Freundlich isotherm

Fig. 7 Van't Hoff plot for CS in 1M HCl

those around -40 kJ.mol^{-1} correspond to the formation of covalent bonds (chemisorption) [48, 49]. In our study, the values ΔG_{ads}° close to -20 kJ.mol^{-1} show that *Cystoseira baccata* extract adsorbed physically on the surface of the steel.

The enthalpy and entropy of adsorption (ΔH_{ads}° and ΔS_{ads}°) can be determined from the Van't Hoff equation expressed by [50]:

$$\ln k_{ads} = -\frac{\Delta H_{ads}^\circ}{RT} + C \quad (12)$$

The slopes of straight lines $\ln k_{ads}$ versus $1/T$ are $(-\Delta H_{ads}^\circ/R)$ and intercepts of $[(-\Delta S_{ads}^\circ/R) - \ln(C_{H_2O})]$. The plot of the variations of $\ln k_{ads}$ versus $1/T$ which gives straight lines (Fig. 7) with slopes of $(-\Delta H_{ads}^\circ/R)$ and intercepts of $[(-\Delta S_{ads}^\circ/R) - \ln(C_{H_2O})]$.

The endothermic character of ΔH_{ads}° always binds to chemisorption, While the exothermic process of adsorption can be associated to physisorption or chemisorption. Depending on its value, physisorption close to -40 kJ.mol^{-1} , otherwise close to -100 kJ.mol^{-1} for chemisorption [51]. Value of ΔH_{ads}° ($-64.92 \text{ kJ mol}^{-1}$) indicates that physical adsorption is more favoured. The negative values ΔS_{ads}° ($-56.14 \text{ J mol}^{-1}$), it might be explained by the inhibitory molecules ordinarily adsorbed onto steel surface [52].

3.5 Kinetic parameters of activation

For a better understanding of the kinetic process of steel corrosion and the determination of the activation energy (E_a) the following Arrhenius Eq. (13) was used [52]:

$$\ln(w) = A - \frac{E_a}{RT} \quad (13)$$

where w is corrosion rate, E_a is the apparent activation energy of the corrosion process, R is the universal gas

Fig. 8 Arrhenius plots for CS in 1M HCl, in the absence and presence of various concentrations of CBE

Fig. 9 Curve of the relationship between $\ln(w/T)$ and $1/T$ of steel for various concentrations of CBE in 1M HCl

constant, A is the Arrhenius pre-exponential factor and T is the absolute temperature.

The Arrhenius diagrams (Fig. 8) of the logarithm of the corrosion rate obtained by measuring the weight loss to $10^3/T$ for the blank and the different concentrations of the extract have a linear constriction, with a slope of $(-E_a/R)$.

The standard activation enthalpy (ΔH_a°) and standard activation entropy (ΔS_a°) of the corrosion process are calculated using the alternative formulation of the Arrhenius equation:

$$\ln\left(\frac{w}{T}\right) = \left[\ln\left(\frac{R}{N_a h}\right) + \frac{\Delta S_a^\circ}{R}\right] - \frac{\Delta H_a^\circ}{RT} \quad (14)$$

where h is Plank's constant, N_a is Avogadro's number, ΔS_a° and ΔH_a° are, respectively, the entropy and enthalpy of activation.

Figure 9 shows the curves of $\ln(w/T)$ versus the reciprocal of the temperature ($10^3/T$), presented in the form of straight lines with an equal slope $(-\Delta H_a^\circ/R)$ and an

Table 5 Activation parameters for CS in 1M HCl, with absence and presence of various CBE concentrations

Concentration (mg/l)	E_a (kJ/mol)	ΔH_a° (kJ/mol)	ΔS_a° (j/mol)	$E_a - \Delta H_a^\circ$ (kJ/mol)
Blank	64.50	61.85	160.50	2.65
100	75.92	73.27	193.77	2.65
200	75.54	72.88	191.38	2.65
300	77.55	74.90	196.99	2.65
400	78.79	76.14	200.14	2.65
500	79.74	77.08	202.66	2.65
600	84.92	82.26	218.15	2.65
700	93.75	91.10	244.93	2.65

ordinate at the origin ($\ln R/Nh + \Delta S_a^\circ/R$). All activation parameters E_a , ΔH_a° & ΔS_a° are grouped in Table 5. The E_a values in the presence of the CBE are higher than those of the un-inhibited acidic solution. This increase in E_a value may be interpreted as physisorption [53]. Moreover, Belgithi et al. [54] explained that the increase in E_a value can be attributed to an appreciable decrease in the adsorption of the inhibitor on the CS-surface with an increase in temperature. This means that an increase of temperature favored desorption over adsorption. Then the adsorption–desorption equilibrium tends towards the desorption of inhibitor molecules at higher temperatures. Due to the increased desorption of adsorbed molecules, the greater surface area of CS comes into contact with a corrosive medium, resulting in increased corrosion rates with increasing temperature. On the other hand, the thermodynamic parameter descriptors, ΔH_a° & ΔS_a° , were calculated and depicted in Table 5. The positive signs of the enthalpies ΔH_a° reflect the endothermic nature of the steel dissolution process. The activation entropy ΔS_a° is positive in absence and presence of inhibitor this value increases positively with the extract concentration indicate that an increase of the disorder during the transformation of the reagents into activated complex [54]. The values of the difference (ΔH_a°) are close to the mean value of the product RT (2.63 kJ mol^{-1}), where T is between 298 K and 328 K, this is explained by the fact that the process of corrosion is a unimolecular reaction. Characterized by the following equation [55].

$$E_a - \Delta H_a^\circ = RT \quad (15)$$

3.6 FTIR spectra analysis

The Fourier Transform infrared spectra of CBE and the scraped product from the steel surface have been presented in Fig. 10a, b, respectively. These spectra can

Fig. 10 FTIR spectra of **a** CBE and **b** the scrapped product from steel surface after immersion in 1M HCl containing 700 mg/l of CBE

provide some information about the nature of the molecules present in the extract and also the possibility of the existence of interactions between them with the surface of the metal. Indeed, the Fig. 10a shows the presence of a band around 3364.6 cm^{-1} , which is often attributed to the stretching vibration (O–H). The peaks at 2923.6 and 2852.5 cm^{-1} can be due to stretching vibration of aliphatic and aromatic (C–H) groups, respectively. The peak at 1730.8 cm^{-1} indicates the presence of the stretching modes of carbonyl groups (C=O). While the peak at 1635.5 cm^{-1} corresponds to the stretching vibration of the aromatic ring (C=C). The peak at 1462.6 cm^{-1} can be assigned to the stretching vibration (C–C), and the peak at 1051 cm^{-1} indicates the presence of C–O stretching [56, 57]. Furthermore, the Fig. 10b shows a shift in the absorption wavelength after immersion in HCl 1M. This wavelength shift indicates that the CBE is by adsorption by forming interaction with the steel surface [58, 59].

3.7 Adsorption mechanism

The adsorption mechanism in the case of natural extracts is generally difficult to interpret. This difficulty is mainly due to the complexity of the chemical composition of the extracts. Generally, the organic molecules can adsorb on the surface of the metal as neutral molecules or as cations through electrostatic interactions [60]. The chemical composition of

Cystoseira baccata mentioned in the bibliography reveals that it is an alga rich in meroditerpenoids compounds that contain carbonyl functions (C=O), benzenyl rings and hydroxyl groups (OH) [19, 61], and phlorotannins, which are polyphenol compounds resulting from the polymerization of phloroglucinol and which contain phenyl rings and hydroxyl groups (OH) [62, 63]. The CBE inhibitor molecules possess ($\pi\pi$ - $\pi\pi$)-electrons (cyclic rings) that can potentially act as proton and/or hydrogen-bond acceptor sites and also contain electronegative elements ($-O-$) that have isolated and/or delocalized lone pairs (σ) of electrons interact with Fe 3d-electrons in CS surface [32, 60]. It can be adsorbed onto the CS surface in several ways. In the case of physical adsorption, the charge on the surface of the metal may promote or hinder the adsorption of a species. A negative surface charge will favour the adsorption of cations, whereas anion adsorption is supported by a positive surface charge [60]. However, in acid solutions, organic molecules can easily be protonated, from which they are presented in the form of cations [33]. The metal charge can be determined from the difference between the corrosion potential E_{corr} and the zero charge potential E_0 . In our study, the surface of the steel positively charged ($E_{corr} - E_0 > 0$) [28]. The Cl^- anions could be specifically adsorbed to the surface of the carbon steel; they create excess negative charge toward the solution and favour more adsorption of the cations on the negatively charged metal surface through electrostatic interactions [28, 33].

4 Conclusion

- The three methods used, gravimetry, polarization curve, electrochemical impedance spectroscopy, show that *Cystoseira baccata* extract acts as a suitable corrosion inhibitor, and the inhibitory efficiency ($IE\%$) increases with concentration.
- The electrochemical studies indicate that extract acts as a mixed type inhibitor. The charge transfer resistance increases; on the other hand, the double-layer capacity decreases with increasing the concentration inhibitor.
- The study of the effect of temperature and the determination of the thermodynamic parameters of adsorption confirms that the CBE adsorbs physically on the metal surface and that the adsorption obeys the Langmuir isotherm.
- The FTIR spectra analysis confirms the adsorption of CBE extract molecules on the CS surface.
- The fractionation operations are being carried out to determine the molecule (s) responsible for the corrosion inhibiting effect.

Compliance with ethical standards

Conflict of interest On behalf of all authors, I declare that there is no conflict of interest.

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