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Burghul Plant Extract as a Green Corrosion Inhibitor for Carbon Steel in Hydrochloric Acid Solution

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ABSTRACT

Carbon steel is very important because it is widely used in many industrial and engineering fields, such as oil and gas. However, engineering materials accounted for 85% of yearly steel production due to their accessibility and affordability. As a result of strict environmental rules and a growing ecological consciousness among scientists, "green" ways to minimize corrosion have been created. In the current study, burghul extract is demonstrated to be an effective corrosion inhibitor and was utilized as an environmentally acceptable anti-corrosive material for carbon steel in a 1M HCl solution. The effectiveness of mitigation methods such as mass loss, electrochemical impedance spectroscopy, frequency modulation, and potentiodynamic polarization (PP) was calculated. Meanwhile, dispersion X-ray (EDX) and scanning electron microscopy (SEM) methods were used to analyze surfaces. Results obtained showed that temperature and extract concentration both affect how effective the mitigation is. The inhibition is attributed to the development of a protective layer that slows the dissolution of carbon steel at its surface. The Langmuir model was validated by the adsorption of burghul extract on steel. The adsorption of the extract affected both anodic and cathodic reactions. Tafel curves showed that burghul is a mixed inhibitor. The Nyquist curves confirmed that the burghul extract prevents the disintegration of steel in acidic media without changing the dissolution reaction mechanism. By using ATR-FTIR analysis and SEM inspection, the burghul extract's adsorption on the metal carbon steel was verified. A maximum inhibitory efficacy of 95% was reached at 313 K using 300 ppm of the Burghul extract, which is thought to be a promising result.
Keywords: Burghul extract; Carbon steel; Corrosion; Green corrosion inhibitors; Plant extract.

INTRODUCTION

Carbon steel is an alloy made of steel and carbon. It is regarded as a common form of steel if the carbon content is at least 2.1%. Many industrial processes require carbon steel, including the refinement of crude oil, acid pickling, industrial cleaning, acid descaling, oil-well acid in oil recovery, and petrochemical operations. Large-scale field applications for construction are also considered, such as marine structures, power plants, transportation, chemical processing, and petroleum production (Hart, 2016).

Depending on the carbon content, steel can be divided into three categories: low, medium, and high carbon steels (Wiewiórowska and Muskalski, 2015). Low-carbon steel, also referred to as "mild steel," is weaker than steel with a higher carbon content. The sort of carbon steel that is most ductile, or machinable, is low carbon steel. In contrast, medium-carbon steel strikes a balance between low and high carbon steel, delivering more strength and hardness than low carbon steel, while being more ductile than high carbon steel (Abboud *et al.*,2016; Abdallah *et al.*,2012). Additionally, manganese and other alloys are frequently added to medium-carbon steel, which enhances its characteristics.

A great challenge with carbon steel is that it corrodes when exposed to aggressive acids and environmental factors (Dwivedi *et al.*, 2017). The acid can target the metal's surface through an interfacial interaction and cause the metal to corrode. This can occur in a variety of industrial processes. Even though corrosion is a natural occurrence that can't be eliminated, it can be mitigated to some extent. Every year, one-third of steel is lost because of corrosion, which results in a loss to the world economy of roughly 3% of GDP. In general, metal corrosion control is crucial for technical, financial, environmental, and cosmetic purposes. One of the finest methods for guarding metals and alloys from corrosion is the use of inhibitors. Many efforts have been made over the years to locate acceptable organic corrosion inhibitors in a variety of corrosive conditions. Therefore, searching for an advanced method to be applied and used as an inhibitor to prevent and limit the metal dissolution process would be inevitable for protecting metals against corrosion in acid solutions (Sivakumar & Srikanth, 2020).

The organic compounds contain heteroatoms and exhibit anti-corrosive activity; however, the synthesis of these organic compounds is not only expensive but also toxic to both humans and the environment. To overcome this problem, many researchers focused their work on searching for organic compounds with a safe impact on the environment. The discovery of green corrosion inhibitors was triggered by the environmental toxicity of organic corrosion inhibitors; these inhibitors are biodegradable and do not include heavy metals or other harmful substances. Plant products are cheap, accessible, and renewable. In addition, they are environmentally friendly and ecologically acceptable (Fazal *et al.*, 2022; Hart, 2016; Rani and Basu, 2012). Researchers showed great interest in the use of these eco-friendly compounds because they are safe and do not contain any heavy metals or dangerous components (Fouda *et al.*,2014). As these extracts are biodegradable, some studies have reported the successful use of naturally occurring substances for inhibiting the corrosion of metals in acidic and alkaline environments (El-Eter, 1998; Yee, 2004; Abiola *et al.*,2007).

Numerous heteroatoms, including O, S, P, and N, are present in the plant extract. Such atoms bind with

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the metal via free electrons and hinder metal disintegration through the formation of a preventive film at the metal surface. Numerous researchers have reported the use of naturalistic materials as dissolution inhibitors for a range of metals in a variety of environments. Numerous plant extracts have been utilized successfully and effectively for the dissolution of steel alloys in acid solutions. In order to stop Q235 steel from corroding in 1 M HCl, Chen et al. (2020) used an extract from Magnolia grandiflora leaves. To prevent mild steel from corroding in an acidic solution, Dehgani and colleagues (2020) utilized an extract from *Aloysia citrodora* leaves. Garlic extract is used by Asfia and others (2020) to inhibit the rusting of AISI 304 stainless steel in HCl media. Steel corrosion in HCl medium is inhibited by *Ficus racemosa* leaf extract, according to Anh *et al*. (2020).

Burghul, wheat product, is a good source of dietary fiber, protein, iron, and vitamin B6 and it contains gluten. Since the early 1900s, burghul has grown in popularity as a health and gourmet food in the United States and Western Europe. The aim of this work is to examine how burghul extract inhibits carbon steel dissolution in a 1M HCl solution. Many techniques are used in this study, such as weight loss, potentio-dynamic polarization, impedance spectroscopy and electrochemical frequency modulation. The adsor-ption behavior of burghul extract on a carbon steel surface is investigated. The investigation also includes the effect of temperature on inhibition efficacy. Furthermore, SEM and ATR-IR techniques were used to examine the surface of carbon steel samples devoid of and with Burghul extract.

MATERIALS AND METHODS

Carbon steel samples

The experiments were conducted on a carbon steel of chemical composition shown in tablet (1). For weight-loss methods, the carbon steel specimens were mechanically prepared with dimensions 2.0 × 2.0 × 0.2 cm^3, polished with silicon carbide (SiC) emery papers of different grades. Then it was degreased with acetone to remove impurities and rinsed with doubly distilled water. Finally, the cleaned carbon steel specimens were dried at room temperature and accurately weighed by analytical balance (Fouda *et al.*,2019; Khadom *et al.*,2018). For the electrochemical measu-reements, the specimens were desiccated at room temperature with an exposed surface area of 1 cm^2 (the residual area covered with the epoxy resin), abraded and degreased following the method of Abdallah *et al*. (2012) .

Preparation of a blank solution

As a corrosive medium, 1M HCl solution was prepared from analytical grade condensed 32% HCl by dilution with double distilled water.

Preparation of burghul plant extract

The burghul plant was ground into fine powder by using an electrical mill at room temperature. The powder (200 mg) was soaked in 800 ml of Methanol at a ratio of 1:4 (powder/solvent). The extract was condensed by evaporation under vacuum using a rotary evaporator (HEM-03). The extract was liquefied in ethanol (1 g/L) and placed in a refrigerator for the activation process, as recommended by Onipe *et al.* (2015) and Shaker *et al*. (2019).

Table (1): Chemical composition of carbon steel

Element	Composition (%)
C	0.280
Si	0.220
S	0.070
P	0.087
Mn	0.600
Ni	0.110
Cr	0.081
Mo	0.001
V	0.001
Cu	0.200
W	0.010
Ti	0.001
Sn	0.310
Co	0.0081
Nb	0.001
Fe	The rest

Measurement techniques

Weight-loss measurements

The pre-weighed carbon steel sample was immersed in 100 ml of a 1 M HCl solution in the absence and presence of different concentrations of burghul extract for 180 minutes. The samples were taken out, washed, dried, and finally reweighed accurately. The corrosion rate (CR) was determined by the following equation (Usman *et al.*,2016):

$$CR = \frac{\Delta W}{At}$$

Where CR refers to corrosion rate ($mg/cm^2/min$), ΔW is the mean weight loss (mg) of a carbon steel sample, A is the surface area (cm^2), and t is the immersion time.

The inhibition efficiency (IE) was calculated from the calculated C.R values through the following equation (Verma *et al.*,2018):

$$IE = \frac{CR_1 - CR_2}{CR_1} \times 100$$

Where, CR_1 and CR_2 are the corrosion rates in the absence and presence of different concentrations of burghul extract, respectively.

Electrochemical measurements

The experiments were carried out by using a Gamry Instrument (PCI 4-G750) Potentiostat/Galvanostat-/ZRA. A conventional three-electrode cell was utilized, involving a platinum electrode as a counter electrode

(CE), a saturated calomel electrode (SCE) placed in a Luggin capillary as a reference electrode, and a carbon steel electrode as the working electrode (WE). The electrode was immersed in the corrosive solution for 0.5 hour prior to each run to achieve a constant open-circuit potential. The polarization curves were recorded from potentials of -500 to 500 mV vs. SCE with a scan rate of 1 mV s^{-1}. For electrochemical impedance spectroscopy (EIS) an AC signals, in the frequency range of 100 KHz to 10 mHz with an amplitude of 10 mV peak-to-peak was utilized (Megahed and Elbahrawi, 2016).

Electrochemical modulation was carried out at two different frequencies: 2, and 5 Hz. The waveform renews at a lowest frequency of 0.1 Hz every second. The spectrum includes inter-modification current peaks as well as current responses that can be harmonically attributed. The larger humps were used to calculate the causation factors as well as the Tafel slopes and corrosion current (Abdallah *et al.*,2012; Megahed *et al*., 2016; Obot and Onyeachu, 2018).

Attenuated Total Refraction Infrared (ATR-IR) analysis

The ATR-IR spectrum of the burghul extract and the film formed on the surface of carbon steel was investigated by Thermo Fisher Scientific, NicoletiS10 model, with wavenumber range of 400 - 4000 cm $^{-1}$ (El-Katori *et al.*,2020).

Surface examination

SEM investigation was performed to learn more about the alterations at the carbon steel surface both before and after the burghul extract was added. The coupons were cleaned, polished, and submerged for 24 hours in 1M HCl without and with 300 ppm burghul extract at 298 K utilizing a JEOL JSM-5500 scanning electron microscope.

RESULTS

Weight-loss tests and the effect of temperature

The weight-loss of steel coupons decreases as the concentration of burghul extract increases. Similarly, the inhibitory efficacy increases with the concentration of the extract. The effect of temperature on the inhibition efficiency was studied with different concentrations of the extract as shown in Table (2). The results show that the maximum efficacy is achieved with 300 ppm of burghul extract at 40 °C.

Thermodynamic activation parameters

The Arrhenius plot (log k vs. $\frac{1}{T}$) of the plant extract is shown in Figure (1). The Arrhenius plots shows a straight line with a slope of $\frac{-Ea*}{2.303R}$, from which the E_a^* value of the carbon steel corrosion process can be estimated. The activation energy, E_a^*, has a value of 98.13 kJ mol^{-1} for the blank solution. As the plant extract inhibits the corrosion process by chemical adsorption on the steel surface, the activation energy significantly decreases with increasing the concentration of the plant extract. The unchanged or lower E_a^* in the inhibit system compared to the blank ascribed to chemisorption, while a higher value of E_a^* suggests a physical adsorption. As shown in Table (3), the values of ΔH^* are positive, However, the values of ΔS^* are positive at low concentrations and negative at high concentrations of plant extract.

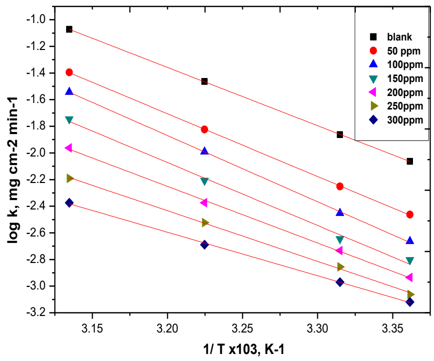

Figure (1): Arrhenius plot for carbon steel corrosion rate (k_{corr}) in 1M HCl in the absence and presence of different concentrations of burghul extract.

Adsorption isotherm

The mechanism of inhibition and the thermodynamic parameters of the corrosion process on carbon steel were studied by adsorption isotherms. Various isotherms, such as Frumkin, Langmuir, Temkin, and Freundlich, were studied. The results obtained for burghul extract follow the Langmuir adsorption isotherm. The Langmuir isotherm is described by the following relationship:

$$\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh}$$

Where, θ is the coverage of the surface; determined from the weight-loss experiments, C_{inh} is the inhibitor concentration, and K_{ads} is the adsorption equilibrium constant. The latter is estimated from the intercept of the straight line on the (C_{inh}/θ) versus C_{inh} plot (Fig. 2). K_{ads} estimated from the reciprocal of the intercept of isothermal lines are given in Table 4. The burghul extract is strongly adsorbed on carbon steel at different temperatures.

The standard Gibbs energy change for the adsorption process, ΔG^o_{ads}, is related to the adsorption equilibrium constant (K_{ads}) via the following equation (Akinbulumo *et al.*,2020):

$$\Delta G^o_{ads} = -RT\ ln(55.5\ K_{ads})$$

Where R is the gas constant, T is the absolute temperature, and 55.5 is the water concentration in the molarity unit. However, the adsorption heat, ΔH^o_{ads}, can be computed in light of the Van't Hoff equation.

$$lnK_{ads} = \left(\frac{-\Delta H^o_{ads}}{RT}\right) + constant$$

The slope of the linkage between (ln K_{ads} and 1/T), which equals $-H^o_{ads}/R$, is used to calculate H^o_{ads}. Entropy change of the inhibitor adsorption (ΔS^o_{ads}) was estimated utilizing the subsequent equation:

$$\Delta G^o_{ads} = \Delta H^o_{ads} - T\Delta S^o_{ads}$$

The obtained ΔS^o_{ads} values are tabulated in Table 4. As the temperature rises from 298 to 313 K, ΔS^o_{ads} decreases from -59.5 to - 67.7 J/K.

Table (2): Measurements of weight loss of Carbon steel in 1M HCl in the presence and absence of different concentrations of burghul extract at 25–40 °C.

Conc. (ppm)	Temp. (°C)	CR (mg cm^{-2} min^{-1})	Θ	%IE
Blank	25	0.008		
	30	0.016		
	35	0.054		
	40	0.084		
50	25	0.002	0.764	76.41±0.6
	30	0.003	0.838	83.8±0.2
	35	0.007	0.869	86.9±0.6
	40	0.013	0.845	84.5±0.4
100	25	0.001	0.819	81.9±0.3
	30	0.003	0.791	79.12±0.2
	35	0.004	0.919	91.9±0.4
	40	0.001	0.988	98.8±0.6
150	25	0.001	0.833	83.3±0.5
	30	0.003	0.834	83.42±0.3
	35	0.004	0.925	92.5±0.2
	40	0.001	0.985	98.5±0.4
200	25	0.001	0.861	86.12±0.6
	30	0.002	0.878	87.9±0.7
	35	0.003	0.939	93.57±0.8
	40	0.001	0.987	98.7±0.3
250	25	0.001	0.875	87.5±0.8
	30	0.001	0.919	91.9±0.2
	35	0.003	0.942	94.21±0.6
	40	0.001	0.992	99.2±0.6
300	25	0.001	0.889	88.91±0.4
	30	0.001	0.939	93.96±0.5
	35	0.001	0.979	97.9±0.6
	40	0.001	0.993	99.3±0.2

Electrochemical measurements

Potentiodynamic polarization (PP) tests

Figure (3) shows the impact of concentration of burghul extract on the polarisation plots of carbon steel in 1M HCl. The addition of burghul extract impacts the polarization curves and inhibits both the cathodic and anodic reactions. The electrochemical parameters, such as corrosion potential (E_{corr}), corros-ion current density (I_{corr}), anodic and cathodic Tafel slopes (β_a, β_c), and inhibition efficiency (IE %) are listed in Table (5). The % IE and surface coverage (θ) were determined from polarization measurements according to the following relations of Rybalka *et al.*, (2021):

$$IE\% = \left(1 - \frac{i_{(inh)}}{i_{(free)}}\right) \times 100$$

$$\theta = \left(1 - \frac{i_{(inh)}}{i_{(free)}}\right)$$

Where, i_{free}, and i_{inh} are the corrosion current densities in the absence and presence of burghul extract.

The results showed that the corrosion current density ($i_{corr.}$) declines with an increase in the dose of the extracts, illustrating that the existence of the extract in a corrosive medium inhibits the corrosion of steel in 1M HCl.

Electrochemical impedance spectroscopy (EIS test)

Nyquist and Bode plots of carbon steel in 1M HCl in the absence and presence of different concentrations of Burghul extract are shown in Figure (4). The electro-chemical factors, like solution resistance, polarization resistance, and capacitance, are estimated. It is also possible to measure the number of time constants used in the electrochemical reaction. The time constant used in the electrochemical method is representative of each semicircle of the Nyquist map, which represented in Table (6). The results revealed that R_{ct} values increase with the dose of the studied extract. This implies the formation of a protective film on the CS surface by adsorption.

For the equivalent Randles circuit is displayed in Figure (5). The circuit contains the charge transfer resistance R_{ct} which is connected in parallel to the double-layer capacitance C_{dl}. The output of both is attached to the solution resistance R_s. R_{ct} was used to estimate the mitigation efficacy (IE) as follows:

$$IE = \frac{R^o_{ct} - R_{ct}}{R^o_{ct}} \times 100$$

Where, R_{ct} and R^o_{ct} are the charge transfer resistances devoid of and with Burghul extract, respectively. Double-layer capacitance magnitudes (C_{dl}) obtained in keeping with the subsequent relation.

$$C_{dl} = Y_o(\omega_{max})^{n-1}$$

Where ω_max=2πf_max and f_max is the frequency when the imaginary part of the impedance is a maximum value.

Table (3): The activation properties of carbon steel with and without different concentrations of Burghul extract in 1M HCl

Conc. (ppm)	E_a* kJ mol^{-1}	ΔH* (kJ mol^{-1})	ΔS* (J mol^{-1} k^{-1})
Blank	98.13	53.45	126.4
50	64.82	47.73	75.4
100	63.72	40.92	19.1
150	52.22	35.73	-24.1
200	47.23	28.72	-79.7
250	39.46	22.58	-128.2
300	31.87	18.66	-160.8

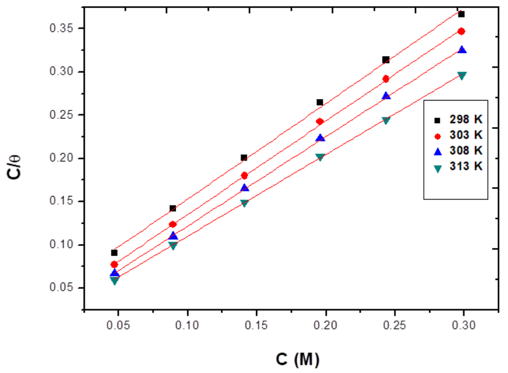

Figure (2): Langmuir adsorption curves for carbon steel in 1M HCl at different concentrations of Burghul extract at different temperatures.

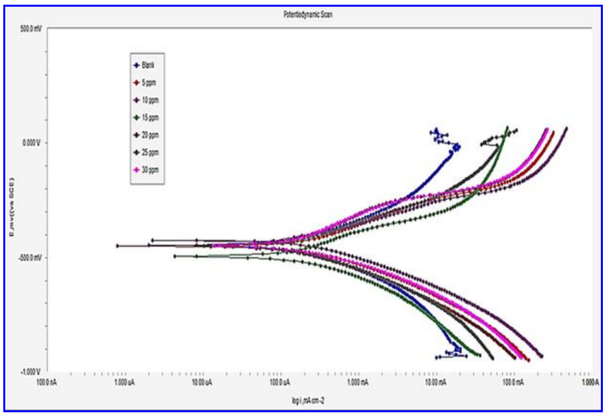

Figure (3): PP curves of corrosion of carbon steel in 1M HCl in the absence and presence of different concentrations of Burghul extract at 25° C.

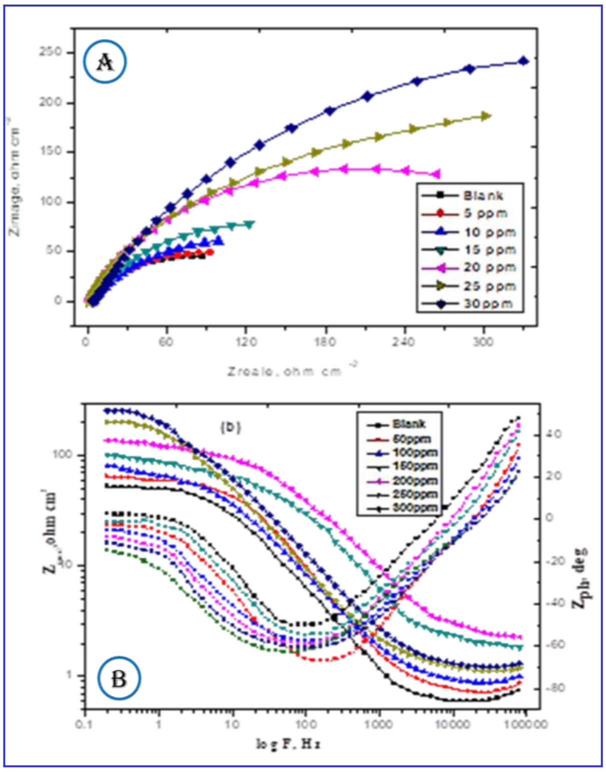

Figure (4): The corrosion of carbon steel in 1M HCl in the absence and presence of different doses of Burghul at 25ºC represented by. A, the Nyquist; B, Bode curves.

Table (4): Adsorption parameters of Burghul extract on carbon steel in 1M HCl.

Temp (K)	Measured parameters			
	K_{ads} (M^{-1})	$-\Delta G^o$ (kJ mol^{-1})	$-\Delta H^o$ (kJ mol^{-1})	$-\Delta S^o$ (J mol^{-1} K^{-1})
298	23.4	17.7	21.1	59.5
303	36.7	19.2		63.3
308	53.2	20.4		66.3
313	62.8	21.2		67.7

Electrochemical frequency modulation (EFM) study

The intermodulation spectra obtained from the EFM test for the corrosion of carbon steel in 1 M HCl in the absence and presence of different concentrations of Burghul extract are shown in Figure (6). The IE, Tafel constants, corrosion rate, and causality factors for different concentrations of the Burghul extract are shown in Table (7). The obtained results showed that the corrosion current density declined and the inhibition efficiency increased by increasing the dose of the examined extract. According to EFM theory, the estimations of CF-2 and CF-3 are near 2 and 3, respectively, suggesting that the obtained experimental results are of high quality.

Attenuated total reflectance infrared (ATR-IR) study

Figure (7) shows the ATR-IR spectra of Burghul extract and the surface of carbon steel metal after soaking for 6 hrs in 1 M HCl in the presence of 300 ppm of Burghul extract. The spectra of Burghul extract comprises the stretching -OH frequency at 3333cm^{-1}, The stretching – C = O frequency at 1650 cm^{-1}, the bending SP3 -C–H frequency at 1406 cm^{-1}, and stretching -C–O frequency at 1054 cm^{-1}. The spectra of steel metal after immersion in 1 M HCl at 300 ppm of Burghul extract, on the other hand are free of the previous functional groups.

Scanning electron microscope study

Figure (8) shows an SEM examination of the surface of carbon steel before and after immersion in 1 M HCl solution in the absence and presence of 300 ppm of Burghul. Picture (A) refers to a pure carbon surface, (B) refers to the surface after immersing in 1M HCl, and picture (C) refers to the surface after exposing to 1M HCl in the presence of 300 ppm of Burghul extract.

DISCUSSION

According to the results of the weight loss, Table (2), the mass of carbon steel coupons decreases with the concentration of Burghul extract. Along the same line, the inhibition efficiency (IE%) increases due to the adsorption of Burghul extract on the carbon steel surface (Abboud *et al*., 2016; Alvarez *et al*., 2018; Soltani *et al*., 2020). Rising temperature enhances the % IE, indicating that the adsorption of Burghul extract on a carbon steel surface follows chemisorption as

Table (5): The potentiodynamic polarisation characteristics of carbon steel were assessed in 1 M HCl at 25°C in the absence and presence of Burghul extract at different concentrations.

Plant Extract Conc. (ppm)	Potentiodynamic polarization measured parameters					
	$E_{corr} \times 10^{-3}$ (V)	$I \times 10^{-6}$ (A / cm^2)	$-\beta_c \times 10^{-3}$ (V/decade)	$\beta_a \times 10^{-3}$ (V/decade)	%IE	Θ
Blank	-527	404	121.7	89.9		
50	-442	74.6	112	99.2	8.4	0.084
100	-412	65.4	119	189	19.7	0.197
150	-405	62.8	111	132	22.9	0.229
200	-371	55.0	122	199	32.4	0.324
250	-360	53.7	161	208	34	0.340
300	-338	45.5	124	217	44	0.44

Table (6): Electrochemical impedance spectroscopy (EIS) measured parameters for corrosion of carbon steel in 1 M HCl at 25ºC in the absence and presence of Burghul extract at different concentrations.

Plant Extract Conc. (ppm)	EIS Measured parameters			
	R_{ct} Ω cm^2	C_{dl} F cm^{-2}	Θ	%IE
Blank	129.30	1.81		
50	145.60	1.84E^{-04}	0.112	11.2
100	189.30	2.45E^{-04}	0.317	31.7
150	226.60	1.94E^{-04}	0.429	42.9
200	368.40	5.41E^{-05}	0.649	64.9
250	545.20	4.97E^{-05}	0.763	76.3
300	694.80	7.94E^{-05}	0.814	81.4

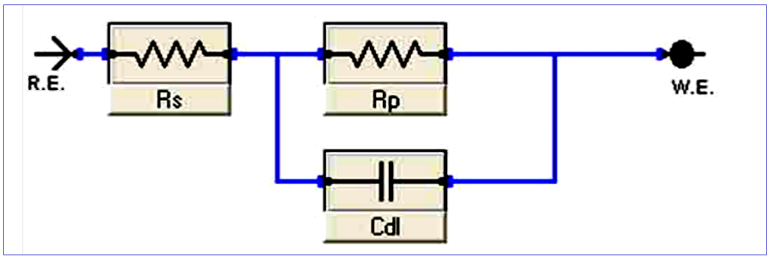

Figure (5): Electrical equivalent circuit used to model the results of impedance.

stated by Alvarez et al. (2018); Hamdy and El-Gendy, (2013); Usman and Okoro, (2015).

The thermodynamic activation parameters for the corrosion process reveal that the value of ΔH^* is positive, indicating that the formation of the activated complex is an endothermic process. (Benabbouha *et al.*, 2018). The negativity of ΔS^* suggests that the molecules of Burghul extract were adsorbed in an organized way over the CS surface. Since the Burghul extract inhibits the corrosion process via chemical adsorption, the activation energy significantly decreases with the addition of varying concentrations of the plant extract (Table 3).

Table (4) represents the adsorption parameters of the adsorption process. ΔG^o_{ads} values for the extract are negative, referring to the fact that the adsorption process proceeds of its own consistency and the stability of the adsorbed layer. When the temperature is 308 K or less, the magnitude values of ΔG^o_{ads} are less than 20 kJ mol^{-1}, showing that physisorption is the method of adsorption. However, as the temperature rises up to 313 K, the ΔG^o_{ads} value becomes -21.2 kJ mol^{-1}, indicating that adsorption has changed to chemisorption.

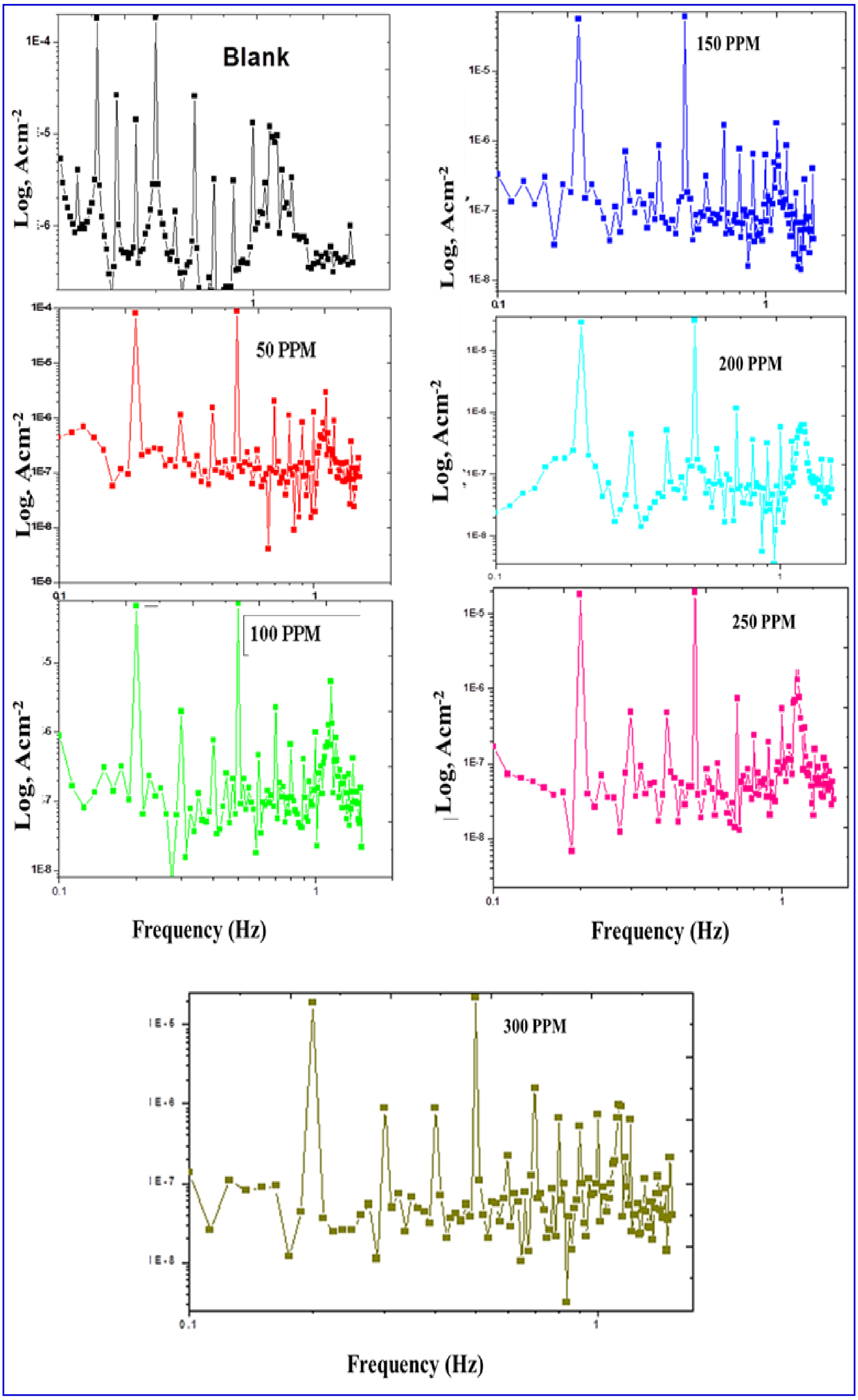

Figure (6): Intermodulation spectra for the corrosion of carbon steel in 1M HCl in the absence and presence of different concentrations of Burghul extract at 25 ºC.

Table (7): Electrochemical kinetic parameters of EFM for carbon steel in 1M HCl in the absence and presence of different doses of Burghul extract at 25ºC.

Plant Extract Conc. (ppm)	Electrochemical kinetic measured parameters							
	$I \times 10^{-6}$ (A/cm^2)	$-\beta c \times 10^{-3}$ (V/decade)	$\beta_a \times 10^{-3}$ (V/decade)	CF-2	CF-3	C.R	IE%	Ө
Blank	628.0	98	126	2.6	2.90	66.31	-	-
50	152.8	126	131	2.52	2.82	63.46	4.3	0.043
100	125.2	132	135	2.43	2.73	52.00	21.6	0.216
150	96.76	139	140	1.58	2.74	40.19	39.4	0.394
200	53.01	149	142	1.48	2.42	22.02	66.8	0.668
250	30.83	120	96	1.21	2.84	12.81	80.7	0.807
300	23.52	112	66	1.53	2.39	9.77	85.3	0.853

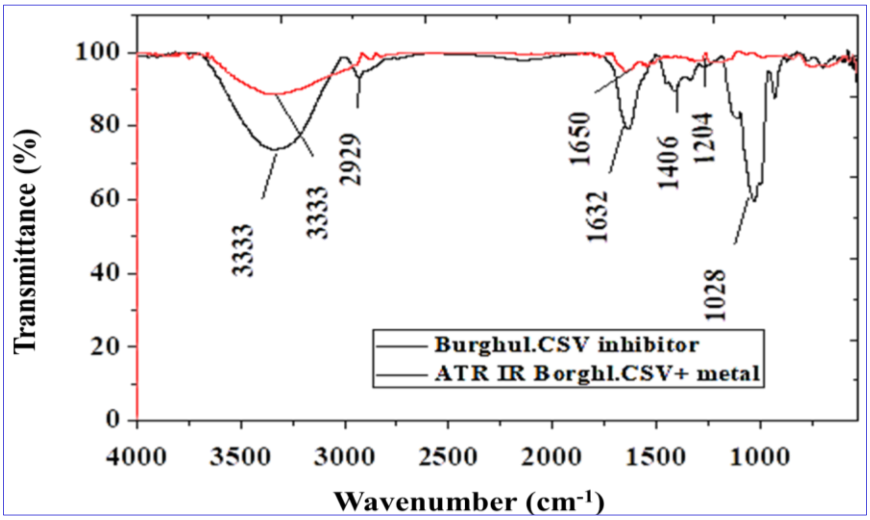

Figure (7): ATR-IR spectra of the Burghul extract verses to Burghul extract with carbon steel immersed in 1M HCl.

On the other hand, as the temperature attains 313 K, the ΔG^o_{ads} value becomes - 21.2 kJ mol^{-1}, referring that the adsorption becomes chemisorption. As a result, the adsorption of Burghul extract on the surface of carbon steel can be classified as both physical and chemical adsorption. As it can be seen in Figure (2), the adsorption of Burghul extract on carbon steel follows the Langmuir's adsorption isotherm.

The value of ΔH^o_{ads} is negative, indicating that the adsorption of the extract is accompanied by an evolution of heat (El-Etre, 2007). The ΔS^o_{ads} calculations are negative, representing the fact that the extract molecules, which move freely in the bulk solution, have been adsorbed to the steel surface in an organized manner. In the absence of plant extracts, Cl^- ions play an important role in steel corrosion, as shown below:

$$Fe_{(s)} + Cl^- \rightarrow (FeCl)_{ads} + e$$
$$(FeCl)_{ads} \rightarrow (FeCl)^+ + e$$
$$(FeCl)^+ \rightarrow Fe^{2+} + Cl^-$$

Since the experiments were carried out in an aerated acid solution, the cathodic reactions comprise both oxygen reduction and hydrogen evolution as follow:

$$4H^+ + O_2 + 4e \rightarrow 2H_2O$$
$$2H^+ + 2e \rightarrow H_2\uparrow$$

Despite the fact that it has been noted that corrosion on steel surfaces reduces dissolved oxygen at pH levels higher than 4, Since there are no other cathodic reactions in this work, the cathodic H2 evolution process is the only one (Abdallah et al., 2012; Akinbulumo *et al.*, 2020; Ayawei *et al.*, 2017; Ghazy *et al.*, 2016).

The effect of Burghul extract on the polarization curves of carbon steel in 1M HCl is displayed in Figure (3). The results indicate that the presence of the extract in the acidic medium shifts the anodic polarization to more positive values and the cathodic polarization towards more negative values (Bourazmi *et al.*, 2018; A. S. Fouda, El-Awady, *et al.*, 2018; Yasin, *et al.*, 2018). The cathodic polarization

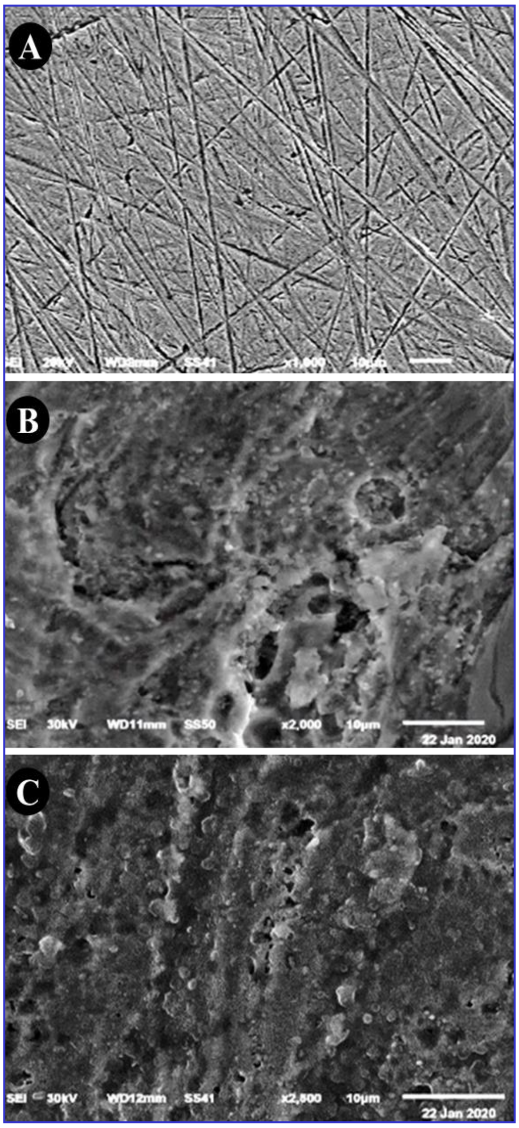

Figure (8): SEM images of polishing carbon steel (A), after exposing to 1 M HCl; (B), and after exposing to 1M HCl and 300 ppm; (C) Burghul extract.

curves in Figure (3) exhibit a similar pattern, indicatiting that the reaction mechanism of the cathode was unaffected by the adsorption of Burghul extract at the metal surface. The slopes of the anodic curves, however, vary, indicating that the anodic reaction's mechanism has changed. This suggests that the corrosion process may be severely hindered by the adsorption of Burghul extract to the metal surface. Therefore, Burghul extract belongs to the mixed-type inhibitors. It is adsorbed at the cathodic sites of steel and minimizes cathodic reactions. In addition, the adsorption of the extract on anodic sites may occur via lone pair electron donation of N and O atoms to the steel substrate. This minimizes the anodic corrosion of steel. The corrosion current density (i_{corr}) declines with raising the dose of the extract, illustrating that the existence of the extract inhibits the corrosion of steel in 1M HCl. The extent of inhibition is based on the concentration and nature of the examined extract, although no definite pattern has been observed when E_{corr} values are moved.

In order to better understand how the dissolving process works, EIS tests were conducted. Figure (4) shows the Nyquist and Bode-phase angle plots of carbon steel in 1M HCl without and with various concentrations of Burghul extract. The extract inhibitor takes control of the activation of the electrochemical reaction without changing the corrosion reaction mechanism. Double layer capacitance values (C_{dl}) and charge-transfer resistance values (R_{ct}) were obtained from impedance measurements. As shown in Table (6), the values of the R_{ct} increase with increasing the concentrations of Burghul extract. Hence, the presence of the plant extract decreases the corrosion rate and consequently increases the inhibition efficiency. C_{dl} values decrease by increasing the concentration of Burghul extract, indicating the adsorption process belongs to the Helmholtz model (Rani & Basu, 2012).

C_{dl} values decrease as extract concentration is increased, Table (6). This is primarily caused by the extract molecules at the steel surface gradually exchanging H_2O molecules. This will lessen the reaction of dissolution. The degradation of the steel slows down as the R_{ct} values rise. The rise in electrical double-layer thickness and decline in the dielectric constant are attributed to the decline in C_{dl} values. This finding suggests that the extract molecules function by adhering to the metal/solution interface. Adsorption occurs as a result of the interaction between the Burghul extract and the adsorbed Cl^- anions. The equivalent circuit that can be seen in Figure (5) is being used to analyze the Nyquist curves, which comprise R_s and *CPE* (constant phase element) parallel to the R_{ct}.

Figure (6) shows the modulation spectra obtained from EFM testing for carbon steel disintegration in 1 M HCl without and with various amounts of Burghul extract. The current response includes the input frequencies and frequency components. The latter is created by multiplying, dividing, and adding the two input frequencies. The response to the stimulation frequencies has two main peaks at 0.2 and 0.5 Hz. The principal peaks are utilized to calculate the Tafel slopes, the corrosion current, and the causality factors (CF-2 and CF-3). For various concentrations of the Burghul extract at 298 K, Table 5 showed the causality factors, Tafel constants, and inhibitory efficacy. As the amount of Burghul extract in the corrosive medium rises, the corrosion current density drops. This is brought on by the carbon steel surface developing a protective film, which minimizes disintegration. Adsorption is caused by the interaction of the Burghul extract with the adsorbed Cl^- anions. The causality factor values are directly correlated with theoretical values 2 and 3. This suggests that the results are of a high caliber. (Fouda *et al.*, 2017; Akkal *et al.*, 2016; Fouda, *et al.*, 2016; Obot and Onyeachu, 2018).

The ATR-IR spectra of Burghul extract alone and the surface of carbon steel metal after soaking for 6 hrs in 1 M HCl in the presence of 300 ppm Burghul extract are shown in Figure (7). The spectra show that the active functional groups in Burghul extract bind to the surface of the carbon steel metal and prevent it from dissolution *(*Alvarez *et al., 2018;* Ganzoury *et al.*, 2015; Kunjiappan *et al.*, 2014).

SEM is performed on the metal surface before and after immersion in a 1M HCl solution free of and containing 300 ppm Burghul extract. Figure (8A) shows the surface shape of the carbon steel metal after polishing. The surface appearance of carbon steel metal after six hours in a 1 M HCl solution is shown in Figure (8B). Because of the pitting effect of chloride ions, it is seen that the entire steel surface has been extensively corroded. The shape of the steel surface that was exposed to the 300 ppm Burghul extract has greatly improved in Figure (8C).The steel surface develops a barrier film that shields it from corrosion because of the Burghul extract.

CONCLUSION

The Burghul extract is a good corrosion inhibitor for carbon steel under acidic condition of 1 M HCl. The efficiency of corrosion inhibition increases as temperature and plant extract concentrations increase. Burghul extract concentration of 300 ppm at 40 ^{o}C had shown an improvement in the inhibitory efficiency of up to 99.3%. The adsorption of the prepared extract of burghul plant follows the Langmuir's adsorption isotherm. The inhibitor is chemically adsorbed onto the surface of the C-steel while the spontaneity of the adsorption process is demonstrated by the negative values of ads Goads. The adsorption of the Burghul extract on the carbon steel metal was verified by ATR-IR analysis and SEM inspection. Burghul is considered a mixed-type inhibitor.

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مستخلص نبات البرغل كمثبط لتآكل الصلب الكربوني فى محاليل حمض الهيدروكلوريك

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الملـخص العربـي

تعد مشكلة تآكل الفلزات من الظواهر الطبيعية علي انها تدمير أو فناء للمادة نتيجة لتفاعلها مع الوسط المحيط. مما تسبب خسائر ماديّة فادحة، كما أنها تؤثر على سلامة وصحة العاملين .وإن استخدام الحديد الكربوني في القطاعات الصناعية يُمثل تحديًا كبيرًا لمهندسي التآكل. حيث يعد حامض الهيدروكلوريك واحداً من أكثر المواد المستخدمة على نطاق واسع في القطاع الصناعي. وبسبب السلوك التآكلي للمحاليل الحامضية تجاه الحديد الكربوني، فإن استخدام المثبطات لمنع عملية تآكل الفلزات سيكون أمرًا ضرورياً. ويعد استخدام المثبطات واحداً من أفضل الخيارات لحماية الفلزات من التآكل في المحاليل الحامضية. ولهذا استهدف البحث دراسة كيفية الحد من تآكل الصلب الكربوني فى الوسط الحامضي وكيفية حمايته عن طريق اختبار تأثير مستخلص نبات البرغل كمثبطات لتآكل الصلب الكربونى وحساب كفاءة هذة المستخلصات النباتية لتثبيط تآكل الصلب الكربوني بواسطة الطرق الكيميائية و الكهروكيميائية المختلفة (الاستقطاب الجهدي الحركي –طيف المعاوقة الكهروكيميائية- التردد المعدل الكهروكيميائي).واثبتت الدراسة ان معدل التآكل للصلب الكربوني يقل مع زيادة تركير مستخلص نبات البرغل وبالتالي زيادة كفاءة التثبيط وأن زيادة تركيز المثبطات في بيئة التآكل يؤدي الي زيادة قيم مقاومة انتقال الشحنات R_{ct} مقابل تدني قيم الطبقة المزوجة C_{dl} وهو مما يؤدي الي اختزال معدل التآكل نتيجة زيادة تغطية المثبط لسطح الصلب الكربوني عن طريق عملية الادمصاص. وبإستخدام تقنية ATR-IR ووجد أن المجموعات الوظيفية والموجودة في جزئيات مستخلص البرغل قد تم إستخدامها لحدوث عملية الادمصاص وتكوين طبقة حماية على سطح الصلب الكربوني.