DOI: 10.2478/auoc-2023-0001

Ovidius University Annals of Chemistry Volume 34, Number 1, pp. 1 - 7, 2023

Evaluation of the inhibitory action of essential oil from *Eucalyptus globulus* leaves on the corrosion of mild carbon steel in 1M HCl medium

Malick BATHILY*,[1] Baba NGOM,[2] Malick MBENGUE,[3] and Diadioly GASSAMA[1]

[1]*Department of Physics and Chemistry, UFR Sciences and Technologies, Iba Der THIAM University of Thies, Thies, Senegal*

[2]*Laboratory of Water and Environmental Sciences and Technologies (LaSTEE), Ecole Polytechnique de Thiès, Thiès, Senegal*

[3]*Laboratory of Applied Microbiology and Industrial Engineering, Ecole Supérieure Polytechnique, Dakar, Senegal*

Abstract. The present work aims to valorize an aromatic and medicinal plant of *Eucalyptus globulus* found in the region of Dakar, Senegal. To do so, we first extracted the essential oil contained in the leaves of the plant harvested in October 2020. We obtained the essential oil by hydrodistillation using a Clevenger type extractor with a yield of 1.70% of the dry plant mass. This value is quite appreciable compared to the different values in the literature. The essential oil extracted from the leaves of *Eucalyptus globulus* was tested as a green inhibitor on carbon steel type XC38 in 1M HCl acid medium by the mass loss method. The results obtained led to a maximum inhibitory efficiency of 89.03% for a concentration of 1.6 g/L of essential oil at room temperature of 298 K. The effect of temperature on the inhibitory behavior of the essential oil was also studied over a range of 298 K to 338 K. In this temperature range, a loss of efficiency was observed with increasing temperature, reaching a value of 15.33% at 338 K. Thermodynamic quantities were then determined. The plot of the different isotherms showed that the adsorption of the essential oil obeys the Langmuir isotherm. The results obtained showed a physical character of adsorption of this essential oil.

Keywords**:** essential oil; *Eucalyptus globulus*; inhibitor; corrosion; steel; mass loss measurement.

1. Introduction

Corrosion is a phenomenon of material degradation. This phenomenon most often affects the industrial sector, particularly the construction sector, but also the aeronautical industry, the chemical and petrochemical industry, the automotive industry, etc. [1]. Today, it can be noted that steel is the basis of mass production in many industrial sectors, particularly those mentioned above. This material is largely affected by corrosion, especially from aggressive solutions. However, the aggressive solutions such as acids are also widely used in the industrial sector for pickling, acid cleaning, removal of localized deposits, oil well stimulation [2, 3]. As a result, the aggressive nature of these acid solutions and their use in the presence of steels has led research to focus on the implementation of means of protecting steels in an acid environment. Among these means of protection, we find corrosion inhibitors. It should be noted that most of the inhibitors used in an acid environment are of the synthetic organic type [4-9]. However, the disadvantage of these types of inhibitors lies in their high toxicity as well as the harmful impacts they can have on the environment. In order to overcome these drawbacks, research has now turned to the use of natural substances. In our research team, a lot of work has been done in the past on the use of these natural substances as corrosion inhibitors for metallic materials. We can cite the work on the evaluation of the inhibiting action of the volcanic clay tuffs of Bafoundou carried out by D. Gassama et al. [10, 11], as well as their work on the evaluation of the inhibiting action of clay compounds of the sedimentary montmorillonite type as corrosion inhibitors for E400 reinforcing steel [11]. These studies resulted in inhibitory efficiencies of up to 70% for volcanic clay tuffs and up to 62% for montmorillonite. Various studies have also been carried out on the evaluation of the inhibitory efficiencies of natural compounds such as natural oils and essential oils extracted from various parts of plants, we can give the example of the work carried out by K. Cissé et al. [12], on the evaluation of the inhibitory effectiveness of the essential oil of *Cyperus articulatus* on the corrosion of S235 steel in HCl medium and their studies resulted in an optimal inhibitory efficacy of 92%. Although other inhibitor types essential oils have been developed in recent years, such as *Eucalyptus camaldulensis* and *Cyperus rotundus* essential oils [13], but also chamomile essential oil [14], *Mentha pulegium* essential oil [15], prickly pear seed oil [16], essential oil extracted from *Carum carvi* L species [17], etc. In one of our previous works, we made an overview of most of the natural substances extracted from various parts of plants with rather high inhibition rates on different metallic materials in acidic medium [18]. This work has shown

* Corresponding author. *E-mail address*: malickbathily@gmail.com (Malick Bathily).

© 2023 Malick Bathily et al.
This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivs Licence (https://creativecommons.org/licenses/by-nc-nd/3.0/).

the growing interest in the use of natural substances as inhibitors around the world over the last two decades.

The objective of this research work is to study the corrosion inhibition process of XC38 steel in 1M hydrochloric acid medium by the essential oil extracted from *Eucalyptus globulus* leaves. This study will be done using the gravimetric measurement method.

In the literature, a number studies have been carried out on the chemical composition of *Eucalyptus globulus* essential oils. In the European pharmacopoeia, *Eucalyptus globulus* essential oil has a composition of 0.05 to 10% α-pinene, 0.05 to 1.5% β-pinene, maximum 0.3% sabinene, 0.05 to 1.5% α-phellandrene, 0.05 to 15% limonene, minimum 70% 1,8-cineole and maximum 0.1% camphor.

Studies carried out by Kumar et al. [19] by gas chromatography coupled with mass spectroscopy show that the essential oil of *Eucalyptus globulus* is composed mainly of 1,8-eucalyptol with a percentage of 33.62%, other compounds such as α-pinene with a percentage of 14.10%, D-limonene representing 10.09% of the composition, 1,4-cineol at 4.07%, α-terpinolen at 5.95%, α- terpineol at 4.72%, β-pirene at 3.70%, β-myrcene at 1.88%, terpineol at 2.42%.

If we refer to the work carried out by Almas et al. [20], we find 1,8-eucalyptol as the majority component but with a percentage of 51.62% lower compared to what is found in the European pharmacopoeia. The α-pinene is represented at a rate of 23.68%, then we have *p*-cymene (10%), β-myrcene (8.74%), terpinen-4-ol (2.74%), γ-terpinene (2.59%), camphene (0.37%), citronellal (0.20%), α-terpineol (0.08%) and many other compounds in trace amounts.

The results obtained in the first study are more in line with those in the pharmacopoeia.

2. Experimental

2.1. Materials

The plant material, consisting of leaves of *Eucalyptus globulus* growing in a spontaneous state, was collected in October 2020 in the region of Dakar. After harvesting, the freshly harvested plant material was cleaned, sorted and freed of various artefacts. The resulting product was extended in the laboratory for drying for 15 days at room temperature and protected from light. It was then recovered and ground in a grinder before extraction.

2.2. Methods

The extraction of the essential oil from the leaves of *Eucalyptus globulus* was carried out by hydrodistillation using a Clevenger type apparatus according to the technique described by the European Pharmacopoeia [21]. The resulting oil was dried over anhydrous sodium sulfate (Na_2SO_4) and stored at 4 °C in a dark bottle until use.

The yield (r) of essential oil was determined relative to the dry matter. It is expressed by the mass of essential oil (g) obtained for 100 g of dry plant matter.

The aggressive solution, which is the corrosive medium, consists of a 1M HCl solution prepared from a commercial 37% HCl solution.

The corrosion tests were carried out on XC38 (C35) type carbon steel plates whose percentage of elements other than iron is: C – 0.32-0.39; Si - 0.40 max.; P - ≤ 0.035; Mn – [0.50 – 0.80]; Si - ≤ 0.035.

The mass loss measurements were carried out on steel sheets cut into rectangular plates with a surface area S = 4.99 cm^2. These plates, which constitute the working electrode, were prepared before the measurements by successive mechanical abrasion using silicon carbide (SiC) papers of increasingly fine granulometry (400-600-1200). The samples were then rinsed with distilled water and dried with compressed air before immersion in 50 mL of the corrosive solution in the absence and presence of different concentrations of the essential oil extracted from the leaves of *Eucalyptus globulus*. The samples are immersed for one week (168 hours).

After the corrosion test, the steel plates were carefully washed with distilled water, degreased with ethanol and then dried in hot air. The plates were then weighed using a precision balance.

For the determination of the temperature factor on the inhibitory effect of the essential oil of *Eucalyptus globulus*, we carried out a study in the temperature range from 298 to 338 K using gravimetric measurements in the absence and presence of the essential oil. For each temperature, the immersion time was set at 48 hours. During the study, we carried out the same pre-treatment of our steel plates as in the concentration effect study before immersing them in 50 mL of the corrosive solution.

3. Results and discussion

3.1. Extraction yield

The *Eucalyptus globulus* leaves provided a yellowish colored essential oil with a very strong odor and an average yield of about 1.70% of the dry plant mass. The yield obtained is appreciable. Compared to those reported in the literature, the yield of our sample is quite similar to that obtained by Ghaffar et al. [22] who reported an average yield of *Eucalyptus globulus* essential oil obtained by hydrodistillation equal to 1.91%. This yield is nevertheless much higher than that obtained by Boukhatem et al. [23] who chose to work on fresh leaves of *Eucalyptus globulus* from Blida (Algeria) and who obtained 0.96% of essential oil.

The good yield is probably due to the pre-treatment that was imposed on the plant material prior to extraction as studies by Zrira et al. [24] have shown that drying in the open air and out of the sun has an impact on the yield.

3.2. Gravimetric measurement

3.2.1. Effect of concentration. Mass loss measurements were carried out in the concentration range of *Eucalyptus globulus* essential oil from 0.1 to 1.6 g/L at 298 K for an immersion time of 168 hours in 1M HCl.

The values of corrosion rate (W_{corr}), inhibition efficiency (E_w %) and metal surface coverage (θ) are given by the following relationships:

$$W = \frac{\Delta m}{S \times t} \qquad (1)$$

$$E_w = \frac{W_{corr\,(0)} - W_{corr\,(inh)}}{W_{corr\,(0)}} \times 100 \qquad (2)$$

$$\theta = \frac{E_w}{100} \qquad (3)$$

where: Δm - the difference in mass of the steel in mg, before and after its immersion in the corrosive solution; S - the surface area of the steel in cm^2; t - immersion time in h; $W_{corr\,(0)}$ and $W_{corr\,(inh)}$ expressed in mg/h·cm are the corrosion rates of XC38 steel in the absence and presence of the inhibitor respectively.

The results obtained for the corrosion rate (W_{corr}), inhibition efficiency (E_w %) and recovery rate (θ) are recorded in Table 1.

Table 1. Gravimetric corrosion results of XC38 steel in 1M HCl acid medium in the absence and presence of different concentrations of *Eucalyptus globulus* essential oil at 298 K during 168 h immersion

***C* (g/L)**	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**
W (mg/h·cm^2)	0.74	0.45	0.42	0.38	0.35	0.31	0.26	0.20	0.16	0.11	0.11	0.11	0.10	0.09	0.08	0.09	0.08
E_w (%)	-	38.8	44.2	49.0	53.3	57.9	65.3	73.1	78.2	84.8	85.1	85.5	87.0	87.9	88.78	88.99	89.03

Figure 1 shows the variation of the corrosion rate (W_{corr}) of steel in 1M HCl and the corresponding inhibitory efficiency (E_w (%)) as a function of the different concentrations of the essential oil studied.

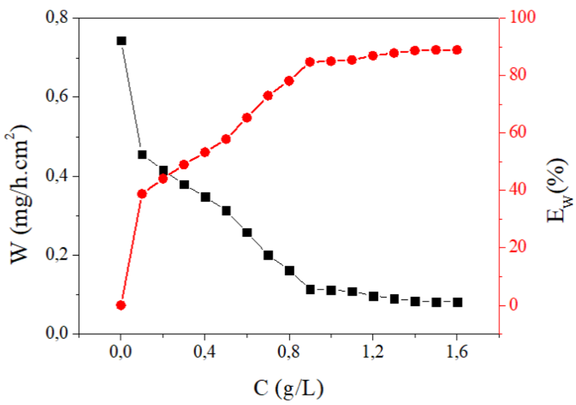


Figure 1. Variation in corrosion rate (W_{corr}) and inhibitory efficiency (E_w) of corrosion of XC38 carbon steel in 1M HCl acid medium in the absence and presence of different concentrations of *Eucalyptus globulus* essential oil at 298 K during 168 h immersion.

The data in Table 1 and Figure 1 show a clear variation in the corrosion rate and inhibiting effectiveness of the essential oil as a function of its concentration. Indeed, the corrosion rate decreases while an increase in efficiency is observed. This can be explained by an increase in the surface area covered by the absorption of the essential oil components on the steel surface by increasing the protection of the steel surface against corrosive ions. This protection is achieved by blocking the active sites, thus creating a protective film at the steel/solution interface [25]. According to the data obtained during the measurements, the addition of 0.1 g/L of essential oil of *Eucalyptus globulus* in the aggressive medium reduces this corrosion rate by 39% and reaches a maximum of 89% at 1.6 g/L.

3.2.2. Effect of temperature. The influence of temperature is a very important factor on the effectiveness of inhibitors. Indeed, a study has made it possible to classify the inhibitors according to the action of temperature.

The study of the effect of temperature was carried over a range between 298 and 338 K, using gravimetric measurements in the absence and presence of 1.6 g/L of essential oil during 48 hours of immersion in 1M HCl medium. The temperature variation was carried out using a water bath. The corrosion rate and inhibitor efficiency data observed for each temperature are presented in Table 2.

Table 2. Effect of temperature on the corrosion of XC38 steel in 1M HCl acid medium in the presence and absence of 1.6 g/L of essential oil of *Eucalyptus globulus* during 48 h of immersion

T (K)	**W_{inh} (mg/cm^2 h)**	**W_0 (mg/cm^2·h)**	**E_w (%)**
298	0.0483	0.4245	89.03
308	0.1396	0.6538	78.65
318	0.2888	1.1441	74.76
328	0.5789	1.1575	49.98
338	0.9811	1.1587	15.33

An analysis of these data shows a clear increase in corrosion rate with temperature in the control solution. The increase in temperature causes an increase in the corrosion rate both in the absence and in presence of the inhibitor. Indeed, the evolution of the corrosion rate in the corrosive solution alone (HCl 1M) shows a regular and rapid growth until a temperature of 318 K confirming an acceleration of the reaction kinetics until a maximum is reached at 318 K then a stabilization of this rate is observed even with the increase of the temperature. However, the increase in the corrosion rate in the presence of the essential oil is lower than for the solution without essential oil. This increase in speed is continuous up to a temperature of 338 K, contrary to what was observed in the absence of the essential oil. This result confirms that the essential oil studied is a good inhibitor in the chosen temperature range. However, although we have a lower increase in the corrosion rate in the presence of essential oil than in the absence of it, we have a loss of the inhibiting efficiency (E_w) of the essential oil of *Eucalyptus globulus*. The efficiency decreases in the temperature range until reaching 15.33% at 338 K. This is probably due to the deterioration of the physically adsorbed layer on the steel surface. This physical adsorption phenomenon, also called physisorption, is related to the van der Waals type bonds between the metal surface and the inhibitor, which tend to disappear with an increase in temperature [26]. This same phenomenon of a decrease in the inhibition rate was observed by G. Karthik et al. [27]. They concluded that the increase in temperature would favor a desorption of the inhibitor and a rapid dissolution of the organic compounds or complexes that form, causing a decrease in the corrosion resistance of the steel. The same phenomenon was explained by E.F. Olasehinde et al. [28] as an increase in the dissolution rate of mild steel and partial desorption of the inhibitor from the metal surface with increasing temperature.

3.2.3. Thermodynamic parameters

In acidic solution, the Arrhenius-type dependence observed between the corrosion rate and temperature, allowed us to calculate the value of the activation energy of the corrosion process, at different temperatures, in the absence and presence of the inhibitor, according to the following relation [29]:

$$W_{corr} = k \exp\left(-\frac{E_a}{RT}\right) \qquad (4)$$

where: W_{corr} is the corrosion rate of the steel in (mg/h.cm^2), E_a is the activation energy (kJ/mol), R is the perfect gas constant (8.32 J/K·mol), k is a pre-exponential factor, T is the absolute temperature in K.

By plotting Arrhenius diagrams [ln (W) = f (1/T)], the apparent activation energies can be determined from their slopes. This plot is show in Figure 3a.

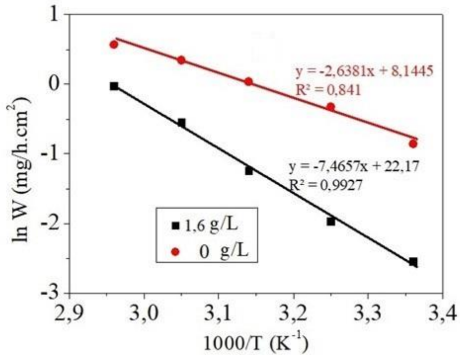
As for the kinetic characteristics of activation such as enthalpy (ΔH°_a) and the entropy of activation (ΔS°_a), we used the Arrhenius transition equation or the activated complex equation [30]:

$$W = \frac{RT}{Nh} \exp\left(\frac{\Delta S^\circ_a}{R}\right) \exp\left(-\frac{\Delta H^\circ_a}{RT}\right) \qquad (5)$$

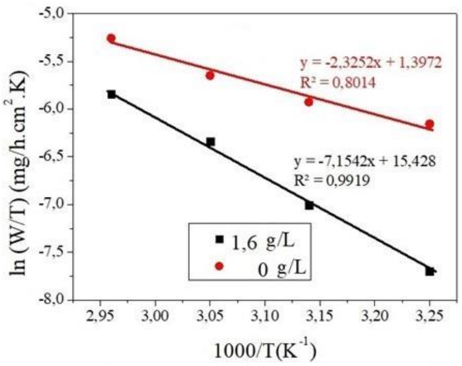
where: h is Plank's constant (6.63 $\times 10^{-34}$ J·s), N is Avogadro's number (6.02$\times 10^{23}$ mol^{-1}), R/N = K_b = 1.38$\times$10 $^{-23}$J/K is the Boltzmann constant.

The calculated values of the activation enthalpies ΔH°_a and entropies of activation ΔS°_a are given in Table 3 as well as the value of the equilibrium constant (b) and the standard free energy of adsorption (ΔG^0_{ads}) at 298 K in the presence of the essential oil.

According to the values obtained, we note an increase in the activation energy E_a in the presence of the essential oil of *Eucalyptus globulus*. This phenomenon of increased activation energy in the presence of the essential oil shows that physisorption is the type of adsorption involved [31-37]. The thermodynamic parameters (ΔH°_a and ΔS°_a) of the dissolution reaction of steel in acidic medium in the presence of inhibitors are higher than those of the acidic HCl solution without inhibitor. The positive values of ΔH°_a mean that the dissolution reaction of steel in 1M HCl acid media is endothermic and this increase in the value of the activation enthalpy is reflected in the increase of the corrosion process in 1M HCl media as a function of temperature.



a.



b.

Figure 3. Arrhenius diagrams (a) and transition state diagrams (b) in the absence and presence of 1.6 g/L of *Eucalyptus globulus* essential oil in 1 M HCl at different temperatures

Table 3. Thermodynamic parameters of XC38 steel in 1M HCl in the absence and presence of 1.6 g/L of *Eucalyptus globulus* essential oil

C (g/L)	R^2	E_a (kJ/mol)	ΔS°_a (kJ/mol)	ΔH°_a (kJ/mol)	b (L/g)	ΔG°_a (kJ/mol)
0	0.8014	21.95	- 186.04	19.32	-	-
1.6	0.9919	62.11	- 69.31	59.52	2.896	19.76

The relatively high and negative values of ΔS°_a imply a dissociation step rather than an association step, signifying an increase in disorder in the reaction medium [38-42]. It is also observed that the values of the activation energy E_a and the activation enthalpy ΔH°_a vary in the same way with the concentration of inhibitor, which makes it possible to verify the thermodynamic relationship between E_a and ΔH°_a which is [40]:

$$E_a - \Delta H^\circ_a = RT \qquad (6)$$

where: R is the constant of perfect gases (8.32 J/K·mol) and T is the absolute temperature in K.

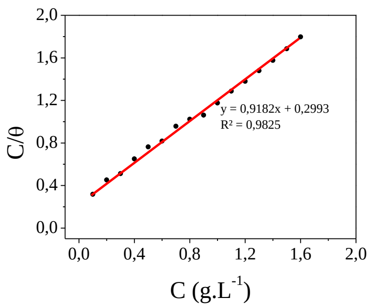


Figure 4. Langmuir adsorption isotherm of XC38 carbon steel in 1M HCl in the presence of *Eucalyptus globulus* essential oil at 298 K

In order to better understand the adsorption mode of the inhibitor on the steel surface, we tested the previous data with several adsorption isotherms such as Langmuir, Frumkin, and Temkin. From these tests, the Langmuir adsorption isotherm C/θ = f(C) which assumes that there is no interaction between the molecules adsorbed on the metal surface, proved to be the best description of the adsorption behavior of *Eucalyptus globulus* essential oil as an inhibitor on steel.

The Langmuir isotherm equation can be written in the following form [43]:

$$\frac{C_{inh}}{\theta} = \frac{1}{b} + C_{inh} \quad (7)$$

The intersection of the line with the axis C_{inh}/θ, gives the value of the equilibrium constant b which is related to the standard free energy of adsorption ΔG°_{ads} by the following equation:

$$\Delta G^{\circ}_{ads} = -RT \log (55.5\ b) \quad (8)$$

where: the value 55.5 is the concentration of water in mol/L (1000 g/L), R is the perfect gas constant. Thus, we calculated the value of the standard free energy of adsorption ΔG°_{ads} characteristic of the interactions between the inhibitor molecules and the metal surface. The results are recorded in Table 3.

For values of ΔG°_{ads} values close to -20 kJ/mol or less negative, the type of adsorption involved is physisorption. Thus, the inhibitory action is due to electrostatic interactions between the charged molecules and the metal charge, while values close to -40 kJ/mol or more negative are associated with chemisorption due to the sharing or transfer of electrons from the inhibitor molecules to the metal surface to form covalent or coordination bonds. For values between -20 and -40 kJ/mol, the adsorption is then mixed or complete, alternating both physisorption and chemisorption [44-46].

In the case of *Eucalyptus globulus* essential oil, we can therefore deduce that the inhibition is due to electrostatic interactions between their charged molecules and the charged metal (physical adsorption) [47, 48]. This statement is supported by the fact that the inhibitory power of this essential oil decreases significantly at high temperatures [49].

4. Conclusions

In this work, we focused on the evaluation of the corrosion inhibiting effect of XC38 steel in 1M HCl medium by the essential oil extracted from *Eucalyptus globulus* leaves by the mass loss method. From the data collected, we concluded that:

- The corrosion of steel decreases significantly in the presence of *Eucalyptus globulus* essential oil, reaching an optimum efficiency of 89.03% for a concentration of 1.6 g/L of essential oil.
- *Eucalyptus globulus* essential oil is a good inhibitor in 1M HCl medium.
- The inhibitory efficiency of the essential oil decreases sharply with increasing temperature to reach a value of 15.33% for a concentration of 1.6 g/L at 338K.
- The adsorption of the essential oil on the metal surface is based on the Langmuir isotherm model.
- The value of the standard free energy of adsorption ΔG°_{ads} which we were able to calculate from the Langmuir isotherm, as well as the decrease in inhibitory efficiency with increasing temperature, led to the conclusion that the mode of action of the essential oil is physisorption.

Acknowledgement

The authors would like to thank the company called Somim (Rue Félix Eboué X route des brasseries, BP 23343 Dakar Ponty, Dakar, Senegal) for supplying the XC38 steel sheets.

Conflict of interest

Authors declare no conflict of interest.

References

[1]. D. Benmessaoud Left, M. Zertoubi, I. Abdellatif, A. Mohammed, Oils and extracts plants as corrosion inhibitors for different metals and alloys in hydrochloric acid medium, Journal of Materials and Environmental Science 4 (2013) 855-866.

[2]. M. Hazwan Hussin, M. Jain Kassim, N.N. Razali, N.H. Dahon, D. Nasshorudin, The effect of *Tinospora crispa* extracts as a natural mild steel corrosion inhibitor in 1 M HCl solution, Arabian Journal of Chemistry 9 (2016) S616-S624.

[3]. Z. Bensouda, M. Driouch, M. Sfaira, A. Farah, M. Ebn Touhami, B. Hammouti, K.M. Emran. Effect of *Mentha piperita* essential oil on mild steel corrosion in hydrochloric acid, International Journal of Electrochemical Science 13 (2018) 8198 - 8221.

[4]. M.A. Amin, K.F. Khaled, Q. Mohsen, H.A. Arida, A study of the inhibition of iron corrosion in HCl solutions by some amino acids., Corrosion Science 52 (2010) 1684.

[5]. M. Outirite, M. Lagrenée, M. Lebrini, M. Traisnel, C. Jama, H. Vezin, F. Bentiss, Ac impedance, X-ray photoelectron spectroscopy and density functional theory studies of 3, 5-bis (N-pyridyl)-1, 2, 4-oxadiazoles as efficient corrosion inhibitors for carbon steel surface in hydrochloric acid solution, Electrochemical Acta 55 (2010) 1670.

[6]. K. Bouhrira, F. Ouahiba, D. Zerouali, B. Hammouti, M. Zertoubi, N. Benchat, The inhibitive effect of 2-phenyl-3-nitroso-imidazo [1, 2-a] pyridine on the corrosion of steel in 0.5 M HCl acid solution, E-Journal of Chemistry 7 (2010) S35-S42.

[7]. Y. Abboud, B. Ihssane, B. Hammouti, A. Abourriche, S. Maoufoud, T. Saffaj, M. Berrada, M. Charrouf, A. Bennamara, H. Hannache, Effect of some new diazole derivatives on the corrosion behaviour of steel in 1 M HCl, Desalination and Water Treatment 20 (2010) 35. Doi: 10.5004/dwt.2010.1576

[8]. B. Zerga, A. Attayibat, M. Sfaira, M. Taleb, B. Hammouti, M.E. Touhami, S. Radi, Z. Rais, Effect

of some tripodal bipyrazolic compounds on C38 steel corrosion in hydrochloric acid solution, Journal of Applied Electrochemistry 40 (2010) 1575. Doi:10.1007/s10800-010-0164-0.

[9]. L. Herrag, B. Hammouti, S. Elkadiri, A. Aouniti, C. Jama, H. Vezin, F. Bentiss, Adsorption Properties and inhibition of mild steel corrosion in hydrochloric solution by some newly synthesized diamine derivatives: Experimental and theoretical investigations, Corrosion Science 52 (2010) 3042-3051. Doi: 10.1016/j.corsci.2010.05.024.

[10]. D. Gassama, S.M. Seck, I. Yade, M. Fall, M.B. Diop, Valorisation of Bafoundou volcanic clay tuffs as corrosion inhibitors for Fe E400 concrete iron, Journal de la Société Ouest-Africaine de Chimie 038 (2014) 64-72.

[11]. D. Gassama, M. Fall, I. Yade, S.M. Seck, M. Diagne, M.B Diop, Clays valorization as corrosion inhibitors for E400 reinforcing steel, Ovidius University Annals of Chemistry 27 (2016) 28-35.

[12]. K. Cissé, D. Gassama, A. Thiam, M. Bathily, M. Fall, Evaluation of the inhibitory effectiveness of *Cyperus articulatus* essential oils on the corrosion of structural steelwork in hydrochloric acid solution, Chemistry Africa 4 (2021) 379-390. Doi: 10.1007/s42250-021-00229-9.

[13]. K. Cisse, D. Gassama, A. Thiam, E.B. Ndiaye, M.T. Gueye, M. Fall, Comparative study of S235 steel corrosion inhibition by *Eucalyptus camaldulensis* and *Cyperus rotundus* essential oils in hydrochloric acid solution, American Journal of Physical Chemistry 10 (2021) 6-15. Doi: 10.11648/j.ajpc.20211001.12.

[14]. D. Ben Hmamou, R. Salghi, A. Zarrouk, B. Hammouti, S.S. Al-Deyab, Lh. Bazzi, H. Zarrok, A. Chakir, L. Bammou, Corrosion inhibition of steel in 1 M hydrochloric acid medium by chamomile essential oils, International Journal of Electrochemical Science 7 (2012) 2361-2373.

[15]. A. Bouyanzer, B. Hammouti, L. Majidi, Pennyroyal oil from *Mentha pulegium* as corrosion inhibitor for steel in 1 M HCl, Materials Letters 60 (2006) 2840-2843.

[16]. D. Ben Hmamou, R. Salghi, L. Bazzi, B. Hammouti, S. Al-Salem, L. Bammou, L. Bazzi, A. Bouyanzer, Prickly pear seed oil extract: A novel green inhibitor for mild steel corrosion in 1 M HCl solution, International Journal of Electrochemical Science 7 (2012) 1303-1318.

[17]. M. Nehiri, E. M. Aouanei, D. Hmounie, M. Ouhssine, B. Bourkhiss, Valorization of the essential oil of *Carum carvi* L species by its use as an inhibitor against corrosion of carbon steel in 1M hydrochloric acid, American Journal of Innovative Research and Applied Sciences 6 (2018) 153-159.

[18]. M. Bathily, B. Ngom, D. Gassama, S. Tamba. Review on essential oils and their corrosion-inhibiting properties. American Journal of Applied Chemistry 9 (2021) 65-73. Doi: 10.11648/j.ajac.20210903.12.

[19]. P. Kumar, S. Mishra, A. Malik, S. Satya, Compositional analysis and insecticidal activity of *Eucalyptus globulus* (family: Myrtaceae) essential oil against housefly (Musca domestica), Acta Tropica 122 (2012) 212-218. Doi: 10.1016/J.ACTATROPICA.2012.01.015.

[20]. I. Almas, E. Innocent, F. Machumi, W. Kisinza, Chemical composition of essential oils from *Eucalyptus globulus* and *Eucalyptus maculata* grown in Tanzania, Scientific African 12 (2021) e00758. Doi: 10.1016/j.sciaf.2021.e00758.

[21]. European pharmacopoeia, Strasbourg: Council of Europe, 7th edition, Volume 1 (2010).

[22]. A. Ghaffar, M. Yameen, S. Kiran, S. Kamal, F. Jalal, B. Munir, A. Jabbar, Chemical composition and in-vitro evaluation of the antimicrobial and antioxidant activities of essential oils extracted from seven Eucalyptus species, Molecules 20 (2015) 20487-20498.

[23]. M.N. Boukhatem, F.M. Amine, A. Kameli, F. Saidi, K. Walid, S.B. Mohamed, Quality assessment of *Eucalyptus globulus* Labill essential oil of Blida origin (Algeria), International Letters of Chemistry, Physics and Astronomy 36 (2014) 303-315.

[24]. S. Zrira, B. Benjilali, G. Lamaty, Effet du séchage à l'air libre des feuilles d'E. camaldulensis sur le rendement et la composition de l'huile essentielle, Revue Marocaine des Sciences Agronomiques et Vétérinaires 15 (1995) 27-35.

[25]. A. El Moussaoui, M. Kadiri, M. Bourhia, A. Agour, A. Salamatullah, A. Alzahrani, H. Alyahya, N. Albadr, M. Chedadi, M. Sfaira, A. Bari, Promising antioxidant and anticorrosion activities of mild steel in 1.0 M hydrochloric acid solution of *Withania frutescens* L. essential oil, Frontiers in Chemistry 9 (2021) 739273. Doi: 10.3389/fchem.2021.739273.

[26]. D. Devaraj Karthik, G. Tamilvendan, P. Venkatesa, Study on the inhibition of mild steel corrosion by 1,3-bis-(morpholin-4-yl-phenyl-methyl)-thiourea in hydrochloric acid medium, Journal of Saudi Chemical Society 18 (2014) 835-844. Doi: 10.1016/j.jscs.2011.10.009.

[27]. G. Karthik, M. Sundaravadivelu, Experimental and theoretical studies of anti-ulcer drugs with benzimidazole rings as corrosion inhibitor for copper in 1 M nitric acid medium, Journal of Adhesion Science Technology 31 (2017) 530-551. Doi: 10.1080/01694243.2016.1222047.

[28]. E.F. Olasehinde, S.J. Olusegun, A.S. Adesina, S.A. Omogbehin, H. Momoh-Yahayah, Inhibitory action of *Nicotiana tabacum* extracts on the corrosion of mild steel in HCl adsorption and thermodynamics study, Natural Science 11 (2013) 83-90.

[29]. P. Sakunthala, S.S. Vivekananthan, M. Gopiraman, N. Sulochana, A.R. Vincent, Spectroscopic investigations of physicochemical interactions on mild steel in an acidic medium by environmentally friendly green inhibitors, Journal of Surfactants Detergents 16 (2013) 251-263.

[30]. S.K. Shukla, M.A Quraishi, The effects of pharmaceutically active compound doxycycline on

the corrosion of mild steel in hydrochloric acid solution, Corrosion Science 52 (2010) 314-321. Doi: 10.1016/j.corsci.2009.09.017.

[31]. O. Radovici, Proceedings of the 2nd European Symposium of corrosion inhibitors, Ferrara, 2 (1965) 178.

[32]. A. Popova, E. Sokolova, S. Raicheva, M. Christov, AC and DC Study of the temperature effect on mild steel corrosion in acid media in the presence of benzimidazole derivatives, Corrosion Science 45 (2003) 33-58. Doi: 10.1016/S0010-938X(02)00072-0.

[33]. E.E. Foad El Sherbini, Effect of some ethoxylated fatty acids on the corrosion behaviour of mild steel in sulphuric acid solution, Materials Chemistry and Physics 60 (1999) 286-290. Doi: 10.1016/S0254-0584(99)00093-0.

[34]. S. Martinez, I. Stern, Thermodynamic characterization of metal dissolution and inhibitor adsorption processes in the low carbon steel/mimosa tannin/sulfuric acid system, Applied Surface Science 199 (2002) 83-89. Doi: 10.1016/S0169-4332(02)00546-9.

[35]. A.H. Al-Moubaraki, Corrosion protection of mild steel in acid solutions using red cabbage dye, Chemistry Engineering Communication 202 (2015) 1069-1080. Doi: 10.1080/00986445. 2014.907565.

[36]. A.S. Fouda, A.S. Abousalem, G. El-Ewady, Mitigation of corrosion of carbon steel in acidic solutions using an aqueous extract of *Tilia cordata* as green corrosion inhibitor, International Journal of Industrial Chemistry 8 (2017) 61-73. Doi: 10.1007/s40090-016-0102-z.

[37]. S.A. Umoren, Biomaterials for corrosion protection: evaluation of mustard seed extract as eco-friendly corrosion inhibitor for X60 steel in acid media, Journal of Adhesion Science Technology 30 (2016) 1858-1879. Doi: 10.1080/01694243.2016.1168339.

[38]. G.M. Schmid, H.J. Huang, Spectro-electrochemical studies of the inhibition effect of 4,7-diphenyl-1, 10-phenanthroline on the corrosion of 304 stainless steel, Corrosion Science 20 (1980) 1041-1057. Doi: 10.1016/0010-938X(80)90083-9.

[39]. M. Elachouri, M.S. Hajji, M. Salem, S. Kertit, J. Aride, R. Coudert, E. Essassi, Some nonionic surfactants as inhibitors of the corrosion of iron in acid chloride solutions, Corrosion 52 (1996) 103-108. Doi: 10.5006/1.3292100.

[40]. G.K. Gomma, M.H. Wahdan, Schiff bases as corrosion inhibitors for aluminium in hydrochloric acid solution, Materials Chemistry and Physics 39 (1995) 209-213. Doi: 10.1016/0254-0584(94)01436-K.

[41]. M.H. Hussin, A.A. Rahim, M.N. Mohamad Ibrahim, N. Brosse, The capability of ultraflattened alkaline and organosolv oil palm (*Elaeis guineensis*) fronds lignin as green corrosion inhibitor for mild steel in 0.5 M HCl solution, Measurement 78 (2016) 90-103. Doi: 10.1016/j.measurement.2015.10.007.

[42]. Y. Abboud, O. Tanane, A. El Bouari, R. Salghi, B. Hammouti, A. Chetouani, S. Jodeh, Corrosion inhibition of carbon steel in hydrochloric acid solution using pomegranate leave extracts, Corrosion Engineering, Science and Technology 51 (2016) 557-565. Doi: 10.1179/1743278215Y.0000000058.

[43]. I. Langmuir, The constitution and fundamental properties of solids and liquids. II. Liquids, Journal of the American Chemical Society 39 (1917) 1848-1906. Doi: org/10.1021/ ja02254a00644.

[44]. L.N. Putilova, S.A. Balezin, V.P. Barannik, Metallic corrosion inhibitors, Pergamon Press, New York (1960) 196.

[45]. I.A. Ammar, F.M. El-Khorafi, Adsorbability of thiourea on iron cathodes, Werkstoffe und Korrosion 24 (1973) 702-707.

[46]. D.D.N. Singh, R.S. Chaudhary, B. Prakash, C.V. Agarwal, Inhibitive efficiency of some substituted thioureas for the corrosion of aluminium in nitric acid, British Corrosion Journal 14 (1979) 235-239.

[47]. A.S. Fouda, G.Y. Elewady, K. Shalabi, S. Habouba, Tobacco plant extracts as save corrosion inhibitor for carbon steel in hydrochloric acid solutions, International Journal of Advance Research 2 (2014) 817-832.

[48]. K. Cissé, D. Gassama, A. Thiam, M. Bathily, M. Fall, Evaluation of the inhibitory effectiveness of *Cyperus articulatus* essential oils on the corrosion of structural steelwork in hydrochloric acid solution, Chemistry Africa 4 (2021) 379-390. Doi: 10.1007/s42250-021-00229-9.

[49]. J. Nakomčić, G. Vastag, A. Shaban, L. Nyikos, Effect of thiazole derivatives on copper corrosion in acidic sulphate solution, International Journal of Electrochemical Science 10 (2015) 5365-5381.

Received: 06.04.2022
Received in revised form: 06.01.2023
Accepted: 07.01.2023