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Using Lignin and Tannin as Green Corrosion Inhibitors for Carbon Steel Petrolum Tanks

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Abstract. The best strategy for combating corrosion is verified by recent studies that employ organic green corrosion inhibitors isolated from plant extracts that are biodegradable, environmentally friendly, suitable priced, and safe. This current research conducted various experiments on Kraft lignin extracted from Iraqi date palm fronds base (DPFB) and tannin to inhibit corrosion. The corrosion monitoring technique includes the weight loss method and surface analysis by optical microscope. The extracted lignin was characterized using 13CNMR. The results showed clear evidence of Kraft lignin's and tannin's corrosion inhibition behavior of carbon steel alloys immersed in 0.5 M HCl solutions. As increasing concentration, Kraft lignin and tannin became more effective inhibitors. Furthermore, Kraft lignin showed more effectiveness as a corrosion inhibitor than tannin.

1 Introduction

Carbon steel is commonly used in several crucial industrial sectors. Most metallic equipment that contacts petroleum products are made of carbon steel [1], like electrical power generation, pipelines, and construction. Carbon steel is usually exposed to contact medium (air, solution, climate, salt spray), causing many degrees of corrosion to the metal products [2]. Carbon steel containing crude oil and petroleum products is subjected to several types of localized corrosion (pitting, crevice, and galvanic corrosion), uniform and differential aeration cells. Corrosion is typically a destructive or degradation process that affects metals and alloys as a result of their electrochemical interactions with the environment. [3]. Many fundamental corrosion protection methods have been implemented [4]. Corrosion inhibitor, among all methods of corrosion protection, offers good steel defense, is affordable, and is simple to apply. Today, most corrosion scientists choose corrosion inhibitors over other available protection strategies due to these benefits. [5]. Natural products have gained great importance due to its many important applications, including in the environmental field [6]. In order to find new inhibitors for corrosion protection and create new clean chemicals for environmentally friendly surroundings, natural materials which can function as corrosion inhibitors are now a popular topic of research. Natural inhibitors are required because they are widely available, environmentally acceptable, and renewable supplies for a variety of critical inhibitors. [5, 7, 8, 9]. Amongst all biobased (poly) phenols, that are well adapted for anti-corrosion application thanks to their aromatic structures, lignin and tannins have received much attention in the past decade [10].

Lignin is a phenolic polymer with a complex structure and is described as a non-crystalline 3D system This can be found in plant tissues. This byproduct of the pulp and paper industry [11] is the second most prevalent and significant natural polymer on the planet after cellulose. Lignin exhibits a broad range of functional group characteristics. These moieties are capable to fulfill manufacturing requirements. The aliphatic, phenolic, and carboxyl hydroxyl groups, as well as the carboxyl groups [12], are primarily responsible for lignin's efficiency. These groupings change depending on the lignin's source and how it was extracted. The proportion of these functional groups affects how soluble lignin is. Because carboxyl and hydroxyl functional groups ionize in alkaline solutions, most kinds of lignin are often fairly soluble in them [13]. Lignin also has a high surface area (180 m^2 g^{-1}) that exhibits surface activity [14]. Due to its oxygen atoms and multiple bond content, akali lignin adsorbs on the metal surface, forming a barrier between the metal and the corrosive environment [14]. several studies reported that performances are mainly dependent on their botanical origin and the extraction process used [12] that are responsible for its high structural diversity, large molecular weight distribution and variability in terms of reactivity and composition. Another family of phenolic biobased compounds, presenting a particular interest as corrosion inhibitors are tannins [15]. Tannins are essential ingredients in the barks of trees since they provide thermal and antimicrobial protection. The family of tannins can be classified into two main categories: hydrolyzable and

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non-hydrolyzable or condensed tannins [15]. Numerous scholars have looked into the use of tannin in corrosion experiments. As an inhibitor of corrosion, tannin was taken from the mangrove bark. Mangrove tannin has been discovered to successfully stop copper metal from corroding in HCl solution. The outcomes of the electrochemical and weight loss tests demonstrated that mangrove tannin's ability to block rises with concentration [16]. Investigations were also conducted into the effects of the halide salts KCl, KBr, and KI on the ability of mangrove tannin to prevent corrosion. As corrosion inhibitors, lignin-based compound and tannin contains plenty of hydroxyl, carboxyl or methoxy groups that can absorb onto iron or another metal surface by sharing their lone pair or p-electron with free d-orbital of metal. It has been reported that the effectiveness of lignin and its modifications as inhibitors is due to the increase in the number of OH and COOH groups in the macromolecule [17, 18].

2 Experimental

2.1 Materials

A local plantation in Yusufiya, Baghdad, Iraq, purchased the date palm fronds base (DPFB) long fiber utilized in the delignification procedures. The QREC provided sodium sulfide (Na_2S), sodium hydroxide (NaOH), and ethanol. The tannin was obtained from Xian Aladdin Bio- Tec Co., Ltd, China. Five concentrations of extracted Kraft lignin (KL) and tannin (TA) were used: 100, 300, 700, 1000, and 1500 ppm. In addition, immersion times were 3, 6, 12, 18, and 24. The concentration of the corrosive solution in experiments was 0.5 M of hydrochloric acid (HCl).

The Alloy specimens selected in this study (steel N-80) were obtained from south petroleum company. The carbon steel coupons' percent (%) chemical compositions are 97.83 Fe, 0.1204 Cr, 0.604 Mn, 0.1809 Cu, 0.0025 Si, 0.0013 P, 0.0020 S.

2.2 Kraft Pulping

Kraft lignin (KL) was extracted from date palm frond base (DPFB) using Kraft pulp extraction. The DPFB was ground up to 72 microns, then dried at 105 °C. The mass fraction between dried DPFB and used solvents was 1:8. One-liter reactor was packed by 45 g of DPFB powder, 25% hydrous sodium sulfide and 19% sodium hydroxide. Pulping process temperature was set up at 170 °C for 3 hrs. After the digestion process, the pulp was washed and isolated from other fractions through screening, then black liquor was gathered.

2.3 Extraction and purification of Kraft lignin

To precipitate KL, the concentrated black liquor was acidified via sulfuric acid of 20 % (v/v). The precipitated KL was dried in a vacuum oven at 50 °C for 48 hrs after filtering and washed through 20% sulfuric acid. Next, the dried KL was purified by passing it over n-pentane and refluxed by soxhlet for 5 hrs to remove undesirable materials such as wax and lipids. Next, the purified Kraft lignin was dried in the vacuum oven for 48 hrs at 50 °C. Moreover, for more purification to remove remaining sugars, KL was treated with hot water [19]. Finally, the acquired KL dried again in the vacuum oven for 48 hrs at 50 °C.

2.4 Coupons Preparation

The chosen materials' rectangular coupons were sized to be 27.4 mm 23,4 mm 10.9 mm. First, coupons surface was grinded with emery paper of 100–800 grit. Next, coupon specimens were washed with diluted hydrochloric acid (0.5M) to remove any oxidation layer on the surface of the coupon. coupon specimens were rinsed with deionized water and dried after being cleaned with acetone and ethanol. Once again, rinse with deionized water, then dry at 120 °C.

2.5 Measurement of Weight Loss

Weight loss measurements were carried in a glass container containing 500 mL of 0.5 M HCl solution. Three weighted clean coupons were suspended vertically and placed in the bowl. To avoid contamination and evaporation, parafilm was used to cover the bowl. After the designated time had passed, the coupons were cleaned by wiping them using tissue paper, washed and rinsed in acetone and deionized water respectively, and then drying them in an oven preheated to 120°C. After cleaning, weigh the specimens. prior to and following the coupons immersion in corrosion solutions in the both when presence and when absent of different concentrations of KL and TA under varied requirements allowed us to compute the weight loss. The corrosion rate was finally calculated based on the average weight loss of the three coupons.

2.6 Corroded metal surface analysis

Using an optical microscope (MM300T advanced polarizing Darkfield Metallurgical Microscope), images of the surfaces of the corroded coupons were taken in both the presence and absence of KL and TA to analyze the corrosion and corrosion inhibition processes.

3 Results and discussion

3.1 FTIR spectroscopy

Using Perkin Elmer model System spotlight 200 equipment, direct transmittance Fourier transform infrared (FTIR) spectroscopy of KL was carried out. Each spectrum was captured employing 20 scans at a resolution of 4 cm^{-1} over a frequency range of 600 cm^{-1} to 4000 cm^{-1}. Kraft lignin FTIR spectra are displayed in Fig. 1. The guaiacyl (G) and syringyl (S) kinds' intense peaks could be seen in the KL spectra. In positions 2, 5, and 6, respectively, of the guaiacyl units, KL demonstrated vibration features for the guaiacyl unit bands at roughly 1115 and 1037 cm^{-1}. These features were attributed to G ring and C=O stretch, CH in-plane deformation, and C-H out-of-plane vibrations. While S faint bands at 1373 cm^{-1} was visible, they showed a low syringyl concentration of KL [12]. A peak near 2925 cm^{-1} was attributed to CH stretching in the methyl and methylene groups in the side chains and aromatic methoxyl groups. A wide band at 3355 cm^{-1} was assigned to phenolic and aliphatic OH stretching vibrations.

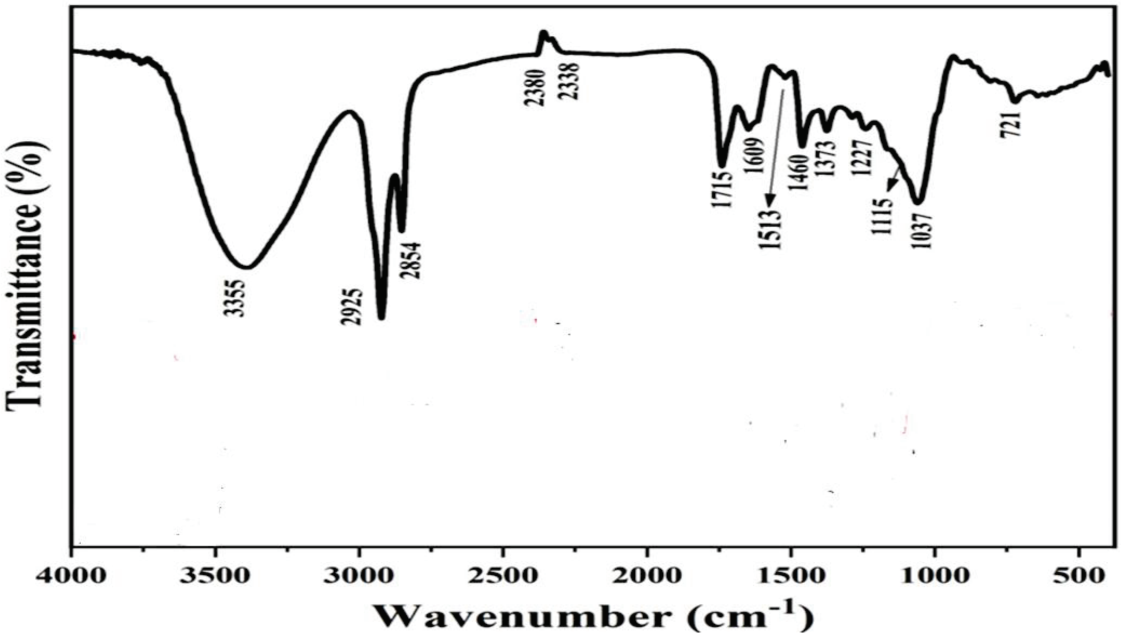

Fig. 1. FTIR spectra of Kraft lignin

3.2 C-NMR spectra of Kraft lignin

NMR spectroscopy analysis was used to study the structure of the various groups of isolated lignin. ^{13}C NMR spectrum of Kraft lignin is displayed in Figure 2. The ph-OH groups (168.6–166 ppm) and the S, G, and p-hydroxyphenyl (H) (lignin moieties) in the spectra were observed with all assignments mentioned in Figure. 2. The ethylene, aromatic, ether and non-ether moieties were ascribed to the intense areas at 112, 119, 136, and 145 ppm produced by the G units in KL. The carbon in the -C=O and -COOH groups, which may originate from aliphatic for both esters and carboxyls, are responsible for the strong area at around 172 ppm and the moderate signals at 170 ppm. The hydroxyphenyl (H) moieties presented signals at 127.4 ppm, implying that the produced KL could be directed to as GSH lignin. The intense regions at 56 ppm are given for the $–OCH_3$ in the syringyl and guaiacy units. Area between 29 and 31 ppm is appointed to alpha (α) and beta (β) for $–CH_2–$ moieties, while the CH_3 that is present in acetyl groups is characterized by a sharp peak at 21 ppm (C_2H_3O). The $-CH_2$ groups on the propyl side chain coupled to an aromatic ring are used to designate the regions between 14 and 15 ppm. These signals confirm Kraft lignin (KL) preparation from date palm fronds base (DPFB).

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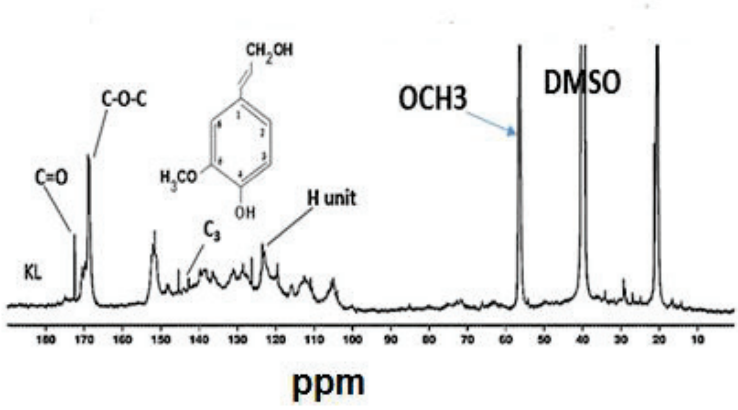


Fig. 2. The [13]C- NMR spectra of Kraft lignin

3.3 Weight loss method

Analysis of weight loss is the most straightforward, typical, effective, and practical approach for evaluating the corrosion process in industrial realities. The weight loss that occurs throughout the exposure time is the main measurement acquired from corrosion coupons. and is reported as corrosion rate [20]. The following two equations [21] were used to calculate the corrosion rate (CR) and the inhibition efficiency percentage (IE%).

$$CR = \frac{WL \times K}{A \times t \times P} \quad (1)$$

$$IE\% = \frac{CR1 - CR2}{CR1} \times 100 \quad (2)$$

Where is CR1 and CR2= corrosion rate in the absence and presence of inhibitors WL= Wight loss (gm), K= constant (3.45×10^6), A= exposed area (cm^2), P= alloy density (gcm^{-3}), t= exposure time (hrs).

The weight loss approach was used to compute the carbon steel while submerged in 0.5 M hydrochloric acid (HCl). All samples were tested with and without corrosion inhibitors (CI) at different concentrations (100, 300, 700, 1000, and 1500 ppm) and immersion times (3, 6, 12, 18, and 24 hrs) for both KL and TA and designated as CR_{KL} and CR_{TA}, respectively. The K value used in the calculation is 3.45×10^6. Depending on the weight loss results and using the equation for calculating the corrosion rate, the corrosion rate of carbon steel alloy without and with corrosion inhibitors was calculated. The results in tables 1 and 2 were obtained, and the figures (3 and 4) show the relationship between the corrosion rates in units (mpy) against time. The corrosion rate increased with time. Figures 3 and 4 demonstrated how corrosion is not entirely stopped by the presence of KL and TA but is instead (moderately) inhibited by a decrease in corrosion rate. It is shown that the KL and TA levels directly affect the inhibition strength. In addition, the weight loss is directly proportional to the time the metal was exposed to the corrosive medium. On the other hand, the amount of weight loss is not uniform due to the formation of oxides films on the surface of the metal. The type and thickness of these films depend on the type of metal and the corrosive medium. The results found that the amount of weight loss in bio-inhibitors (Kraft lignin and tannin) is much less than in the absence of the inhibitor.

Table 1. The rate of corrosion of carbon steel in 0.5 M HCl without inhibitors and various concentrations of KL and at different times.

No	Time (hr)	CR1	CR_{KL100}	CR_{KL300}	CR_{KL700}	CR_{KL1000}	CR_{KL1500}
1	3	296.7146	205.6125	199.286	96.16338	36.06127	30.36738
2	6	248.0003	122.4185	119.2552	57.88783	24.98983	21.1939
3	12	143.7706	82.40316	79.23989	34.95412	14.7092	14.07655
4	18	181.6771	62.00008	52.51027	36.3776	15.28913	10.43879
5	24	227.2018	77.8955	74.8904	52.3521	17.79339	14.07655

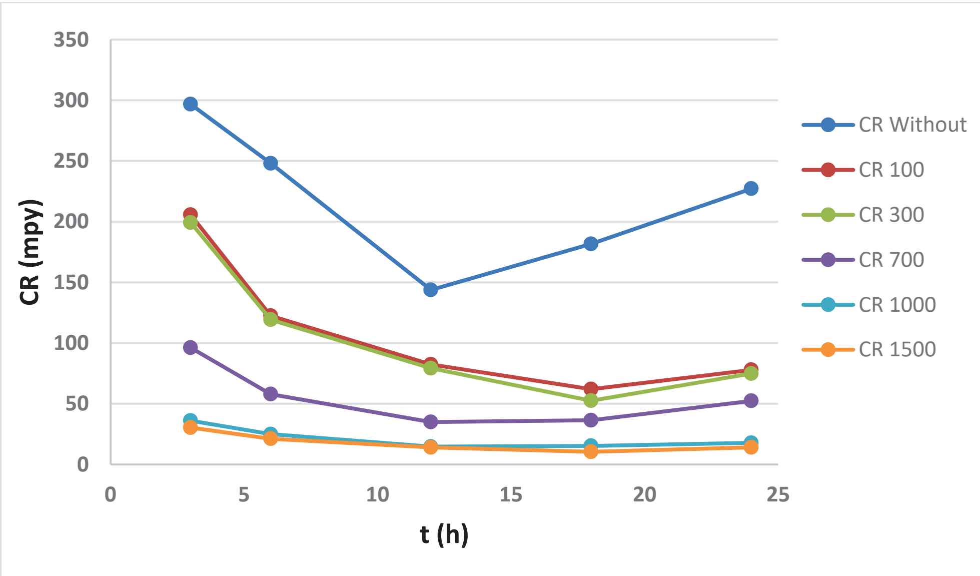


Fig. 3. The corrosion rate of carbon steel in 0.5 M HCl in the absence and different concentrations of Kraft lignin.

Table 2. The corrosion rate of carbon steel alloy in 0.5 M HCl in different concentrated tannin and at various times.

No	Time (hr)	CR1	CR_{TA100}	CR_{TA300}	CR_{TA700}	CR_{TA1000}	CR_{TA1500}
1	3	296.7146	268.8779	246.1023	146.7757	48.08169	41.75515
2	6	248.0003	148.041	126.2144	85.09194	29.73473	25.62248
3	12	143.7706	99.80114	68.8011	59.62762	21.03574	15.02553
4	18	181.6771	72.96608	51.3504	41.8606	18.13608	15.60546
5	24	227.2018	8.066336	68.64294	60.97201	27.83677	23.8036

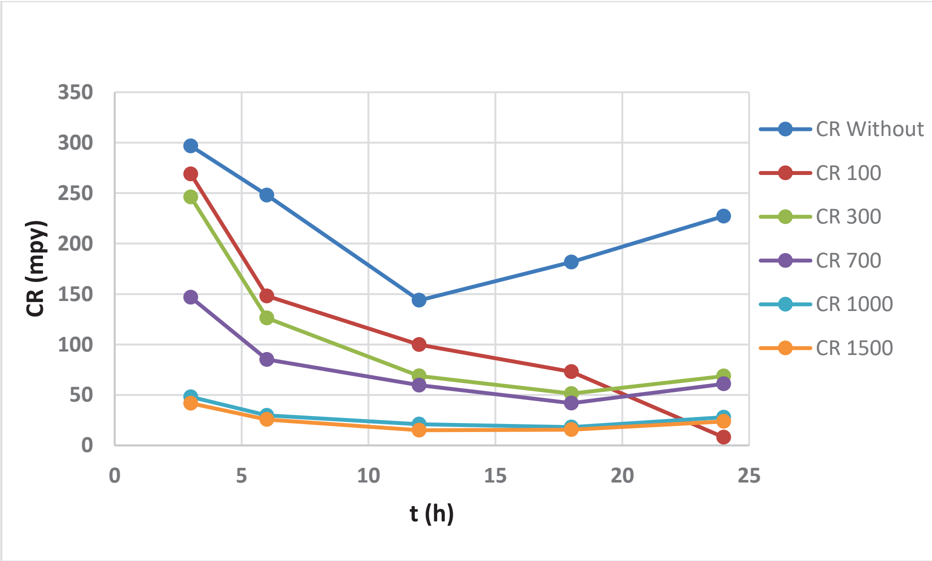


Fig. 4. The corrosion rate of carbon steel in 0.5 M HCl in the absence and different concentrations of tannin.

In addition to the obvious decrease in the intensity of the corrosion current (figures3 and 4), an increase in the inhibition efficiency showed as a result of the increase in the concentration of inhibitors, as indicated in tables 3 and 4 , which exhibited inhibition efficiency (IE) with different concentrations of KL and TA and designated as % IE_{KL} and % IE_{TA}.

As shown in Figures 3 and 4, the corrosion rate of the carbon steel has a comparatively high value in 0.5 M hydrochloric acid (HCl) solution. However, this corrosion rate significantly decreased with KL and TA in the corrosive medium.

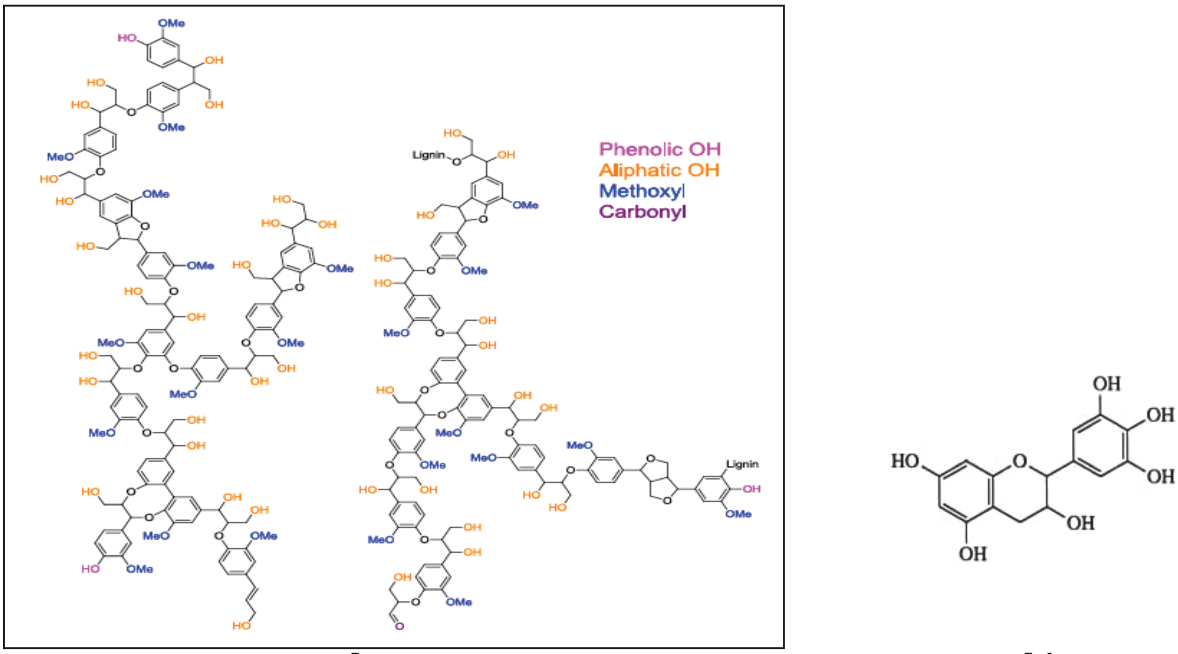
Table 3. The inhibition efficiency of carbon steel alloy in different concentrations of KL and at different times.

No	Time (hr)	% IE_{KL100}	% IE_{KL300}	% IE_{KL700}	% IE_{KL1000}	% $IE_{KL\ 1500}$
1	3	30.7036247	32.8358209	67.5906183	87.8464819	89.7654584
2	6	50.6377551	51.9132653	76.6581633	89.9234694	91.4540816
3	12	42.6842684	44.8844884	75.6875688	89.7689769	90.2090209
4	18	65.8734765	71.096924	79.9767847	91.5844457	94.2542078
5	24	65.7152802	67.0379394	76.9578837	92.168465	93.8043857

Table 4. The inhibition efficiency of carbon steel alloy in different concentration of tannin and at different times.

No	Time (hr)	% IE_{TA100}	% IE_{TA300}	% IE_{TA700}	% IE_{TA1000}	% IE_{TA1500}
1	3	9.381663	17.05757	50.53305	83.79531	85.92751
2	6	40.30612	49.10714	65.68878	88.0102	89.66837
3	12	30.58306	52.14521	58.52585	85.36854	89.54895
4	18	59.83749	71.73535	76.95879	90.01741	91.41033
5	24	96.4497	69.78768	73.16394	87.748	89.52315

Kraft lignin and tannin, consisting of polyphenolic monomers (Figures 5a and 5b), are expected to adsorb onto the metal due to the presence of the oxygen electron donating groups via the different adsorption modes described. The results showed that the reduction of the corrosion current densities by lignin and tannin could be attributed to the monomers structure, functional groups and their electron donating capability. Furthermore, the comparison of corrosion efficiency between lignin and tannin results demonstrated the effectiveness of lignin as a corrosion inhibitor more than tannin due to the absence of carboxyl groups in the monomer structure of tannin., it has been reported that lignin's effectiveness as an inhibitor is due to an increase in the number of OH and COOH groups in the macromolecule or monomer (22).



5-a 5- b

Fig. 5. [a : chemical structure of lignin (Adler, 1977)][b: condensed tannins (Pizzi, 1983)]

Tables (5 and 6) show that the value of theta (θ) increases with time and for both inhibitors (Kraft lignin and tannin) with a clear distinction for the lignin. This means that with increasing time the process of adsorption of the bio-inhibitor on the metal surface increases, and then the surface area increases, the efficiency of the inhibitor increases. In contrast, the corrosion rate and the lost weight decrease.

Table 5. The inhibitor (θ) values that covered carbon steel's surface area with different concentrations of Kraft lignin.

No	Time (hr)	θ(100)	θ(300)	θ (700)	θ (1000)	θ (1500)
1	3	0.307036	0.328358	0.675906	0.878465	0.897655
2	6	0.506378	0.519133	0.766582	0.899235	0.914541
3	12	0.426843	0.448845	0.756876	0.89769	0.90209
4	18	0.658735	0.710969	0.799768	0.915844	0.942542
5	24	0.657153	0.670379	0.769579	0.921685	0.938044

Table 6. The inhibitor (θ) values that covered carbon steel's surface area with different concentrations of tannin.

No	Time (hr)	θ(100)	θ(300)	θ(700)	θ(1000)	θ(1500)
1	3	0.093817	0.170576	0.50533	0.837953	0.859275
2	6	0.403061	0.491071	0.656888	0.880102	0.896684
3	12	0.305831	0.521452	0.585259	0.853685	0.89549
4	18	0.598375	0.717353	0.769588	0.900174	0.914103
5	24	0.964497	0.697877	0.731639	0.87748	0.895231

3.4 Surface analysis of the carbon steel coupons

Optical microscope images of carbon steel coupons submerged in 0.5 M hydrochloric acid (HCl) for 24 h with and without the inclusion of Kraft lignin and tannin with 40x magnification are shown in Figure 6. In contrast to the second image (B) which was obtained after the carbon steel had been immersed in the HCl solution, which clearly showed that the acid had corroded the metal's surface in the form of grains and cracks, image A showed the carbon steel before it had been immersed. These cracks allow the corrosion medium to penetrate the surface through which formation of the corrosion cell consisting of the base metal and the corrosion medium. After placing the carbon steel in the used inhibitors, image (C) representing the use of tannin and image (D) representing the use of Kraft lignin showed that these inhibitors had formed a protective layer on the surface of the carbon steel and prevented corrosive substances from reaching the metal surface. Thus there were no cracks or pits on the surface of the metal after being immersed in 0.5 HCl M for 24 h, confirming the effective of polymers (lignin and tannin) against corrosion Meanwhile, the images (C and D) from Figure 5 showed the difference between Kraft lignin and tannin as corrosion inhibitors and indicated that the use of Kraft lignin is better than the tannin, which is consistent with obtained results of the corrosion rate and inhibition efficiency.

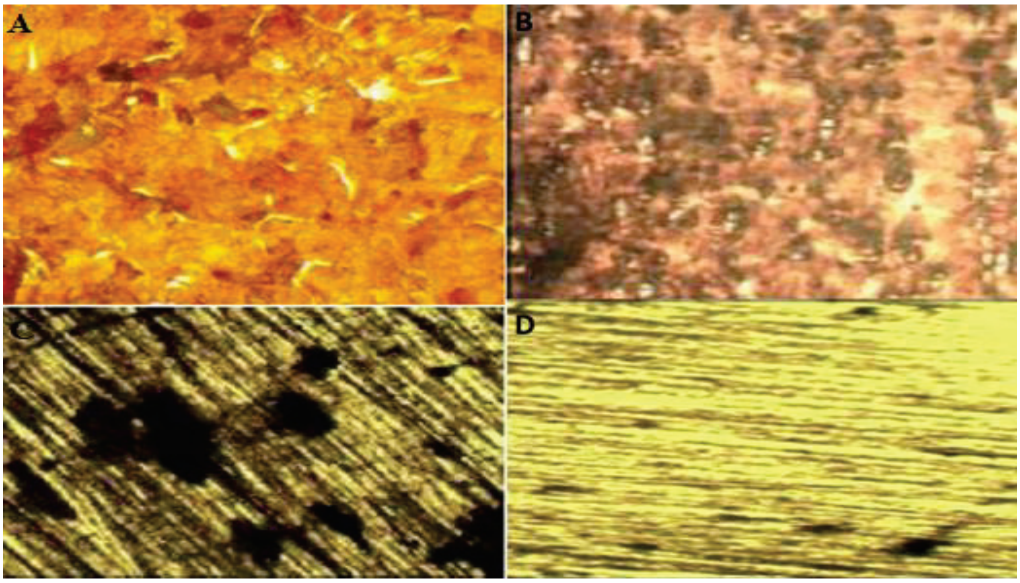


Fig. 6. The optical microscope images of carbon steel coupons: [A- carbon steel coupon before immersion in 0.5 M of HCl solution; B- carbon steel coupon after immersion in 0.5 M of HCl solution for 24 hrs; C- carbon steel coupon submerged in 0.5 M HCl in the presence of tannin for 24 hrs; D- carbon steel coupon submerged in 0.5 M HCl in the presence of KL for 24 hrs]

4 Conclusions

As a consequence of the research, it was shown that kraft lignin and tannin provide varying degrees of corrosion prevention against corrosion of the carbon steel under investigation in HCl solutions. It has been observed that the concentration of KL and tannin directly affects the strength of the inhibition. The corrosion rate of KL was 30.36 at 3 hrs and 14.07 at 24 hr at a concentration of 1500 ppm. However, at the same level of tannin (1500 ppm), the rate of tannin corrosion was 41.75 at 3 hrs and 23.80 at 24 hr. Inhibition effectiveness was higher in KL than in tannin. From the date palm fronds base, the delignification process was effectively completed.

References

1. D. B Hmamou, , R. Salghi, A. Zarrouk, H. Zarrok, B. Hammouti, S. S. Al-Deyab, A. El Assyry, N. Benchat, M. Bouachrine, Electrochemical and gravimetric evaluation of 7-methyl-2-phenylimidazo [1, 2-α] pyridine of carbon steel corrosion in phosphoric acid solution, Int. J. Electrochem. Sci. 8, no. 9 (2013): 11526-11545.
2. Z. Hu, Y. Meng, X. Ma, H. Zhu, J. Li, C. Li, and D. Cao, Experimental theoretical studies of benzothiazole derivatives as corrosion inhibitors for carbon steel in 1 M HCl, Corros. Sci. 112 (2016): 563-575.
3. A.Salhi, S. Tighadouini, M. El-Massaoudi, M. Elbelghiti, A. Bouyanzer, S.Radi, S. El Barkany, F. Bentiss, A. Zarrouk, Keto-enol heterocycles as new compounds of corrosion inhibitors for carbon steel in 1 M HCl: weight loss, electrochemical and quantum chemical investigation, J. Mol. Liq. 248 (2017): 340-349.
4. P. Parthipan, J. Narenkumar, P. Elumalai, P. S. Preethi, A. U. R. Nanthini, A. Agrawal, A. Rajasekar, Neem extract as a green inhibitor for microbiologically influenced corrosion of carbon steel API 5LX in a hypersaline environments, J. Mol. Liq. 240 (2017): 121-127.
5. N. M'hiri, D.Veys-Renaux, E. Rocca, I. Ioannou, N. M. Boudhrioua, M. Ghoul, Corrosion inhibition of carbon steel in acidic medium by orange peel extract and its main antioxidant compounds, Corros. Sci. 102 (2016): 55-62.
6. A. M. Naji, S. H. Kareem, O.A. Nief, H.C. Flaeeh , Fruit and agricultural waste cortex as natural resins adsorbents for removal of heavy metal ions from waste water, Plant Arch.19, no. 2 (2019): 966-971.
7. M.A., Abu-Dalo, N. A. Al-Rawashdeh, A. Ababneh, Evaluating the performance of sulfonated Kraft lignin agent as corrosion inhibitor for iron-based materials in water distribution systems, Desalination 313 (2013): 105-114.
8. K. R. Ansari, M. A. Quraishi, Bis-Schiff bases of isatin as new and environmentally benign corrosion inhibitor for mild steel, J. Ind. Eng. Chem. 20, no. 5 (2014): 2819-2829.
9. P. Muthukrishnan, B. Jeyaprabha, and P. Prakash. Adsorption and corrosion inhibiting behavior of Lannea coromandelica leaf extract on mild steel corrosion, Arab. J. Chem. 10 (2017): S2343-S2354.
10. C.S. Proença, B. Serrano, J. Correia, M. E. M. Araújo, Evaluation of tannins as potential green corrosion inhibitors of aluminium alloy used in aeronautical industry, Metals 12, no. 3 (2022): 508.
11. A.H. Faris, "Fillers in Wood Adhesives." In Fillers. IntechOpen, 2021.
12. A.H. Faris, A. A. Rahim, M. N. M. Ibrahim, M. H. Hussin, A. M. Alkurdi, A. Salehabadi, Investigation of oil palm based Kraft and auto-catalyzed organosolv lignin susceptibility as a green wood adhesives, Int. J. Adhes. Adhes. 74 (2017): 115-122.
13. A.H. Faris, A. A. Rahim, M. N. M. Ibrahim, A. M. Alkurdi, and I. Shah, Combination of lignin polyol–tannin adhesives and polyethylenimine for the preparation of green water-resistant adhesives, J.Appl. Polym. Sci.133, no. 20 (2016).
14. D. Guo, D.Hu, Z. Yan, K. Yuan, L. Sha, H. Zhao, J. Chen, and B. Liu, Preparation and characteristic of high surface area lignin-based porous carbon by potassium tartrate activation, Microporous and Mesoporous Mater. 326 (2021): 111340.
15. C.S. Proença, B. Serrano, J. Correia, and M. E.M. Araújo, Evaluation of tannins as potential green corrosion inhibitors of aluminium alloy used in aeronautical industry, Metals 12, no. 3 (2022): 508.

16. F. Gambier, A. M. Shah, M. N. M. Ibrahim, A. A. Rahim, and N. Brosse, Condensed tannins from mangrove and grape pomace as renewable corrosion inhibitors and wood adhesive, J. Adv. Chem. Eng. 8, no. 01 (2018): 1000182.
17. E.A.Noor, A.H. Al-Moubaraki, Thermodynamic study of metal corrosion and inhibitor adsorption processes in mild steel/1-methyl-4 [4′(-X)-styryl pyridinium iodides/hydrochloric acid systems, Mater. Chem. Phys. 110, no. 1 (2008): 145-154.
18. J.,Ruwoldt , FH Blindheim, G.Chinga-Carrasco . Functional surfaces, films, and coatings with lignin - a critical review. RSC Adv. 24;13(18), 2023 Apr:12529-12553.
19. M. Borrega, S. Concha-Carrasco, A. Pranovich, and H. Sixta, Hot water treatment of hardwood kraft pulp produces high-purity cellulose and polymeric xylan, Cellulose. 24 (2017): 5133-5145.
20. 20- S. Elhady, H. Inan, M. Shaaban and I. S. Fahim. Investigation of olive leaf extract as a potential environmentally-friendly corrosion inhibitor for carbon steel Scientific Reports | (2023) 13:17151
21. X . Zhang, Y. Zhang, Y. Su, X. Wang, and LV.Renqing .Synthesis and Corrosion Inhibition Performance of Mannich Bases on Mild Steel in Lactic Acid Media ACS Omega 2022, 7, 32208−32224
22. C. Gao, X. Zhao, P. Fatehi, X. Dong, K.Liu, S.Chen, S. Wang, and F. Kong, Lignin copolymers as corrosion inhibitor for carbon steel, Ind. Crops. Prod. 168 (2021): 113585.