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Kinetic study, surface characterization, and corrosion inhibition of mild steel in acidic media using septrin and flagyl

ABSTRACT

Over the years, there has been increasing interest in the use of pharmaceutical compounds as corrosion inhibitors owing to their eco-friendly nature and their high efficiency in inhibiting corrosion in metallic materials. The corrosion inhibition effectiveness of the two drugs, septrin and flagyl, on mild steel in a 2MHCl solution at 30°C for different exposure times of 48, 96, 144, 192, and 240 hrs is studied. In the research work, the main objectives focused on adsorption behavior and the kinetics process. The weight-loss method showed that Septrin had an inhibition efficiency (IE) value of 97.7%, and Flagyl had an IE value of 76.7%. This means that both of them were effective at reducing corrosion in the acidic medium. The isothermal models, the free energy of adsorption values, suggest physisorption for both drugs and show the nature of the interaction between the inhibitor molecules and the metal surface. Kinetic studies further indicated that mild steel exhibits a longer half-life in the presence of septrin compared to flagyl, suggesting superior protection.Also, the scanning electron microscopy (SEM) analysis confirmed the presence of a protective film on the steel surface, which averted further corrosion on the steel. This research highlights the promising use of Septrin and Flagyl as corrosion inhibitors for mild steel in acidic conditions.

Keywords: *Gravimetric Technique, Inhibition efficiency, inhibitory drugs, physisorption mechanism, Adsorption mechanism, Protective film, Dissolution.*

1.0. INTRODUCTION

Corrosion of mild steel in aggressive media is a persistent challenge across many industries—particularly in refining and petrochemicals—where equipment is routinely exposed to strong acids, elevated temperatures, and corrosive process streams that accelerate material degradation [1]. Mild steel is widely used for storage tanks and petrochemical infrastructure because it is inexpensive, easy to fabricate, and mechanically robust; however, its inherent susceptibility to corrosion remains a major drawback [2].

To mitigate this vulnerability, corrosion inhibitors are commonly employed. These compounds reduce corrosion rates by forming protective films on metal surfaces, thereby acting as barriers between the substrate and the environment [2–4].

Inhibitor performance often stems from heteroatoms such as N, O, and S, which provide adsorption and coordination sites on the metal surface. In recent years, pharmaceutical drugs have received growing attention as corrosion inhibitors due to their molecular diversity (e.g., heterocycles, carboxylates), availability, and functionality [5–11]. Compared with many traditional synthetic inhibitors, these drug-based candidates are frequently described as more eco-friendly and less toxic [12,13], and their efficacy has been examined in a range of corrosive media [14–21]. Samuel et al. reported FTIR evidence that both Septrin and Flagyl exhibit multisite adsorption on steel, involving O/N/S donor groups, π-aromatic systems, and in Septrin distinct metal–S and carbonyl metal–ligand features. Together, these functionalities promote the formation of stable, protective interfacial films that underpin the observed inhibition performance. Despite considerable progress on corrosion mechanisms and inhibitor design, kinetic adsorption behavior for pharmaceutical-based inhibitors such as Septrin (sulfamethoxazole/trimethoprim) and Flagyl (nitroimidazole) remains insufficiently

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characterized.. To address this gap, the present work investigates the adsorption kinetics, comprehensive spectroscopic characterization, and corrosion-protection efficacy of Septrin and Flagyl for mild steel in acidic environments. Structural representations of the active drug components are provided in Figure 1.

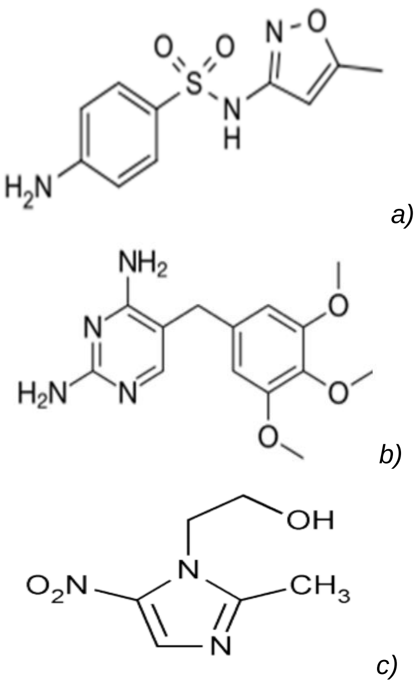


Figure 1. Molecular structure (a) sulfamethoxazole (b) Trimethoprim (c) metronidazole (1-Hydroxy ethyl-2-methyl-5-nitroimidazole; CAS: 443-48-1

2.0. EXPERIMENTAL

2.1 Materials

Septrin ($C_{24}H_{29}N_7O_6S$, molecular weight 543.6) and Flagyl ($C_6H_9N_3O_3$, molecular weight 171.15) were obtained from Unique Pharmaceutical Ltd. Ikeja Lagos State, Nigeria, and Vinco Pharmaceutical Nigeria Ltd Sango-Ota Ogun State, Nigeria, respectively. Solutions of these pharmaceuticals were formulated with double distilled water. Stock solutions of the corrosive medium (HCl) were generated using deionized water, achieving the target drug concentrations of 0.0, 25.0, 50.0, and 75.0 g/L by dilution. Corrosion studies were performed on mild steel samples having the following composition (wt. %): 0.03% P, 0.01% Mn, 0.26% C, 0.03% S, 0.3% Cr, and 0.4% Si, with the remainder being Fe.

2.2.Methods

The gravimetric method, adsorption isotherm, and kinetic analysis were used in the study. Characterizations such as FTIR spectroscopy and scanning electron spectroscopy were used. These methods were useful to determine the corrosion inhibition efficiency and to unravel the corrosion mechanism that reveals interactive processes at the surface and molecular level.

2.3. Gravimetric Technique

The mild steel coupons used in the study measured 2 cm in width, 1.5 cm in thickness, and 0.3 cm in length, providing a total surface area of 8.05 cm². These coupons were polished with emery paper to achieve a smooth surface, followed by thorough washing with absolute ethanol. The treated specimens were stored in a moisture-free desiccator until further use. The samples were initially weighed using a highly sensitive balance. Subsequently, the specimens were suspended and fully submerged in glass beakers containing 100 ml of 2MHCl, both for inhibited and uninhibited drugs according to procedure [22-26]. After exposure periods of 48, 96, 144, 192, and 240 hours at 30°C, the samples were removed, rinsed with distilled water to eliminate any corrosion products, and then rinsed with acetone, dried, and reweighed. This procedure was conducted in triplicate. The recorded weight loss was used to calculate the corrosion rate in mg/cm²/hr. The corrosion rate (CR) of the samples was determined using the established relationship [27].

$$\Delta m = m_f - m_i \quad (1)$$

$$CR = \frac{\Delta m}{S \times t} \quad (2)$$

Where (Δm) is the mass loss, m_f is the final mass loss, m_i is the initial mass loss (s) the area and (t) is the submerged time.

The percentage inhibition efficiency [IE] were determined according to [28].

$$IE = \frac{m_{corr} - m_{corr(inh)}}{m_{corr}} \times \frac{100}{1} \quad (3)$$

Where m_{corr} and m_{corr} (inh) are the mass loss values obtained in the absence and presence of inhibitor, respectively.

2.4. Fouriertransform infrared spectrophotometry (FTIR) Characterization

The dry Septrin and Flagyl drugs were ground into fine powders and mixed with KBr (1:10) ratio for solid-state analysis. Thermo Fisher FTIR equipment was then used to compress the mixture into a thin, transparent pellet using a hydraulic press. The pellet was carefully prepared to ensure that it was free of impurities that could interfere with the FTIR measurements. The Septrin and Flagyl samples were run in the range of 4000–400 cm⁻¹, using 4 cm⁻¹ resolution and 16-32 scans. FTIR spectroscopy was then used to identify the active functional groups present in the inhibitive drugs [29, 30].

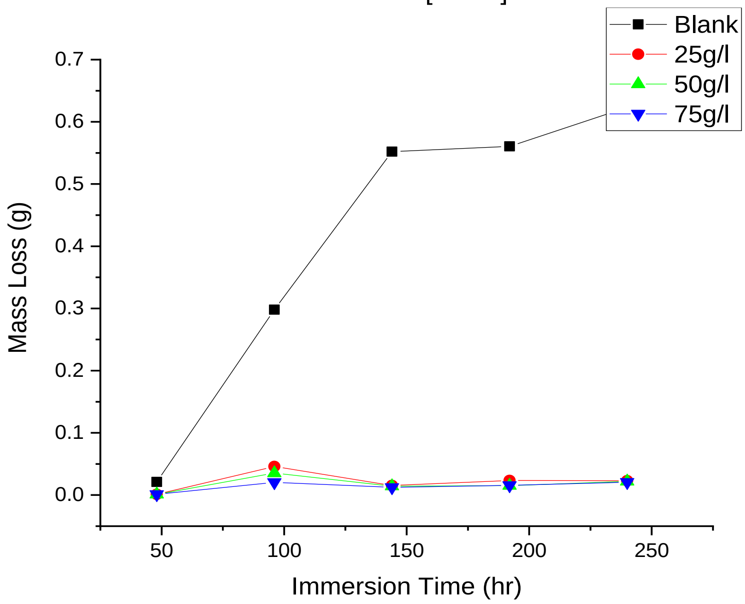
2.5. Surface Characterization

The microstructure characteristics of the Septrin and Flagyl drugs were observed under scanning electron microscopy JSM-7800F. The drug samples were pulverized into very fine powder, then coated with a platinum layer, which provides conductivity. Mild steel specimens were prepared and immersed in 2MHCl under different conditions. Following incubation for 3 hrs at room temperature, the specimens were washed, dried, and presented on SEM stubs with the aid of double-sticky carbon tabs. The magnification and voltage were 3.0 nm and 0.5–30 kV, respectively.

3.0. RESULTS AND DISCUSSION

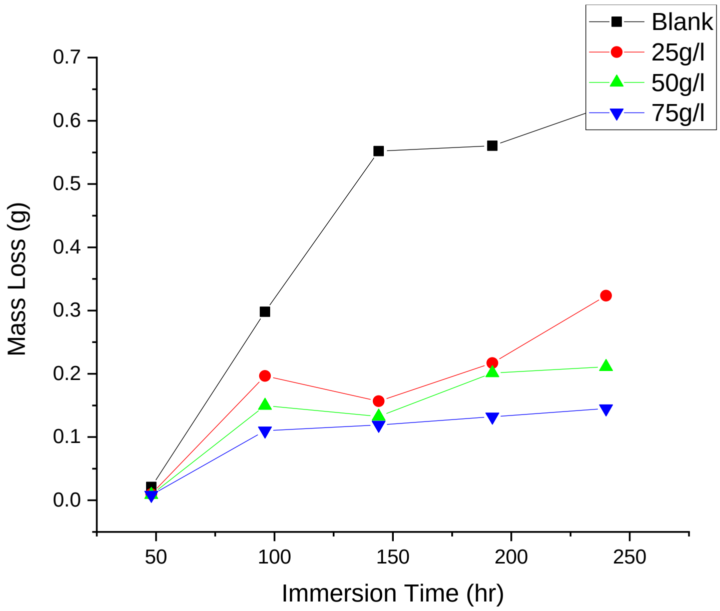
3.1. Gravimetric analysis

Figures 2(a-b) shows the graphical representation of mass loss against immersion time of mild steel in 2MHCl solution. Figure 2(a-b) reveals that the blank sample showed a gradual and persistent mass loss over the period, suggesting that the material had been corroding gradually over time. However, when Septrin and Flagyl drugs inhibitors were used , the weight reduction of the mild steel specimens considerably reduced with the concentration of these inhibitors [33-35].



(a)

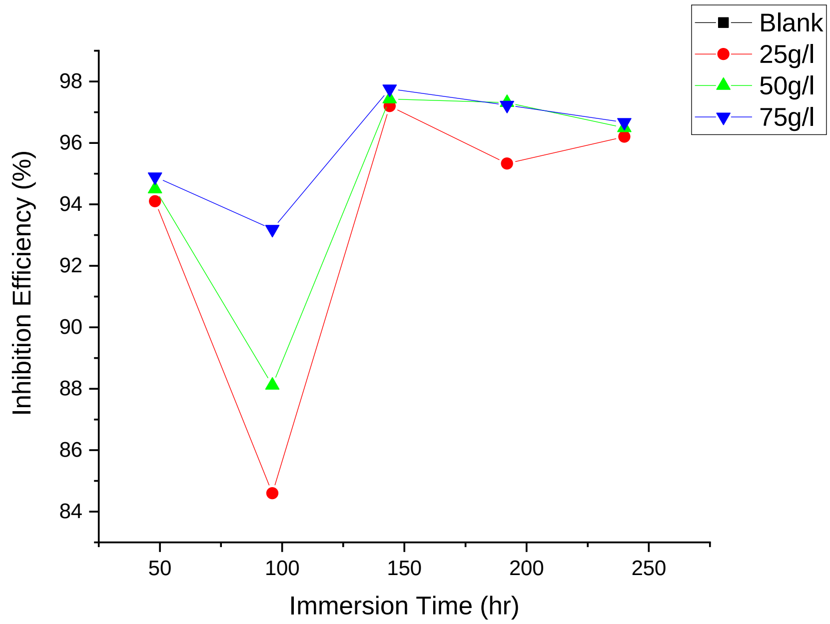
Figure 2(a). Plot of mass loss against immersion time of mild steel in acidic environment using Septrin inhibitor



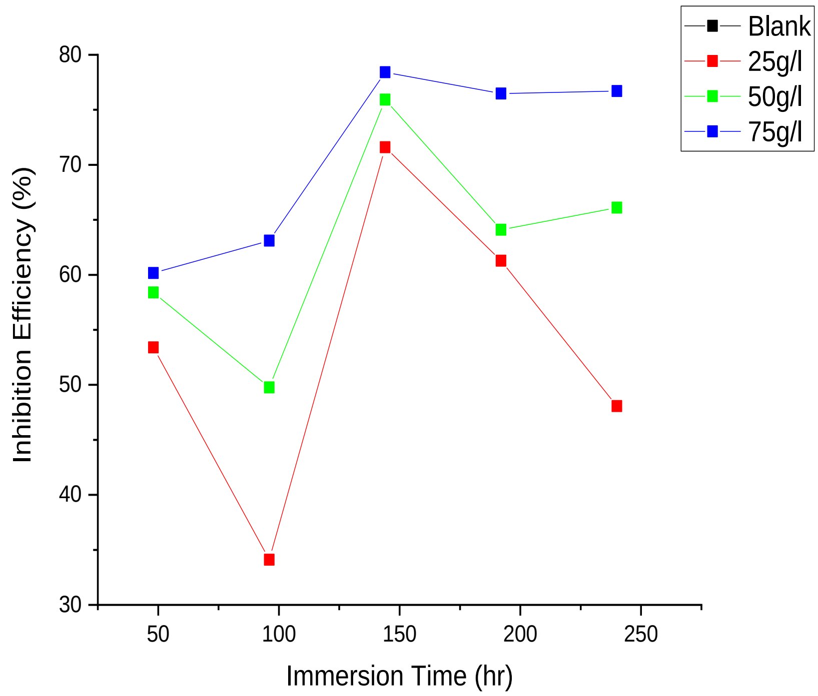
(b)

Figure 2(b). Plot of mass loss against immersion time of mild steel in acidic environment using Flagyl inhibitor

The inhibition efficiency diagrams of the steel specimens exposed to different concentrations of Septrin and Flagyl inhibitors in 2MHCl are presented in Figs. 3(a-b). Comparing the data expressed in these figures, there is an increase in inhibition efficiencies along with an increasing concentration of the inhibitors. In particular, as the concentration of both Septrin and Flagyl inhibitors increases, inhibition efficiency also increases, which points to better protection against corrosion in the concentrated acid environment. The observed trend is in agreement with previous arguments that higher concentrations of inhibitors result in better adsorption on the metal surface so that a protective barrier is formed to prevent the acidic medium from attacking the metal. The findings are in concurrence with Abdullah et al. [36] and Zlatić et al. [37], who found that inhibition efficiency improved as the concentration of the inhibitor increased.



(a)



(b)

Figure 3. Plots of inhibition efficiency against immersion time for the corrosion of mild steels specmen in 2.0 M HCl medium at 25^{0}C in different inhibitor concentrations of (a) Septrin and (b) Flagyl

3.3. Kinetic Study

The kinetic study of the experimental from these results in table 1 following the work of Tanwer and Shukla. The half-life of the inhibitor was determined using the equation as stated below;

$$ln(W_f/W_0) = -kt \quad (4)$$

k is the rate constant. The values of was obtained from the slope of the graph of $ln(W_f/W_0)$,where W_f is final weight loss and W_o initial weight lossagainst exposure time in hours at room temperature. Half-life were calculated using;

$$t1/2 = \frac{0.693}{k} \quad (5)$$

Figures 4 and 5 show the outcomes of this analysis.This graph validates equation 5's linear corrosion rate relation. The slope of the plot, m, is half the reaction rate constant (k), and the y-intercept, a, is the coupons' starting mass. The corrosion process's half-life values in tables 1 and 2 also show its dynamics.These statistics again show that inhibitor concentration increased mild steel specimen half-life, slowing metal breakdown. The long half-life suggests that corrosion inhibitors reduce mild steel corrosion, protecting it from the corrosive media. .Tables 1 and 2 demonstrate that the concentration of the inhibitor reduces the corrosion reaction rate constant. According to this inverse proportionality, Septrin and Flagyl inhibitor concentrations lower corrosion rates. The studies also show that mild steel half-life increases with inhibitor concentration. This shows that metal dissolution in HCl decreases as inhibitor concentration increases, indicating increased protection [38].These findings are consistent with Abeng [39], who found a similar corrosion inhibition tendency.

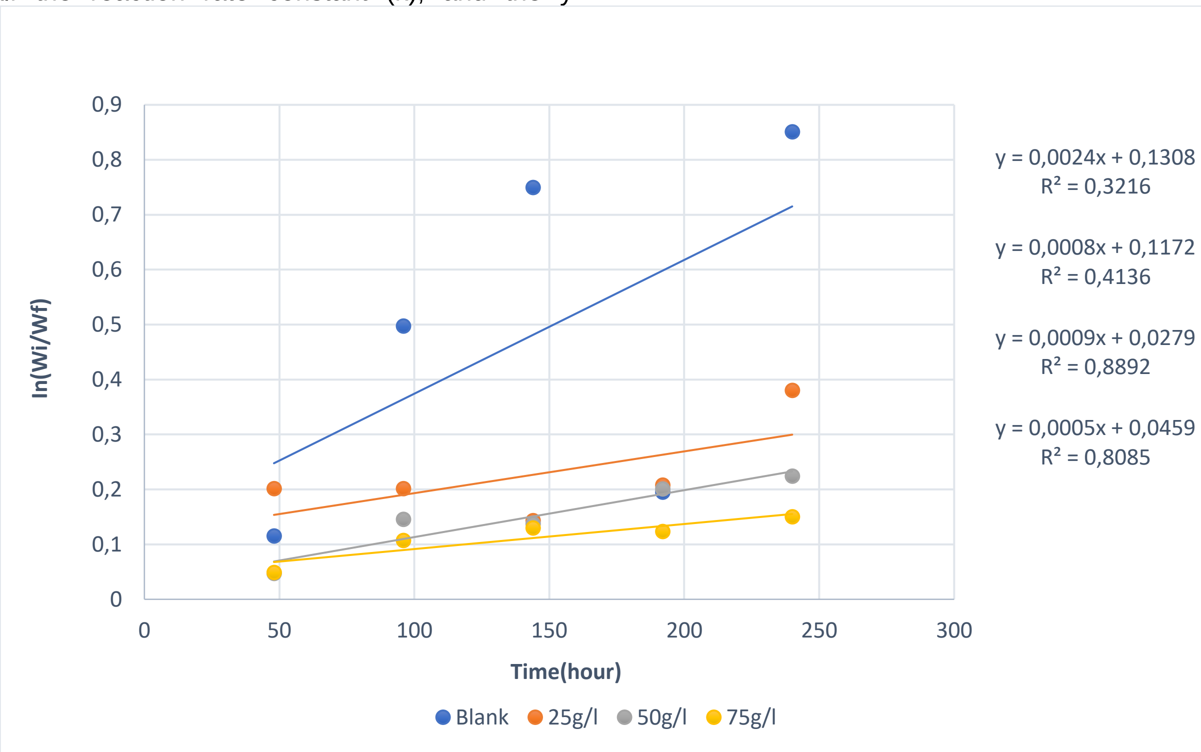


Figure 4. The kinetic Study of Flagyl drug in 2MHCl on Mild Steel

Table 1. Kinetic Study of Flagyl drug in 2MHCL on Mild Steel.

Inhibitor conc. (g/l)	t1/2 (hour)	K	R^2
0	288.75	0.0024	0.3216
25	770	0.0009	0.8892
50	866.25	0.0008	0.4136
75	1386	0.0005	0.8085

Table 2. Kinetic Study of Septrin drug in 2MHCL on Mild Steel

Inhibitor conc. (g/l)	$t_{1/2}$ (hour)	K	R^2
0	288.75	0.0024	0.3216
25	9900	0.00007	0.983
50	11550	0.00006	0.9528

75	13860	0.00005	0.253

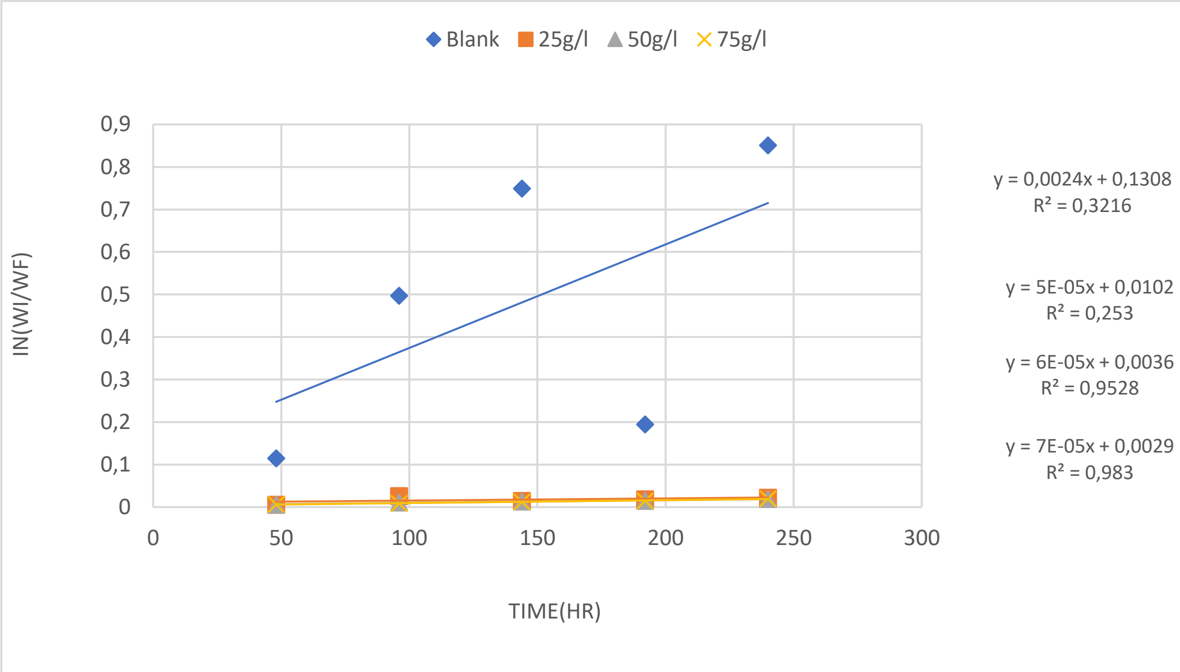


Figure 5. The kinetic Study of Flagyl drug in 2MHCl on Mild Steel.

3.4. Adsorption Study

The negative ΔGads value in Tables 3-10 suggests spontaneous adsorption of Septrin and Flagyl on mild steel surfaces. The immersion at 30°C lasted 48,96,144,192, and 240 hours. Drug molecules appear to create a covalent connection with metal surface atoms. This interaction predominantly causes Septrin and Flagylphysisorption on mild steel [40, 41]. Organic corrosion prevention works by forming a single layer on metal to reduce corrosion [42].

Langmuir Isotherm

Langmuir relationship is represented by equation (6);

$$C/\theta = 1/K_{ad} + C \qquad (6)$$

where K is the equilibrium constant of adsorption (M^{-1}) which was employed in calculating the Gibb's free energy, C is the inhibitor concentration, g/ml, and ϴ is the degree of surface coverage [43,44]. Gibb's free energy of adsorption ΔG (kJ/mol) was determined according to equation (7) below:

$$\Delta G^o = -RT\ In\ (55.5K_{ad}) \qquad (7)$$

R is the gas constant (8.314J/mol), T is temperature (K), and 55.5 is solution water standard molar [43].

Figures 6 and 7 present the Langmuir adsorption isotherms, with their results summarized in Tables 3 and 4. In all cases, the data from all exposure times fit the Langmuir adsorption model. This is clear from the fact that both Septrin and Flagyl have high regression values ($R^2 = 1$). The closely related slopes indicate that the process follows the trend associated with physisorption. Also, where the Gibbs free energy values are less than or almost equal to -20 kJ/mol, which supports the spontaneity of the adsorption on the metal surface.

Table 3. Values from Langmuir Isotherm for Septrin drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	ΔG (KJ/mol)
48	0.9487	1	-13.28062
96	0.9563	0.9991	-13.30735
144	0.9775	1	-13.38081
192	0.9738	1	-13.36811
240	0.9667	1	-13.34359

Table 4. Values from Langmuir Isotherm for Flagyl drug on 2MHCl Mild Steel

Time (hr)	K	R^2	ΔG (KJ/mol)
48	0.8513	0.9669	-9.71228
96	1.2379	0.988	-10.65547

144	0.8234	0.9411	-9.62834
192	0.873	0.971	-9.77569
240	1.0923	0.9997	-10.11708

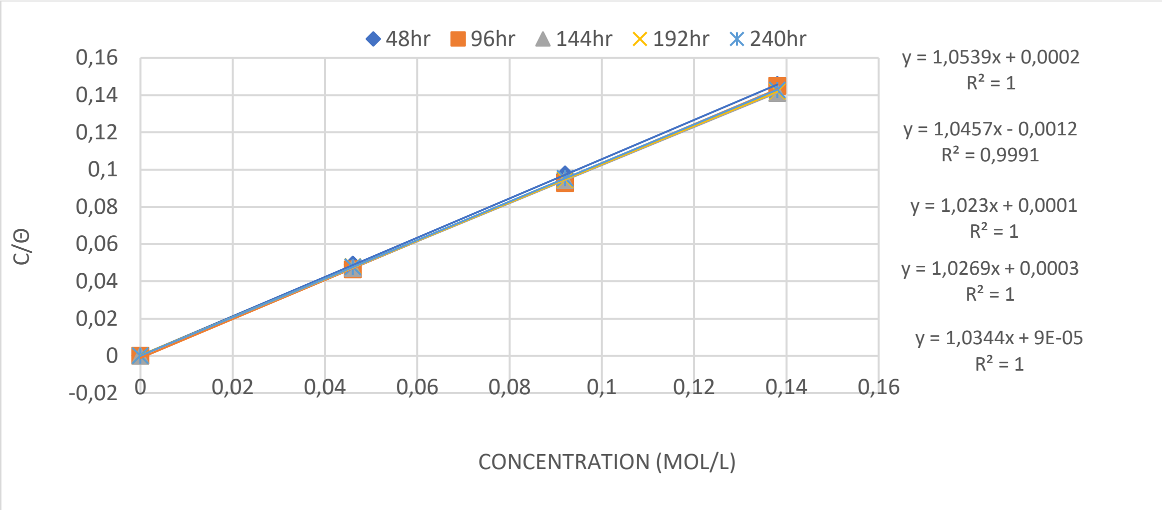


Figure 6. Langmuir Isotherm for Septrin drug in 2MHCl

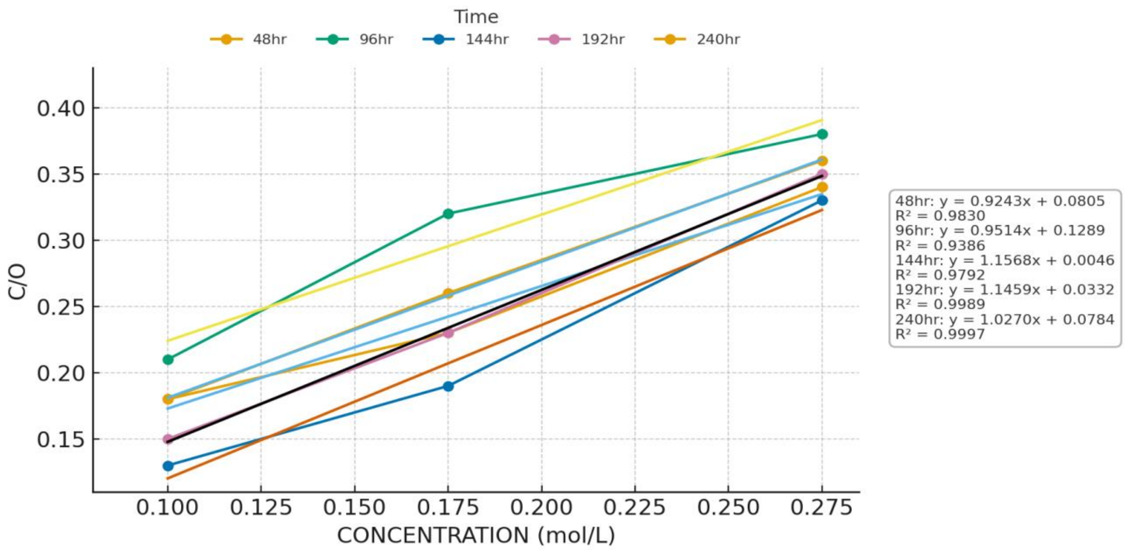


Figure 7. Langmuir Adsorption Isotherm for Flagyl drug in 2MHCl

Temkin isotherm

According to Tekmin adsorption isotherm,

$$\Theta = \ln C + \ln K \quad (8)$$

K is the adsorption equilibrium constant, C is the inhibitor concentration (g/mL), and ϴ is a linear function of ln C [45]. A straight line plot of ϴ against lnC is obtained when following the Temkin isotherm.

The results of the model are shown graphically and in tabular form in Figures 8 and 9 and in Tables 5 and 6, respectively, and were deduced from the Temkin adsorption isotherm [46]. This is particularly evident for exposure times where the regression values are closest to 1: Both drugs were presented at 48, 96, and 192 hours, as well as 240 hours for 2MHCl.

Table 5. Values from Temkin Isotherm for Septrin drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	ΔG°(KJ/mol)
48	1.007	0.9761	10.1366
96	0.9683	0.6108	10.0379
144	1.0049	0.9339	10.1314
192	1.0137	0.8287	10.1533
240	1.0034	0.9862	10.1276

Table 6. Values from Temkin Isotherm for Flagyl drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	ΔG (KJ/mol)
48	1.1632	0.8524	-10.4999
96	1.3404	0.9894	-10.8572
144	1.0977	0.1701	-10.3539
192	1.1363	0.7715	-10.441
240	1.2977	1	-10.7756

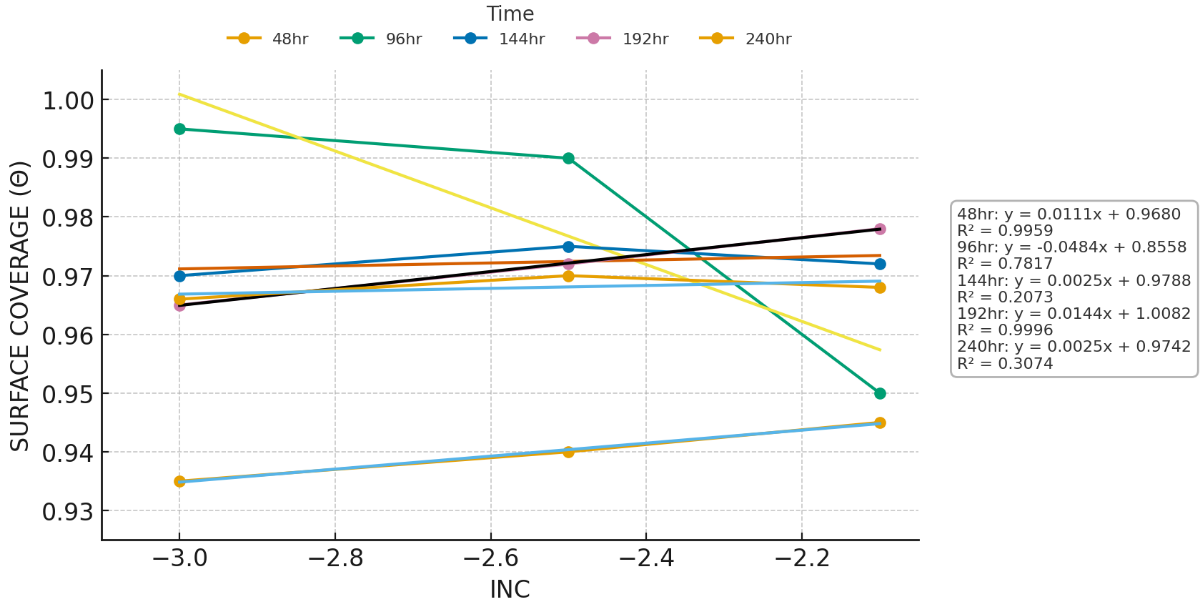


Figure 8. Temkin Adsorption Isotherm for Septrin drug in 2MHCl

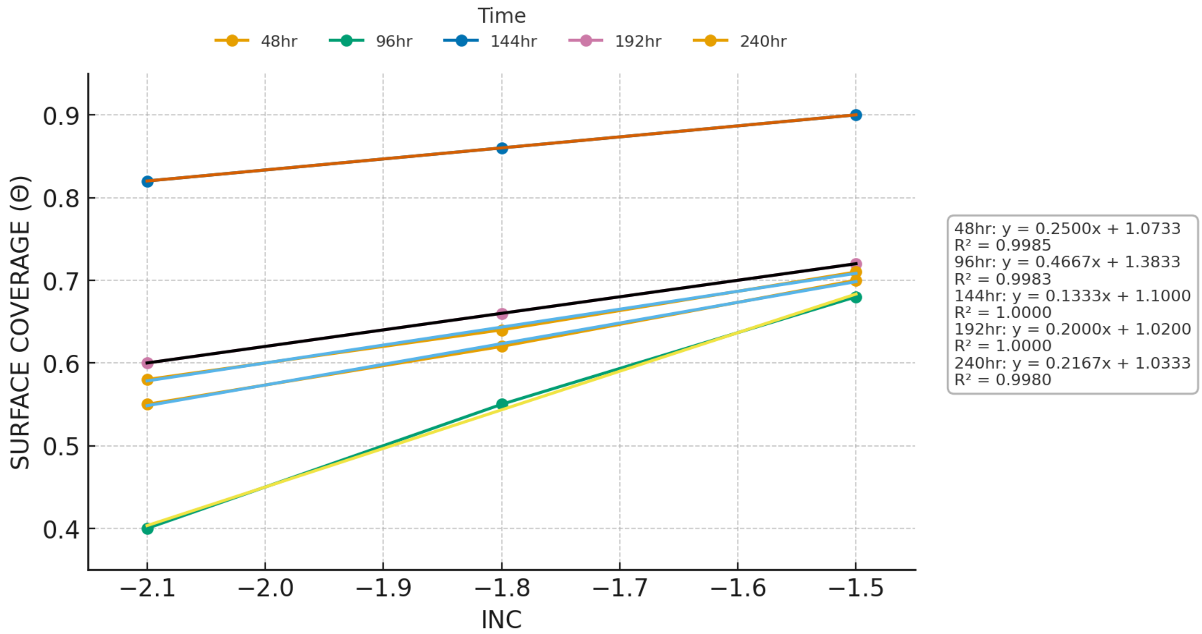


Figure 9. Temkin Adsorption Isotherm for Flagyl drug in 2MHCl

Frednulich Isotherm

Freundlich adsorption isotherm [44]. This is expressed in equation (9):

$$\Theta = KC^n \quad (9)$$

This further derived to

$$\ln\theta = \ln K + n\ln C \quad (10)$$

In Figures 10 and 11, and in Tables 7 and 8, the regression results are 1 or approximately 1, indicating that Septrin follows the Freundlich adsorption isotherm at all exposure durations. When Flagyl's regression value reached 0.2 at 144 hrs, the isotherm did not hold. Flagyl adsorption somewhat matches Freundlich adsorption isotherm model predictions. Tables 7 and 8 show that both drugs' Gibbs free energy of adsorption is less than -20 kJ/mol. Furthermore, the negative Gibbs free energy values confirm that the adsorption process is not only physisorption but also spontaneous.

Table 7. Values from Frednulich Isotherm for Septrin drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	n	ΔG° (KJ/mol)
48	1.0074	0.9765	0.016	-10.1376
96	0.9674	0.6108	0.0432	-10.0356
144	1.005	0.9342	0.0055	-10.1316
192	1.0141	0.829	-0.0009	-10.1543
240	1.0035	0.9863	0.0113	-10.1279

Table 8. Values from Frednulich Isotherm for Flagyl drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	n	ΔG° (KJ/mol)
48	1.2789	0.8751	0.0237	-10.7388
96	1.7498	0.9997	-0.1611	-11.5287
144	1.1268	0.1961	-0.0041	-10.4198
192	1.2055	0.7864	0.026	-10.5899
240	1.5359	0.9967	-0.1277	-11.2002

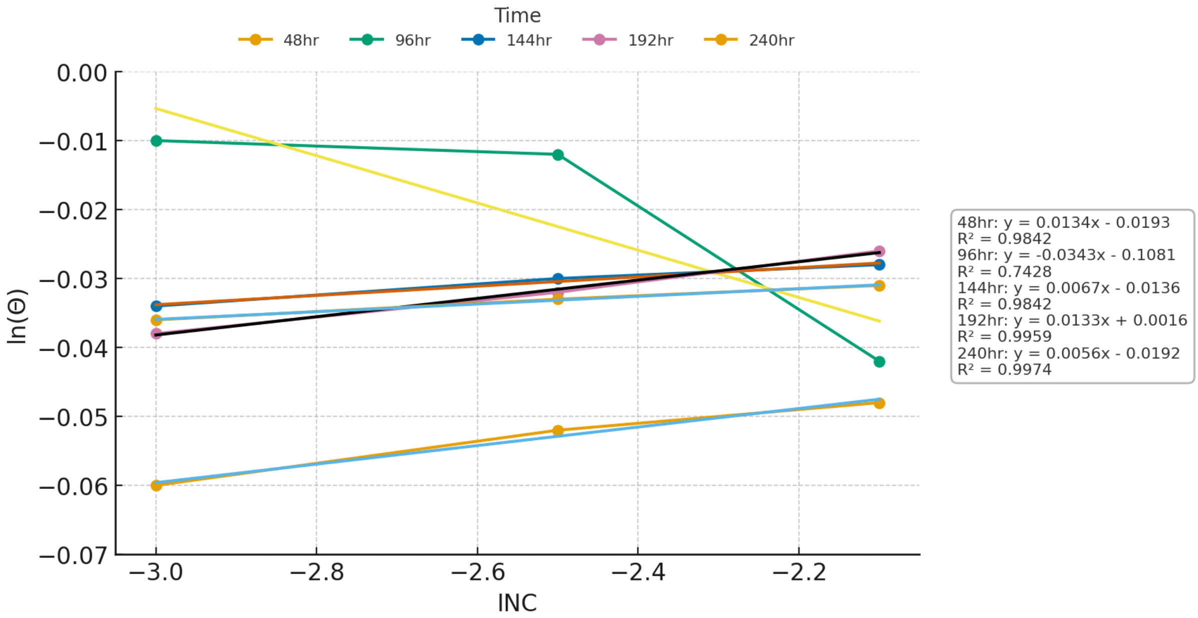


Figure 10. Frednulich Adsorption graph for Septrin drug in 2MHCl

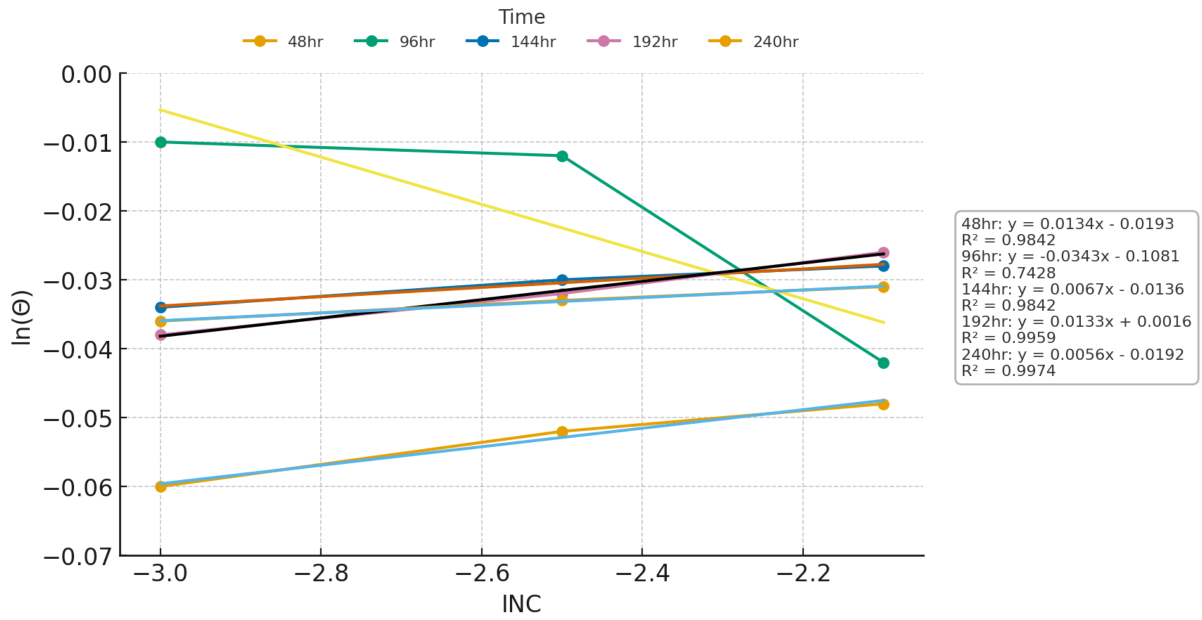


Figure 11. Frednulich Adsorption Isotherm for Flagyl drug in 2MHCl

El-Awady Isotherm

The experimental data were fitted into the El-Awady's isotherm. The characteristic of the isotherm is given by;

$$Log\left(\frac{\theta}{1-\theta}\right) = LogK + yLogC \qquad (11)$$

C = inhibitor concentration (g/mL), ø = surface coverage, Kad = adsorption equilibrium constant, and y = adsorption equilibrium constant [47].

Figures 12 and 13 and tables 9 and 10 show that the model matches El-Awady isotherm for adsorption. Results with regression coefficients of 1 or around 1 indicate that Septrin drug follows the El-Awady adsorption isotherm regardless of exposure period. Flagyl follows the isotherm for all exposure intervals except 144 hrs, when the regression value decreases to 0.1, showing partial adherence to the El-Awadyisotherm.Tables 9 and 10 show that physisorption occurs because the Gibbs free energy of adsorption is smaller than -20 kJ/mol. Negative values confirm spontaneous processes.The high Langmuir regression coefficients, the ΔGads∘ values indicative of physisorption, and the near-unit Langmuir slopes demonstrate that adsorption of both Septrin and Flagyl on mild steel in 2 M HCl at 30 °C is predominantly Langmuir-type monolayer physisorption. Occasional departures (most notably for Flagyl at specific times) likely reflect minor surface heterogeneity, for which Temkin/Freundlichprovide secondary descriptions, but they do not change the overall Langmuir character of the system.

Table 9. Values from El-Awady Isotherm for Septrin drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	ΔG°(KJ/mol)
48	1.3624	0.9698	-5.0742
96	0.0325	0.6108	4.3379
144	1.5823	0.9186	-5.4511
192	2.5781	0.8192	-6.6811
240	1.2552	0.9825	-4.8677

Table 10. Values from EL-Awady Isotherm for Flagyl drug in 2MHCl on Mild Steel

Time (hr)	K	R^2	ΔG°(KJ/mol)
48	4.472	0.8393	-13.8928
96	13.2611	0.9847	-16.6314
144	4.4106	0.0891	-13.8579
192	4.0124	0.756	-13.6195
240	14.0088	0.9976	-16.7676

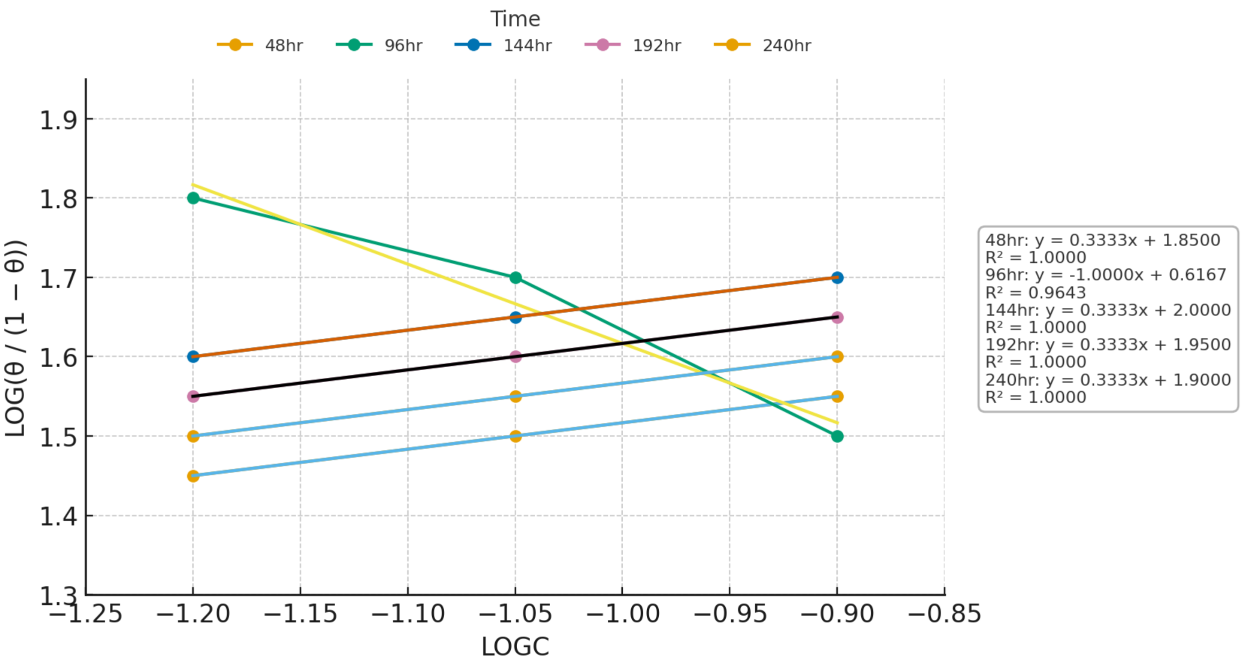


Figure 12. EL-Awady Adsorption Isotherm for Septrin drug in 2MHCl

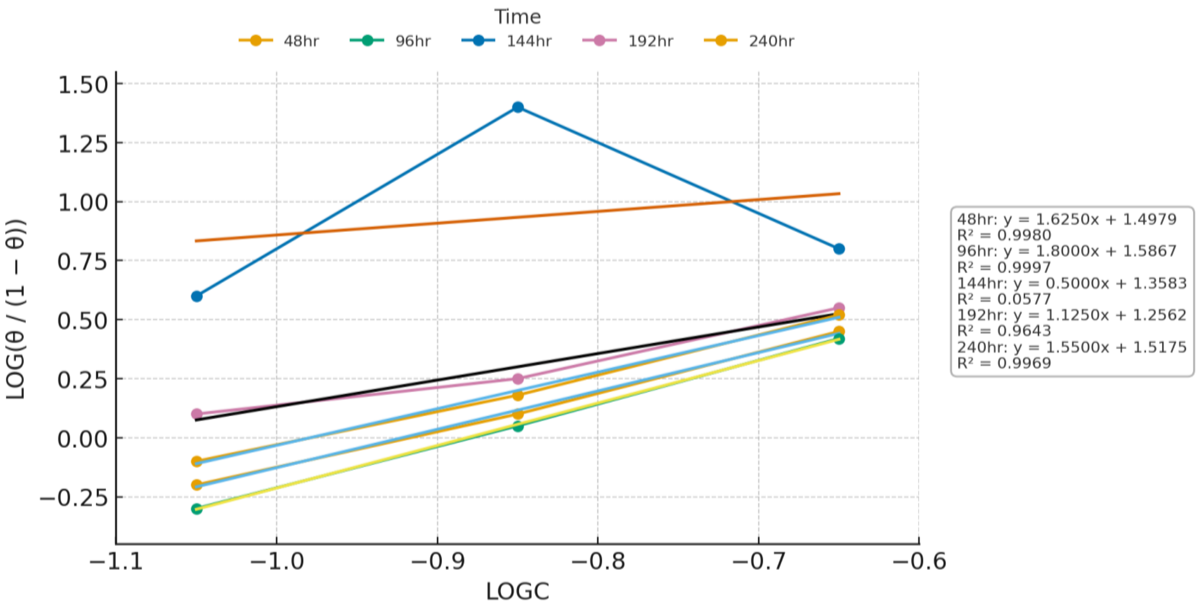


Figure 13. EL-Awady Adsorption Isotherm for Flagyl drug in 2MHCl

3.5. SEM analysis

In Figs. 14(a–d), scanning electron microscopy (SEM) images of mild steel coupons evaluated in 2MHCl solution with and without Septrin and Flagyl illustrate their surface morphology [48]. The rough surface with cracking and pitting reveals that mild steel subjected to acidic conditions has suffered considerable damage compared to unexposed mild steel in Fig. 16(d).

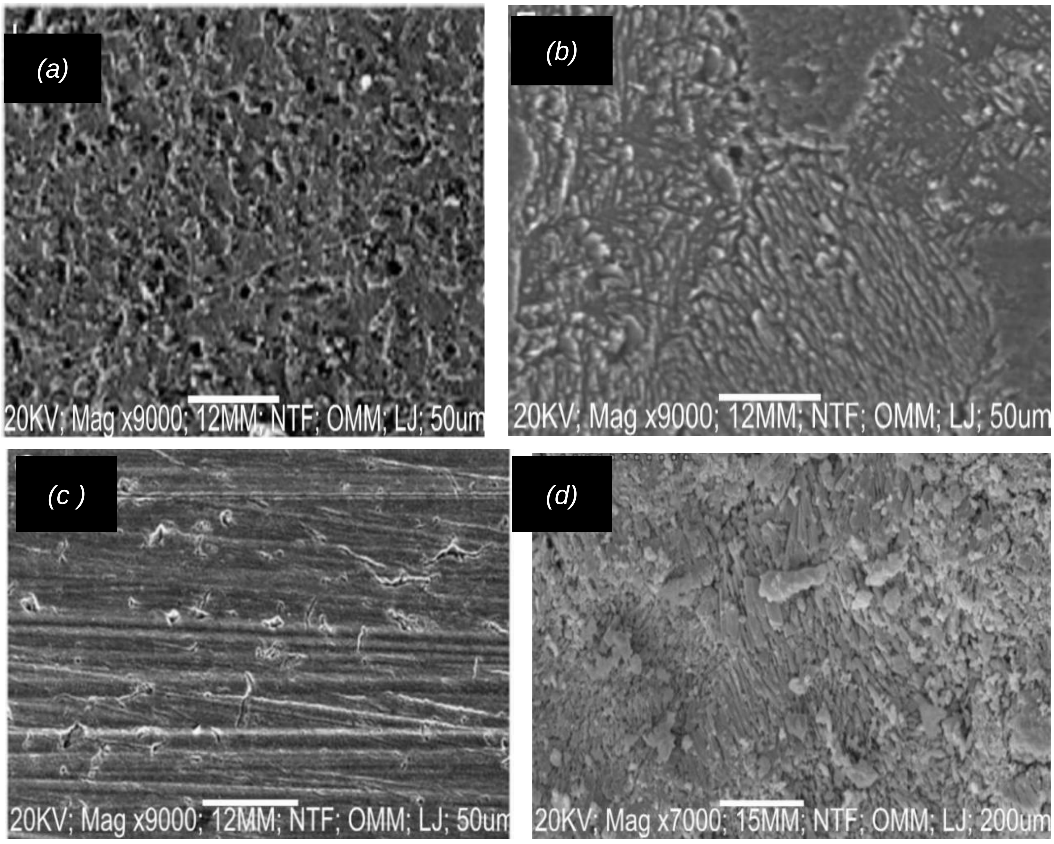


Figure 14. Scanning Electron Microscopy (a) of Mild Steel dipped in 2MHCl for 240hrs at 30⁰C, (b) for Mild Steel dipped in 2MHCl in the presence of 75.0g/l of Septrin drug for 240hr at 30⁰C, (c) for Mild Steel dipped in 2MHCl in the presence of 75.0g/l of Flagylfor 240hours at 30⁰C, d) for the unexposed Mild Steel

The coupon exposed to Septrin has a thick, well-distributed protective film over the exposed surface, indicating a high inhibitory efficiency of 96.60% after 240 hours (Fig. 14(b)). As shown in Fig. 14(c), mild steel coupon surface morphology subjected to Flagyl under identical conditions showed inhibitory efficiency of 76.60% for 240 hours, which is lower than Septrin. The surface has few pits and is coated with a durable thin film of white and ash, suggesting partial protection.

4. CONCLUSIONS

In recent years, drugs have been increasingly studied for their potential to mitigate and reduce the corrosion of metallic materials due to their environmental impact and high inhibitory properties. In this study, the corrosion behaviour of mild steel was investigated in the presence of Septrin and Flagyl as corrosion inhibitors in an HCl solution. Both Septrin and Flagyl were successfully applied as corrosion inhibitors for mild steel in a 2MHCl solution at 30°C over exposure periods of 48, 96, 144, 192, and 240 hours. The inhibition efficiency (IE%) values of 97.7% for Septrin and 76.7% for Flagyl, obtained using gravimetric techniques, clearly demonstrate the effectiveness of these drugs as corrosion inhibitors in an acidic environment. The free energy of adsorption values, derived from four isothermal models, indicate a physisorption mechanism for both drugs. This provides valuable insight into the nature of the interaction between the drug molecules and the metal surface. Further analysis of the rate constant and half-life revealed that in the presence of Septrin, mild steel exhibits a longer half-life compared to Flagyl, indicating superior protection capability. Additionally, scanning electron microscopy (SEM) analysis confirmed the formation of a protective film on the mild steel surface by both drug inhibitors, which effectively shielded the surface from further corrosion. This research work has successfully demonstrated the suitability of Septrin and Flagyl as corrosion inhibitors of mild steel in acidic environments.

Declarations

The authors declare that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

Author Contributions

B.U.O. conceptualized the research ,B.U.O and B.S carried out the experiment, B.S and S.O.O drafted the manuscript text, B.U.O, S.O.O and S.O edited the manuscript. All authors reviewed the manuscript.

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IZVOD

KINETIČKA STUDIJA, KARAKTERIZACIJA POVRŠINE I INHIBICIJA KOROZIJE MEKOG ČELIKA U KISELIM SREDINAMA UPOTREBOM SEPTRINA I FLAGILA

Tokom godina, raste interesovanje za upotrebu farmaceutskih jedinjenja kao inhibitora korozije zbog njihove ekološki prihvatljive prirode i visoke efikasnosti u inhibiciji korozije u metalnim materijalima. Proučava se efikasnost inhibicije korozije dva leka, septrina i flagila, na mekom čeliku u rastvoru 2MHCl na 30°C za različita vremena izlaganja od 48, 96, 144, 192 i 240 sati. U istraživačkom radu, glavni ciljevi su bili usmereni na ponašanje adsorpcije i kinetički proces. Metoda gubitka težine pokazala je da je Septrin imao vrednost efikasnosti inhibicije (IE) od 97,7%, a Flagil je imao vrednost IE od 76,7%. To znači da su oba bila efikasna u smanjenju korozije u kiseloj sredini. Izotermni modeli, vrednosti slobodne energije adsorpcije, sugerišu fizisorpciju za oba leka i pokazuju prirodu interakcije između molekula inhibitora i površine metala. Kinetičke studije su dodatno pokazale da meki čelik pokazuje duže vreme poluraspada u prisustvu septrina u poređenju sa flagilom, što ukazuje na superiornu zaštitu. Takođe, analiza skenirajućom elektronskom mikroskopijom (SEM) potvrdila je prisustvo zaštitnog filma na površini čelika, što je sprečilo dalju koroziju čelika. Ovo istraživanje ističe obećavajuću upotrebu septrina i flagila kao inhibitora korozije za meki čelik u kiselim uslovima.

Ključne reči: *gravimetrijska tehnika, efikasnost inhibicije, inhibitorni lekovi, mehanizam fizisorpcije, mehanizam adsorpcije, zaštitni film, rastvaranje.*

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