


Cite this: *RSC Adv.*, 2021, **11**, 25314

Novel pyrimidine-bichalcophene derivatives as corrosion inhibitors for copper in 1 M nitric acid solution

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This study targets the investigation of three pyrimidine-bichalcophene derivatives (MA-1230, MA-1231, MA-1232) for the prevention of corrosion on copper in 1 M HNO₃ via weight loss (WL), potentiodynamic polarization (PDP), and electrochemical impedance spectroscopy (EIS) techniques. The surface morphology was also analyzed by different methods. It was found that the inhibition efficiency (% η) increased by increasing the doses of pyrimidine derivatives and the temperature of the medium. Weight loss data revealed the better adsorption of MA-1232 on the Cu surface at increased inhibitor dose, reaching a maximum efficiency of 99.14% at a dose of 21 μ M at 45 °C. The best description of the adsorption of the investigated derivatives on the copper surface was given by the Langmuir isotherm. Some important thermodynamic parameters for the studied inhibitors were computed and are discussed herein. The polarization studies showed that the pyrimidine-bichalcophenes act as mixed inhibitors. Computational chemical approaches were used with informative yields, including quantum-chemical and molecular dynamics simulation techniques, which agree with the experimental results. The results obtained from all tested methods are strongly accepted.

Received 8th May 2021

Accepted 4th July 2021

DOI: 10.1039/d1ra03603c

rsc.li/rsc-advances

1. Introduction

Copper is among the most widely used metals for industrial and domestic purposes due to its excellent electrical conductivity, good mechanical workability, low cost, and other properties. However, a range of environmental effects can easily cause the corrosion of copper. Nitric acid is the most widely used corrosive solution for copper.¹ Corrosion is an electrochemical process involving anodic and cathodic reactions on the surface of metals.² Any alteration in the physical components of metals, due to physicochemical contact with their environments, which results in the deterioration of the metal's character is also called corrosion.³ Corrosion is expensive, as well as harmful. Every year, billions of dollars are spent on repairing corroded buildings, equipment, and parts. Early failure can lead to the loss of human life and security damage. By adding chemical compounds to a corrodent, the surface metal corrosion can be controlled and minimized. The most effective method for dealing with the corrosion of metals is using inhibitors. A

corrosion inhibitor is a substance that, when added in small amounts to the corrosive solution, lowers the corrosion rate of the metal. In recent studies, not only are new inhibitors with high inhibition efficiency being developed, but other characteristics are also considered, such as low-cost, low-toxicity and readiness for production processes.⁴ The use of inhibitors is the most practical method for defending against the successive dissolution of metal by corrosion. The use of O, S and N-containing organic compounds to minimize metal corrosion has been studied.⁵ The presence of hetero atoms in the inhibitor's chemical structure plays a significant role in the action of corrosion inhibition. Other factors have a significant influence on the efficiency of inhibition, such as molecular weight, aromatic rings, and inhibited metal load.^{6–10} Furan and thiophene-containing compounds have been recently reported for their corrosion inhibition effects^{11–13} and are described with a wide biological potential range as anticancer agents,¹⁴ anti-mutagenic agents,¹⁵ and antimicrobial activities.¹⁶ Heterocycle-containing pyrimidine has been found to be a safe inhibitor at concentrations that have excellent corrosion inhibition effects on copper metal in acidic media.^{17,18} Some pyrimidine derivatives were utilized as corrosion inhibitors for steel in HCl and H₂SO₄ solutions with their percentage inhibition (% IE) predicted in Table 1. To the authors' best knowledge, pyrimidine-bichalcophene scaffolds have not been evaluated as corrosion inhibitors. In the current study, we evaluated the corrosion inhibition characteristics of three novel pyrimidine-

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Table 1 A list of pyrimidine derivatives used for the corrosion inhibition of steel coupons in altered acid medium

| Compound | Sample | Medium | % IE | Ref. |
|--|--------------|------------------------------------|--|------|
| (a) 5-(2,5-Dimethylthiophen-3-yl)-4-(4-(6-(2,5-dimethylthiophen-3-yl)-2-hydroxypyrimidin-4-yl)phenyl)pyrimidin-2-ol (DTPH) | Mild steel | 1 M H ₂ SO ₄ | 85.7, 92.6 respectively at 0.05 mM | 19 |
| (b) 5-(2,5-Dimethylthiophen-3-yl)-4-(4-(6-(2,5-dimethylthiophen-3-yl)-2-mercaptopyrimidin-4-yl)phenyl)pyrimidin-2-thiol (DTPT) | Mild steel | 1 M HCl | 84.8, 63.2, 75.4 respectively, at 2×10^{-4} M | 20 |
| (a) Benzylidene-pyrimidin-2-yl-amine | Mild steel | 15% M HCl | 86.6, 87.3 respectively at 50 ppm | 21 |
| (b) (4-Methyl-benzylidene)-pyrimidine-2-yl-amine | Mild steel | 1 M HCl | 84, 85 respectively at 10^{-3} M | 22 |
| (c) (4-Chloro-benzylidene)-pyrimidine-2-yl-amine | Mild steel | 1 M HCl | 97.8, 95.2, 93.9 respectively at 10.15×10^{-5} M | 23 |
| (a) 7-Methoxypyrido[2,3- <i>d</i>]pyrimidin-4-amine (MPPA) | Mild steel | 1 M HCl | 91 at 5 mM | 24 |
| (b) 4-Amino-7-methoxypyrido[2,3- <i>d</i>]pyrimidin-2(1 <i>H</i>)-one (AMPO) | Carbon steel | 1 M HCl | 57.4, 71.8, 64.4, 49.5 respectively, at 1×10^{-4} M | 25 |
| (i) Ethyl(2-amino-5-methyl[1,2,4]-triazolo[1,5- <i>a</i>]pyrimidin-7-yl)acetate | Mild steel | 1 M HCl | | |
| (ii) Ethyl(5-methyl[1,2,4]triazolo[1,5- <i>a</i>]pyrimidin-7-yl)-acetate | Mild steel | 1 M HCl | | |
| (i) 2-((1 <i>E</i>)-2-Aza-2-pyrimidine-2-ylvinyl)-thiophene (PT) | Mild steel | 1 M HCl | | |
| (ii) 2-((1 <i>Z</i>)-1-Aza-2-(2-pyridyl)vinyl)pyrimidine (PP) | Mild steel | 1 M HCl | | |
| (iii) 2-((1 <i>E</i>)-2-Aza-2-(1,3-thiazol-2-yl)vinyl)thiophene (TT) | Mild steel | 1 M HCl | | |
| (iv) 2-((1 <i>Z</i>)-1-Aza-2-(2-thienyl)vinyl)benzothiazole (TBT) | Mild steel | 1 M HCl | | |

bichalcophene compounds: 5-([2,2'-bifuran]-5-ylmethylene)-1,3-dimethylpyrimidine-2,4,6(1*H*,3*H*,5*H*)-trione (**3a**, MA-1230), 5-([2,2'-bithiophen]-5-ylmethylene)-1,3-dimethylpyrimidine-2,4,6(1*H*,3*H*,5*H*)-trione (**3b**, MA-1231) and 5-([2,2'-bithiophen]-5-ylmethylene)-1,3-diethyl-2-thioxodihydropyrimidine-4,6(1*H*,5*H*)-dione (**3c**, MA-1232). The outcomes indicate that these compounds are brilliant corrosion inhibitors and necessitate further study. In addition to this, considering the actual ecological problems, the interest in these compounds is also highlighted due to their non-toxic characteristics coupled with high solubility in the test solution, which enhance their inhibition efficacy. In this point of view, our aim is to shed more light on the corrosion inhibitive properties of these newly investigated bichalcophene derivatives. Some advanced techniques are used, and surface examination was conducted *via* scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) spectroscopy. Quantum chemical calculations and molecular dynamics simulation were conducted and discussed. The study also portrays the influence of molecular structure on the capability of these molecules to be adsorbed on the metal surface.

2. Experimental procedures

2.1. Materials and solutions

The samples of copper were cut out from a copper sheet with chemical composition (wt%) 0.0023 Pb, 0.005 Zn, 0.0023 P, 0.004 Ni, 0.0018 Al, 0.015 Si, 0.0011 S, Co 0.0019, and the rest was Cu. For WL tests, the geometric scale of copper samples was 20–20–2 mm, and for electrochemical measurements, it was 10–10 mm. Prior to the assessment, the samples were abraded with various grades of emery papers (320–2500) till a mirror finish was obtained.

2.1.1. Inhibitors. Three investigated pyrimidine-bichalcophene inhibitors **3a–c** were synthesized as presented in Scheme 1. The chemical structures and molecular formulas are listed in Table 2. The investigations were done at different concentrations (5×10^{-6} , 9×10^{-6} , 13×10^{-6} , 17×10^{-6} and 21×10^{-6} M) in the presence and absence of the investigated inhibitors. All experiments were conducted under thermostatic conditions.

2.1.2. Preparation of pyrimidine-bichalcophene inhibitors **3a–c**

2.1.2.1. 5-([2,2'-Bifuran]-5-ylmethylene)-1,3-dimethylpyrimidine-2,4,6(1*H*,3*H*,5*H*)-trione (3a**, MA-1230).** A mixture of 1,3-

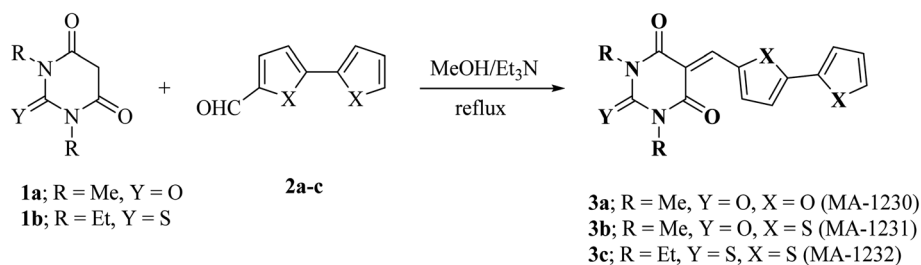
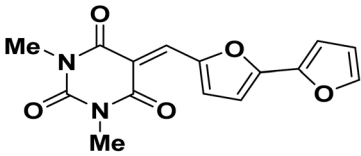
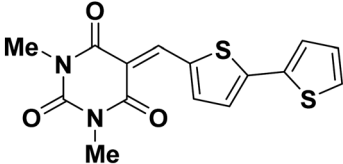
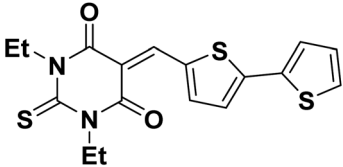
**Scheme 1** Synthetic routes of the investigated pyrimidine-bichalcophene derivatives.

Table 2 Molecular structures, formulas, weights of pyrimidine-bichalcophene derivatives

| Inhibitor code | Molecular structures/chemical names | Mol formulas (mol. wt.) |
|----------------|---|---|
| (3a), MA-1230 |  | C ₁₅ H ₁₂ N ₂ O ₅ (300.27) |
| (3b), MA-1231 | <p>5-([2,2'-bifuran]-5-ylmethylene)-1,3-dimethylpyrimidine-2,4,6(1H,3H,5H)-trione</p>  | C ₁₅ H ₁₂ N ₂ O ₃ S ₂ (332.39) |
| (3c), MA-1232 | <p>5-([2,2'-bithiophen]-5-ylmethylene)-1,3-diethyl-2-thioxodihydropyrimidine-4,6(1H,5H)-dione</p>  | C ₁₇ H ₁₆ N ₂ O ₂ S ₃ (376.51) |

dimethylbarbituric acid (**1a**) (5 mmol) and 2,2'-bifuran-5-carboxaldehyde²⁶ **2a** (5 mmol) was refluxed in methanol (30 mL) in the presence of Et₃N (0.5 mL) for 6 h. The precipitate was filtered off, washed with methanol, and recrystallized from DMF/EtOH to afford pyrimidine-bifuran derivative **3a** in 83% yield, mp 249–250 °C. IR (KBr) ν 3129, 3108 (sp² C–H stretch), 2957, 2923 (sp³ C–H stretch), 1722, 1658 (CO), 1608, 1563, 1534 (C=C) cm^{−1}. ¹H-NMR (DMSO-*d*₆); δ 3.23 (s, 6H; 2 × CH₃), 6.75–6.77 (m, 1H), 7.18 (d, *J* = 4.0 Hz, 1H), 7.22 (d, *J* = 3.5 Hz, 1H), 7.97 (d, *J* = 1.0 Hz, 1H), 8.12 (s, 1H), 8.64 (d, *J* = 4.0 Hz, 1H). MS (EI) *m/z* (rel. int.); 300 (M⁺, 100). Anal. calcd. for C₁₅H₁₂N₂O₅ (300.27): C, 60.00; H, 4.03; N, 9.33 found: C, 60.17; H, 3.94; N, 9.01%.

2.1.2.2. 5-([2,2'-Bithiophen]-5-ylmethylene)-1,3-dimethylpyrimidine-2,4,6(1H,3H,5H)-trione (**3b**, MA-1231). The same procedure used for the preparation of **3a** was adopted using 2,2'-bithiophene-5-carboxaldehyde **2b** (ref. 26) instead of the formyl bifuran derivative **2a** to afford pyrimidine-bithiophene derivative **3b** in 80% yield, mp 240–242 °C, lit.²⁷ mp not reported. Spectroscopic data not previously reported: IR (KBr) ν 3094, 3074 (sp² C–H stretch), 2953 (sp³ C–H stretch), 1719, 1649 (CO), 1551, 1520 (C=C) cm^{−1}. MS (EI) *m/z* (rel. int.); 332 (M⁺, 100).

2.1.2.3. 5-([2,2'-Bithiophen]-5-ylmethylene)-1,3-diethyl-2-thioxodihydropyrimidine-4,6(1H,5H)-dione (**3c**, MA-1232). The same procedure used for the preparation of **3a** was employed using

1,3-diethyl-2-thiobarbituric acid (**1b**) instead of compound **1a** and 2,2'-bithiophene-5-carboxaldehyde (**2b**) instead of the formyl bifuran derivative **2a** to afford pyrimidine-bithiophene derivative **3c** in 76% yield, mp 224.5–226 °C. IR (KBr) ν 3083 (sp² C–H stretch), 2978, 2930 (sp³ C–H stretch), 1686, (CO), 1652, 1552, 1518 (C=C), 1290 (CS) cm^{−1}. ¹H-NMR (DMSO-*d*₆); δ 1.19–1.25 (m, 6H, 2 × CH₃ of CH₃CH₂), 4.41–4.48 (m, 4H, 2 × CH₂ of CH₃CH₂), 7.21–7.23 (m, 1H), 7.69 (d, *J* = 4.0 Hz, 1H), 7.74 (d, *J* = 4.0 Hz, 1H), 7.79 (d, *J* = 4.0 Hz, 1H), 8.24 (d, *J* = 4.0 Hz, 1H), 8.62 (s, 1H). MS (EI) *m/z* (rel. int.); 376 (M⁺, 100). Anal. calcd. for C₁₇H₁₆N₂O₂S₃ (376.52): C, 54.22; H, 4.28; N, 7.44 found: C, 53.93; H, 4.34; N, 7.21%.

2.2. Weight loss (WL) measurements

The inhibition efficiency of the investigated inhibitors was calculated using eqn (1) when copper coins were pre-weighed and tested in the presence and the absence of these inhibitors in 1 M HNO₃ solution. The samples were removed, dried, and measured after 3 h:²⁸

$$\% \eta = \theta \times 100 = \left(1 - \left(\frac{W}{W^0} \right) \right) \times 100 \quad (1)$$

where *W*⁰ is the WL value for blank and *W* is the WL value for the solution with inhibitor.



2.3. Electrochemical techniques

Electrochemical studies were conducted using the Volta-Master 4 software package V7.8 with the Volta-Lab model PGZ402 potentiostat. The potentiostat was attached in the following way to a conventional cell with three electrode arrangements: copper metal as the working electrode (WE), platinum wire as the counter electrode (CE) and the saturated calomel electrode (SCE) as the reference electrode. The measurements started with the immersion of WE in the electrolyte for 1 h to determine the steady state of the open circuit potential (OCP). EIS measurements were measured with an AC signal in the range of frequency between 100 kHz to 0.03 Hz at 10 mV amplitude OCP. PDP measurements were carried out at potentials from -250 mV to $+250$ mV and at a scan rate of 0.5 mV s^{-1} at controlled temperature. All experimental techniques were performed three times to achieve better data repeatability.

2.4. Surface morphology investigation by SEM and EDX techniques

The metal surface morphology was examined using scanning electron microscopy (SEM) (SEM model JOEL, JSM-T20, Japan) after the immersion of copper coins with and without the highest

concentrations of the three pyrimidine derivatives for 24 hours in acid solutions. The copper samples were analyzed using energy dispersive X-ray (EDX) spectroscopy (Zeiss Evo 10 instrument model). The voltage of the accelerating beam was 25 kV.

2.5. Quantum calculations

Gaussian version 4.4.0 used density functional theory (DFT) to measure the quantum chemical parameters and indexes.²⁹ The quantum parameters associated with corrosion inhibition were calculated, including the energy gap ($\Delta E = E_{\text{LUMO}} - E_{\text{HOMO}}$), (I_p) the ionization ($I_p = -E_{\text{HOMO}}$), (E_A) the electron affinity ($E_A = -E_{\text{LUMO}}$), the dipole moment (debye), the global hardness (η), softness (σ), and chemical potential (μ).

2.6. Quantum Monte Carlo (MC) simulation

MC simulations were performed using Materials Studio program version 7.0 (Accelrys Inc., San Diego, CA, USA) in a simulation box with periodic boundary conditions. The pure copper crystal was adopted and cleaved along the most stable (less energy) plane (1 0 0), constructing a 30 \AA vacuum slab. The plane Cu surface of (1 0 0) was relaxed by decreasing its energy, then extending the surface of Cu (1 0 0) to a supercell (10/10). The simulation analysis

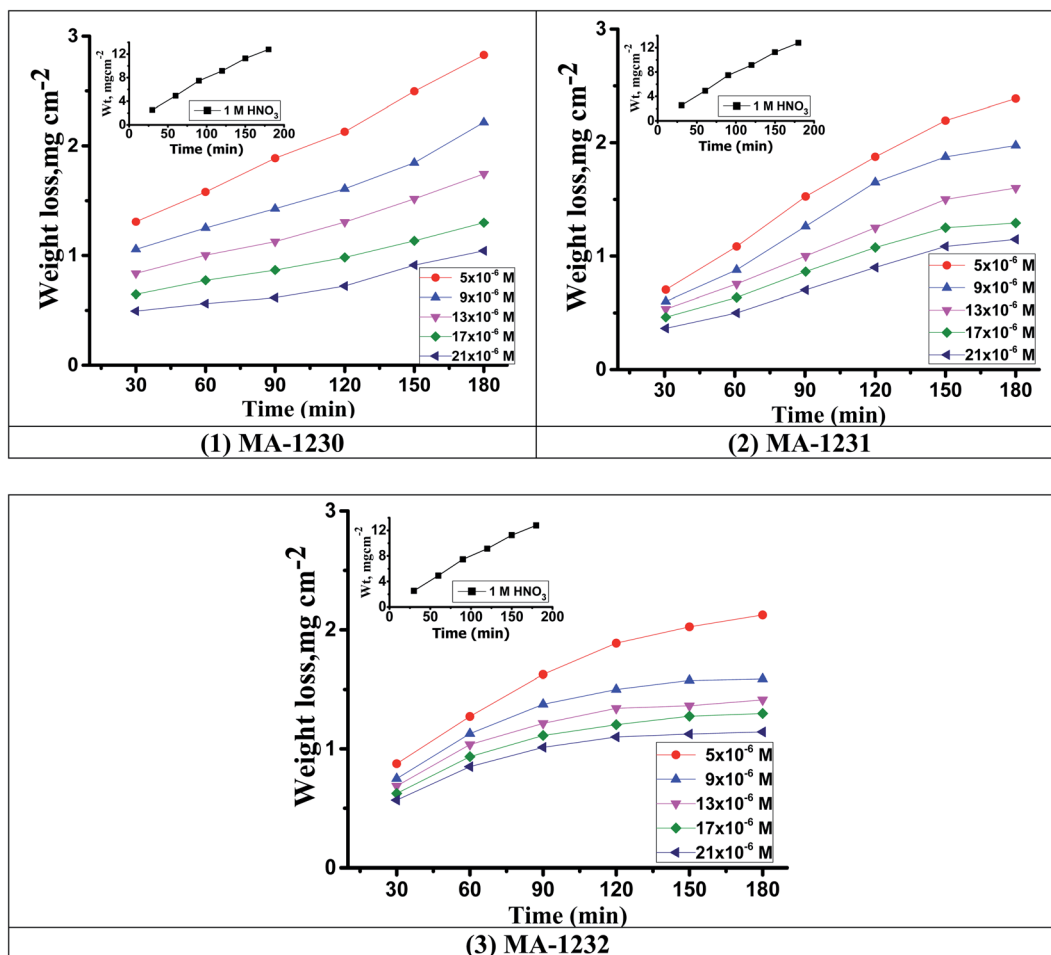


Fig. 1 WL–time curves for the dissolution of copper metal in 1 M HNO₃ at different derivative concentrations (1) MA-1230, (2) MA-1231 and (3) MA-1232 at 25 °C.

was carried out using the MC quest in a test box containing the simulated corrosive species and one molecule of each inhibitor and assigning the high-quality force field known as COMPASS to combine organic parameters and inorganic substances.³⁰

3. Results and discussion

3.1. Weight loss (WL) measurements

3.1.1. The effects of concentration and temperature. The effects of the pyrimidine derivatives examined on copper metal corrosion were measured in a solution of 1.0 M HNO₃ using the WL method at 25 °C as in Fig. 1. The temperature effects on inhibition efficiency and corrosion rate (k_{corr}) are demonstrated in Table 3. Fig. 1 illustrates that by increasing the concentration of derivatives, % η_{WL} increases and k_{corr} decreases. Also, by increasing temperature % η_{WL} increases and k_{corr} decreases, indicating that these derivatives are excellent inhibitors at higher temperatures. % η_{WL} increases from (78.24–96.75) at 25 °C to (92.51–99.14) at 45 °C. The increase in % η_{WL} is due to the adsorption of additives on the copper surfaces and this leads to the accumulation of a protective layer on the surface of the Cu^{31,32} which increases by increasing the temperature. % η_{WL} of the investigated derivatives are in the order of MA-1232 > MA-1231 > MA-1230 at different temperatures.³³

3.1.2. Thermodynamic activation parameters. There is an agreement that corrosion is related to the Arrhenius equation,

noting that by the Arrhenius equation, the activation energy E_a^* is measured by using k_{corr} .³⁴

$$\log k_{\text{corr}} = \left(\frac{-E_a^*}{2.303RT} \right) + \log A \quad (2)$$

where R is the universal gas constant, T is the absolute temperature, A is the Arrhenius pre-exponential factor and k_{corr} is the corrosion rate. Straight lines were obtained when plotting ($\log k_{\text{corr}}$) versus ($1/T$) with the intercept of A and slope $E_a^*/2.303R$ for the investigated derivatives as shown in Fig. 2; from this, E_a^* values can be calculated. The data in Table 4 show that on increasing the inhibitor concentration, the E_a^* values decreased, suggesting that the adsorption of these derivatives on the Cu surface is through chemical means.^{35–37} The entropy of activation ΔS^* and standard enthalpy ΔH^* are computed from the transition state equation:^{38,39}

$$\log k_{\text{corr}} = \log \left(\frac{R}{Nh} \right) + \frac{\Delta S^*}{2.303R} + \frac{\Delta H^*}{2.303RT} \quad (3)$$

where N is Avogadro's number and h is Planck's constant. Plots of ($\log k_{\text{corr}}/T$) versus ($1/T$) for all additives gave straight lines with intercepts of ($\ln(R/Nh) + \Delta S^*/R$) that were used to give the values of ΔS^* , and slopes of ($-\Delta H^*/R$) to obtain the values of ΔH^* , which are listed in Table 4. Fig. 3 shows transition state for the three additives. ΔH^* values are positive and this is

Table 3 % η and k_{corr} of the inhibitors at different concentrations calculated from WL measurements for copper metal at various temperatures

| Temp, °C | Conc., μM | MA-1230 | | MA-1231 | | MA-1232 | |
|----------|----------------------|---|----------|---|----------|---|----------|
| | | k_{corr} , $\text{mg cm}^{-2} \text{min}^{-1}$ | % η | k_{corr} , $\text{mg cm}^{-2} \text{min}^{-1}$ | % η | k_{corr} , $\text{mg cm}^{-2} \text{min}^{-1}$ | % η |
| 25 | Blank | 0.052 \pm 0.0012 | — | 0.052 \pm 0.0013 | — | 0.052 \pm 0.0012 | — |
| | 5 | 0.015 \pm 0.0023 | 75.05 | 0.015 \pm 0.0015 | 79.51 | 0.008 \pm 0.0021 | 92.63 |
| | 9 | 0.012 \pm 0.0015 | 78.04 | 0.014 \pm 0.0012 | 81.97 | 0.008 \pm 0.0023 | 92.74 |
| | 13 | 0.018 \pm 0.0018 | 79.04 | 0.016 \pm 0.0026 | 86.34 | 0.009 \pm 0.0026 | 92.84 |
| | 17 | 0.017 \pm 0.0009 | 81.04 | 0.016 \pm 0.0020 | 88.25 | 0.009 \pm 0.0023 | 95.32 |
| | 21 | 0.019 \pm 0.0029 | 78.24 | 0.052 \pm 0.0023 | 89.21 | 0.008 \pm 0.0038 | 96.75 |
| 30 | Blank | 0.089 \pm 0.0020 | — | 0.089 \pm 0.0020 | — | 0.089 \pm 0.0020 | — |
| | 5 | 0.012 \pm 0.0020 | 76.05 | 0.013 \pm 0.0017 | 84.05 | 0.008 \pm 0.0018 | 93.07 |
| | 9 | 0.012 \pm 0.0009 | 79.28 | 0.009 \pm 0.0020 | 89.06 | 0.007 \pm 0.0020 | 94.67 |
| | 13 | 0.015 \pm 0.0023 | 81.08 | 0.012 \pm 0.0023 | 93.60 | 0.007 \pm 0.0020 | 95.39 |
| | 17 | 0.018 \pm 0.0017 | 84.10 | 0.013 \pm 0.0026 | 94.18 | 0.007 \pm 0.0029 | 95.85 |
| | 21 | 0.016 \pm 0.0020 | 85.92 | 0.031 \pm 0.0026 | 94.30 | 0.006 \pm 0.0023 | 96.47 |
| 35 | Blank | 0.101 \pm 0.0017 | — | 0.101 \pm 0.0017 | — | 0.101 \pm 0.0017 | — |
| | 5 | 0.011 \pm 0.0015 | 80.13 | 0.0137 \pm 0.0002 | 86.52 | 0.008 \pm 0.0015 | 93.17 |
| | 9 | 0.012 \pm 0.0020 | 80.96 | 0.009 \pm 0.0020 | 89.22 | 0.007 \pm 0.0023 | 94.87 |
| | 13 | 0.012 \pm 0.0021 | 89.15 | 0.012 \pm 0.0026 | 94.70 | 0.006 \pm 0.002333 | 95.85 |
| | 17 | 0.014 \pm 0.0017 | 85.29 | 0.013 \pm 0.0015 | 94.87 | 0.005 \pm 0.0017 | 96.47 |
| | 21 | 0.013 \pm 0.0023 | 94.22 | 0.031 \pm 0.0023 | 95.04 | 0.005 \pm 0.0018 | 97.10 |
| 40 | Blank | 0.137 \pm 0.0020 | — | 0.137 \pm 0.0020 | — | 0.137 \pm 0.0020 | — |
| | 5 | 0.010 \pm 0.0020 | 80.90 | 0.010 \pm 0.0018 | 88.18 | 0.007 \pm 0.0017 | 94.61 |
| | 9 | 0.011 \pm 0.0018 | 82.20 | 0.005 \pm 0.0020 | 90.45 | 0.006 \pm 0.0020 | 95.32 |
| | 13 | 0.011 \pm 0.0026 | 89.33 | 0.006 \pm 0.0020 | 95.15 | 0.005 \pm 0.0020 | 95.98 |
| | 17 | 0.012 \pm 0.0023 | 91.03 | 0.006 \pm 0.0023 | 95.91 | 0.003 \pm 0.0023 | 97.23 |
| | 21 | 0.012 \pm 0.0020 | 91.40 | 0.027 \pm 0.002 | 95.98 | 0.004 \pm 0.0023 | 98.11 |
| 45 | Blank | 0.151 \pm 0.0015 | — | 0.151 \pm 0.0015 | — | 0.151 \pm 0.0015 | — |
| | 5 | 0.009 \pm 0.0017 | 81.96 | 0.008 \pm 0.0027 | 89.23 | 0.006 \pm 0.0015 | 92.74 |
| | 9 | 0.011 \pm 0.0017 | 83.15 | 0.005 \pm 0.0023 | 93.57 | 0.005 \pm 0.0015 | 95.92 |
| | 13 | 0.009 \pm 0.0020 | 91.26 | 0.006 \pm 0.0023 | 94.32 | 0.004 \pm 0.0017 | 96.32 |
| | 17 | 0.011 \pm 0.0018 | 91.89 | 0.005 \pm 0.0017 | 97.24 | 0.002 \pm 0.0017 | 97.36 |
| | 21 | 0.010 \pm 0.0015 | 92.51 | 0.012 \pm 0.0018 | 97.45 | 0.001 \pm 0.0010 | 99.14 |



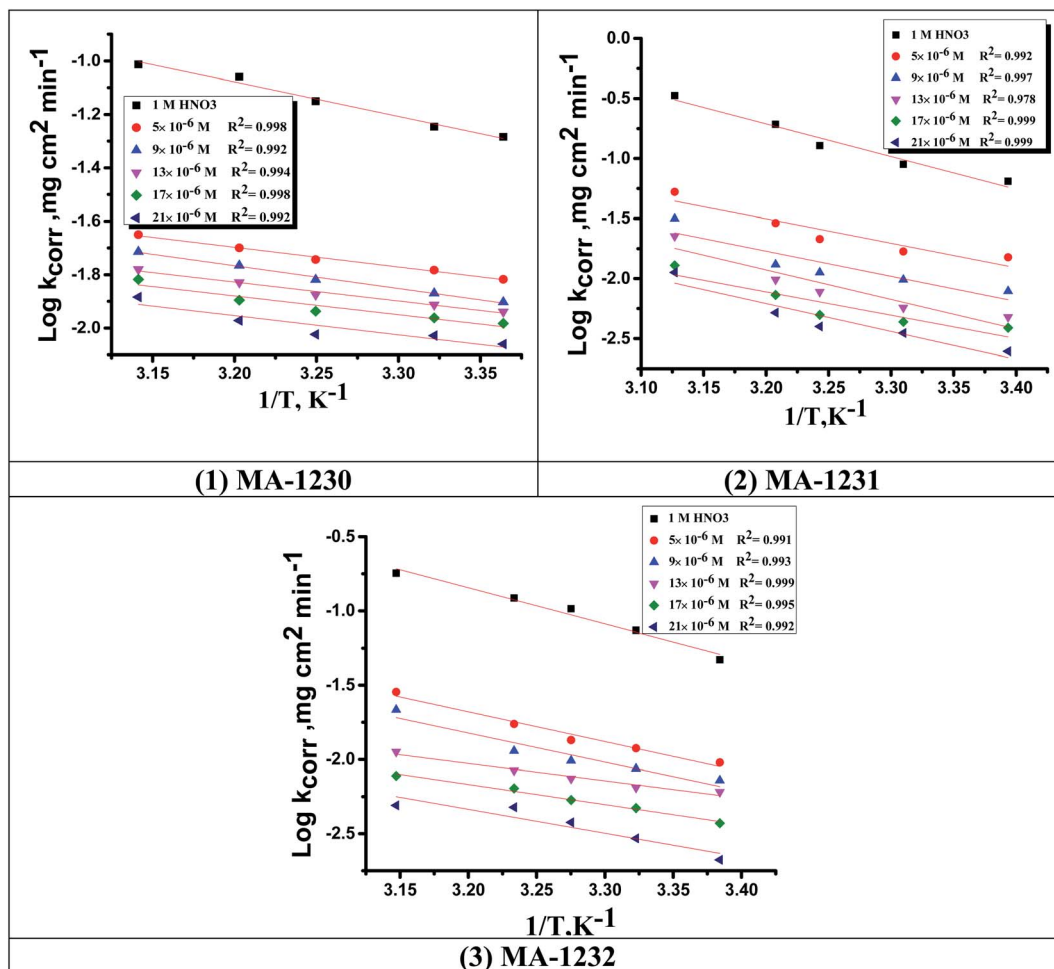


Fig. 2 Arrhenius plots for Cu corrosion in the 1 M HNO₃ solution of inhibitors (1) MA-1230, (2) MA-1231, and (3) MA-1232.

a reference that the copper metal dissolution is an endothermic process^{40,41} and confirms the chemical adsorption of these derivatives on the Cu surface. With increasing concentration of

additives, the sign of ΔS^* is negative indicating that at the rate determining step of the activated complex, there is association rather than dissociation.^{42,43}

Table 4 Activation parameters for copper metal corrosion in 1 M HNO₃ solution without and with various concentrations of inhibitors

| Inhibitor | Conc., $\times 10^6$ M | Activation parameters | | |
|-----------------------------------|------------------------|--------------------------------|-------------------------------------|---|
| | | E_a^* , kJ mol ⁻¹ | ΔH^* , kJ mol ⁻¹ | $-\Delta S^*$, J mol ⁻¹ K ⁻¹ |
| Free acid (1 M HNO ₃) | | 68.7 \pm 0.2028 | 88.2 \pm 0.2603 | 175 \pm 0.2404 |
| MA-1230 | 5 | 18.5 \pm 0.2309 | 13.5 \pm 0.2309 | 234 \pm 0.1528 |
| | 9 | 13.7 \pm 0.2028 | 17.4 \pm 0.2603 | 223 \pm 0.2333 |
| | 13 | 13.6 \pm 0.20278 | 15.0 \pm 0.1732 | 232 \pm 0.2309 |
| | 17 | 13.4 \pm 0.2603 | 12.8 \pm 0.2333 | 240 \pm 0.2729 |
| | 21 | 12.7 \pm 0.2333 | 11.0 \pm 0.2404 | 252 \pm 0.1453 |
| MA-1231 | 5 | 47.1 \pm 0.1732 | 40.9 \pm 0.1453 | 143 \pm 0.1453 |
| | 9 | 44.4 \pm 0.2028 | 40.0 \pm 0.2028 | 151 \pm 0.1764 |
| | 13 | 38.9 \pm 0.1732 | 50.3 \pm 0.2028 | 121 \pm 0.1528 |
| | 17 | 38.2 \pm 0.2603 | 40.9 \pm 0.2333 | 154 \pm 0.1732 |
| | 21 | 37.1 \pm 0.2646 | 35.8 \pm 0.1732 | 173 \pm 0.1764 |
| MA-1232 | 5 | 38.3 \pm 0.2028 | 23.2 \pm 0.2333 | 206 \pm 0.1856 |
| | 9 | 37.4 \pm 0.1528 | 23.2 \pm 0.2309 | 216 \pm 0.1764 |
| | 13 | 30.8 \pm 0.2028 | 19.5 \pm 0.2603 | 223 \pm 0.1528 |
| | 17 | 25.9 \pm 0.2603 | 21.1 \pm 0.2333 | 221 \pm 0.1453 |
| | 21 | 22.45 \pm 0.2048 | 27.0 \pm 0.1764 | 206 \pm 0.2646 |



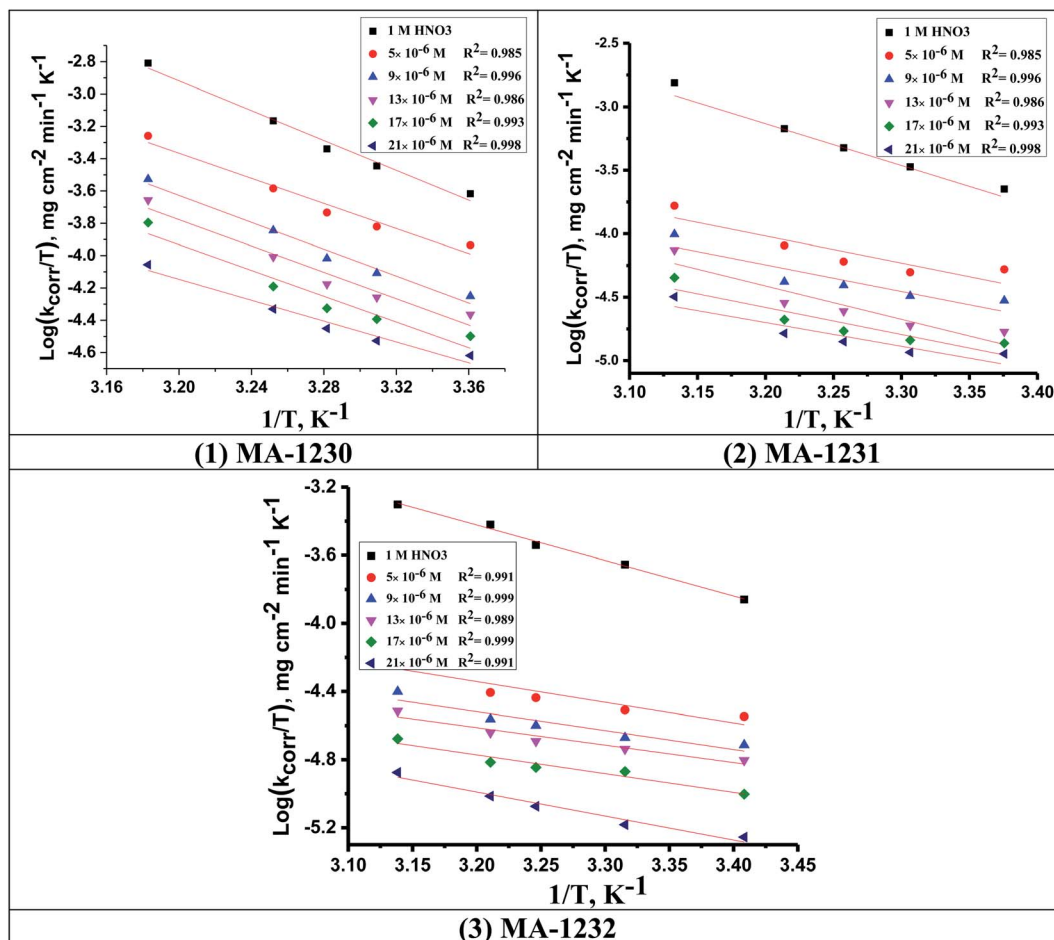


Fig. 3 Transition state plots ($\log k_{\text{corr}}/T$ vs. $1/T$) for Cu in 1 M HNO_3 in the absence and presence of different concentrations of (1) MA-1230, (2) MA-1231, and (3) MA-1232.

3.1.3. Adsorption study. The adsorption isotherm is an effective method for modeling the metallic surface adsorption activity of the investigated derivatives. The results were applied to a variety of adsorption isotherm models from WL

experiments at different temperatures. It was noted that the Langmuir adsorption isotherm is the optimal one for testing the adsorption of the three derivatives of pyrimidine. The constant is given by eqn (4) (ref. 44)

Table 5 Thermodynamic adsorption parameters of MA-1230, MA-1231, MA-1232 adsorbed on the surface of the copper metal in 1 M HNO_3 acid at different temperatures

| Inhibitor | Temp, °C | $-\Delta G_{\text{ads}}^{\circ}$, kJ mol ⁻¹ | $\Delta H_{\text{ads}}^{\circ}$, kJ mol ⁻¹ | $\Delta S_{\text{ads}}^{\circ}$, J mol ⁻¹ K ⁻¹ |
|-----------|----------|---|--|---|
| MA-1230 | 25 | 42.7 ± 0.1732 | 30 | 24.4 ± 0.2028 |
| | 30 | 44.6 ± 0.2028 | | 24.6 ± 0.2333 |
| | 35 | 44.9 ± 0.1453 | | 24.3 ± 0.2028 |
| | 40 | 46.4 ± 0.2028 | | 24.4 ± 0.1453 |
| | 45 | 51.2 ± 0.1764 | | 25.5 ± 0.1453 |
| MA-1231 | 25 | 44.5 ± 0.1732 | 149 | 65.1 ± 0.1732 |
| | 30 | 46.2 ± 0.2028 | | 64.5 ± 0.1453 |
| | 35 | 48.4 ± 0.1732 | | 64.2 ± 0.2028 |
| | 40 | 55.3 ± 0.1000 | | 65.4 ± 0.1453 |
| | 45 | 55.7 ± 0.1453 | | 64.5 ± 0.1732 |
| MA-1232 | 25 | 44.5 ± 0.1732 | 135 | 60.2 ± 0.1764 |
| | 30 | 46.2 ± 0.2028 | | 59.8 ± 0.1453 |
| | 35 | 48.4 ± 0.1732 | | 59.5 ± 0.1732 |
| | 40 | 55.3 ± 0.1000 | | 60.8 ± 0.2028 |
| | 45 | 55.7 ± 0.1453 | | 60.1 ± 0.2309 |



$$\frac{C}{\theta} = \left(\frac{1}{K_{\text{ads}}} \right) + C \quad (4)$$

where K_{ads} is the adsorption equilibrium constant and C is the concentration of the derivatives in μM . The values of adsorption Gibbs free energy $\Delta G_{\text{ads}}^{\circ}$ were calculated from eqn (5):

$$K_{\text{ads}} = \frac{1}{55.5} \exp\left(\frac{\Delta G_{\text{ads}}^{\circ}}{RT}\right) \quad (5)$$

Table 5 displays the negative values of the calculated $\Delta G_{\text{ads}}^{\circ}$, which indicate the spontaneity of the adsorption process.⁴⁵ When the $\Delta G_{\text{ads}}^{\circ}$ values reached -55 kJ mol^{-1} , this indicated a highly chemical adsorption on the copper surface.^{46,47} As a result of the value of $\Delta G_{\text{ads}}^{\circ}$ and η increasing with increasing temperature, the adsorption of these derivatives of pyrimidine often occurs through chemisorption. The heat of adsorption $\Delta H_{\text{ads}}^{\circ}$ was calculated from the Van't Hoff equation:^{48,49}

$$\ln K_{\text{ads}} = \frac{-\Delta H_{\text{ads}}^{\circ}}{RT} + \text{constant} \quad (6)$$

Plots of $\log K_{\text{ads}}$ vs. $1/T$ for the tested derivatives of pyrimidine (Fig. 4) gave straight lines with slopes equal to $\Delta H_{\text{ads}}^{\circ}/2.303R$. We then calculated the value of the standard adsorption entropy $\Delta S_{\text{ads}}^{\circ}$ from the thermodynamic basic eqn (7) (ref. 50–52) by introducing the values of $\Delta G_{\text{ads}}^{\circ}$ and the values of $\Delta H_{\text{ads}}^{\circ}$ at various temperatures:

$$\Delta G_{\text{ads}}^{\circ} = \Delta H_{\text{ads}}^{\circ} - T\Delta S_{\text{ads}}^{\circ} \quad (7)$$

3.2. Potentiodynamic polarization (PDP) measurements

Fig. 5 shows the PDP curves for the copper metal in 1 M HNO_3 solution with and without various concentrations of the tested derivatives (1–21 μM) at 25 °C. The cathodic and anodic curves shifted to lower values of the current density in the presence of the tested derivatives, thereby causing a decrease in the corrosion rate of Cu. The presence of these derivatives greatly reduced corrosion current density. A shift in the Tafel plot towards the cathodic region was observed. This indicated the repressive effect of these derivatives on the cathodic reaction. The differences in the profiles of anodic curves in the presence of these additives indicate the action of these additives on the anodic reaction. Therefore, these additives act as mixed inhibitors. The difference in the profile could be due to the formation of a barrier layer on the metal surface. Polarization parameters such as the corrosion current density (i_{corr}), corrosion potential (E_{corr}) for blank and inhibited specimens at various concentrations, cathodic and anodic Tafel slopes (β_c & β_a), and the inhibition efficiency ($\eta\%$) for the pyrimidine derivatives are collected in Table 6. $\eta\%$ was calculated using the following relation:⁵³

$$\% \eta_{\text{PDP}} = \left(\frac{i_{\text{corr}} - i'_{\text{corr}}}{i_{\text{corr}}} \right) \times 100 \quad (8)$$

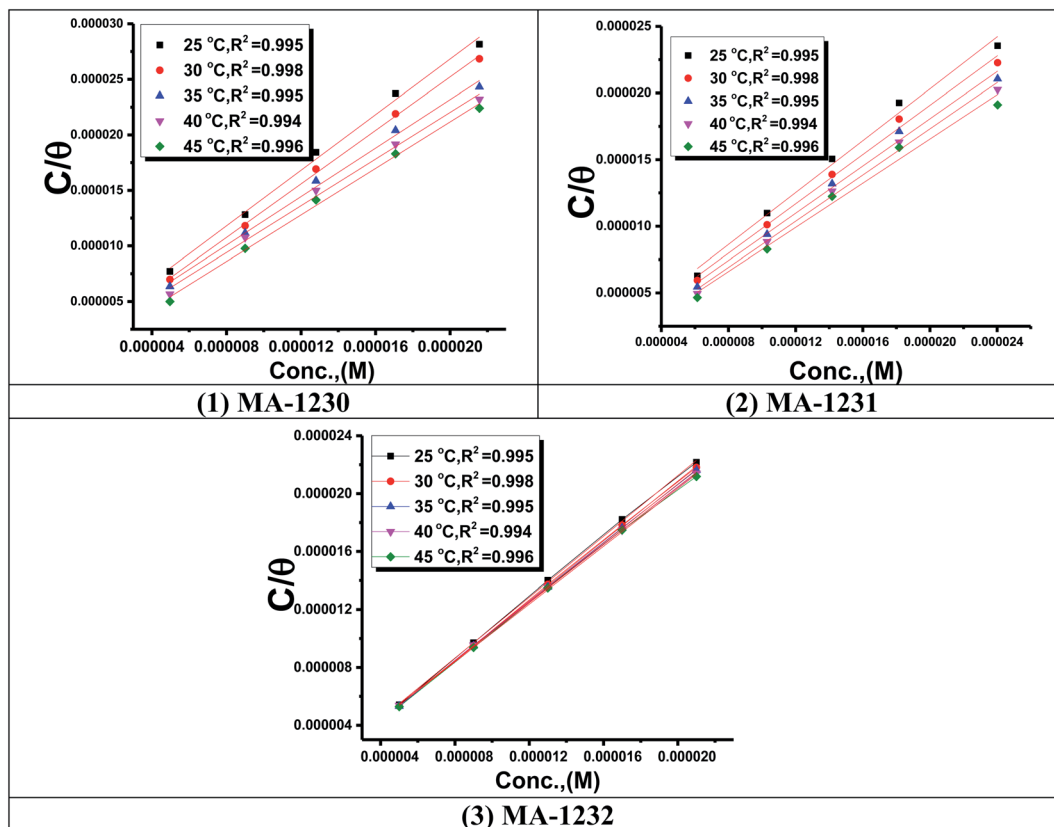


Fig. 4 Langmuir isotherm plots for the corrosion of copper in the 1 M HNO_3 with optimum concentrations of (1) MA-1230, (2) MA-1231, and (3) MA-1232 derivatives.



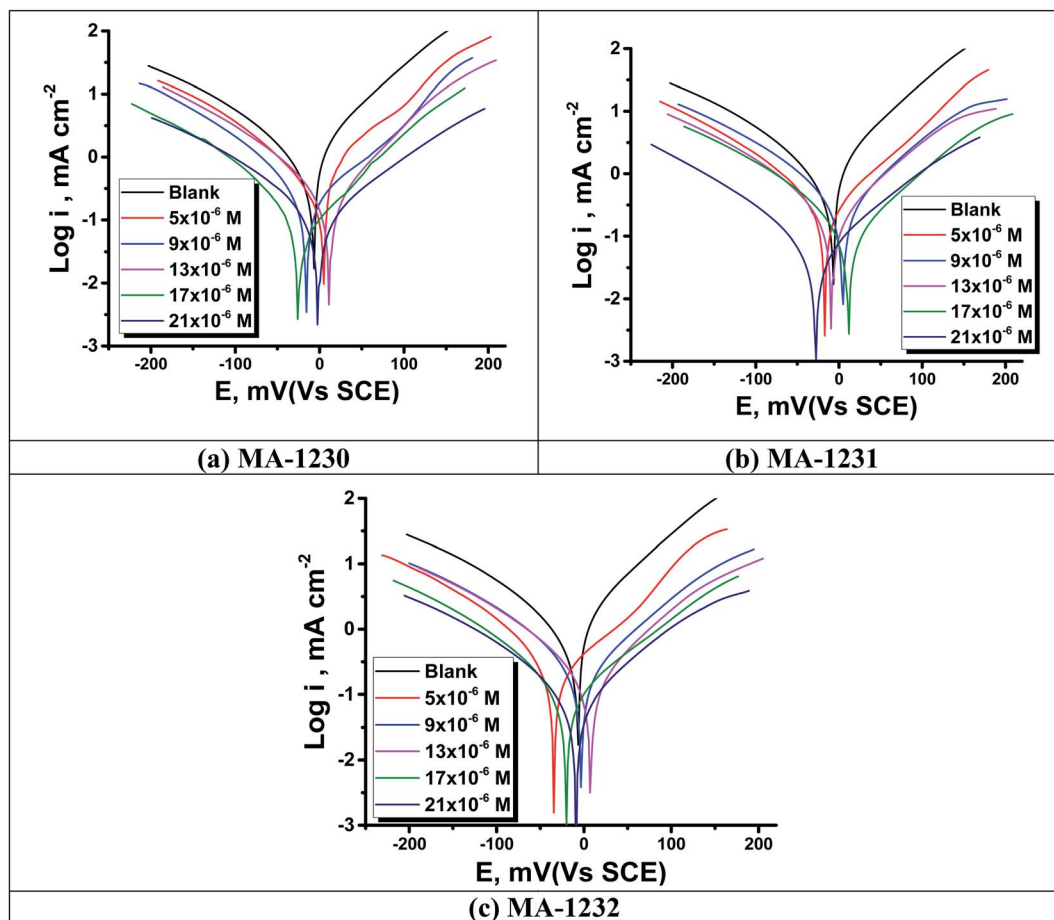


Fig. 5 PDP curves for Cu metal in the 1 M HNO_3 solution at different concentrations of derivatives (a) MA-1230, (b) MA-1231, and (c) MA-1232 at 25 °C.

where i_{corr} and i_{corr} refer to the corrosion current densities of the copper metal with and without inhibitors, respectively. With decreasing (i_{corr}), the % η values increased as the inhibitor concentration increased as observed in Table 6.⁵⁴ The inhibitor can be anodic or cathodic if E_{corr} is greater than -85 mV per SCE

as compared to the potential for the corrosion of the uninhibited blank, whereas the inhibitor can be considered as a mixed form if E_{corr} is less than -85 mV per SCE.⁵⁵ In our research, the shift was less than -27 mV per SCE, suggesting that the investigated derivatives are mixed type inhibitors.⁵⁶

Table 6 PDP measurements for Cu metal in 1 M HNO_3 with and without various concentrations of the tested derivatives at 25 °C

| Inhibitor | Conc., μM | $-E_{\text{corr}}$, mV vs. SCE | i_{corr} , $\mu\text{A cm}^{-2}$ | β_a , mV dec^{-1} | $-\beta_c$, mV dec^{-1} | θ | % η |
|-----------|----------------------|---------------------------------|---|----------------------------------|-----------------------------------|----------|----------|
| Blank | — | 6.4 ± 0.2309 | 352.7 ± 0.1732 | 86.4 ± 0.2309 | 145.2 ± 0.2028 | — | — |
| MA-1230 | 5 | 5.3 ± 0.2333 | 195.1 ± 0.1155 | 99.7 ± 0.2309 | 165.8 ± 0.3528 | 0.447 | 44.7 |
| | 9 | 15.5 ± 0.2028 | 153.6 ± 0.2028 | 102.9 ± 0.1453 | 126.9 ± 0.2028 | 0.565 | 56.5 |
| | 13 | 11.4 ± 0.1453 | 115.3 ± 0.2603 | 85.1 ± 0.1732 | 111.8 ± 0.1453 | 0.673 | 67.3 |
| | 17 | 26.4 ± 0.1453 | 81.6 ± 0.1764 | 88.7 ± 0.2309 | 98.0 ± 0.2906 | 0.769 | 76.9 |
| | 21 | 2.6 ± 0.1732 | 34.1 ± 0.2028 | 153.8 ± 0.2028 | 172.5 ± 0.1732 | 0.903 | 90.3 |
| MA-1231 | 5 | 16.8 ± 0.1732 | 191.3 ± 0.1732 | 111.5 ± 0.2028 | 159.7 ± 0.1732 | 0.458 | 45.8 |
| | 9 | 5.1 ± 0.1453 | 149.6 ± 0.1764 | 127.1 ± 0.1732 | 157.3 ± 0.2028 | 0.576 | 57.6 |
| | 13 | 9.7 ± 0.1732 | 112.1 ± 0.1732 | 128.4 ± 0.1732 | 156.6 ± 0.17638 | 0.682 | 68.2 |
| | 17 | 12.7 ± 0.2082 | 73.2 ± 0.1732 | 118.8 ± 0.2309 | 142.2 ± 0.1732 | 0.792 | 79.2 |
| | 21 | 27.5 ± 0.2309 | 30.8 ± 0.2028 | 123.8 ± 0.1202 | 137.0 ± 0.2082 | 0.913 | 91.3 |
| MA-1232 | 5 | 34.5 ± 0.2028 | 171.7 ± 0.1732 | 97.5 ± 0.2333 | 118.1 ± 0.1732 | 0.513 | 51.3 |
| | 9 | 3.2 ± 0.1732 | 139.2 ± 0.2309 | 121.7 ± 0.1453 | 183.8 ± 0.1155 | 0.605 | 60.5 |
| | 13 | 7.4 ± 0.1453 | 107.3 ± 0.1732 | 123.6 ± 0.20278 | 145.8 ± 0.2028 | 0.696 | 69.6 |
| | 17 | 20.3 ± 0.1453 | 64.1 ± 0.1453 | 157.9 ± 0.2603 | 166.9 ± 0.1764 | 0.818 | 81.8 |
| | 21 | 9.1 ± 0.2028 | 27.9 ± 0.1732 | 105.8 ± 0.2309 | 191.5 ± 0.2028 | 0.921 | 92.1 |



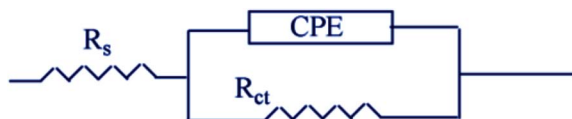


Fig. 6 An equivalent circuit model for measuring EIS data.

3.3. Electrochemical impedance spectroscopy (EIS) measurements

EIS studies afford details about the kinetics of the electrode processes and, concurrently, about the surface properties of the examined systems. Information can be derived from the shape of the impedance diagram.⁵⁷ The copper corrosion efficiency in the 1 M HNO₃ solution was examined by the EIS technique at 25 °C after 30 min of immersion in the presence and absence of various inhibitor concentrations. Fig. 6 shows an equivalent circuit used to consider all the processes involved in the electrical response of the system, which is a parallel combination of the charge-transfer resistance (R_{ct}) and the constant phase element (CPE), both in series with the solution resistance (R_s). The CPE element is used to explain the depression of the capacitance semi-circle, which corresponds to surface heterogeneity resulting from surface roughness impurities, dislocations, grain boundaries, adsorption of inhibitors, and the formation of porous layers.⁵⁸ The impedance of the CPE is represented by the following equation:

$$Z_{CPE} = 1/Y^\circ(j\omega)^n \quad (9)$$

where Y° represents the CPE constant, j is the imaginary root, ω is the angular frequency, n ($-1 < n < 1$) stands for the deviation index. The “ n ” values seem to be associated with the non-uniform distribution of current because of roughness and possible oxide surface defects. When $n = 1$, CPE is an ideal capacitor but true capacitive behavior is rarely obtained. The “ n ” values close to 1 (Table 7) represent the deviation from the ideal capacitor. A constant phase element (CPE) was utilized for data

fitting instead of an ideal capacitor; since the “ n ” values obtained were in the range of 0.9, the value gained from the data fitting was taken as the capacitance. The quality of fitting to the equivalent circuit was assessed by the chi square value.⁵⁹ The obtained chi square values (0.000065 to 0.000123) in Table 7 indicate a good fitting to the proposed circuit. The Nyquist and Bode plots of the systems studied are indicated in Fig. 7 and 8, respectively. It is evident from Fig. 7 that Cu exhibited typical impedance behavior in 1 M HNO₃ solution for the investigated inhibitors examined and displayed a marked increase in the diameter for each concentration studied. The Nyquist graph of copper metal in 1 M HNO₃ solution deviated from the ideal circular shape because of the frequency dispersion.⁶⁰ It is worth noting that the changes in the concentration of the investigated inhibitors did not alter the profile of the impedance behavior, suggesting a similar mechanism for the corrosion inhibition of Cu by these inhibitors. This indicates that in the absence of inhibitors, the Nyquist plot for copper metal has a slightly depressed semicircular design, showing that in the 1 M HNO₃ solution, the charge transport mechanism mainly controls copper metal corrosion.⁶¹ Fig. 8 represents two time constants; the first one appeared in the middle-frequency region and is related to the capacitive loop of the oxide layer on the Cu surface. The second time constant appeared in the low-frequency region and is attributed to the inductive loop arising from the relaxation process of the adsorbed inhibitor molecules on Cu surface or re-dissolution of the Cu oxide layer surface.⁶² On adding the investigated inhibitors to the solution, the diameter of the semi-circle increased and retarded the corrosion of Cu by increasing the polarization resistance, R_p and decreasing the CPE values. Thus, the effectiveness of the investigated compounds was associated with higher values of R_p and low CPE values. This increase became more obvious as the inhibitor concentration increased, suggesting the adsorption of inhibitors on the copper specimen surface.⁶³ Bode diagrams illustrated the same behavior. From the Bode plots, a characteristic with one time constant was observed, corresponding to

Table 7 EIS parameter measurements for copper metal in 1 M HNO₃ with and without different concentrations of additives at 25 °C

| Conc, μ M | | R_s , Ω cm ² | Y° (CPE), $\mu\Omega^{-1}$ s ^{n} cm ⁻² | N | C_{dl} , μ F cm ⁻² | R_{ct} , Ω cm ² | % η_{EIS} | χ^2 |
|---------------|----|----------------------------------|---|--------|-------------------------------------|-------------------------------------|----------------|----------|
| Blank | | 1.839 | 576.2 | 0.983 | 316.2 \pm 0.2333 | 68.2 \pm 0.1453 | — | 0.000087 |
| MA-1230 | 5 | 2.117 | 427.3 | 0.969 | 193.1 \pm 0.1453 | 134.5 \pm 0.1764 | 49.32 | 0.000341 |
| | 9 | 2.238 | 381.6 | 0.985 | 171.4 \pm 0.17634 | 176.1 \pm 0.2028 | 61.29 | 0.000653 |
| | 13 | 2.291 | 332.1 | 0.951 | 127.9 \pm 0.1453 | 245.3 \pm 0.2028 | 72.21 | 0.000453 |
| | 17 | 2.418 | 291.2 | 0.985 | 91.3 \pm 0.1732 | 387.2 \pm 0.2309 | 82.40 | 0.000654 |
| | 21 | 2.782 | 250.9 | 0.871 | 63.2 \pm 0.1732 | 805.7 \pm 0.1732 | 91.54 | 0.000745 |
| MA-1231 | 5 | 1.941 | 418.5 | 0.928 | 188.3 \pm 0.1453 | 139.4 \pm 0.2028 | 51.10 | 0.000065 |
| | 9 | 1.987 | 378.1 | 0.985 | 167.2 \pm 0.2333 | 181.1 \pm 0.1732 | 62.36 | 0.000451 |
| | 13 | 2.169 | 324.6 | 0.963 | 124.6 \pm 0.1453 | 254.3 \pm 0.2028 | 73.20 | 0.000123 |
| | 17 | 2.397 | 285.7 | 0.995 | 87.5 \pm 0.1000 | 412.9 \pm 0.1732 | 83.49 | 0.000231 |
| | 21 | 2.489 | 231.4 | 0.926 | 58.4 \pm 0.1202 | 859.6 \pm 0.1732 | 92.07 | 0.000129 |
| MA-1232 | 5 | 1.147 | 406.2 | 0.964 | 173.9 \pm 0.1732 | 157.9 \pm 0.1453 | 56.83 | 0.000238 |
| | 9 | 1.976 | 371.5 | 0.9931 | 162.5 \pm 0.1732 | 184.1 \pm 0.2028 | 62.98 | 0.000454 |
| | 13 | 2.081 | 319.1 | 0.985 | 119.2 \pm 0.2309 | 267.4 \pm 0.1732 | 74.51 | 0.000462 |
| | 17 | 2.673 | 274.6 | 0.913 | 75.4 \pm 0.2028 | 491.5 \pm 0.1732 | 86.13 | 0.000653 |
| | 21 | 2.927 | 211.9 | 0.895 | 47.1 \pm 0.2028 | 1016.2 \pm 0.1732 | 93.29 | 0.000762 |



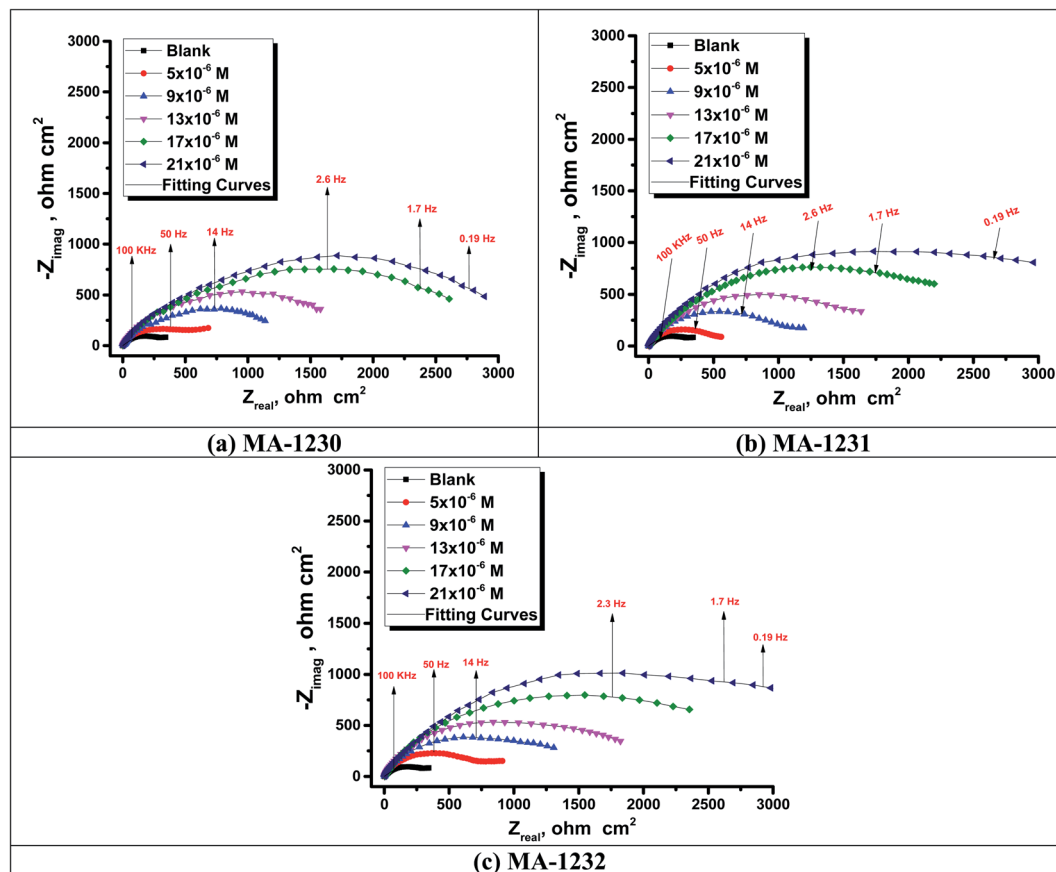


Fig. 7 Nyquist plots for copper metal in 1.0 M HNO_3 without and with different concentrations of (a) MA-1230, (b) MA-1231, and (c) MA-1232 at 25 °C.

the capacitance loop. These results suggest that Cu has better corrosion resistance in the presence of these derivatives. In Table 7, the various impedance parameters, namely, charge transfer resistance (R_{ct}), double layer capacitance (C_{dl}), Y° (CPE), n , goodness of fit χ^2 and % η_{EIS} are cited. The CPE and their n values represent double-layer capacitors with some holes.⁶⁴ The decrease in Y° (CPE) values with increasing concentration of inhibitors resulted from a decrease in the local dielectric constant and/or an increase in the thickness of the double layer, suggested that these inhibitor molecules inhibited the Cu corrosion by adsorption at the Cu/ HNO_3 interface. The increase in the R_{ct} values with increasing inhibitor concentration was always greater as compared to in its absence, which indicates that these additives are adsorbed on the Cu surface, forming a protective layer. This layer performs as a barrier for mass and charge transfer.⁶⁵ The R_{ct} values reached the maximum value at 21 μM for all additives, which indicates the decrease in the corrosion rate. On the other hand, the C_{dl} values decreased on raising the concentration of additives due to the increase in the inhibitor concentration.⁶⁶

The C_{dl} value was obtained from the following equation:⁶⁷

$$C_{dl} = \frac{1}{2\pi f_{max} R_{ct}} \quad (10)$$

The corrosion % η was calculated by using the following equation:

$$\% \eta_{EIS} = \left(\frac{R_{ct} - R_{ct}^*}{R_{ct}} \right)$$

where R_{ct}^* is the charge transfer resistance without the inhibitor, R_{ct} is the charge transfer resistance with the inhibitor. $\eta\%$ increases due to the formation of an adsorbed layer from additives on the copper surface, and this layer increases in thickness by increasing the concentration of the additives.⁶⁸ The EIS research also gave approximately the same efficiency of inhibition as obtained in WL and PDP measurements.

3.4. Surface analysis

3.4.1. Scanning electron microscope (SEM) analysis. The morphology of the copper metal surface was investigated by scanning electron microscopy when the copper samples were immersed in 1 M HNO_3 solution for 24 h with and without the tested inhibitors. Fig. 9a represents the freshly abraded copper sample before immersion, showing a smooth surface, while Fig. 9b shows the image of the Cu sample dipped in HNO_3 for 24 h, where the surface of Cu was corroded due to the aggressive attack of the acid solution. In the presence of pyrimidine inhibitors with a 21 μM concentration, the surfaces of the Cu samples became smoother, as shown in Fig. 9c–e.⁶⁹ The presence of pyrimidine derivatives as



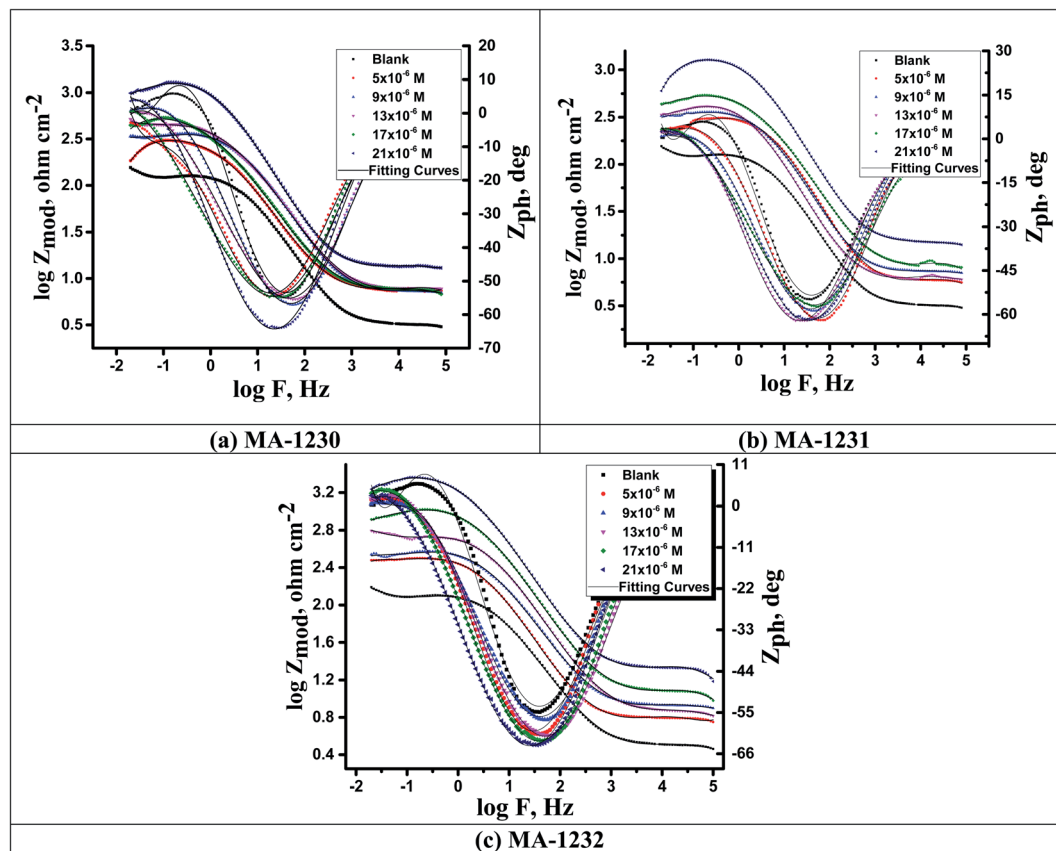


Fig. 8 Bode plots for copper metal in 1 M HNO₃ without and with different concentrations of (a) MA-1230, (b) MA-1231, and (c) MA-1232 at 25 °C.

a corrosion inhibitor in the corrosive medium leads to a relatively cleaner surface. This also implies a greater ability for corrosion inhibition by pyrimidine molecules. The morphology of the copper metal samples was smoother in the following order: MA-1232 > MA-1231 > MA-1230. From the results, one can conclude that a protective film was formed by the used inhibitor molecules on the Cu surface, which led to the significant inhibition of the corrosion of Cu in acid medium.

3.4.2. Energy dispersive X-ray (EDX) analysis. Energy Dispersive X-ray Analysis (EDX) is a technique used to get information on the composition of the corrosion substance on the copper metal surface in the absence and presence of the highest concentration of inhibitor when immersed in a 1 M HNO₃ solution. Fig. 10a shows that the polished surface of the copper metal has a large copper peak and shows great surface properties, whereas after immersing in 1 M HNO₃ without the inhibitors (Fig. 10b), there was great damage to the copper sample due to the strong corrosion; the iron peak strength was increased in the presence of the inhibitor, which indicates the coverage of the copper surface with the inhibitor molecules, as shown in Fig. 10c–e.⁷⁰ By adding 21×10^{-6} M of inhibitors, the enhancement of the copper metal surface was observed due to the strong protective film of the inhibitor molecules on the surface of the copper sample; a decrease in the iron band was observed, as indicated in Fig. 10c–e. The protective layer

produced by inhibitor molecules was strongly surface adherent, which leads to evidence of efficient inhibition performance.⁷¹

3.5. Quantum calculations

The gap in the energy band ($\Delta E = E_{\text{LUMO}} - E_{\text{HOMO}}$), which is the energy required to eliminate an electron from the last orbital occupied, may influence the efficiency of inhibition and small absolute energy band gap values would have strong inhibition efficiencies.⁷² The dipole moment (μ) is a measure of the polarity of the covalent bond between the compounds studied. It is accepted that high μ values improve the adsorption tendency on the metal surfaces of the compounds tested. The order of ΔE values in theoretical calculations of band gap energy is as follows: MA-1230 > MA-1231 > MA-1232. The decreasing inhibition efficiency order showed a good correlation with corrosion efficiency. All results in Fig. 11 and Table 8 illustrate the lowest total energy in the inhibitor MA-1232 (1,3-diethyl-2-thiobarbituric acid-bithiophene scaffold), which means that the adsorption of the inhibitor MA-1232 is highest, with the highest softness. The global hardness (η), softness (σ), and chemical potential (μ) were calculated in terms of I_p and E_A ⁷³ from the following equations:

$$\mu = -\chi = -\frac{I_p + E_A}{2} \quad (11)$$



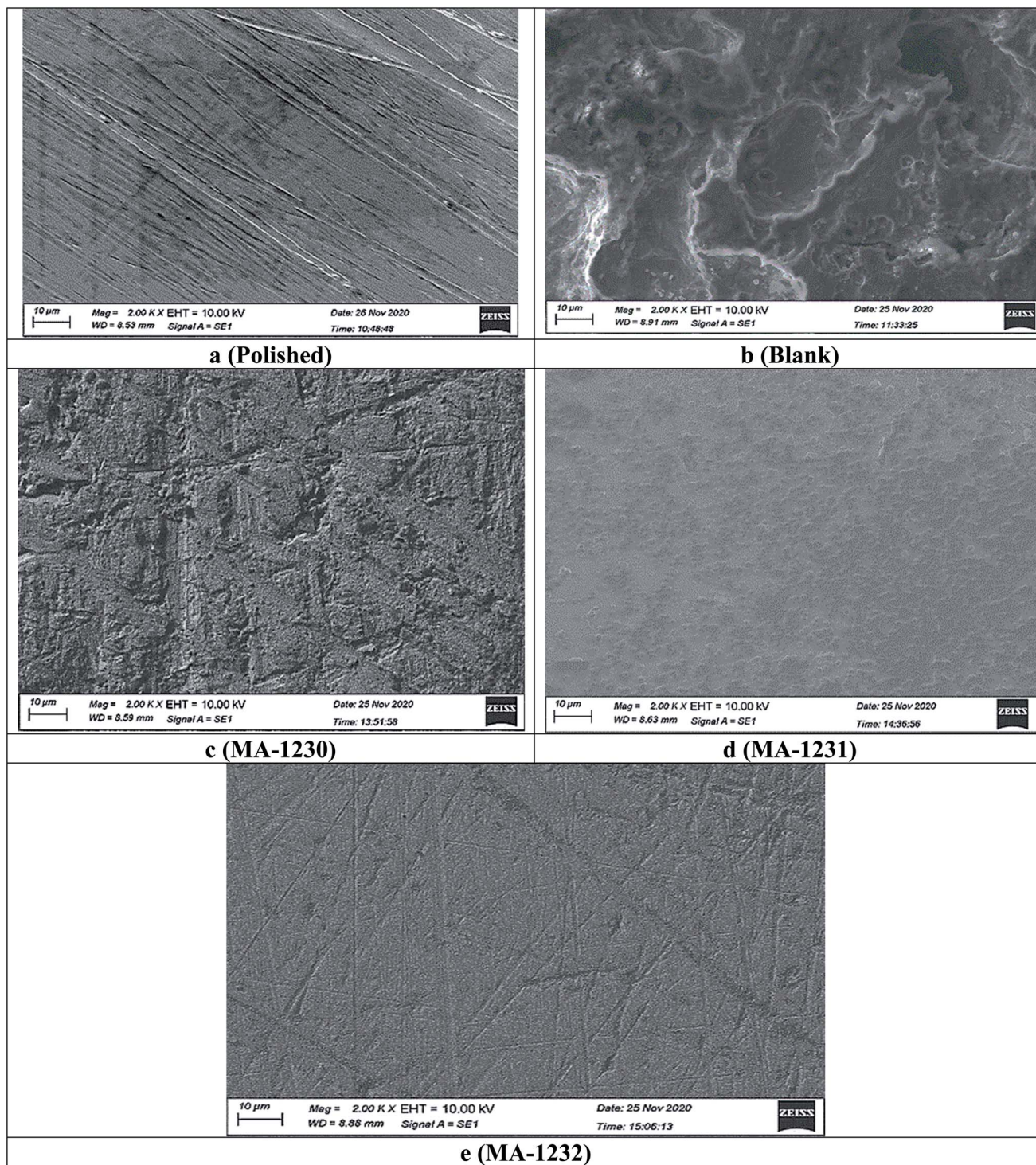


Fig. 9 SEM micrographs of copper metal without (blank) and with 21 μM of the tested derivatives (a–e).

$$\chi = \frac{I_p + E_A}{2} \quad (12)$$

$$\eta = \frac{I_p - E_A}{2} \quad (13)$$

$$\sigma = \frac{1}{\eta} \quad (14)$$

The above results reveal that the heteroatoms (N, O, and S) in inhibitor molecule structures have a great influence on the quantum chemical parameters. This theoretically demonstrates that the heteroatom (S) could cause effects on the adsorption of the inhibitor molecules on the metal. We performed further molecular dynamics calculations on the adsorption of the inhibitors on the copper surface as outlined in the following.



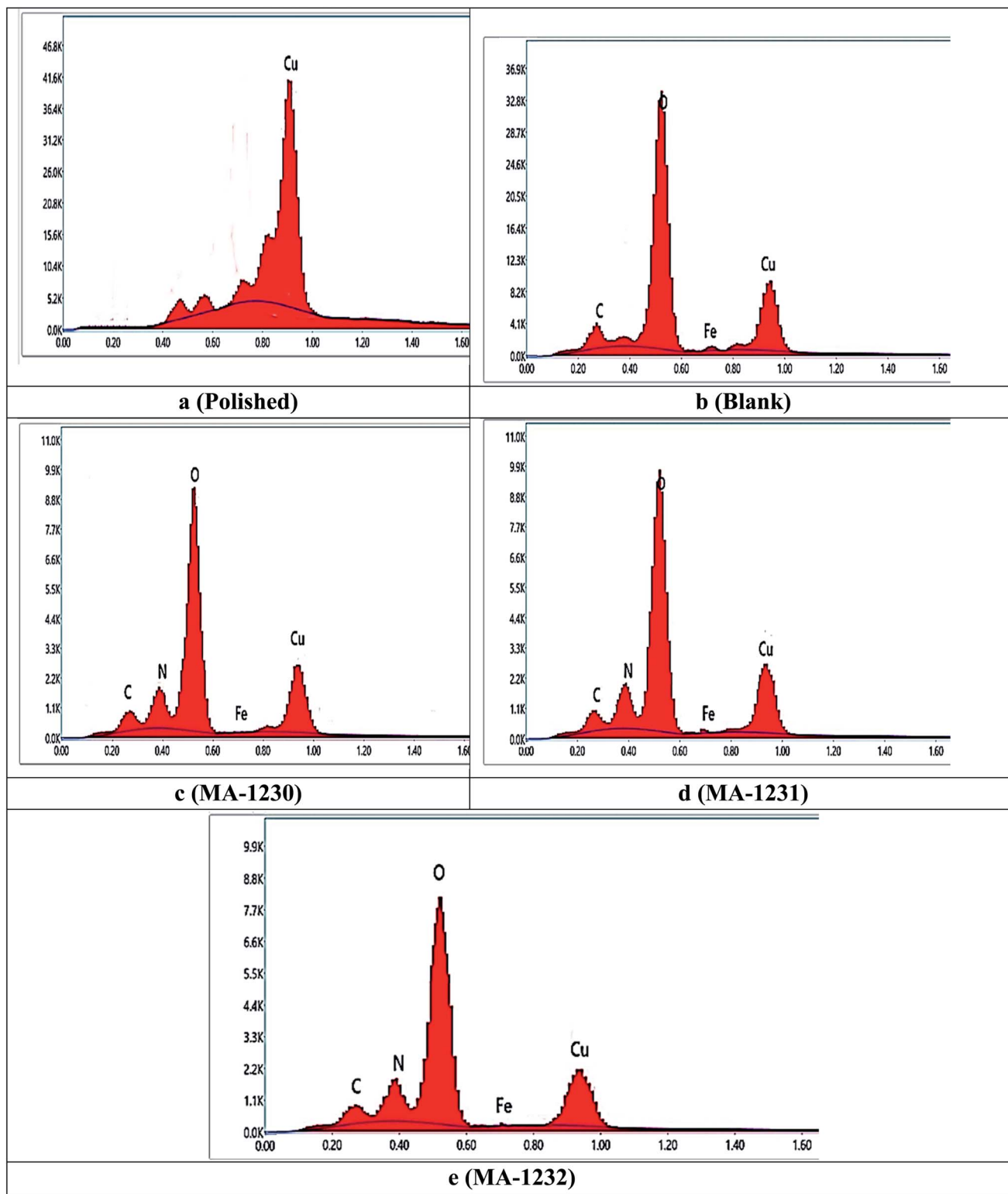


Fig. 10 EDX micrographs of copper metal without (blank) and with 21×10^{-6} M of the investigated derivatives (a–e).

3.6. Monte Carlo (MC) simulation

MC simulation is a perfect simulation tool for finding the most stable adsorption conformations in 1 M HNO_3 of the substituted pyrimidine-bichalcophene derivatives. The results of the simulations of the investigated derivatives are shown in

Fig. 12 and are listed in Table 9. Fig. 12 shows the most favorable configuration of the adsorbed molecules on the metal surface of Cu (110). The molecules mentioned are adsorbed on the surface of the metal from the motive, which is rich in electrons from these inhibitory molecules. The established

interactions between the occupied orbitals of the investigated derivatives and the unoccupied orbitals of Cu (110) are expressed by the values of adsorption energy (E_{ads}), rigid energy (E_{rigid}), deformation energy (E_{def}), and energy ratios ($dE_{\text{ads}}/E_{\text{Ni}}$) of the inhibitors; these values are collected in Table 9. The results indicate that these inhibitory structures behave as active voltages. Adsorption energy is characterized as declining energy when two materials are mixed during the adsorption process in which an electron, ion, or molecule (adsorbent) is bound to the solid surface.⁷⁴ As seen in Table 8, the order of higher energy of relative adsorption is MA-1232 > MA-1231 > MA-1230, which predicts the heavy adsorption of MA-1232 (1,3-diethyl-2-thiobarbituric acid-bithiophene scaffold) on the hardened copper surface creating a stable adsorbed layer that protects the copper from dissolution. These derivatives protect the Cu studied in HCl medium from corrosion. This is in keeping with experimental studies.

4. Mechanism of corrosion hindrance

Adsorption can be demonstrated by physicochemical characteristics (e.g. types of electron density, functional groups) and the Cu charge, based on experimental studies and theoretical calculations. Fig. 13 shows the possible inhibition mechanism of these pyrimidine derivatives on the surface of Cu. Several

studies have indicated that the Cu surface in HNO₃ solution is positively charged, i.e., on the Cu surface, there are several positive charges.⁷⁵ The positively charged Cu surface prefers NO³⁻ adsorption to create a negatively charged surface, which makes it easier to adsorb the cations in the solution. These organic pyrimidine-bichalcophenes can be protonated in the solution because of the unshared electron pairs of the N, O and S electrons. Electrostatic interactions lead to the adsorption of protonated molecules on the specimen surface, i.e.,

Table 8 Quantum chemical parameters for the studied organic inhibitors

| Compound | MA-1230 | MA-1231 | MA-1232 |
|------------------------|---------|---------|---------|
| E_{HOMO} , eV | −10.1 | −9.28 | −8.97 |
| E_{LUMO} , eV | −1.62 | −1.71 | −1.96 |
| ΔE , eV | 8.48 | 7.57 | 7.01 |
| I_{p} , eV | 10.1 | 9.28 | 8.97 |
| E_{A} , eV | 1.62 | 1.71 | 1.96 |
| η , eV | 4.240 | 3.785 | 3.505 |
| σ , eV | 0.236 | 0.264 | 0.285 |
| μ , eV | 5.860 | 5.495 | 5.465 |
| Dipole moment (debye) | 2.790 | 3.170 | 4.300 |

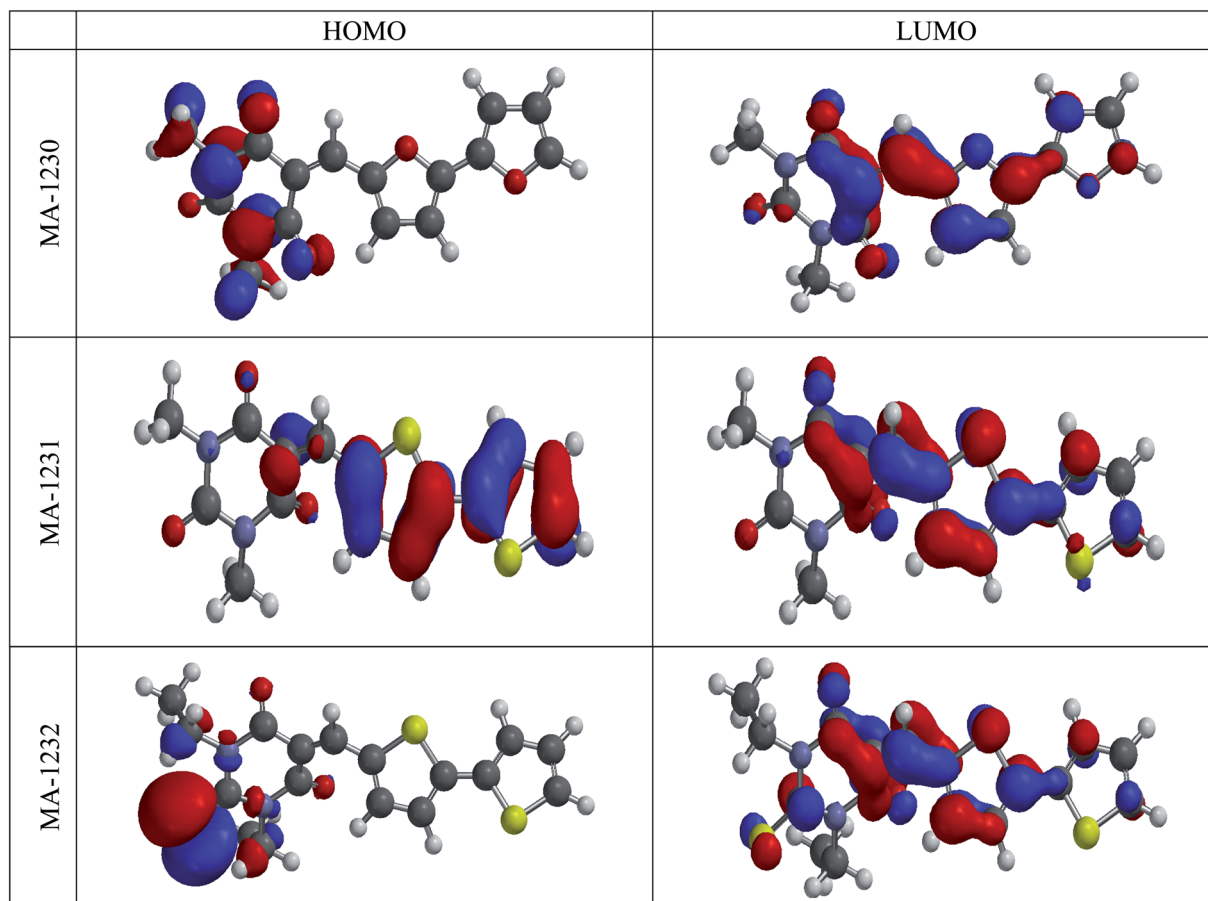


Fig. 11 The frontier molecular orbital provides the electron density maps of HOMO and LUMO for the tested inhibitors.



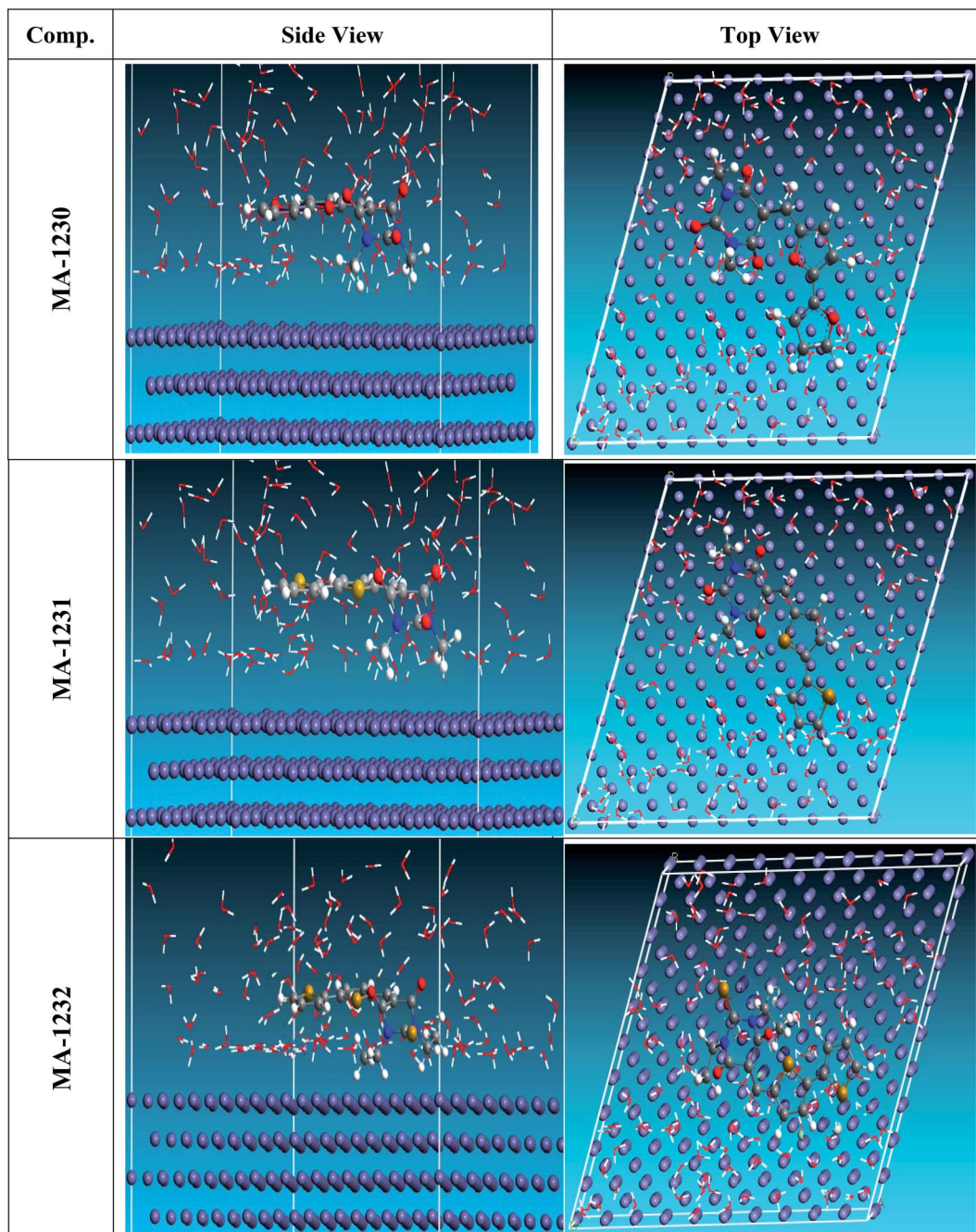


Fig. 12 The most suitable configuration for the adsorption of the organic molecules on the Cu (1 0 0) substrate obtained by the adsorption locator module.

physisorption. Meanwhile, by forming covalent bonds (chemisorption), further adsorption of these inhibitor molecules could be realized, as shown in Fig. 13. Quantum chemical

measurements of both WL and electrochemical values indicated the % IE of the three investigated pyrimidine-bichalcophene derivatives as follows: MA-1232 > MA-1231 >

Table 9 Data and descriptors calculated by the Monte Carlo simulation for the adsorption of compound molecules on copper (1 0 0)

| Structures | Total energy | Adsorption energy | Rigid adsorption energy | Deformation energy | Compound dE_{ad}/dNi | H ₂ O dE_{ad}/dNi |
|-------------------------------------|--------------|-------------------|-------------------------|--------------------|------------------------|--------------------------------|
| Cu (1 0 0)/MA-1232/H ₂ O | −3211.16 | −4108.929 | −4039.791 | −69.138 | −263.097 | −12.522 |
| Cu (1 0 0)/MA-1231/H ₂ O | −3205.42 | −4103.314 | −4034.503 | −68.811 | −278.272 | −8.06 |
| Cu (1 0 0)/MA-1230/H ₂ O | −3198.75 | 4099.094 | −4029.213 | 69.881 | −288.447 | −6.926 |



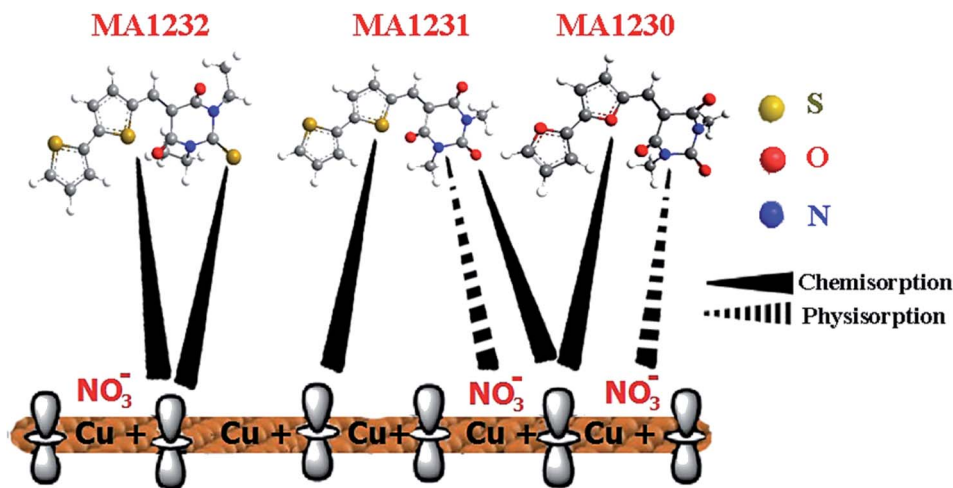


Fig. 13 A schematic diagram of the corrosion protection of Cu dipped in 1 M HNO_3 corrosion medium with pyrimidine derivatives (MA-1232, MA-1231, and MA-1230).

MA-1230. MA-1232 is the most efficient inhibitor because it contains 3 S, 2 N and 2 O atoms, 2 ethyl groups as substituents and has the highest molecular size, which covers more surface area; however, MA-1231 contains 2 S, 2 N, 2 O atoms, 2 methyl groups as substituents and has a smaller molecular size than MA-1232 (ethyl groups are more efficient than methyl groups). MA-1230 is the least efficient at inhibition due to its containing 2 N and 5 O atoms ($\text{S} > \text{N} > \text{O}$ in basicity) and it has the smallest molecular size.

5. Conclusions

Pyrimidine-bichalcophene derivatives (MA-1232, MA-1231, and MA-1230) were studied as inhibitors in 1 M HNO_3 for Cu corrosion. The data gained from chemical tests (WL) and electrochemical (PDP, and EIS) procedures revealed that the protection was dependent on the dose of the pyrimidine-bichalcophenes and the temperature. The investigated pyrimidine-bichalcophenes predominantly acted as mixed inhibitors on the copper in 1 M HNO_3 and the adsorption was described by the Langmuir adsorption isotherm. C_{dl} diminished while R_{ct} increased with increasing the doses of the tested inhibitors, which can be attributed to the adsorbed inhibitor molecules. Pyrimidine-bichalcophene molecules established a protective layer over the copper surface. There was strong agreement between the chemical and electrochemical techniques. A comparative study of pyrimidine-bichalcophene derivatives (MA-1232, MA-1231, and MA-1230) using quantum chemical study confirmed the experimental results. The results obtained by MC simulation showed that the binding performance between the products used and the metal surface of Cu (110) was in the following order: E_{binding} MA-1232 $>$ E_{binding} MA-1231 $>$ E_{binding} MA-1230.

Conflicts of interest

The authors declare that there is no conflict of interest between them and anybody else.

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