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Cationic Surfactants as Efficient Corrosion Inhibitors for C-Steel in Oil and Gas Production: Synthesis, Performance Evaluation and Chemical Cleaning

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Abstract

The development of efficient and structurally tunable corrosion inhibitors is essential for mitigating the aggressive action of acidic environments on C- steel. In this study, two quaternary ammonium cationic surfactants, CS-PA (*N,N*-dimethyl-*N*-(2-oxo-2-((1*E*,2*E*)-3-phenylallylidene)amino)ethoxy)ethyl)dodecan-1-aminium chloride) and CS-MB ((*E*)-*N*-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-*N,N*-dimethyldodecan-1-aminium chlorides), bearing Schiff-base moieties, were synthesized and structurally characterized, and their ability to protect C-steel in 1 M HCl was systematically investigated. Their interfacial activity was first examined through surface tension measurements, followed by an integrated evaluation of their corrosion-inhibition behavior using weight-loss, potentiodynamic polarization (PDP), and electrochemical impedance spectroscopy (EIS) measurements. Both compounds provided substantial protection against acid-induced corrosion, with the inhibition efficiency strongly dependent on inhibitor concentration and temperature. At 1×10^{-3} M and 25 °C, CS-PA and CS-MB afforded inhibition efficiencies of 91.8% and 93.1%, respectively, indicating a particularly high protective capability for the methoxy-functionalized CS-MB molecule. Electrochemical measurements confirmed the development of an adsorbed protective layer that markedly restricted the electrochemical reactions responsible for metal dissolution. Complementary AFM

observations revealed a significant reduction in surface damage and roughness in the presence of the investigated surfactants, providing morphological evidence for their protective action. The decrease in inhibition efficiency at elevated temperature further supports the importance of adsorption in establishing the inhibitor film at the steel/acid interface. The combined experimental and theoretical findings demonstrate that molecular structure, surface activity, and interfacial adsorption collectively govern the corrosion-inhibition performance of these quaternary ammonium surfactants. The results identify CS-MB as a particularly promising candidate for the protection of C-steel under strongly acidic conditions.

Keywords: Cationic surfactants; Corrosion inhibition; C-steel; Tafel; EIS; AFM; Adsorption; Chemical cleaning.

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1. Introduction

Acid pickling or acid cleaning is a metal cleaning process, that is considered one of the most prevalent options in large scale industrial processes for treating steel surfaces, as it's used to remove unwanted surface layers such as rust and scale, formed during industrial operations [1-4].

The most commonly used corrosion inhibitors for protecting metals from corrosion in acidic media are organic compounds (cationic quaternary ammonium compounds or cationic surfactants) containing heterogeneous atoms such as (N, O, S, P and Cl) [5-10] and multiple bonds (as in aromatic benzene ring), all of the previously mentioned represent the sites of electronic dense adsorption which strongly stimulates the

inhibitor's adsorption onto steel surface [11-39]. Adsorption results in the formation of a protective layer on the carbon steel surface, shielding it from aggressive media such as acidic liquids [36-38, 40].

Schiff base-based cationic surfactants containing aliphatic alkyl chains, quaternary N-atoms, and azomethine group (C=N) can be efficiently adsorbed onto metal surfaces [36]. Cationic surfactants, which have good adsorption capabilities, have a number of notable benefits in the area of corrosion prevention that distinguish them from other types. These surfactants, which carry positive charges (such as the positive charge on N-atoms in the molecular structure of quaternary ammonium cationic surfactants), strongly bind to the negative charges on the metal substrate and can quickly and stably adsorb onto metal surfaces through their strong electrostatic attraction to form a stable protective/shielding layer. Due to their excellent adsorption and stability, cationic surfactants provide better protection for metal surfaces [41, 42].

Therefore, the use of corrosion inhibitors is a crucial issue to preserve C-steel equipment and metals from corrosion and to extend their usable life, as well as to decrease the percentage of significant losses caused by corrosion.

The synthesized compounds, N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl)dodecan-1-aminium chloride and (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride, constitute a new class of multifunctional corrosion inhibitors that markedly outperform conventional systems for C-steel in 1 M HCl. Their superior performance originates from a deliberately engineered molecular architecture that unifies a conjugated Schiff base fragment, a quaternary ammonium center, and a long hydrophobic alkyl chain within a single framework, thereby enabling highly efficient and cooperative adsorption at the metal/solution interface.

In contrast to traditional quaternary ammonium inhibitors that rely predominantly on electrostatic interactions, these compounds operate through a synergistic dual adsorption mechanism. The extended π -conjugated system associated with the (1*E*,2*E*)-phenylallylidene moiety promotes strong donor–acceptor interactions with the vacant d-orbitals of iron, while the cationic ammonium head ensures robust electrostatic attraction to the negatively charged steel surface under acidic conditions. This cooperative interaction significantly enhances adsorption strength and stability. Moreover, the pronounced amphiphilic character, arising from the combination of a hydrophilic charged head and a hydrophobic dodecyl chain, drives spontaneous interfacial organization, leading to the formation of a compact, highly adherent protective film that effectively blocks active sites and suppresses chloride ion penetration. The incorporation of ester and ether linkages further provides conformational adaptability, facilitating optimal molecular packing and maximizing surface coverage. Collectively, this integrated structural design establishes a clear advancement over existing inhibitor systems, offering enhanced adsorption efficiency, improved film integrity, and superior corrosion protection performance in aggressive acidic environments. The aim of this work was to synthesize surfactants and evaluate their surface properties, as well as assessing their corrosion-inhibition performance using both chemical and electrochemical techniques, including weight loss (WL), EIS for charge-transfer resistance, and Tafel plot methods. Comprehensive analysis was also conducted using surface characterization, theoretical calculations, and AFM imaging.

2. Materials and experimental methods

2.1. Synthesis of the two new surfactants [CS-PA & CS-MB]

The Purity, Suppliers and Specifications have been included in the **supplementary materials** (Table 1).

2.1.1. Synthesis of CS-PA

CS-PA was synthesized in 3 steps, which are described in **Scheme 1**, and further below:

1. Condensation reaction: in the first step, (0.05 mol, 3.054 g) 2-aminoethanol was mixed with (0.05 mol, 6.608 g) cinnamaldehyde in 50 ml solvent “absolute ethanol”. The mixture was refluxed for 2.5 h at 80 °C, after which the solvent was evaporated to obtain the Schiff base, named: 2-(((1*E*,2*E*)-3-phenylallylidene)amino)ethan-1-ol.
2. Esterification reaction: in the second step, the first-step product (0.05 mol, 8.761 g) Schiff base, named: 2-(((1*E*,2*E*)-3-phenylallylidene)amino)ethan-1-ol was added to (0.05 mol, 4.724 g) chloroacetic acid in 50 ml of solvent “xylene”. Then the mixture was heated under reflux for 16 hours at 150 °C, then ester was obtained by evaporating xylene from the product, this ester is named: 2-(((1*E*,2*E*)-3-phenylallylidene)amino)ethyl-2-chloroacetate.
3. Quaternization reaction: in the third step, the second-step product (0.05 mol, 12.585 g) ester, named: 2-(((1*E*,2*E*)-3-phenylallylidene)amino)ethyl-2-chloroacetate was added to (0.05 mol, 10.670 g) N,N-dimethyldodecan-1-amine in 50 ml absolute ethanol “solvent”, and the mixture of these substances was then refluxed at 80 °C, the solvent is then evaporated by heating to obtain the desired final product, which is quaternary ammonium cationic surfactant [CS-PA], and

named: N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride.

2.1.2. Synthesis of CS-MB

The CS-MB was prepared in three steps, as depicted in **Scheme 2**, as described below:

1. Condensation reaction: in the first step, (0.05 mol, 3.054 g) 2-aminoethanol was added to (0.05 mol, 6.807 g) 4-methoxybenzaldehyde in 50 ml absolute ethanol solvent. The mixture was heated under reflux for 2.5 hours at 80 °C, then absolute ethanol was vaporized from the product to give Schiff base, named: (*E*)-2-((4-methoxybenzylidene)amino)ethan-1-ol.
2. Esterification reaction: in the second step, the first-step product (0.05 mol, 8.961 g) Schiff base, named: (*E*)-2-((4-methoxybenzylidene)amino)ethan-1-ol was added to (0.05 mol, 4.724 g) chloroacetic acid in amount of xylene solvent equal to 50 ml, then this combination of compounds was refluxed at 150 °C for 16 h, then xylene was separated from the product by heating and evaporating it to give an ester, named: (*E*)-2-((4-methoxybenzylidene)amino)ethyl-2-chloroacetate.
3. Quaternization reaction: in the third step, the second-step product (0.05 mol, 12.785 g) ester, named: (*E*)-2-((4-methoxybenzylidene)amino)ethyl-2-chloroacetate was added to (0.05 mol, 10.670 g) N,N-dimethyldodecan-1-amine in 50 ml of the solvent "absolute ethanol". The resulting mixture was refluxed at 80 °C for 32 h. After completion of the reaction, the solvent was removed by evaporation to afford the quaternary ammonium cationic surfactant [CS-MB], named: (*E*)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride.

Several spectroscopic applications, such as FT-IR, Mass and ^1H -NMR, were used to confirm and validate the chemical structure of the prepared quaternary ammonium cationic surfactants [CS-PA & CS-MB].

2.2. Solutions

Analytical grade 37% HCl was diluted with distilled water to provide the corrosive environment (1M HCl) employed in this work. Corrosion measurements were conducted using surfactant concentrations starting from 5×10^{-5} to 1×10^{-3} M.

2.3. Specimens

Composition of C-steel (wt.%) is: 0.19% of C & 0.009% of P & 0.004% of S & 0.016% of V & 0.05% of Si & 0.94% of Mn & 0.014% of Ni & 0.009% of Cr & 0.034% of Al & 0.003% of Ti & 0.022% of Cu & the rest is iron. Tests were performed on it.

2.4. Weight loss measurements

A series of sandpaper sheets (grades 320-400-600-800-1000-1200) was used to polish the 3 cm x 6 cm x 0.5 cm C-steel sheets. After polishing, the specimens were cleaned with distilled water and acetone. The materials were carefully weighed before being immersed in 150 milliliters of 1M HCl with and without various concentrations of synthesized surfactants. After a day (24 h), the C-steel specimens were removed. Following two rounds of distilled water rinsing, acetone degreasing, drying, and precise weighting, they were examined. To increase the accuracy of the results, the experiments were repeated three times and the average was calculated. Three C-steel sheets in parallel were weighed and their average weight loss was determined. At each investigated temperature, the immersion period for the weight loss measurements was 24 hours.

2.5. Surface tension measurements

A Du Nouy Tensiometer (Kruss 6) was used to measure surface tension at different doses of corrosion inhibitor (surfactant). Each solution concentration was made at 298 K in bi-distilled H₂O with a surface tension of 72 mN m⁻¹.

2.6. Electrochemical Measurements

Using a Potentiostat/Galvanostat PGZ 301 operated by Voltalab 40, EIS & PP methods were chosen to track the electrochemical activity of C-steel alloy in 1M HCl. After 30 minutes of immersion in the tested solution, the PP and EIS tests for C-steel were conducted at room temperature and under static conditions. At open circuit potential, the working electrode's exposed surface area was subjected to a small alternating voltage perturbation (10 mV) at a frequency that ranged from 100 kHz to 30 mHz. Following that, the electrode potential was polarized in the cathodic direction to -900 mV and in the anodic direction to -200 mV at a scan rate equal 0.2 mV per second. The reference electrode for the measured potential values is the Saturated Calomel Electrode (SCE).

2.7. Surface tests (AFM)

In the morphological analyses of C-steel surfaces immersed for twenty-four hours in 1M HCl in presence and absence of the prepared surfactants with a concentration equal to 1×10^{-3} M at 25 °C, three-dimensional images are obtained using an effective instrument, namely atomic force microscopy (AFM, MFP, Asylum Research).

3. Results and Discussion

3.1. Confirmation of the chemical structure of the synthesized surfactants by FT-IR, mass and ¹H-NMR spectroscopy.

3.1.1. FT-IR Spectroscopy

3.1.1.1. FT-IR spectrum of Schiff bases of CS-PA & CS-MB

The Schiff bases of two synthesized surfactants exhibited a strong and broad band at (3377–3379 cm^{-1}) for hydroxyl group $\nu(\text{O-H})$ stretching vibration in the FT-IR spectra of them. A strong band was observed for the Schiff bases of synthesized surfactants at (1636–1644 cm^{-1}) characteristic of the azomethine (C=N) stretching vibrations. The aromatic (C=C) stretching exhibited two absorption bands around 1450 and 1550 cm^{-1} in the FT-IR spectra of Schiff bases of the synthesized surfactants, aromatic (C-H) stretching exhibited an absorption band after 3000 cm^{-1} in the FT-IR spectra of Schiff bases of synthesized surfactants, and aromatic (C-H) bending exhibited two absorption bands at 698 and 753 cm^{-1} in FT-IR spectra of Schiff bases of CS-PA in (**Supplementary materials, Fig. 1**) but it exhibited one absorption band at 833 cm^{-1} in FT-IR spectra of Schiff bases of CS-MB in (**Supplementary materials, Fig. 2**). Aliphatic (C-H) stretching exhibited an absorption band before 3000 cm^{-1} in the FT-IR spectra of Schiff bases of synthesized surfactants. The FT-IR spectra confirmed the presence of the expected functional groups in the synthesized Schiff bases of the two cationic surfactants.

3.1.1.2. FT-IR spectrum of esters of CS-PA & CS-MB

The esters of the two synthesized surfactants exhibited a strong as well as broad band at (3360–3382 cm^{-1}) for hydrated (O-H) stretching vibration due to these esters are hygroscopic compounds. A strong band was observed for the esters of synthesized surfactants at (1641–1668 cm^{-1}) characteristic of the azomethine (C=N) stretching vibrations. The aromatic (C=C) stretching exhibited two absorption bands around 1450 and 1550 cm^{-1} in the FT-IR spectra of esters of synthesized surfactants, aromatic (C-H) stretching exhibited an absorption band after 3000 cm^{-1} in the FT-IR spectra of esters of synthesized surfactants, and aromatic (C-H) bending exhibited two absorption bands around 701 and 759 cm^{-1} in FT-IR spectra of esters of CS-PA in

(**Supplementary materials, Fig. 3**) but it exhibited one absorption band at 835 cm^{-1} in FT-IR spectra of esters of CS-MB in (**Supplementary materials, Fig. 4**). Aliphatic (C–H) stretching exhibited an absorption band before 3000 cm^{-1} in the FT-IR spectra of esters of synthesized surfactants. It is worth to mention that, the region of $\nu_{\text{asym}}(\text{COO}^-)$ overlapped with $\nu(\text{C}=\text{N})$. The FT-IR spectrum confirmed the expected functional groups in the synthesized esters of the two cationic surfactants.

3.1.1.3. FT-IR spectrum of CS-PA & CS-MB

The FT-IR spectrum of CS-PA, named: N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl)dodecan-1-aminium chloride is depicted in **Fig. 1,a**. The alkyl group exhibited characteristic bands at 2921 and 2853 cm^{-1} for each of asymmetric and symmetric stretching aliphatic (C–H). While, the band of symmetric bending (CH_3) appeared at 1348 cm^{-1} , the band of asymmetric bending (CH_2) appeared at 1465 cm^{-1} , and the band of $-(\text{CH}_2)_n-$ rock appeared at 760 cm^{-1} . The aromatic (C=C) stretching appeared as two absorption bands at 1465 and 1542 cm^{-1} , aromatic (C–H) stretching exhibited an absorption band at 3057 cm^{-1} , and aromatic (C–H) bending exhibited two absorption bands at 702 and 760 cm^{-1} . Imine or azomethine (C=N) stretching exhibited an absorption band at 1645 cm^{-1} . This inhibitor exhibits a strong as well as broad band at 3384 cm^{-1} for hydrated (O–H) stretching vibration due to this inhibitor is a hygroscopic compound. It is worth to mention that, the region of $\nu_{\text{asym}}(\text{COO}^-)$ overlapped with $\nu(\text{C}=\text{N})$. The FT-IR spectrum verified the expected functional groups in CS-PA.

The FT-IR spectrum of CS-MB, named: (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyldodecan-1-aminium chloride is shown in **Fig. 1,b**. It shows the significant bands for alkyl part appeared at 2925 and 2854 cm^{-1} for both asymmetric and symmetric stretching aliphatic (C–H).

However, band of symmetric bending (CH_3) observed at 1381 cm^{-1} , band of asymmetric bending (CH_2) observed at 1460 cm^{-1} , and band of $-(\text{CH}_2)_n-$ rock appeared at 756 cm^{-1} . Two absorption bands observed at 1460 and 1513 cm^{-1} for aromatic ($\text{C}=\text{C}$) stretching, an absorption band exhibited at 3060 cm^{-1} for aromatic ($\text{C}-\text{H}$) stretching, and an absorption band appeared at 835 cm^{-1} for aromatic ($\text{C}-\text{H}$) bending. The azomethine or imine ($\text{C}=\text{N}$) stretching exhibited an absorption band at 1646 cm^{-1} . This inhibitor exhibits a strong as well as broad band at 3394 cm^{-1} for hydrated ($\text{O}-\text{H}$) stretching vibration due to this inhibitor is a hygroscopic compound. It is worth to mention that, the region of $\nu_{\text{asym}}(\text{COO}^-)$ overlapped with $\nu(\text{C}=\text{N})$. The FT-IR spectrum confirmed the expected functional groups in CS-MB.

3.1.2. ^1H -NMR spectroscopy of CS-PA & CS-MB

The ^1H -NMR spectrum of CS-PA (**Fig. 2,a**) was carefully re-evaluated, and the observed signals were consistent with the proposed structure.

The aromatic protons appeared as a multiplet in the region $\delta \approx 6.90\text{-}7.70\text{ ppm}$, corresponding to a substituted benzene ring. A broad and intense signal envelope was observed in the region $\delta \approx 3.0\text{-}4.2\text{ ppm}$, which is attributed to overlapping contributions from $\text{N}(\text{CH}_3)_2$, methylene protons adjacent to the quaternary ammonium center ($-\text{CH}_2-\text{N}^+$), and $-\text{CH}_2-\text{O}$ groups. The $\text{N}(\text{CH}_3)_2$ signal is centered around $\delta \approx 3.0\text{ ppm}$; however, it does not appear as a well-resolved singlet due to strong overlap with neighboring signals and broadening effects associated with the ionic nature of the molecule. The aliphatic chain was clearly evidenced by a terminal methyl triplet at $\delta \approx 0.85\text{ ppm}$ and methylene signals in the region $\delta \approx 1.20\text{-}1.60\text{ ppm}$. The observed peak broadening and overlap are attributed to intermolecular interactions and aggregation behavior, which are commonly reported for quaternary ammonium surfactants in solution. Such peak overlap and broadening are commonly observed in long-chain

quaternary ammonium surfactants due to restricted molecular mobility and aggregation behavior in solution.

Overall, despite partial overlap in the crowded 3.0-4.0 ppm region, the spectral features are fully consistent with the proposed structure.

The ^1H -NMR spectrum of CS-MB (**Fig. 2,b**) was carefully analyzed and showed good agreement with the proposed structure.

The aromatic protons appeared as a multiplet in the region $\delta \approx 6.90$ -7.60 ppm, consistent with a para-substituted benzene ring. A characteristic singlet corresponding to the methoxy group ($-\text{OCH}_3$) was observed at $\delta \approx 3.75$ -3.85 ppm, confirming the presence of the para-methoxy substituent. The region between $\delta \approx 3.0$ -4.2 ppm exhibited a broad and intense signal envelope due to overlapping contributions from $\text{N}(\text{CH}_3)_2$, methylene protons adjacent to the quaternary ammonium center ($-\text{CH}_2-\text{N}^+$), and $-\text{CH}_2-\text{O}$ groups. The $\text{N}(\text{CH}_3)_2$ signal was centered around $\delta \approx 3.0$ ppm but appeared broadened and partially overlapped rather than as a sharp singlet. The aliphatic chain is clearly evidenced by a terminal methyl triplet at $\delta \approx 0.85$ ppm and a series of methylene signals in the region $\delta \approx 1.20$ -1.60 ppm.

The observed peak broadening and overlap in the 3.0-4.0 ppm region may be attributed to the ionic nature of the compound and possible intermolecular interactions or aggregation behavior in solution, which are commonly reported for quaternary ammonium surfactants.

Overall, despite partial overlap in the crowded 3.0–4.0 ppm region, the spectral features were consistent with the proposed structure.

3.1.3. Mass spectroscopy of CS-PA & CS-MB

The mass spectrum of CS-PA is indicated in **Fig. 3**. It showed a molecular "parent" ion peak at m/z 465.12 (14.91%) with a base peak at m/z 248.5 (100.00%)

$C_{14}H_{31}NCl$. Other characteristic fragment peaks were observed at m/z 57 (23.02%) C_4H_9 , 116 (19.87%) C_9H_8 , 158 (22.49%) $C_{11}H_{12}N$, 169 (42.78%) $C_{12}H_{25}$, 213 (78.39%) $C_{14}H_{31}N$, 262.5 (44.51%) $C_{15}H_{33}NCl$, 337.5 (20.01%) $C_{18}H_{26}N_2O_2Cl$, 365.5 (17.03%) $C_{20}H_{30}N_2O_2Cl$, 393.5 (5.02%) $C_{22}H_{34}N_2O_2Cl$, and 421.5 (2.66%) $C_{24}H_{38}N_2O_2Cl$. The mass spectrum data supported the proposed chemical structure of CS-PA.

The mass spectrum of CS-MB is exhibited in **Fig. 4**. It showed a parent "molecular" ion peak at m/z 469.11 (19.39%) and a base peak at m/z 57 (100.00%) C_4H_9 . The other significant peaks of fragmentation appeared at m/z 104 (7.11%) C_7H_6N , 120 (52.05%) C_8H_8O , 134 (91.71%) C_8H_8NO , 162 (69.41%) $C_{10}H_{12}NO$, 213 (79.02%) $C_{14}H_{31}N$, 264 (39.67%) $C_{14}H_{20}N_2O_3$, 299.5 (8.64%) $C_{14}H_{20}N_2O_3Cl$, 306.5 (2.54%) $C_{16}H_{33}NO_2Cl$, and 361.5 (1.98%) $C_{19}H_{38}N_2O_2Cl$. The mass spectrum data confirmed the chemical structure of CS-MB.

3.2. Surface tension

Table 1 represents the surface tension (γ) data of aqueous solutions of the two synthetic surfactants, namely CS-PA and CS-MB, measured over a wide concentration range at 25 °C. The variation in surface tension (γ) with logarithm of surfactant concentration ($\log C$) was graphically represented. Subsequently, Equations (1–3) were employed to evaluate some parameters, including: the maximum surface excess concentration (Γ_{max}), the surface pressure (effectiveness) (π_{cmc}) and the minimum surface area (A_{min}) [43-47].

Surface tension (γ) gradually decreased with increasing of CS-PA and CS-MB concentration ($-\log C$) until the critical micelle concentration (C_{cmc}), after which stability occurs as seen in **Fig. 5**. The surface tension measurements provided information on the following parameters: π_{cmc} , A_{min} , and Γ_{max} of CS-PA and CS-MB.

C_{cmc} was determined from the intersection points of $\gamma - \log C$ curve as shown in **Table 1**. When comparing the C_{cmc} values of CS-PA and CS-MB, It was observed that increasing the hydrophobicity of cationic surfactant molecules resulted in lower C_{cmc} values. In terms of overall hydrophobicity, 4-metoxyphenyl in CS-MB is more hydrophobic than cinnamyl in CS-PA. As a result, the CS-PA & CS-MB undergo aggregation, in which the hydrophilic head is oriented toward water, while the hydrophobic tail is directed inward to form micelles. This arrangement reduces unfavorable interactions with the aqueous medium and consequently lowers the free energy in the system. Therefore, increasing the number of hydrophobic groups, enhances the surfactants's tendency to form micelles and decreases C_{cmc} [43-47]. Effectiveness (π_{cmc}) of CS-PA & CS-MB can be assessed using the following eq. [43-48] are presented in **Table 1**:

$$\pi_{cmc} = \gamma_o - \gamma_{cmc} \quad (1)$$

where γ_o refers to the surface tension of pure water & γ_{cmc} represents the surface tension of surfactants solution at critical micelle concentration (C_{cmc}).

The π_{cmc} values of these surfactants increased with increasing hydrophobicity in aqueous media.

Γ_{max} at the link was calculated using the following equation [43-47, 49]:

$$\Gamma_{max} = \left(\frac{-1}{nRT} \right) \left(\frac{d\gamma}{d \log C} \right) \quad (2)$$

where n is the no. of species ions in a liquid phase, R is the universal gas constant, T is the absolute temperature and $d\gamma/d \log C$ is the slope of straight line before C_{cmc} of (γ vs. $-\log C$) plot.

The Γ_{max} values decreased in the following order: CS-MB > CS-PA. The Γ_{max} values increased as the hydrophobicity structure of CS-PA & CS-MB in solution increases.

Furthermore, the A_{min} was calculated using the following equation [43, 44, 50]:

$$A_{\min} = \frac{10^{14}}{N_A \Gamma_{\max}} \quad (3)$$

where N_A is Avogadro's no. and $\Gamma_{\max}$ is the maximum surface excess of surfactant particles that have been adsorbed onto the interface.

$A_{\min}$ values decreased according to the following order: CS-MB < CS-PA. The $A_{\min}$ values decreased as the hydrophobicity structure of CS-PA & CS-MB increases.

3.3. Weight loss measurements

Weight loss measurements were performed to investigate the corrosion behavior of C-steel in 1 M HCl in the absence and presence of various concentrations of the synthesized surfactants, [CS-PA & CS-MB]. Then the corrosion inhibiting effectiveness (η_w) was estimated applying the next equation [43, 44, 50-53]:

$$\eta_w = \frac{W_{\text{corr}} - W_{\text{corr}}(\text{inh})}{W_{\text{corr}}} \times 100 \quad (4)$$

where W_{corr} and $W_{\text{corr}}(\text{inh})$ represent the weight loss of CS without & with adding synthesized surfactant, respectively.

The results showed that the corrosion inhibition efficiency (η_w) of CS-PA & CS-MB increased with increasing inhibitor concentration. This behavior is due to surface covering through adsorption of CS-PA & CS-MB [43, 44, 50-54]. *i.e.* Increasing synthesized surfactant concentration, increases both metal surface area (θ) covered by adsorbed surfactant molecules and inhibition efficiency (η_w), resulting in lower corrosion rates (k).

The weight loss approach was used to determine the heat effect on C-steel in temperatures ranging from 25 °C to 70 °C in a corrosive medium with and without varying CS-PA & CS-MB concentrations, as exhibited in (**Supplementary materials, Figs. 5& 6**) and displayed in **Table 2**. Results of measurements showed that in the presence of CS-PA & CS-MB, the corrosion rate (k) values increased slightly, while

the inhibition efficiency (η_w) decreased with increasing temperature over the range of 25-70 °C. These results indicate that CS-PA & CS-MB act as effective inhibitors in acidic media [43, 44, 50-54]. This indicates that the protection of CS-PA & CS-MB to C-steel surface in the tested medium may be due to physical adsorption rather than chemical adsorption [51, 53]. Finally, it was discovered that the anti-corrosion efficacy of CS-MB is greater than CS-PA due to the presence of methoxy group in the CS-MB.

3.4. Electrochemical impedance spectroscopy (EIS results)

The corrosion behavior of C-steel in 1 M HCl solution was assessed using electrochemical impedance spectroscopy (EIS) measurements at 25 °C with and without varying amounts of CS-PA and CS-MB. **Fig. 6(a,b)** shows the corresponding Nyquist plots. The Nyquist diagrams show a single depressed capacitive semicircle, suggesting that a charge transfer mechanism is primarily responsible for controlling the corrosion process. The electrode's roughness and surface heterogeneity are responsible for the departure from perfect semicircular behavior. The semicircle's width dramatically increases when the synthesized surfactants are present, indicating a rise in the charge transfer resistance (R_{ct}) (**Table 3**). The development of a protective adsorbed coating on the CS surface, which successfully stops the corrosion process, is confirmed by this behavior. Stronger adsorption of the inhibitor molecules and improved surface coverage are suggested by the rise in R_{ct} with increasing inhibitor concentration. At low and high frequencies, variations in the actual impedance were associated with the polarization resistance (R_p) [43, 44, 53-56]. The following types of resistances which contain "cumulative types resistance & charges transfer resistance (R_{ct}) & diffuse layer resistance (R_d)" are all included in the polarization resistance (R_p). Weight loss measurements were performed to investigate

the corrosion behavior of C-steel in 1 M HCl in the absence and presence of various concentrations of the synthesized surfactants, [CS-PA & CS-MB]. As the concentration of the synthesized surfactants increases, the charge-transfer resistance (R_{ct}) increases, indicating enhanced corrosion inhibition. This behavior can be attributed to the increased adsorption of surfactant molecules onto the C-steel surface, which progressively covers the active corrosion sites and hinders charge transfer between the metal surface and the acidic solution. Consequently, the corrosion reaction is suppressed, resulting in a slower corrosion process.

However, pure capacitance or double layer capacitance (C_{dl}) is substituted with CPE. An equivalent circuit made up of solution resistance (R_s), charge transfer resistance (R_{ct}), and a constant phase element (CPE), which substitutes the ideal double-layer capacitance because of the surface non-ideality, was used to fit the impedance data. Frequency dispersion related to surface inhomogeneities is taken into account while using CPE. A convenient equivalent circuit for EIS spectrum is provided in **(Supplementary materials, Fig. 7)**.

Using the CPE parameters and Eq. (5), the double-layer capacitance (C_{dl}) values were computed. C_{dl} falls when the inhibitor's concentration rises, as **Table 3** illustrates. According to the Helmholtz model, this reduction can be explained by surfactant molecules replacing water molecules at the metal/solution interface, which results in a decrease in the local dielectric constant and/or an increase in the electrical double layer's thickness.

$$C_{dl} = Y_o(\omega_{max})^{n-1} \quad (5)$$

Impedance (Z_{CPE}) is calculated by this equation:

$$Z_{CPE} = \frac{1}{Y_o(j\omega)^n} \quad (6)$$

$$\omega = 2\pi f_{max} \quad (7)$$

where Y_0 = constant phase element, $J^2 = -1$, $\omega_{\max}$ = angular frequency, n = phase shift and $f_{\max}$ = frequency at maximum impedance-imaginary component.

The equivalent circuit was used to evaluate EIS variables. **Table 3** clearly shows that range of n values from 0.5 - 1, indicates a non-ideal capacitive behavior, which becomes closer to ideality with increasing inhibitor concentration, suggesting improved surface homogeneity due to the adsorption of the inhibitor molecules. As demonstrated in **Table 3**, double layer capacitance (C_{dl}) values decreased as the concentrations of CS-PA & CS-MB increased. The synthesized surfactant replaces water molecules on the surface of C-steel, lowering C_{dl} levels. As a result, C_{dl} value is lower in the presence of CS-PA & CS-MB than in their absence. Adsorption of the synthesized surfactant may increase the thickness of the double layer according to the Helmholtz pattern [43, 44]. **Fig. 7(a,b)** shows the Bode and Phase curves for CS in the investigated medium with and without the synthesized surfactant. The Bode and phase angle plots further support these findings, where the increase in impedance magnitude and phase angle with inhibitor concentration confirms the formation of a more protective and capacitive surface film.

The inhibition efficiency (η_I) is calculated by applying this equation [43, 44, 53-58]

$$\eta_I = \frac{R_{ct} (inh) - R_{ct}}{R_{ct} (inh)} \times 100 \quad (8)$$

where $R_{ct} (inh)$ & R_{ct} refers to values of charge transfer resistance in various solutions that were inhibited and those that were not inhibited simultaneously.

Equation (8) was used to compute the inhibition efficiency (η_I), and **Table 3** shows that the values rise as the surfactant concentration increases. The high inhibitory efficacy of the produced surfactants is confirmed by this trend, which is in line with the polarization and weight loss results.

Overall, the EIS data show that the adsorption of surfactant molecules on the carbon steel surface, which forms a compact barrier layer that prevents charge transfer and shields the metal from hostile chloride ions, is the main mechanism governing the inhibition.

3.5. Potentiodynamic polarization

Fig. 8(a,b) shows potentiodynamic polarization curves for C-steel in studied medium at various concentrations of CS-PA & CS-MB at 25 °C. Deterioration current densities (i_{corr}) & deterioration potential (E_{corr}) & cathodic Tafel slope (β_c) & anodic Tafel slope (β_a) which gained are reported in **Table 4**. It is evident that the i_{corr} values decrease significantly with increasing inhibitor concentration, indicating an effective reduction in the corrosion rate. Meanwhile, the observed slight shift in E_{corr} towards more positive values (< 85 mV) suggests that both surfactants act as mixed-type inhibitors, influencing both anodic metal dissolution and cathodic hydrogen evolution reactions without preferentially altering either process [43, 44, 53, 55, 59]. Additionally, the Tafel slopes (β_a and β_c) show relatively slight alterations, suggesting that the inhibitors do not alter the basic corrosion mechanism. Rather, the blockage of active sites on the metal surface is the primary cause of the inhibition process. This behavior demonstrates that the surfactant molecules adsorb on the C-steel surface, creating a barrier that prevents hostile species from reaching the electrode surface. The surface-blocking process, in which the inhibitors decrease the effective surface area accessible for electrochemical reactions without altering the reaction pathways, is further supported by the parallel displacement of both anodic and cathodic branches toward lower current densities. This is attributed to the inhibition activity of the synthesized surfactants, which work by active sites deactivation of C-steel surface, thus reducing surface area susceptible to damage [43,

44, 53, 55, 60]. The inhibition efficiency (η_p) was calculated using the following equation [43, 44, 53, 55, 61]:

$$\eta_p = \frac{i_{\text{corr}} - i_{\text{corr}}(\text{inh})}{i_{\text{corr}}} \times 100 \quad (9)$$

where i_{corr} & $i_{\text{corr}}(\text{inh})$ are deterioration current densities with and without synthesized surfactant different concentrations.

As concentration of synthesized surfactants increases, the values of (η_p) increase, as clearly shown and reported in **Table 4**. This pattern demonstrates that at greater concentrations, inhibitor molecule adsorption becomes more noticeable, improving surface coverage and corrosion prevention.

Overall, the high adsorption of the synthesized surfactants on both anodic and cathodic active sites is responsible for the decrease in i_{corr} and the increase in η_p with increasing inhibitor concentration. A compact and stable protective coating is created as a result of this adsorption, successfully separating the metal surface from the corrosive liquid. The findings unequivocally show that CS-PA and CS-MB have outstanding inhibitory performance because of their capacity to adsorb firmly and evenly on the surface of C-steel.

3.6. Activation energy (E_a) for corrosion process

Arrhenius equation was used to estimate the activation energy (E_a) values of metal dissolution with and without of the synthesized surfactants [CS-PA & CS-MB], as shown below [43, 51, 52, 54]:

$$\ln k = \frac{-E_a}{RT} + \ln A \quad (10)$$

where A = Arrhenius constant (pre-exponential factor), R = gas constant (8.314 J mol⁻¹), T = absolute temperature, and K = corrosion rate.

Fig. 9(a,b) shows C-steel degradation plots ($\ln k$ vs. $1/T$) in 1 M HCl solution with and without varying concentrations of the synthesized surfactants. E_a values were calculated and recorded in **Table 5**. E_a values of the synthesized surfactants in 1 M HCl solutions were greater than those of the blank solution. E_a values increased with increasing the concentration of the synthesized surfactants. This results from the CS surface developing a protective layer that is physically adsorbed on it. [43, 51, 52, 54].

3.7. Adsorption isotherm (thermodynamic adsorption variables)

Surfactant molecules are known for their ability to prevent metal dissolution via adsorption on metal surfaces, effectively displacing water molecules that an inhibitor has adsorbed on the C-steel surface. The adsorption isotherm explains how the synthesized surfactants [CS-PA & CS-MB] adsorb on the surface of C-steel “adsorption mechanism” [43, 50, 51]. Adsorption isotherms are critical for understanding the organo-electrochemical reactions mechanisms as well as the inhibition mechanisms of the synthesized surfactants. The next equation was applied to estimate the surface covering grade (θ) for various concentrations of synthesized surfactants in corrosive environments [43, 44, 50, 51]:

$$\theta = \frac{W_{\text{corr}} - W_{\text{corr}}(\text{inh})}{W_{\text{corr}}} \quad (11)$$

where W_{corr} & $W_{\text{corr}}(\text{inh})$ refer to the weight loss of CS in absence and presence of synthesized surfactants.

The Langmuir adsorption isotherm in 1M HCl is shown in **Fig. 10(a,b)** and plotted as C/θ vs. C . Equilibrium constant (K_{ads}) in the following equation is utilized to define Langmuir adsorption isotherm [43, 44, 50, 51]:

$$\frac{C}{\theta} = \frac{1}{K_{\text{ads}}} + C \quad (12)$$

where K_{ads} symbolizes equilibrium constant of synthesized surfactants adsorption process & C symbolizes synthesized surfactants concentration.

Fig. 10(a,b) shows linear Langmuir adsorption graphs (C/θ vs. C) with slopes close to one. This shows that the adsorption of the two synthesized surfactant on the C-steel surface is compatible with Langmuir adsorption isotherm, or that both CS-PA & CS-MB met the Langmuir isotherm model requirements. K_{ads} equals reciprocal intercept (**Fig. 10(a,b)**); for CS-PA & CS-MB was determined and recorded in **Table 6**. High K_{ads} values indicate that CS-PA & CS-MB have high adsorption efficiency on the CS surface. On the other hand, CS-MB has more adsorption sites than CS-PA and so CS-MB has a higher adsorption efficiency than CS-PA.

The thermodynamic adsorption parameters that are commonly acknowledged are the standard free energy ($\Delta G^{\circ}_{\text{ads}}$), enthalpy ($\Delta H^{\circ}_{\text{ads}}$) and entropy ($\Delta S^{\circ}_{\text{ads}}$). **Table 6** shows the $\Delta G^{\circ}_{\text{ads}}$, $\Delta H^{\circ}_{\text{ads}}$, $\Delta S^{\circ}_{\text{ads}}$ parameters of the synthesized surfactants adsorption at two variables (concentrations & temperatures) on a metal surface in one molar HCl. The standard free energy of adsorption ($\Delta G^{\circ}_{\text{ads}}$) is based on K_{ads} and determined using this equation [43, 44, 50, 51]:

$$\Delta G^{\circ}_{\text{ads}} = -RT \ln(55.5 K_{\text{ads}}) \quad (13)$$

where R symbolizes universal gas constant & the 55.5 symbolizes value of molar concentration of water in solution & T symbolizes absolute temperature.

When $\Delta G^{\circ}_{\text{ads}}$ values are ≥ -20 kJ/mol, they indicate the presence of electrostatic attraction between charged C-steel surface and synthesized surfactants molecules (physical adsorption) while $\Delta G^{\circ}_{\text{ads}}$ values ≤ -40 kJ/mol, it indicates coordination bond between C-steel surface and synthesized surfactants (chemical adsorption) [43, 50, 51]. In the present research, the adsorption behavior is further supported by thermodynamic parameters (**Table 6**), where the negative values of $\Delta G^{\circ}_{\text{ads}}$ indicate

spontaneous adsorption of the inhibitor molecules on the carbon steel surface. The magnitude of $\Delta G^{\circ}_{\text{ads}}$ (≈ -36 to -42 kJ mol⁻¹) suggests that the adsorption process of CS-PA & CS-MB on C-steel surface in 1M HCl involves both electrostatic interactions (physisorption) and coordinate bonding between the inhibitor molecules and the metal surface (chemisorption).

This combined electrochemical and thermodynamic evidence suggests that the inhibition mechanism is predominantly governed by the adsorption of surfactant molecules through their active centers (e.g., imine group, heteroatoms, and π -electrons), forming a compact barrier film that limits the access of aggressive chloride ions to the metal surface. The higher inhibition efficiency observed for CS-MB can be attributed to its enhanced electron-donating ability and stronger adsorption affinity, resulting in a more stable and protective adsorbed layer [43, 50, 51]. Great $\Delta G^{\circ}_{\text{ads}}$ values & their -ve signs refer to a strong interaction and very efficient adsorption [43]. $\Delta H^{\circ}_{\text{ads}}$ is estimated using the Van't Hoff equation [43, 50, 51]:

$$\ln K_{\text{ads}} = \left(\frac{-\Delta H^{\circ}_{\text{ads}}}{RT} \right) + \text{const} \quad (14)$$

We can get $\Delta H^{\circ}_{\text{ads}}$ values from the slope of the resulting straight line by plotting $\ln K_{\text{ads}}$ versus $1/T$ according to **Eq. (14)** as displayed in (**Supplementary materials, Fig. 8**). The -ve sign of $\Delta H^{\circ}_{\text{ads}}$ values refer to the adsorption process of CS-PA & CS-MB on the C-steel surface was exothermic [43, 50, 51].

Inhibitor adsorption Entropy ($\Delta S^{\circ}_{\text{ads}}$) was obtained from the basic equation of thermodynamic [43, 50, 51]:

$$\Delta G^{\circ}_{\text{ads}} = \Delta H^{\circ}_{\text{ads}} - T\Delta S^{\circ}_{\text{ads}} \quad (15)$$

The +ve values of $\Delta S^{\circ}_{\text{ads}}$ refer to the natural adsorptive capability of CS-PA & CS-MB molecules on CS surface [43, 50, 51].

3.8. Atomic force microscope (AFM)

AFM is the most common application used in studying and imaging the surface of metals (surface morphology). **Fig. 11** shows AFM microscope images of C-steel surface after 24 hours of immersion without & with 1×10^{-3} M of the synthesized surfactants at 25 °C. In a blank sample (without 1×10^{-3} M of inhibitor), the damage and corrosion were visible. Also, the high average roughness (R_a) values (626 nm) measured for C-steel after immersion in a corrosive environment without the prepared surfactants may be due to the corrosive species that form on the C-steel. However, the damage or corrosion disappeared significantly upon addition of 1×10^{-3} M of synthesized surfactants in the corrosive media, as evidenced by the reduction in (R_a) values to 183.9 nm with CS-PA and to 162 nm with CS-MB. Furthermore, it suggested that the ranking agrees with the inhibitory performance of cationic surfactants [CS-MB > CS-PA] which could protect the C-steel from corrosion. As seen in **Fig. 11**, the inclusion of synthetic surfactants greatly decreased the damage to the iron surface, and coupons looked smooth, resulting from generation of a protective cover of synthetic surfactants on metal surface, demonstrating adsorption of these molecules onto active sites of metal surface.

3.9. Inhibition mechanism

The corrosion inhibition efficiency of the two cationic surfactants is strongly influenced by their molecular structures and the nature of their active adsorption sites. In particular, electron-rich centers, such as heteroatoms bearing lone pairs of electrons, and different functional groups like imine/azomethine (C=N), carbonyl (C=O), and the double bond in benzene ring” can facilitate strong interactions with the C-steel surface, thereby promoting adsorption and the formation of a protective interfacial film. These centers enable the surfactants to adsorb onto the metal surface

through both physisorption and chemisorption, depending on the temperature. Physical adsorption occurs at low temperatures through the formation of electrostatic attraction forces between charged atoms “such as ammonium ion (N^+) and counter ion (Cl^-)” in these compounds and opposite charged anodic-cathodic sites on C-steel surface, while chemical adsorption occurs at high temperatures through the formation of coordination bonds between electron-donating sites “represented by the electron-rich active centers in the compounds” and electron-accepting sites “represented by the empty d-orbitals in iron atoms on C-steel surface”. The compounds studied in this research have shown excellent performance in inhibiting the corrosion of iron. CS-MB exhibited higher corrosion- inhibition efficiency than CS-PA. This may be attributed to the stronger electron donating ability of CS-MB due to the presence of the methoxy ($-\text{OCH}_3$) group on benzene ring, as well as its greater hydrophobicity and r planarity. (**Supplementary materials, Fig. 9**) illustrates a possible mechanism for preventing corrosion through physical and chemical adsorption of CS-MB on C-steel surface. The superior performance of the methoxy-substituted surfactant compared to its hydrogen-substituted counterpart can be attributed to its stronger electron-donating effect, which enhances adsorption strength and leads to improved surface coverage. This improved performance should be confirmed by electrochemical experiments, where the inhibitor would normally show mixed-type activity with a predominant anodic suppression, decreased corrosion current density (i_{corr}), and increased charge transfer resistance (R_{ct}). According to the suggested adsorption model, thermodynamic characteristics ($\Delta G^{\circ}_{\text{ads}} = -40 \text{ kJ}\cdot\text{mol}^{-1}$) would further indicate a spontaneous adsorption process incorporating both chemical and physical contributions.

Overall, these quaternary ammonium salts rational hybrid design, which integrates several adsorption-active sites and interfacial capabilities into a single molecule, is what makes it novel overall. This comprehensive approach sets it apart from its conventional competitors and highlights its potential for advanced corrosion protection applications by producing greater inhibitory efficiency and increased stability under severe acidic conditions.

3.10. Comparing the inhibition efficiency of two prepared surfactants for carbon steel in acidic environment in this study with some cationic surfactants in other studies

Table 7 shows the inhibition efficiency of CS-PA & CS-MB for C-steel corrosion in acidic medium (1M HCl), as well as several previously reported cationic surfactants [63- 65]. As documented in this table, CS-PA & CS-MB's efficiencies are higher than that of cationic surfactants published in other research and were under the same conditions.

4. Conclusions

This study explains how to synthesize and characterize two new cationic surfactants, CS-PA and CS-MB. The obtained analytical and physiochemical information confirmed their composition and structure.

1. FT-IR, $^1\text{H-NMR}$ and mass spectroscopy were used to characterize the two new synthesized cationic surfactants.
2. C-steel corrosion in 1 M hydrochloric acid was effectively inhibited by the two new cationic surfactants.
3. Several properties and parameters of the two synthesized cationic surfactants, including surface tension (γ), critical micelle concentration (C_{cmc}) were determined and discussed in 1 M hydrochloric acid solution at 25°C.

4. Anti-corrosion efficiency (η_w) increases as increases synthesized surfactants concentration while it decreases as increases temperature in the range of 25-70°C.
5. EIS spectra demonstrate individual capacitive loop. Existence of synthesized surfactants in solutions of 1 M HCl form a protective film, which explains the higher inhibition efficiency (η_i) and charges transfer resistance (R_{ct}) values while reducing the pure capacitance or double layer capacitance (C_{dl}) values. It was found that as the synthesized surfactants concentration increases, the impedance value increases. This is due to the synthetic surfactants' efficient adsorption on iron surface and the creation of a shield that keeps iron from degrading in an acidic environment.
6. Tafel polarization plots refer that deterioration current densities (i_{corr}) decrease and deterioration potential (E_{corr}) changes slightly during presence of manufactured cationic surfactants, indicating that CS-PA & CS-MB are a mixed kind. It was found that as the surfactants concentration increased, the deterioration current densities decreased (i_{corr}) and the corrosion inhibition efficiency (η_p) increased. This can be related to the adsorption of the synthesized surfactants over cathodic and anodic active corroded surface and the increase in inhibition efficiency of the studied surfactants and this indicates that these surfactants [CS-PA & CS-MB] have excellent inhibitive properties of the metal surface.
7. Activation energy increases with increasing the synthesized surfactants concentration.
8. Adsorption of studied surfactants on C-steel surface is compatible with Langmuir isotherm and has two types of adsorptions (physisorption and chemisorption). The adsorption efficiency (K_{ads}) of cationic surfactants follow the order: CS-MB > CS-PA. The obtained adsorption free energy (ΔG^0_{ads}) values showed that the

adsorption process, in both its physical and chemical forms, of these surfactants on C-steel in hydrochloric acid at a concentration of 1 molar, took place. $\Delta G^{\circ}_{\text{ads}}$, with both their high values and their -ve charges, indicates the presence of highly effective interaction.

9. During imagining the C-steel surface using AFM method, it was observed that the surface was less rough and smoother, confirming that the synthesized surfactants had been well adsorbed and had formed a very good protective layer on the surface.
10. Anti-corrosion efficiency of prepared cationic surfactants follows the order: CS-MB > CS-PA.

CRedit authorship contribution statement

M.A.Hegazy: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing, review & editing.

Hanaa A. El-Boraey: Supervision, Validation, Visualization, Writing, review & editing.

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Conflict of interest

The authors have no conflicts of interest to declare.

Data availability

“The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.”

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Caption of Figures

Scheme 1. Synthesis of CS-PA.

Scheme 2. Synthesis of CS-MB.

Fig. 1. FT-IR spectra of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 2. ¹H-NMR spectra of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 3. Mass spectra of N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA).

Fig. 4. Mass spectra of (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 5. Curve of (γ vs. $-\log C$) plot of N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 6. Nyquist plot for CS in 1 M HCl at 25 °C in the presence and absence of different concentrations of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

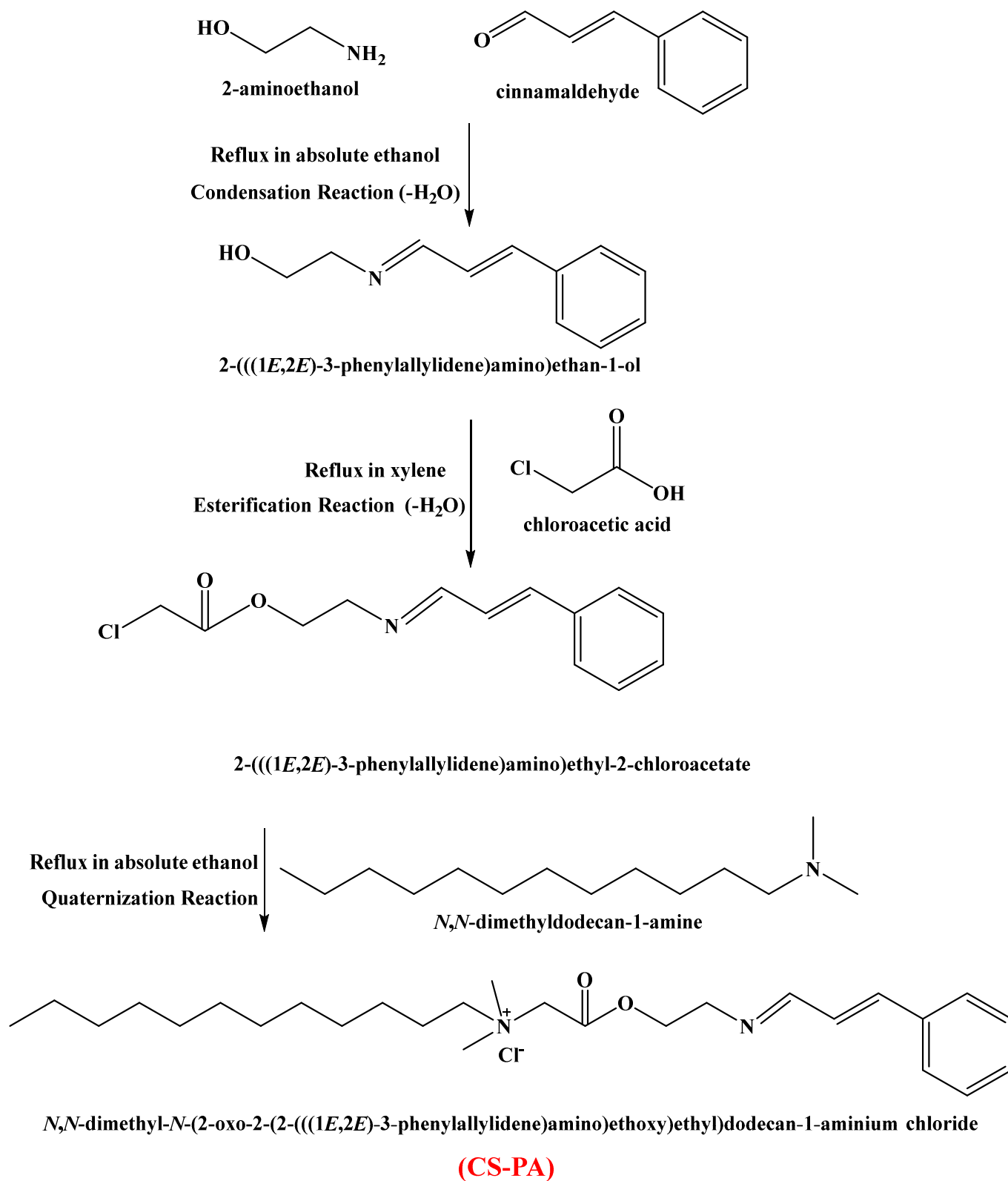
Fig. 7. Bode and Phase angle curve for CS in 1 M HCl at 25 °C in the presence and absence of different concentrations of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 8. Potentiodynamic polarization curves for CS in 1 M HCl at 25 °C in the presence and absence of different concentrations of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

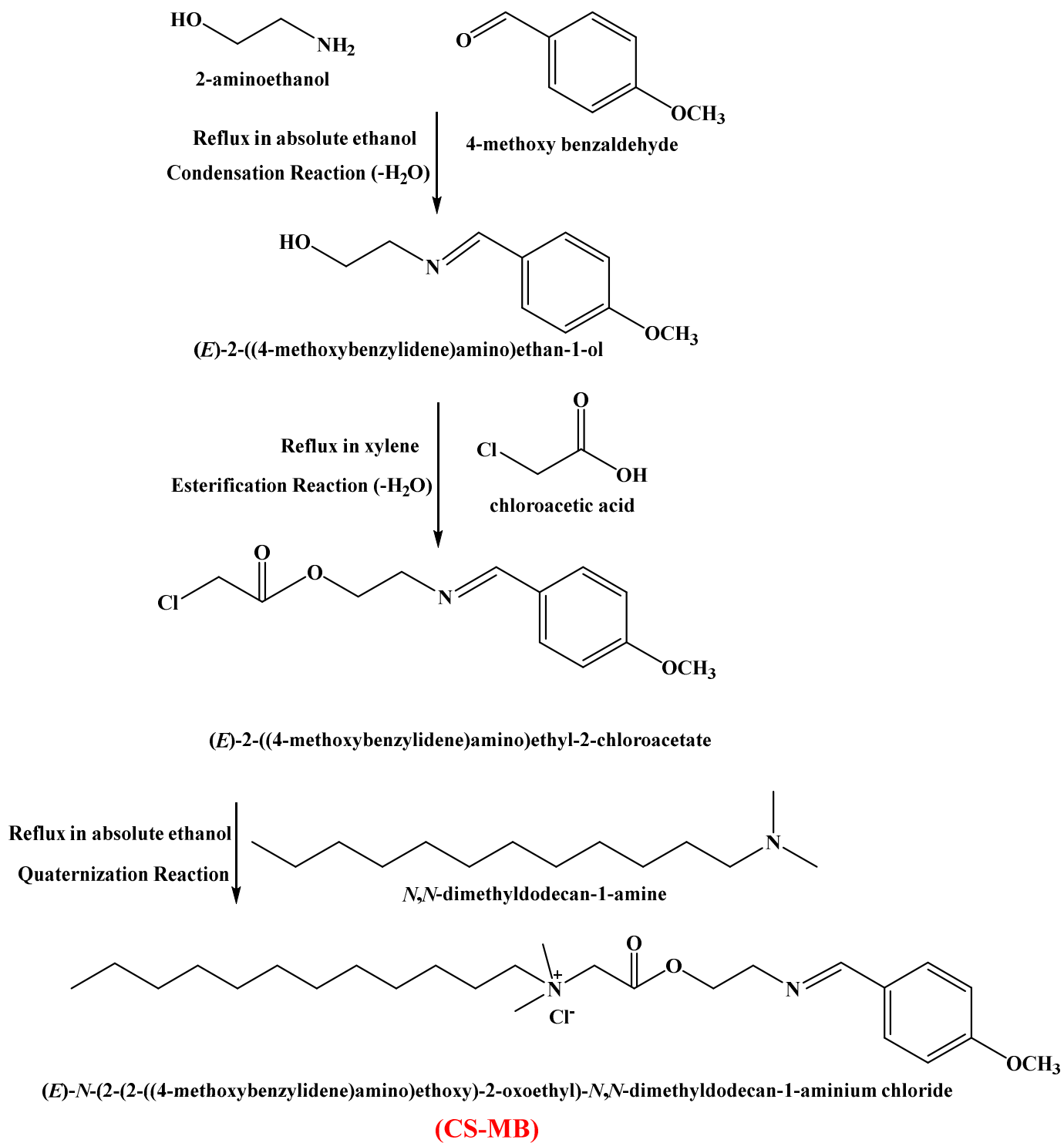
Fig. 9. Arrhenius plot ($\ln k$ vs. $1000/T$) for CS in 1 M HCl at various temperatures in the presence and absence of different concentrations of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 10. Langmuir isotherm adsorption pattern of CS in 1 M HCl at various temperatures in the presence and absence of different concentrations of: (a) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride (CS-PA) & (b) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride (CS-MB).

Fig. 11. AFM photos of CS samples: (a) blank HCl (without surfactants), (b) N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl)dodecan-1-aminium chloride (CS-PA) & (c) (E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyldodecan-1-aminium chloride (CS-MB).



Scheme 1.



Scheme 2.

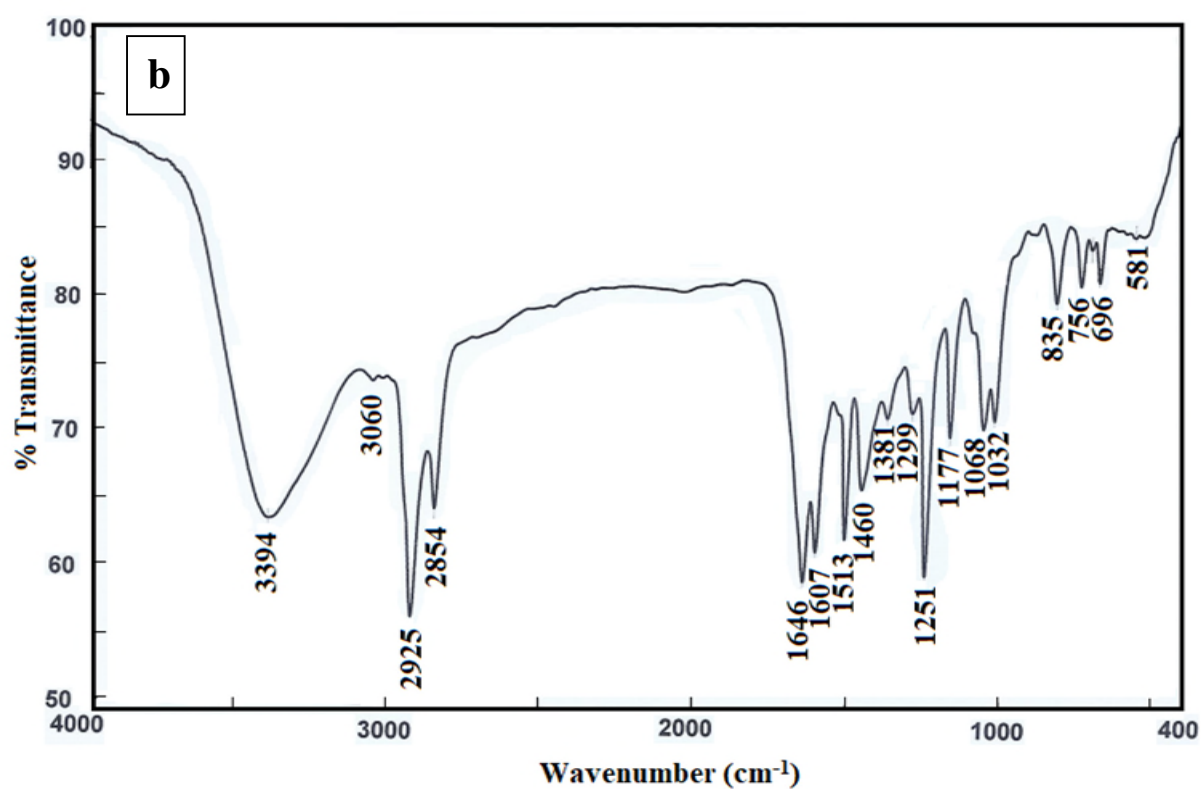
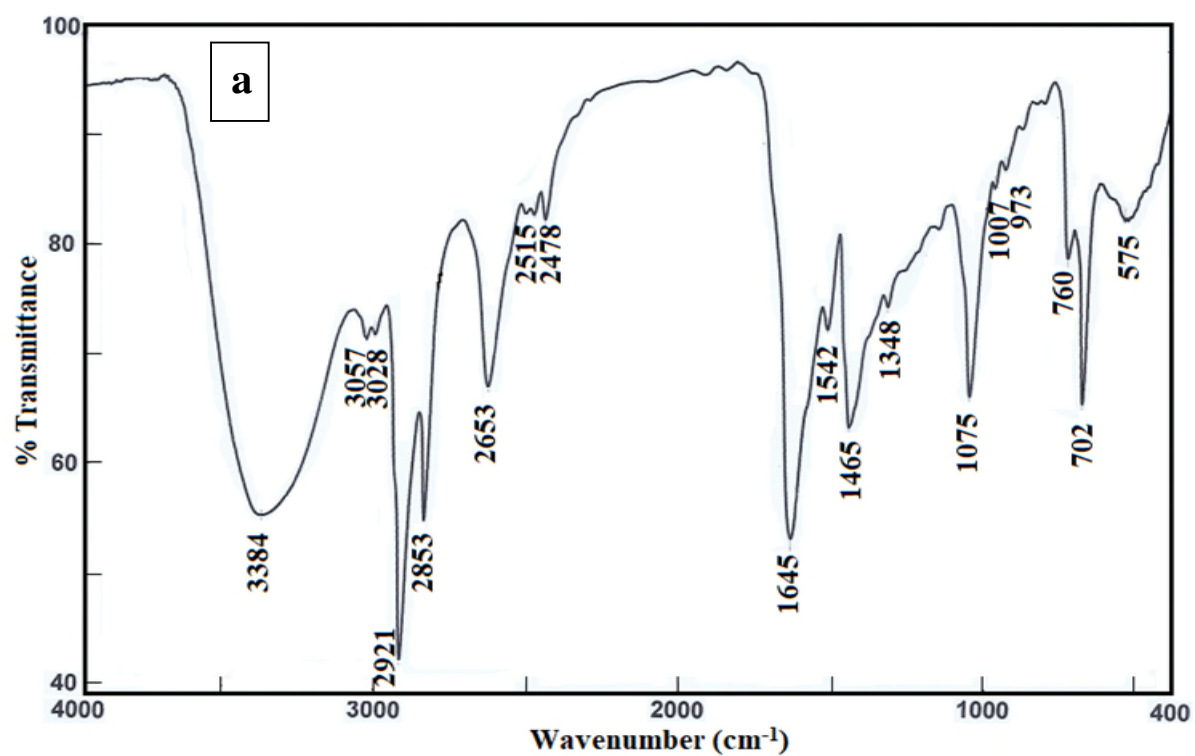
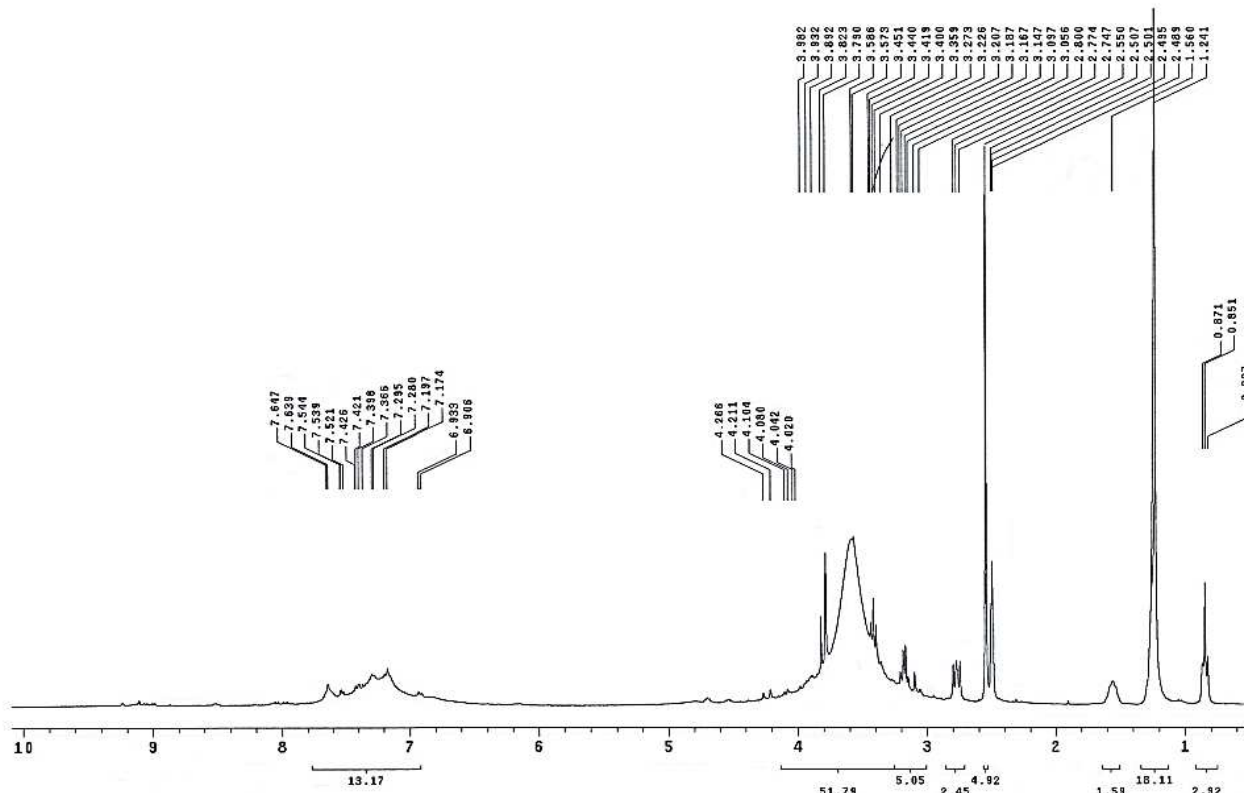


Fig. 1.

a



b

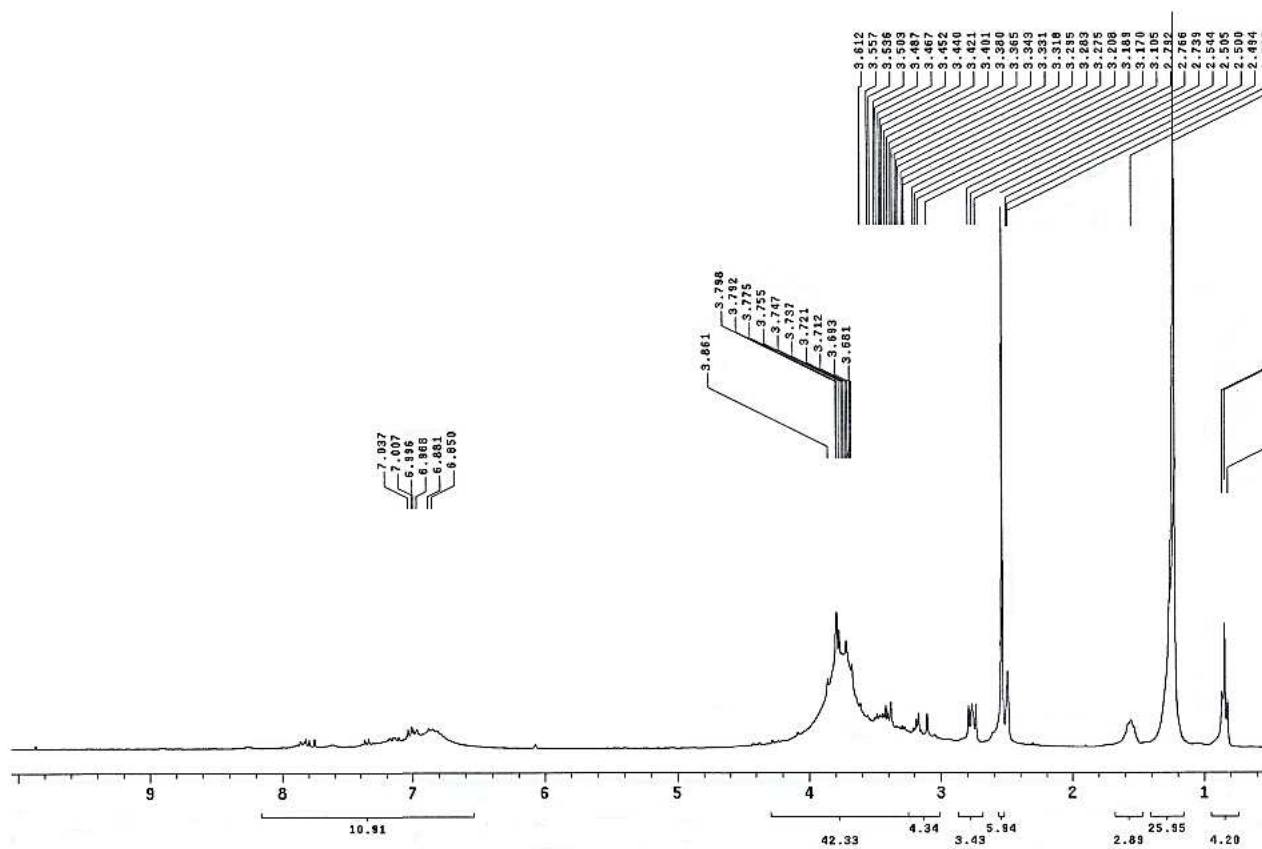


Fig. 2.

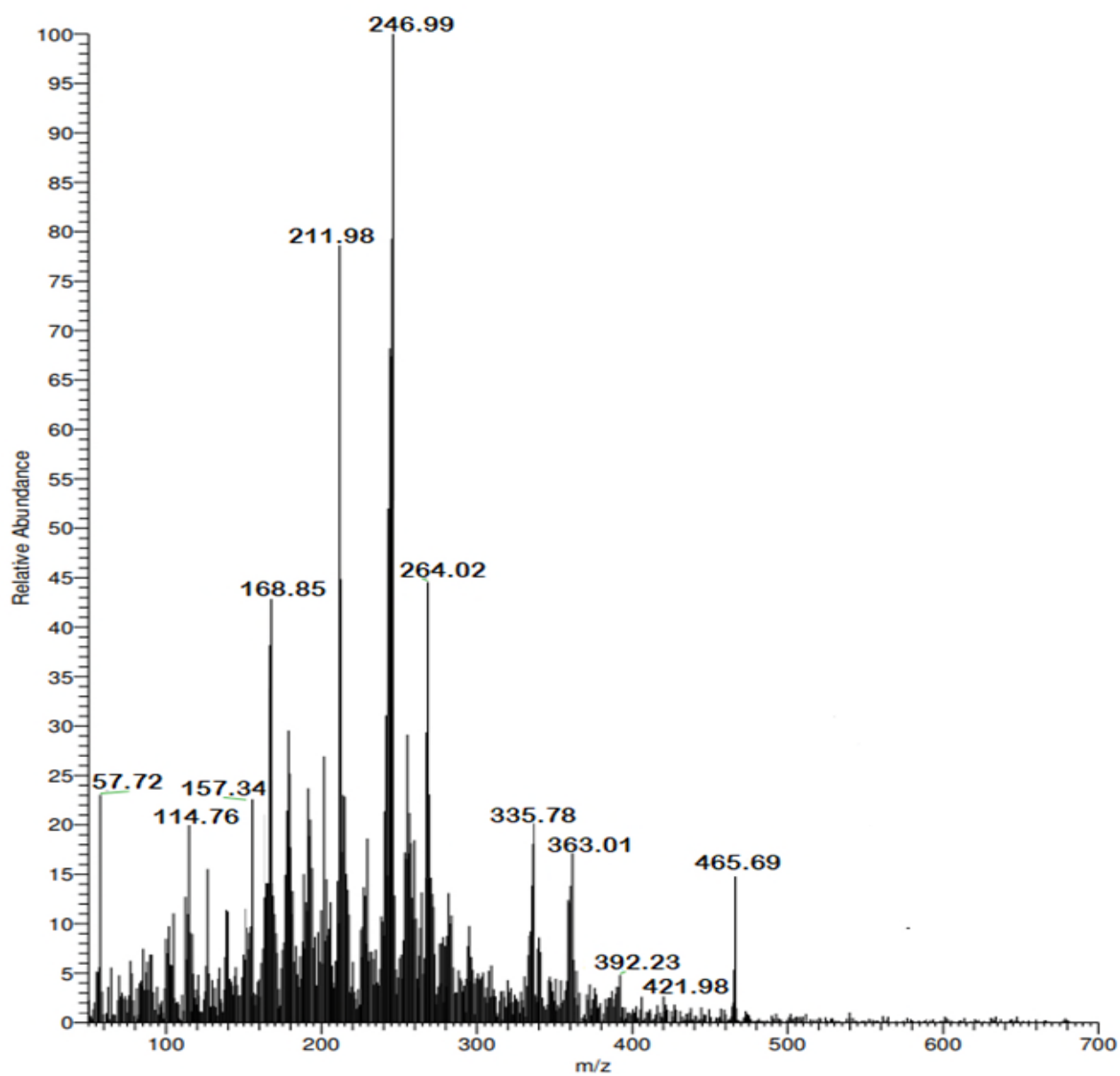


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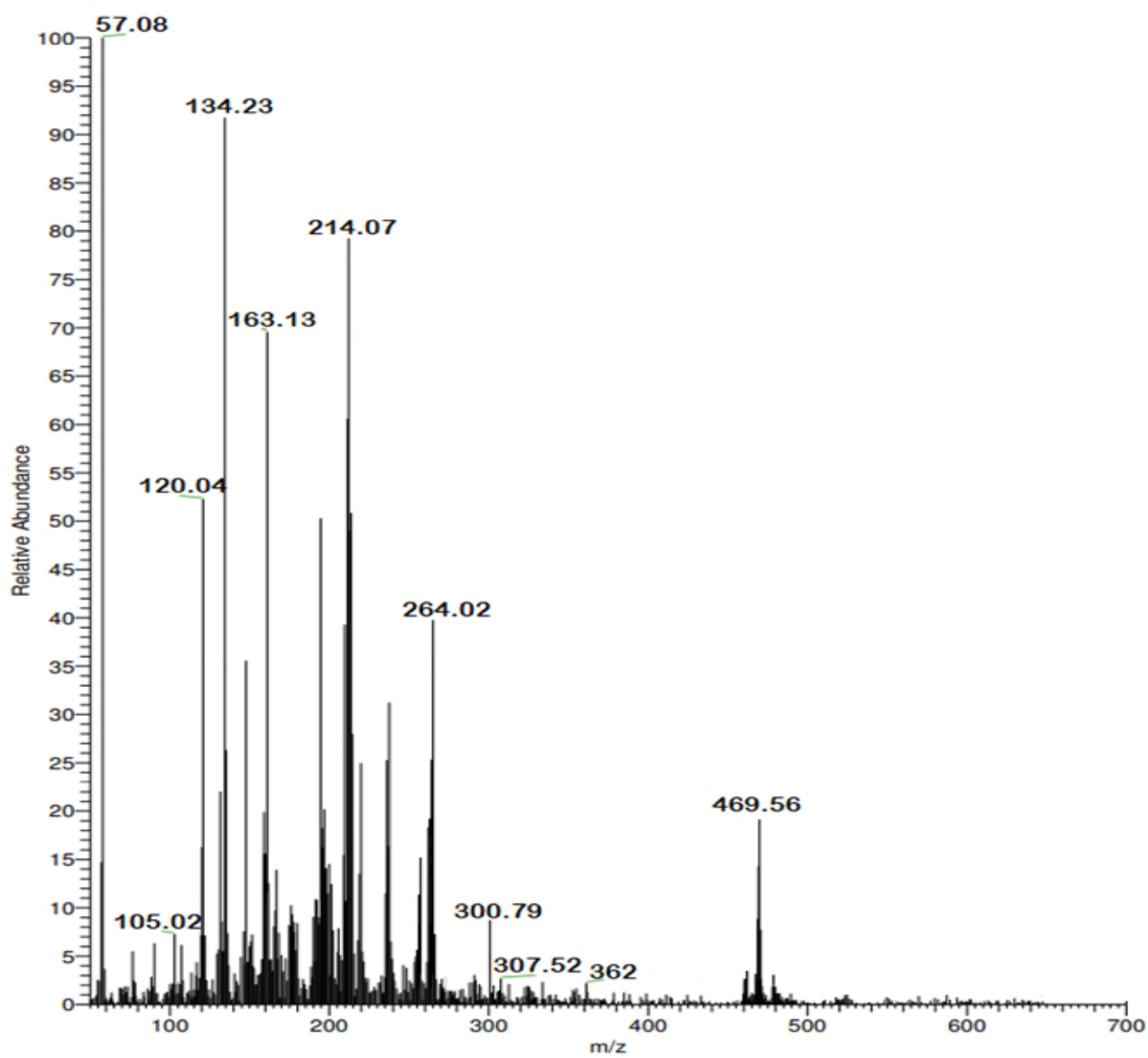


Fig. 4.

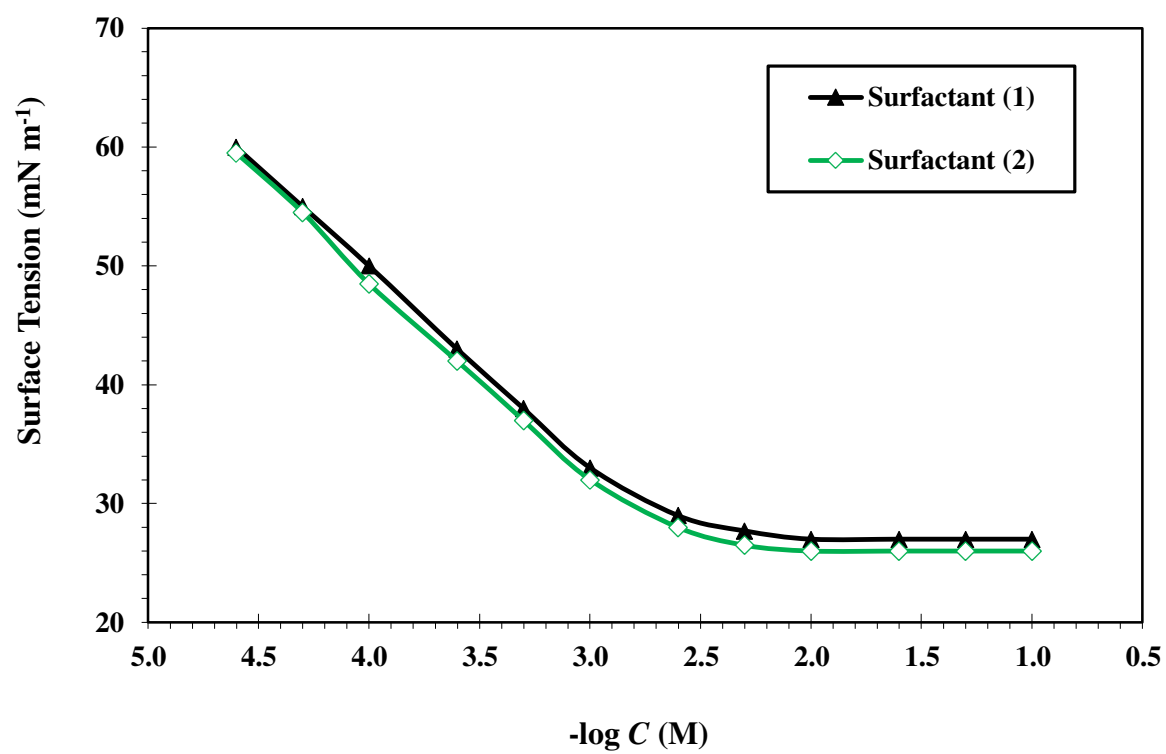


Fig. 5.

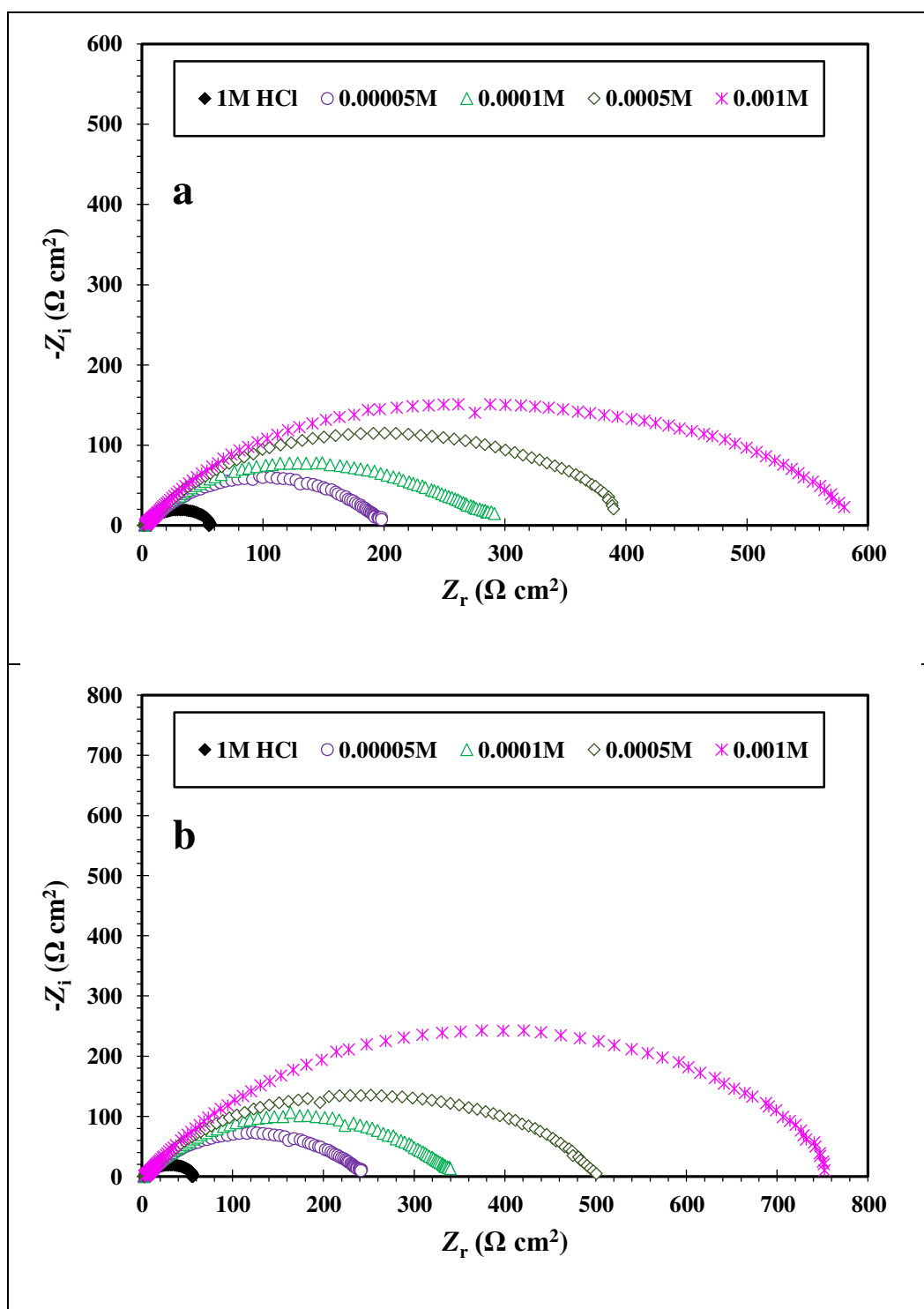


Fig. 6.

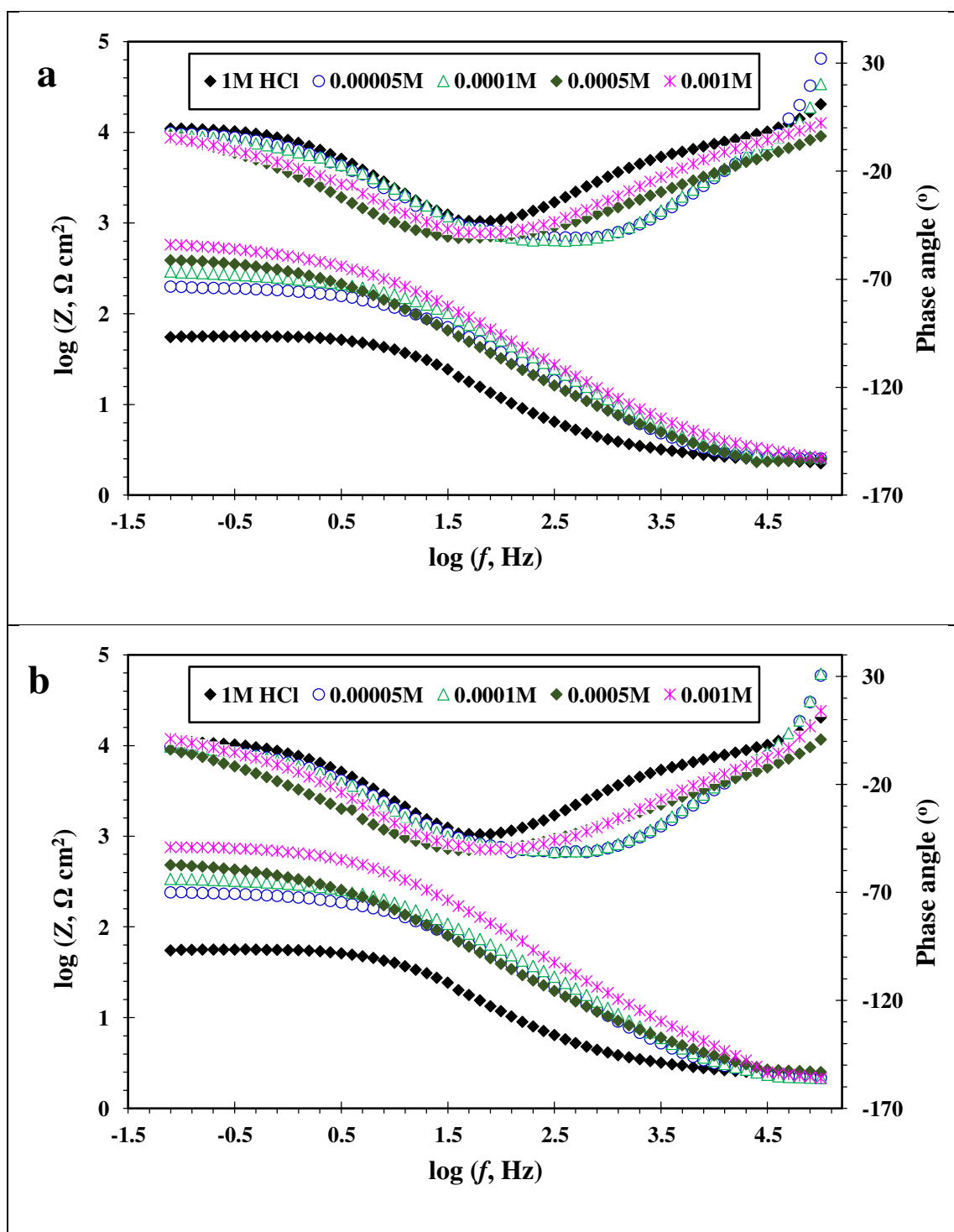


Fig. 7.

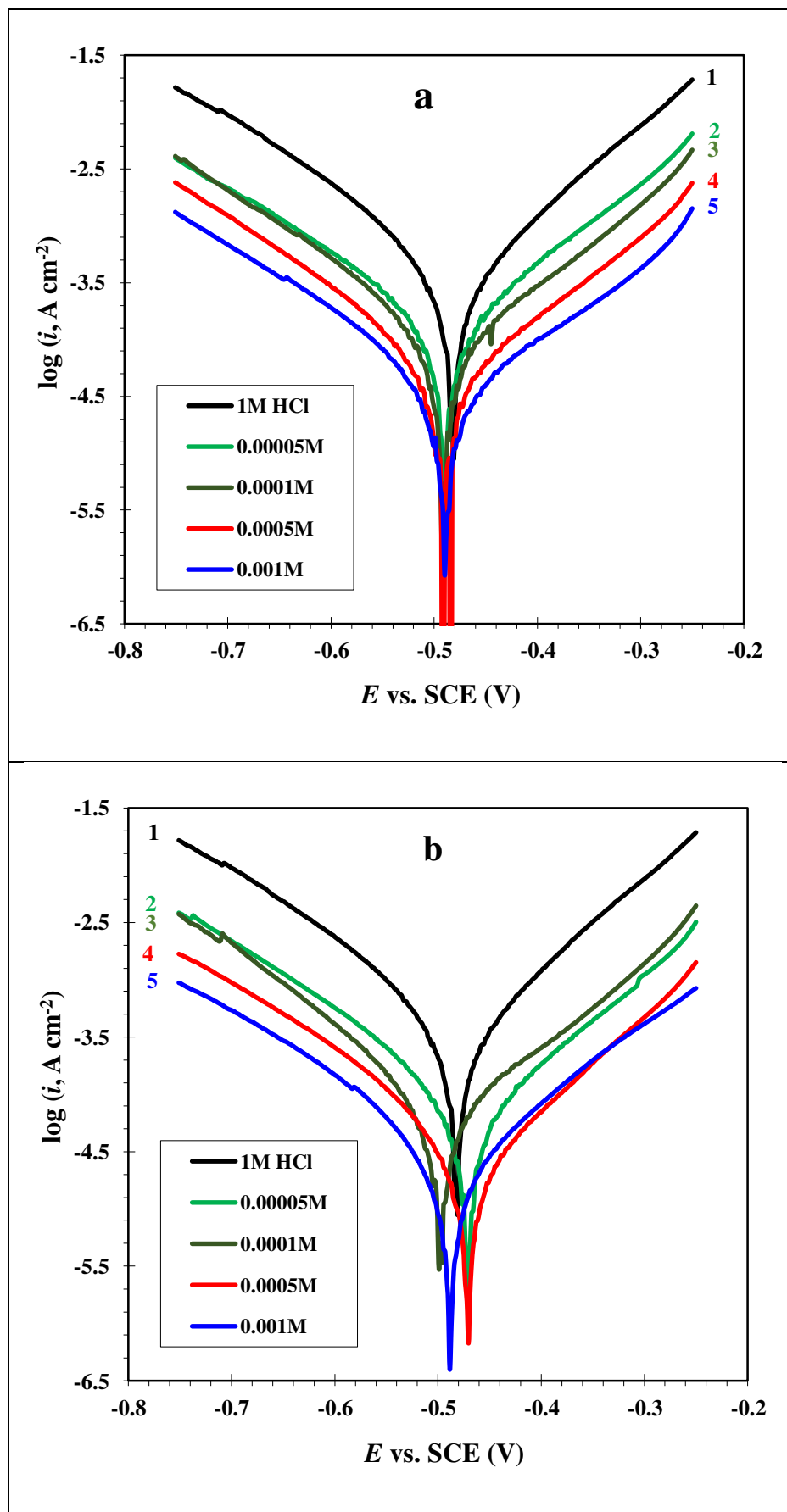


Fig. 8.

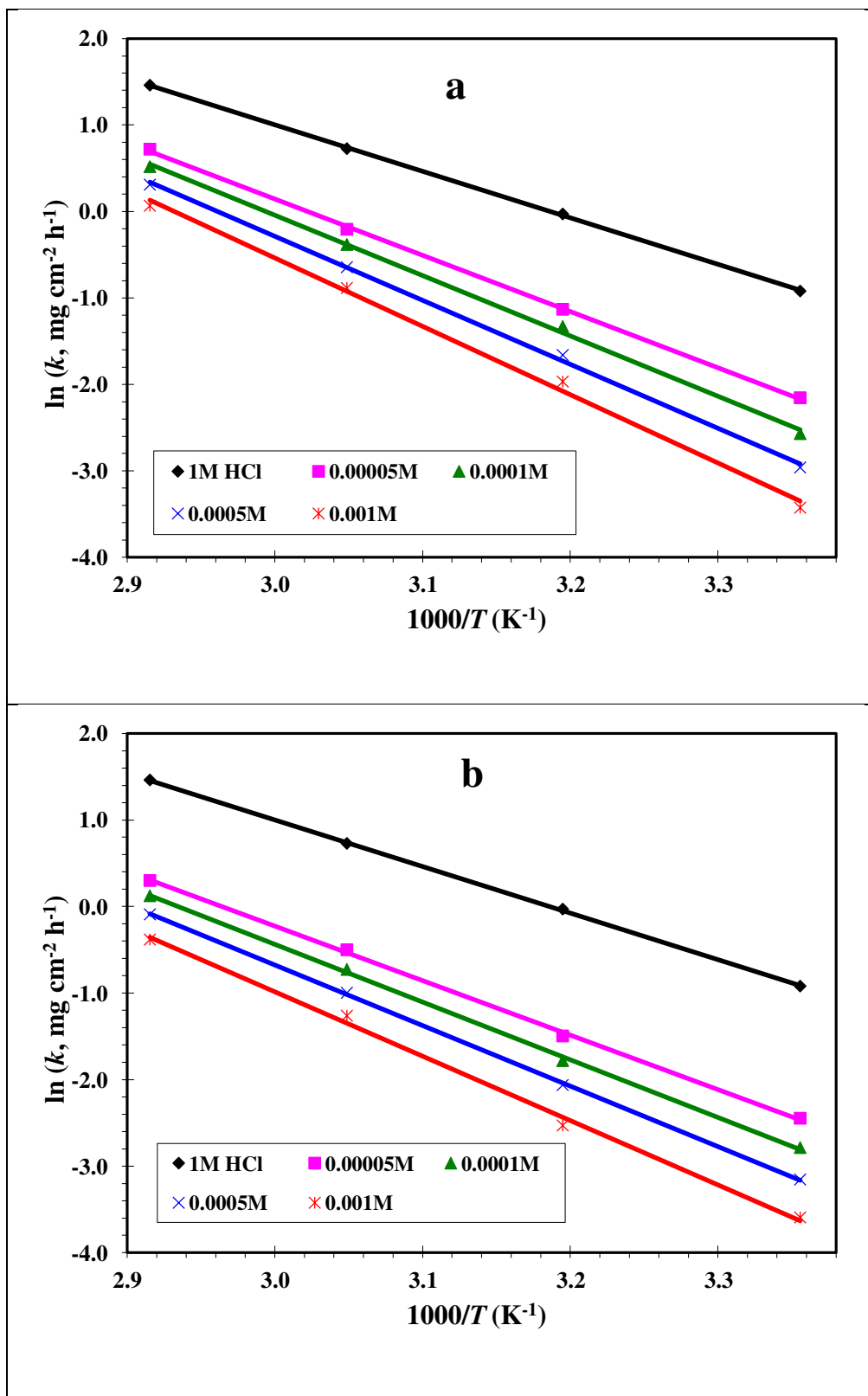


Fig. 9.

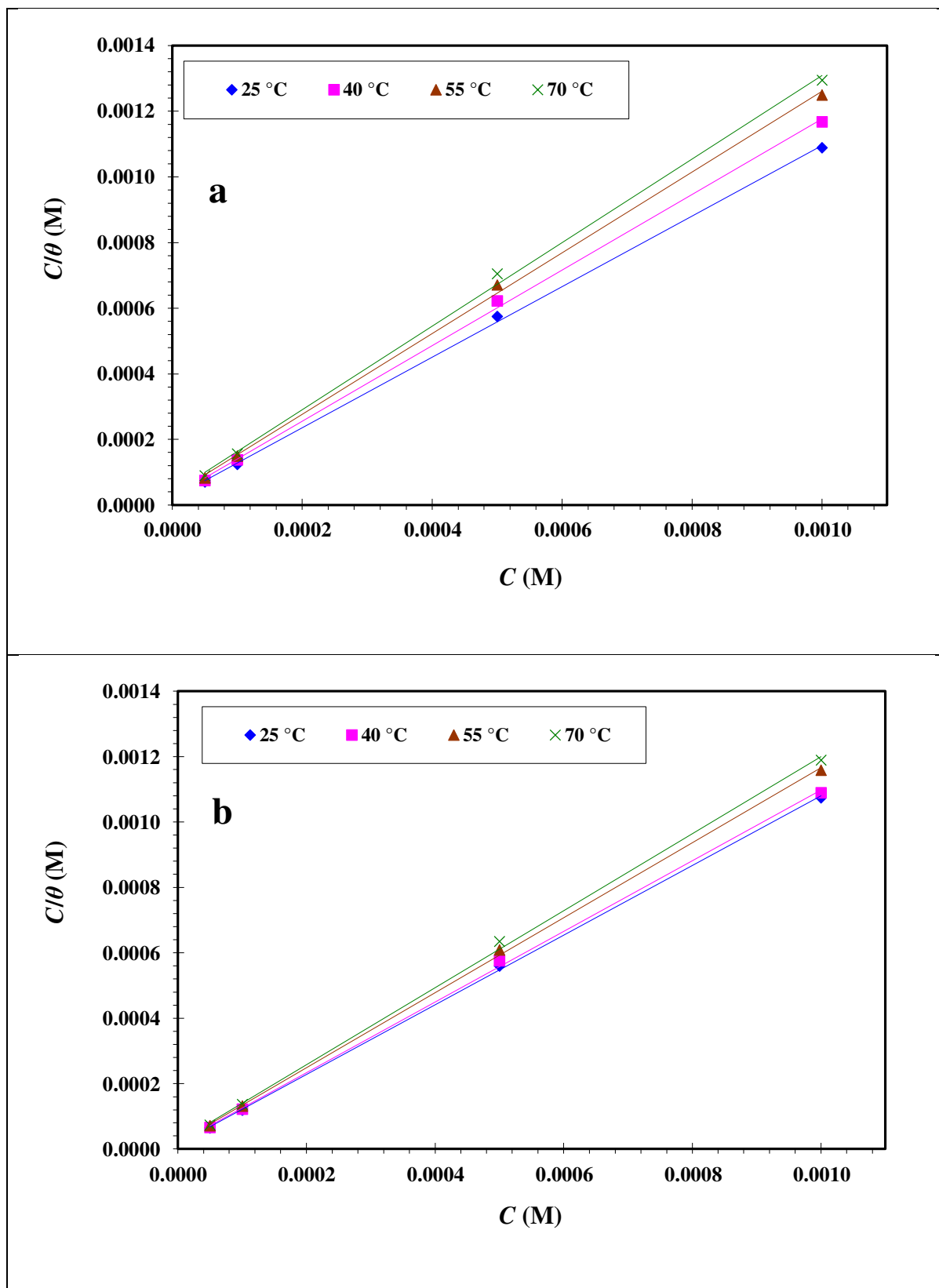


Fig. 10.

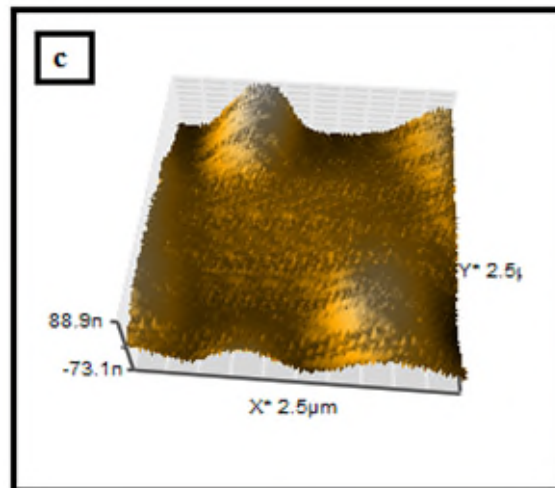
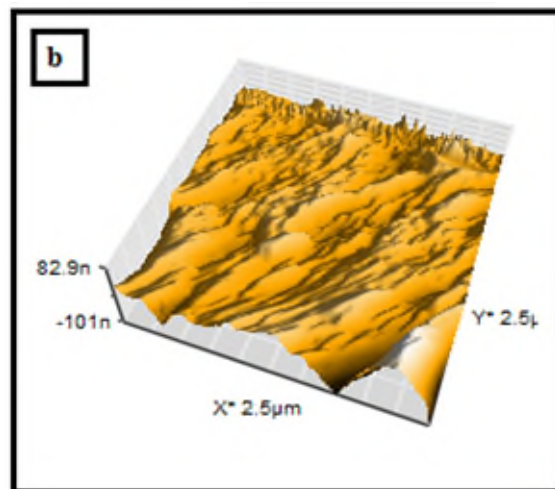
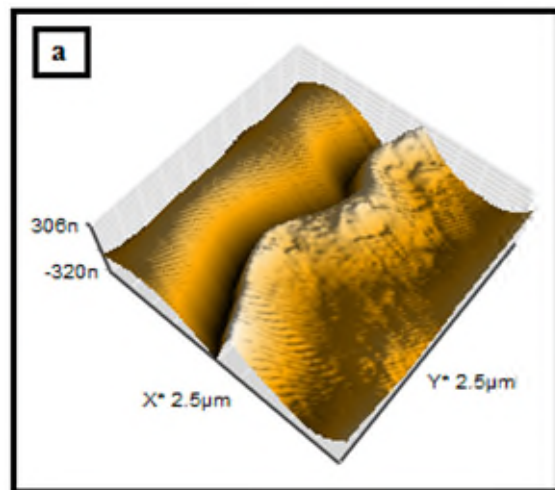


Fig. 11.

Table 1

Critical micelle concentration (C_{cmc}), effectiveness (π_{cmc}), maximum surface excess (Γ_{max}), and minimum area (A_{min}) values of the synthesized cationic surfactants [CS-PA & CS-MB] at 25 °C

Surfactant name	$C_{\text{cmc}} \times 10^3$ (mol dm ⁻³)	γ_{cmc} (mN m ⁻¹)	π_{cmc} (mN m ⁻¹)	$\Gamma_{\text{max}} \times 10^{10}$ (mol cm ⁻²)	A_{min} (nm ²)
CS-PA	2.29	29.0	43.0	1.48	1.12
CS-MB	2.34	28.7	43.3	1.51	1.10

Table 2

Weight loss data of carbon steel in 1 M HCl in the absence and presence of different concentrations of the synthesized cationic surfactants [CS-PA & CS-MB] at different temperatures

Inhibitor name	Inhibitor conc. (M)	25 °C			40 °C			55 °C			70 °C		
		k (mg cm ⁻² h ⁻¹)	θ	η_w (%)	k (mg cm ⁻² h ⁻¹)	θ	η_w (%)	k (mg cm ⁻² h ⁻¹)	θ	η_w (%)	k (mg cm ⁻² h ⁻¹)	θ	η_w (%)
Blank	1M HCl	0.3989	-	-	0.9705	-	-	2.0687	-	-	4.3041	-	-
CS-PA	5.0×10 ⁻⁵	0.1157	0.71	70.99	0.3222	0.67	66.80	0.8134	0.61	60.68	2.0551	0.56	56.23
	1.0×10 ⁻⁴	0.0764	0.81	80.85	0.2638	0.73	72.82	0.6822	0.67	67.02	1.6809	0.64	64.20
	5.0×10 ⁻⁴	0.0516	0.87	87.06	0.1895	0.80	80.47	0.5256	0.75	74.59	1.3644	0.71	70.94
	1.0×10 ⁻³	0.0325	0.92	91.85	0.1393	0.86	85.65	0.4128	0.80	80.04	1.0677	0.77	77.26
CS-MB	5.0×10 ⁻⁵	0.0862	0.78	78.38	0.2243	0.77	76.88	0.6059	0.71	70.71	1.3490	0.69	68.66
	1.0×10 ⁻⁴	0.0615	0.85	84.57	0.1686	0.83	82.63	0.4825	0.77	76.67	1.1298	0.74	73.75
	5.0×10 ⁻⁴	0.0425	0.89	89.34	0.1270	0.87	86.91	0.3695	0.82	82.14	0.9117	0.79	78.82
	1.0×10 ⁻³	0.0275	0.93	93.11	0.0794	0.92	91.82	0.2827	0.86	86.33	0.6830	0.84	84.13

Table 3

EIS parameters for CS corrosion in 1 M HCl in the absence and presence of different concentrations of CS-PA & CS-MB at 25 °C

The inhibitor	Conc. of inhibitor (M)	R_s ($\Omega \text{ cm}^2$)	Q_{dl} ($\text{m}\Omega^{-1}\text{s}^n \text{ cm}^{-2}$)	n	R_{ct} ($\Omega \text{ cm}^2$)	$Chsq$ $\times 10^3$	C_{dl} ($\mu\text{F cm}^{-2}$)	η_i (%)
Absence	0.00	2.49	0.5876	0.72	56.73	4.455	156.38	-
CS-PA	5×10^{-5}	2.50	0.1644	0.70	197.30	1.308	37.12	72.23
	1×10^{-4}	2.23	0.1147	0.71	281.90	1.328	24.87	80.56
	5×10^{-4}	1.62	0.0798	0.74	408.20	3.335	18.73	86.58
	1×10^{-3}	2.51	0.0554	0.77	601.40	4.292	11.62	90.89
CS-MB	5×10^{-5}	2.79	0.1358	0.71	242.00	1.108	35.56	77.36
	1×10^{-4}	2.22	0.0964	0.73	336.60	3.764	25.69	83.72
	5×10^{-4}	1.92	0.0655	0.83	502.60	3.552	17.16	89.10
	1×10^{-3}	3.22	0.0429	0.88	764.50	3.310	11.31	92.83

Table 4

Potentiodynamic polarization parameters for CS in 1M HCl with and without different concentrations of CS-PA & CS-MB at 25 °C

The inhibitors	Conc. of inhibitor (M)	E_{corr} (mV vs SCE)	i_{corr} (mA cm ⁻²)	β_a (mV dec ⁻¹)	β_c (mV dec ⁻¹)	η_p (%)
Blank	0.00	-484.3	0.4564	148.8	-164.0	-
CS-PA	5x10 ⁻⁵	-492.6	0.1326	155.5	-169.0	70.95
	1x10 ⁻⁴	-493.8	0.0883	168.6	-140.5	80.65
	5x10 ⁻⁴	-492.9	0.0636	174.8	-161.9	86.06
	1x10 ⁻³	-491.9	0.04339	204.2	-185.4	90.38
CS-MB	5x10 ⁻⁵	-473.4	0.0975	159.9	-167.8	78.64
	1x10 ⁻⁴	-500.1	0.0686	171.1	-131.5	84.97
	5x10 ⁻⁴	-473.2	0.0495	171.1	-177.4	89.15
	1x10 ⁻³	-490.5	0.0393	183.8	-184.9	91.39

Table 5

Activation energy (E_a , kJ mol⁻¹) values for carbon steel in 1 M HCl in the absence and presence of different concentrations of the synthesized cationic surfactants [CS-PA & CS-MB]

Conc. of inhibitor (M)	E_a (kJ mol ⁻¹) of CS-PA	E_a (kJ mol ⁻¹) of CS-MB
1M HCl	44.74	44.74
5×10^{-5}	54.12	52.38
1×10^{-4}	58.03	55.43
5×10^{-4}	61.54	58.17
1×10^{-3}	65.69	61.81

Table 6

Standard thermodynamic parameters of adsorption on carbon steel surface in 1 M HCl containing different concentrations of the synthesized cationic surfactants [CS-PA & CS-MB]

Inhibitor	Temperature (°C)	K_{ads} (M⁻¹)	ΔG°_{ads} (kJ mol⁻¹)	ΔH°_{ads} (kJ mol⁻¹)	ΔS°_{ads} (J mol⁻¹ K⁻¹)
CS-PA	25	48255	-36.67	-10.19	88.85
	40	39817	-38.02		88.89
	55	33189	-39.34		88.87
	70	28151	-40.67		88.86
CS-MB	25	69030	-37.56	-7.91	99.50
	40	59314	-39.05		99.51
	55	52825	-40.61		99.70
	70	45023	-42.01		99.43

Table 7

Some cationic surfactants investigated as corrosion inhibitors by other authors and this work for carbon steel in 1 M HCl

Inhibitor name	Inhibition efficiency (%)	References
4-amino-5-(2-hydroxy)phenyl-4H-1,2,4,-triazole-3-thiol (AHPTT)	70.5	[63]
4-amino-5-styryl-4H-1,2,4,-triazole-3-thiol (ASTT)	76.7	[63]
N-(3-(benzylideneamino)propyl)-N,N-dimethyldecan-1-ammonium bromide	82.93	[64]
N,N-bis(2-hydroxyethyl)-N-octylbenzo[d]thiazol 2-ammonium bromide	87.26	[65]
N-(3-(benzylideneamino)propyl)-N,N-dimethyldodecan-1-ammonium bromide	87.45	[64]
N-(3-(benzylideneamino)propyl)-N,N-dimethylhexadecan-1-ammonium bromide	88.02	[64]
N,N-dimethyl-N-(2-oxo-2-(2-(((1E,2E)-3-phenylallylidene)amino)ethoxy)ethyl) dodecan-1-aminium chloride [CS-PA]	91.85	This work
(E)-N-(2-(2-((4-methoxybenzylidene)amino)ethoxy)-2-oxoethyl)-N,N-dimethyl dodecan-1-aminium chloride [CS-MB]	93.11	This work

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