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Synthesis of selected Gemini Surfactants: Surface, biological activity and corrosion efficiency against hydrochloric acid medium

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ABSTRACT

In this paper, a family of novel Gemini surfactants from mono alkyl glycerol ether with different hydrophobe lengths (C_{12}, C_{18}) and different spacers as ethylene glycol, hydroquinol, N,N,N',N', tetramethylene diamine and sodium-bis-N,N(carboxymethyl) ethylene diamine were synthesized on a laboratory scale. The compounds were characterized by elemental analysis and spectroscopic data. Surface tension measurements were used to determine the critical micellar concentration (cmc), the maximum surface excess concentration (Γ_{max}), minimum area per molecule ($A_{min.}$) at air/water interface, Gibb's free energy of adsorption (ΔG_{ads}) and other parameters.The inhibition of dimeric surfactants on the corrosion of carbon steel (CS) in (1M) HCl was studied at 25℃ by weight loss. The obtained results showed that the prepared gemini compounds are excellent. The antimicrobial activity of dimeric compounds were tested against Gram-positive bacteria, Gram-negative bacteria and fungi. Dimeric surfactants are very attractive for catalysis and adsorption applications, biotechnology, enhanced oil recovery and as a paint additive.

Keywords : Dimeric surfactant, surface activity, inhibition efficiency, Biocidal activity.

INTRODUCTION

Gemini surfactants which consist of two hydrophobic chains and two polar head groups covalently attached by a spacer group, have attracted much attention in recent years[1,2]. Compared with conventional single-chain surfactants, Gemini surfactants show many superior features owing to their unique structures, such as good water solubility, low cmc, low kraft point, and excellent surface activity in aqueous solution[3]. Moreover, the nature of spacer group (length, hydropbobicity, flexibility and chemical structure is shown to be utmost importance in determining the solution properties of Gemini surfactant[4]. Geminis are also characterized by the number of heads (dimer, trimer, teteramer, etc.), spacer solubility (i.e., hydrophilic or hydrophobic), spacer length and molecular rigidity. This last property is determined largely by spacer type. Flexible spacers (such as methylene chains) allow to the head groups to move relative to one another, and to adopt a preferred separation distance and orientation based on

solvation energetics and entropic consideration. Inflexible spacers (such as stilbene derivatives) restrict the relative positions of the head groups and result in rigid molecules.

In the present work, the efficiency of prepared gemini surfactants as inhibitors for the corrosion of carbon steel in 1M HCl was discussed on the basis of weight loss. The adsorption of the surfactant on the metal surface can markedly change the corrosion – resisting property of the metal[5].

Organic compounds containing electronegative functional groups and π-electrons in triple or conjugated double bonds are usually good inhibitors of corrosion for many metals and alloys in an aggressive media; they can be adsorbed on the metal surface through the heteroatoms such as nitrogen, oxygen and sulphur. Corrosion inhibitors block the active sites and enhance the adsorption process, thus decreasing the corrosion rate and extending the life of the equipment. Nitrogen-based organic surfactants have been used successfully as corrosion inhibitor in the oil and gas filed even without an understanding of the inhibitor mechanism[6].

It is moreover known that Gemini surfactants demonstrate more effective antibacterial potency than the corresponding mono-surfactant[7,8].

Thus, the antibacterial activities of the synthesized surfactants (dodecyl and octadecyl) derivatives were tested against Gm +ve bacteria, Gm –ve bacteria and Fungi.

A series of double chain gemini surfactants was synthesized by two steps, the first step is the reaction of long chain fatty alcohol (C_{12}, C_{18}) with epichlorohydrin to form (3-alkyloxy-1-chloro-2-propanol, I, II). The second step was synthesis of the gemini surfactants by the reaction between compounds (I,II) and different spacer such as, ethylene glycol, hydroquinol, N,N, N\',N\' tetramethylene diamine and sodium –bis-N,N\' (carboxymethyl) ethylene diamine. The aim of this study is to investigate the effectiveness of these gemini surfactant as corrosion inhibitors and also as biocides for different microorganisms.

MATERIALS AND METHODS

Fatty alcohol, Epichlorohydrine, N,N,N\',N\', tetramethylene tetramine and ethylene diamine were purchased from Merck. Toluene isopropyl alochol, ethylene glycol, hydroquinol, chloroacetic acid and ethyl alcohol were supplied from Aldrich chemicals Co. as reagent grades and used as received.

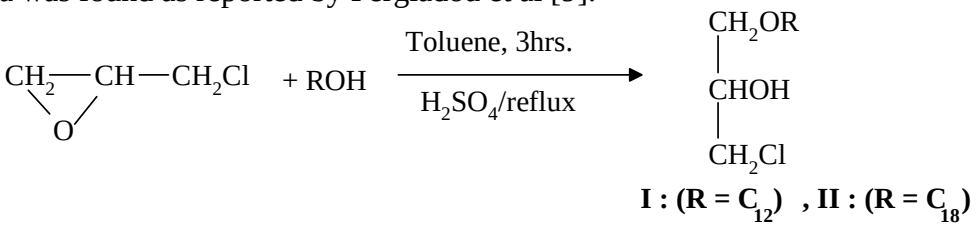
Tests were performed on carbon steel (CS) of the following composition : 0.11%C, 0.45% Mn, 0.04% P, 0.05% S, 0.25% Si, and the reminder is Fe. Doubly distilled water was used to prepare the solutions in all experiments. The surface tensions of the prepared surfactants were measured by using K6 Tensiometer (Krüss Corporation, Germany) using the du- Nouy ring method. Element analysis of the surfactants was carried out using a Perkin – Elmer series II analyzer.

Infrared spectroscopy IR (Perkin-Elmer FTIR 08) was used for infrared analysis and (NMR) spectrometer was used for ^{1}HNMR analysis (Bruker, 400 MHz, Russ, Germany) with tetramethylsilane as an internal standard.

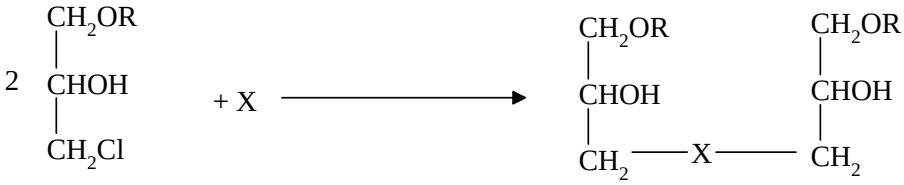
Synthetic procedures

General procedure for the synthesis of 3-alkyloxy-1-chloropropan-2-ols (I, II).

In a round–bottomed flask, aliphatic alcohol (C_{12}, C_{18}), (0.01 mmol), epichlorohydrin (0.01 mol) and concentrated sulfuric acid (0.l ml) were stirred under reflux in dried toluene as solvent for 3 hours. Pure compounds were obtained in yields of 60-75%. Their elemental analysis and ^{1}HNMR spectra was found as reported by Pergiadou et al [9].



I : (R = C_{12}) , II : (R = C_{18})



(Ia-d) , (IIa-d)

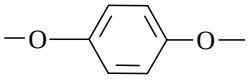
I , II	R	X
a	$C_{12}H_{25}$	$-O-(CH_2)_2-O-$
b	$C_{18}H_{37}$	
c		$(CH_3)_2N-(CH_2)_2-N(CH_3)_2$
d		$(CH_2COONa)-N-(CH_2)_2-N-(CH_2COONa)$

Table 1. Physicochemical properties of Gemini surfactants

Comp.	Formula	M.Wt.	Yield (%)	Elemental analysis (found/calculated) (%)		
				C	H	N
I_a	$C_{32}H_{66}O_6$	546	70.3	70.32 70.29	12.08 12.03	--
I_b	$C_{42}H_{78}O_2$	594	72.6	84.84 84.79	13.13 13.07	--
I_c	$C_{36}H_{78}O_4N_2Cl_2$	673	75.6	64.19 64.12	11.58 11.53	4.16 4.12
I_d	$C_{30}H_{70}O_8N_2Na_2$	704	74.4	51.13 51.09	9.94 9.89	3.97 3.91
II_a	$C_{44}H_{90}O_6$	714	69.8	73.94 73.89	12.60 12.57	--
II_b	$C_{48}H_{90}O_6$	762	75.1	75.59 75.56	11.81 11.77	--
II_c	$C_{48}H_{102}O_4N_2Cl_2$	841	76.3	68.48 68.45	12.12 12.08	3.32 2.99
II_d	$C_{48}H_{94}O_8N_2Na_2$	872	68.3	66.05 66.01	10.77 10.73	3.21 3.19

General procedure for synthesis of Gemini surfactants (I-II$_{a,b,d}$)

A solution of absolute ethanol containing, (1 mmol) of ethylene glycol or hydroquinol or sodium-bis-N,N\(carboxy methyl) ethylene diamine acetate were mixed with (2.2 mmol) of 3-alkyloxy-1-chloropropan-2-ol in the presence of 0.2 gm of sodium hydroxide as a catalyst. The reaction was stirred under reflux for 8hrs, acidified by an aqueous solution of hydrochoric acid. Compounds were purified by crystallization from acetone and characterized by elemental analysis in Table 1 and spectral data as shown in Fig.1. ^{1}HNMR ($CDCl_3$) of I_b as example δ 0.85

ppm (6H, t, $2CH_3$), 1.24 (m. $(CH_2)_x$, 3.37-3.41 (m, 8H, $CH_2O–CH_2$), 3.55-3.67 (m, 4H, $O–CH_2$), 4.8(s, 2H, OH) and 6.8 (4H,s, benzene ring spacer). Mass spectrum of compound I_b showed that, molecular ion peak at m/z 92 (100%) and 594 (6.76%) .

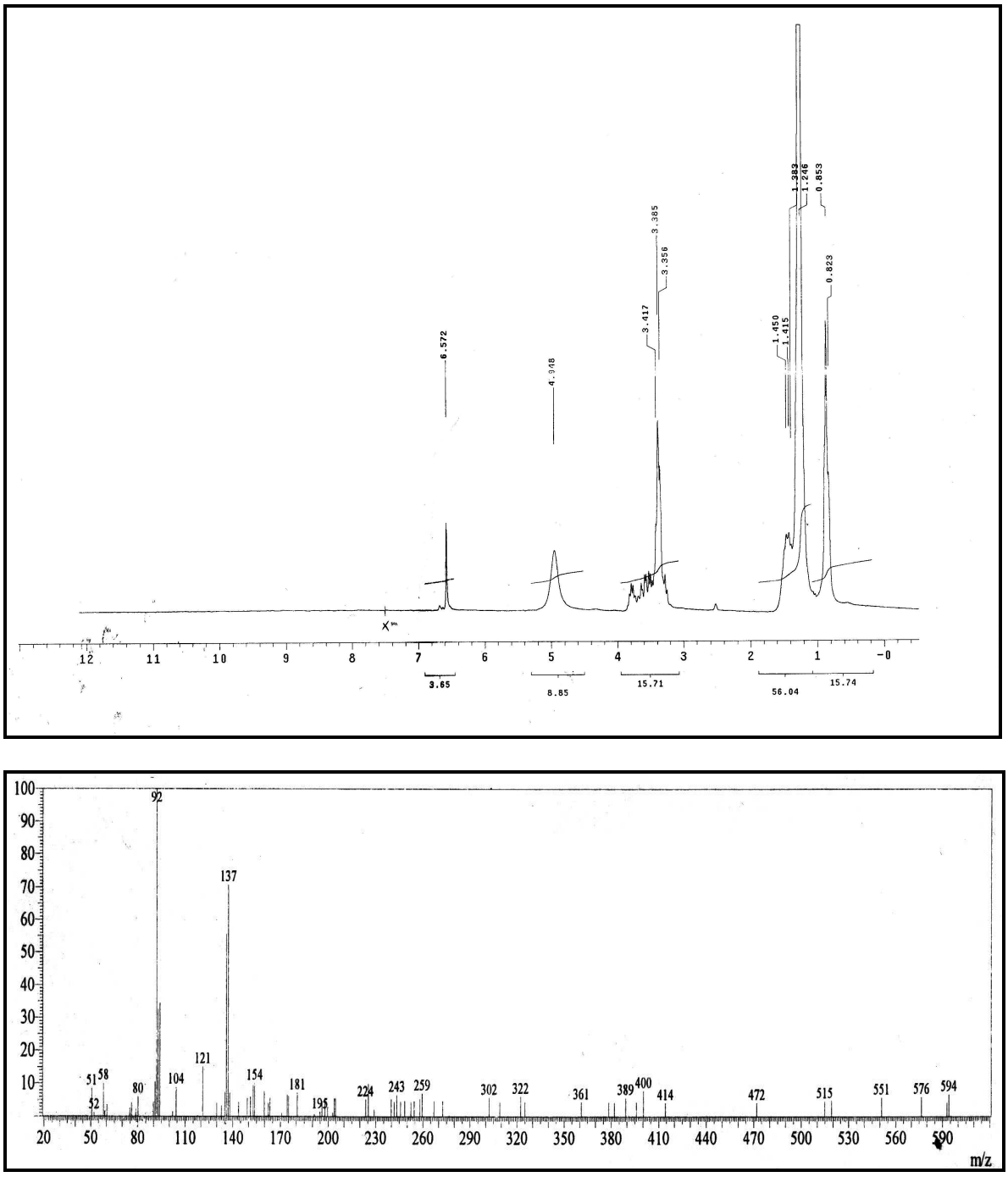


Fig. 1. ^{1}HNMR and mass spectra of compound of I_b (bis [(2-hydroxy-3-alkyloxy) propyloxy] benzene

Synthesis of Gemini surfactants (Ic,IIc)

In a round flask, a mixture of N,N,N\, N\-tetramethylene diamine (1 mmol) and (2.2. mmol) of 3-alkyloxy-1-chloropropan-2-ol in isopropyl alcohol (50 ml) was hearted under reflux for 8 hrs. After removal of the solvent by evaporation, the crude surfactants were recrystallized twice in dry acetone. The elemental analysis of the product is shown in Table 1. and spectral data in Fig. 2. ^{1}HNMR ($CDCl_3$) δ 0.88 (t, 6H, $2CH_3$), 1.2 (m, $(CH_2)_x$), 2.1 (4H,m, $2CH_2$) spacer), 3.29 (12H, s, $4NCH_3$)

3.44 (4H,t, 2-N–CH_2), 2.56(2H, s, 2OH), 3.37-3.53 (8H, CH_2O–CH_2). Mass spectrum for compound I_c showed that molecular ion peak at m/z 116 (100%) and 674 (25.21%) .

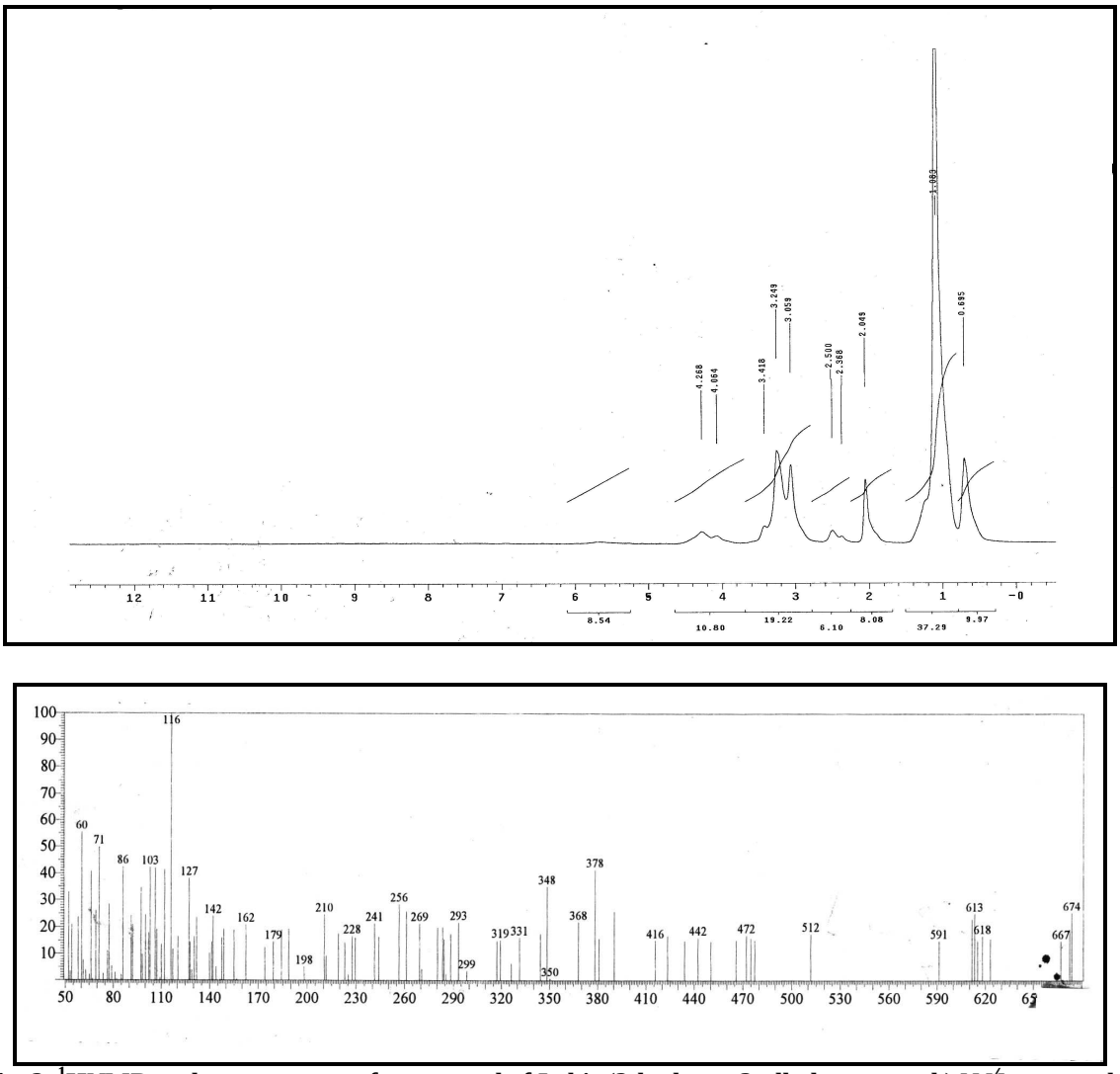


Fig. 2. ^{1}HNMR and mass spectra of compound of I_c bis (2-hydroxy-3-alkyloxy propyl) N,Ń tetramethyl ethylene diamine dichloride

Corrosion Measurement

A weight-loss technique[10] was used to measure the inhibiting efficiency of the prepared surfactants for corrosion of mild steel in HCl solutions at 25°C for 3hrs.

The experiments were performed on carbon steel of the following composition: 0.11% C, 0.45% Mn, 0.04% P, 0.05% S, 0.25% Si and the remainder is Fe.

Biological Activity

Biological activity of the synthesized surfactants was measured at the Fermentation Biotechnology and Applied Microbiology Center (FBAM, El-Azhar University) using inhibition zone technique in methanol as a solvent. The studied microorganisms were identified for each strain as G-ve bacteria: *Escherichia coli*, *Pseudomonas aeruginosa*, Gm+ve bacteria: *Staphylococcus aureus, Bacillis subtilis* and Fungi: *Aspergillus fumigatus, Penicillium italicum, Syncephalistrum racemosum* and *Candida albicans*[11].

RESULTS AND DISCUSSION

Surface Activity

The surface tension of water (72 mN/m at 25°C) is normally reduced to a value of 30-40 at the cmc of a surfactant. Gemini surfactants are generally superior over a conventional surfactant in terms of surface activity. This is due to the distortion of water by hydrophobic groups. In gemini surfactant two hydrophobic groups in a single molecule are more disruptive than individual chains in conventional surfactants. This in turn promotes the migration of a micelle to the air/water interface.

The cmc values of synthesized Gemini surfactants under study were determined from the break point of the surface tension (mN/m) versus concentration (on log scale) curve Fig. 3. As shown in Table 2, surface tension values depend on the hydrophobic chain length. Increasing the hydrocarbon length of the synthesized surfactants increases the surface tension considerably due to to the hydrophobic effect of the alkyl chains, the same results were recorded for other gemini surfactants [12, 13].

Table 2. Surface properties of the Gemini surfactants investigated (t = 25°C)

Surfactants	γ_{cmc} mN\m	CMC mol/L^{-1}	Γ_{max} x 10^6 (mol/m^2)	A x10^{20} (cm^2)	C_{20}	PC_{20}(mol dm^{-3})	cmc/C_{20}	$\Delta G°_{ads.}$ KJ/mol	$\Delta G°_{mic}$ KJ/mol	π_{cmc} (mN/m)
I_a	27	$2.24x10^{-3}$	2.92	56.85	$1.77 x10^{-3}$	2.75	1.27	-14.86	-15.42	46
I_b	27	$2.57x10^{-3}$	3.27	50.77	$1.56 x10^{-3}$	2.80	1.64	-14.52	-15.71	46
I_c	25	$5.01x10^{-3}$	2.92	56.85	$2.22 x10^{-3}$	2.65	2.25	-12.90	-14.87	48
I_d	26	$3.98x10^{-3}$	3.02	54.86	$2.79 x10^{-3}$	2.55	1.42	-13.46	-14.30	47
II_a	29.5	$1.99x10^{-3}$	2.63	63.13	$1.58 x10^{-3}$	2.8	1.26	-15.14	-17.70	43.5
II_b	33	$2.51x10^{-3}$	3.18	52.21	$1.55 x10^{-3}$	2.81	1.61	-14.58	-15.76	40
II_c	28	$4.67x10^{-3}$	2.90	57.25	$2.21 x10^{-3}$	2.66	2.11	-13.07	-14.92	45
II_d	31	$2.81x10^{-3}$	2.91	57.05	$1.98 x10^{-3}$	2.70	1.41	-14.31	-15.14	42

γ_{CMC}, surface tension at the CMC, CMC critical micelle concentration; Γ_{max}= the surface excess at the air/water interface; A, area occupied by the surfactant molecule at the interface; PC_{20}, (-log) to reduce the surface tension of water by 20mN/m; $\Delta G°_{mic}$, standard free energies of micellization;' $\Delta G°_{ads}$, energies of adsorption.

It was observed that the γ_{CMC} values increased with increased bulkiness of spacer phenylene connecting group (I_b and II_b), which is rigid and bulky as compared with other connecting group, makes a negative contribution to effective adsorption on the surface. The CMC values of $I_{a,b}$, $II_{a,b}$ with ethylene and phenylene connecting groups were found to be relatively lower than the others.

The surface pressure at the cmc is given as $\pi_{cmc} = \gamma_o - \gamma_{cmc}$, where γ_o and γ_{cmc} are the surface tension of pure water and the surface tension at cmc. The efficiency can be characterized by the value of logarithm of the surfactant concentration C_{20} at which the surface tension of water is reduced by 20 mNm^{-1}. The PC_{20} (–log C_{20}) value measures the efficiency of adsorption of surfactant at the air/water interface. The values of PC_{20} of compounds (I_{a-d}) and (II_{a-d}) listed in Table 2. It was showed that the efficiency of adsorption is not significantly effected by the chain length of the hydrophobic alkyl group of these types of gemini surfactants.

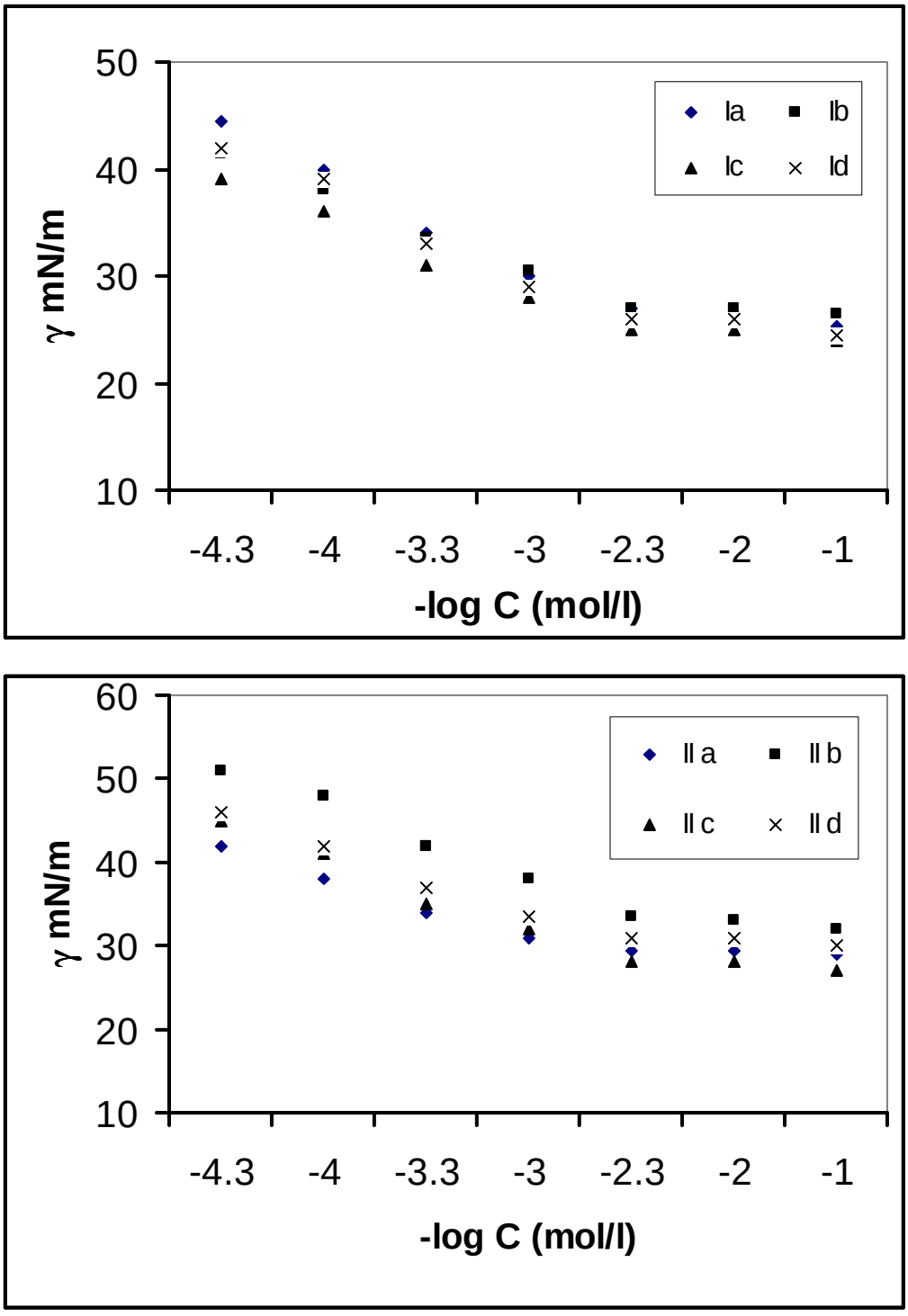


Fig. 3. Surface tension versus -log of concentration c, for Gemini surfactants (I_{a-d}) and (II_{a-d}) at 25°C

From the surface excess concentration values (Γ_{max}), it is possible to calculate the minimum area per molecule at air/water interface (A_{min}) by Gibbs adsorption isotherm [14] equation. From equation[14]. From Table 2 Γ_{max} values were observed to decrease and A_{min} values were observed to inverse when head group polarity of bis-surfactants increased from (C_{12}–C_{18}).

The negative values of ΔG of micellization (ΔG_{mic}) and ΔG of adsorption (ΔG_{ads}) mean that gemini surfactants have ability to form micelles in solution and to adsorb at the air/water interface.

The change in the values of both $-\Delta G^{\circ}_{mic}$ and $-\Delta G^{\circ}_{ads}$ suggesting that a driving force of micellization or adsorption is derived from the hydrophobic moieties due to the interaction between hydrocarbon chains[15].

Corrosion inhibition efficiencies

The inhibition effect of Gemini surfactants on carbon steel (CS) in 1M HCl was studied at different concentrations by weight loss method. The use of hydrochloric acid in pickling of metals, acidization of oil wells and cleaning of scales in more economical, efficient and trouble-free, than other mineral acids[16].

The most well-known acid inhibitors are organic compounds containing nitrogen, phosphorus, sulfur, and oxygen atoms. Iron is well known for its coordination affinity to nitrogen, sulfur and oxygen bearing ligands. Efficient adsorption may be due to either the electronegative donor atom N, O and Cl, the π electron of the aromatic system or the quaternary ammonium ion. The surfactant inhibitors have many advantages such as high inhibition efficiency, low price, low toxicity and easy production[17,18].

The corrosion rate (k) was calculated from the following equation[19].

$$K = \frac{W}{St}$$

Where W is the average weight loss of three parallel carbon steel sheets, S the total area of the specimen and t is the immersion time with the calculated corrosion rate, the inhibition efficiency ($\eta_w\%$) and surface coverage (θ) of inhibitors on surface of carbon steel was calculated using the following equation[20]:

$$\eta_w\% = \left(\frac{(K_o - K)}{K^o} \right) x100$$

Where K^o and K are the values of the corrosion rate without and with addition of inhibitor, respectively.

$$\theta = \frac{(K^o - K)}{K^o}$$

Since the corrosion inhibition mechanism of surfactants depends on their ability to adsorb on the corroding surface, forming a protective layer, so, the critical micelle concentration (cmc) may be considers a key factor in determining the effectiveness of surfactants as corrosion inhibitors[21]. Below the cmc, as the surfactant concentration increases, the surfactant molecules tent to adsorb adsorbed on the metal surface, leading to increase the inhibition efficiency of the surfactant.

The corrosion parameters namely corrosion rate (K), inhibition efficiency ($\eta_w\%$) and surface coverage (θ) at different concentration of the synthesized surfactants in 1 M HCl at 25°C are listed in Tables 3-4.

The negative value of ΔG_{ads} means that the adsorption of the prepared gemini surfactants on carbon steel surface is a spontaneous process and also show a strong interaction of the inhibitor molecule onto the carbon steel surface[22,23] .

Table 3. Weight loss results of carbon steel corrosion for different concentrations of the synthesized Gemini surfactants (I_{a-d}) at 25°C for 3hrs

Molecule	Conc. of inhibitor (M)	K($mgcm^2 h^{-1}$)	θ	η_w%
1 M HCl	0.00	0.107	00	00
Ia	1×10^{-3}	0.028	0.7383	73.83
	5×10^{-3}	0.025	0.7663	76.64
	1×10^{-2}	0.022	0.7943	79.44
	5×10^{-2}	0.019	0.8224	82.24
	1×10^{-1}	0.017	0.8411	84.24
Ib	1×10^{-3}	0.029	0.7289	72.90
	5×10^{-3}	0.623	0.7850	78.50
	1×10^{-2}	0.018	0.8317	83.18
	5×10^{-2}	0.011	0.8971	89.72
	1×10^{-1}	0.009	0.9158	91.59
Ic	1×10^{-3}	0.015	0.8598	85.98
	5×10^{-3}	0.012	0.8878	88.79
	1×10^{-2}	0.010	0.9065	90.65
	5×10^{-2}	0.008	0.9252	92.52
	1×10^{-1}	0.005	0.9532	95.33
Id	1×10^{-3}	0.022	0.7943	79.44
	5×10^{-3}	0.016	0.8504	85.05
	1×10^{-2}	0.013	0.8785	87.85
	5×10^{-2}	0.010	0.9065	90.65
	1×10^{-1}	0.007	0.9343	93.46

Table 4. Weight loss results of carbon steel corrosion for different concentrations of the synthesized Gemini surfactants (IIa-d) at 25°C for 3hrs

Molecule	Conc. of inhibitor (M)	K($mgcm^2 h^{-1}$)	θ	η_w%
1 M HCl	0.00	0.957	--	--
II_a	1×10^{-3}	0.153	0.8401	84.01
	5×10^{-3}	0.123	0.8714	87.15
	1×10^{-2}	0.109	0.8861	88.61
	5×10^{-2}	0.093	0.9028	90.28
	1×10^{-1}	0.078	0.9184	91.84
II_b	1×10^{-3}	0.168	0.8244	82.45
	5×10^{-3}	0.113	0.8819	88.19
	1×10^{-2}	0.085	0.9111	91.12
	5×10^{-2}	0.067	0.9299	92.99
	1×10^{-1}	0.058	0.9393	93.94
II_c	1×10^{-3}	0.180	0.8119	81.19
	5×10^{-3}	0.043	0.9550	95.50
	1×10^{-2}	0.033	0.9655	96.55
	5×10^{-2}	0.029	0.9696	96.97
	1×10^{-1}	0.024	0.9749	97.49
II_d	1×10^{-3}	0.071	0.9258	92.58
	5×10^{-3}	0.054	0.9435	94.36
	1×10^{-2}	0.042	0.9561	95.61
	5×10^{-2}	0.034	0.9613	96.13
	1×10^{-1}	0.025	0.9738	97.39

Generally, values of ΔG_{ads} around – 20Kj mol^{-1} or lower are consistent with the electrostatic interaction between the charged molecules and the charged metal (physisorption),

while those more negative than -40Kj mol^{-1} involve charge sharing or transfer from the inhibitor molecules to the metal surface to form a coordinate type of bond (chemisorption)[24,25]. The calculated ΔG_{ads} values indicated that the adsorption mechanism of the prepared gemini surfactants on carbon steel in 1M HCl solution is a physical adsorption.

The high value of Γ_{max} indicates that more molecules are adsorbed on the metal surface, which implies close packing of the adsorbed molecules leading to more electrostatic interaction of the well packed adsorbed layer and more homogenous adsorbed film.

It is clear that the inhibition efficiency generally increased by increasing the number of repeated methylene groups in the hydrophobic chains and the concentration of the synthesized inhibitors

The maximum inhibition efficiency is observed for compounds (I_c, II_c, I_d, II_d). This means that these compounds are then excellent inhibitors due to the presence of the polar atoms such as nitrogen and oxygen.

Fig. 4-5 represents the relation between the inhibitor concentration (-log C) and inhibition efficiency of the prepared surfactants. It is clear that the inhibition efficiency increased by increasing concentration.

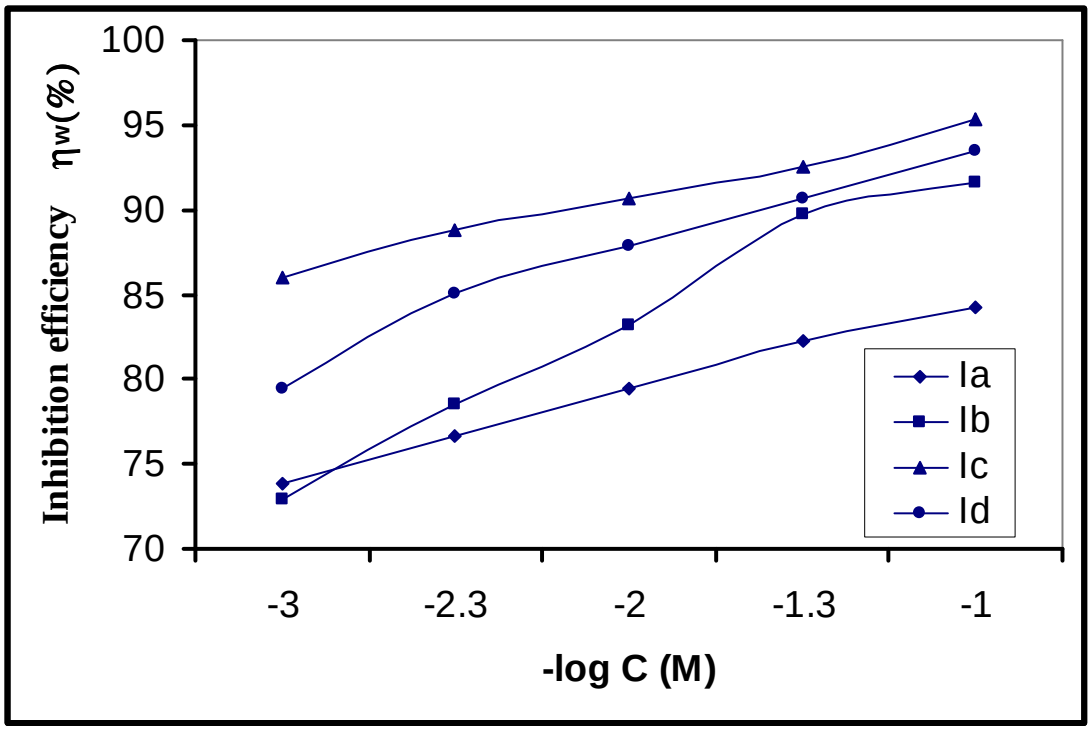


Fig. 4. Variation of the inhibition efficiency with concentration of the synthesized Gemini surfactants (I_{a-d}) at 25°C.

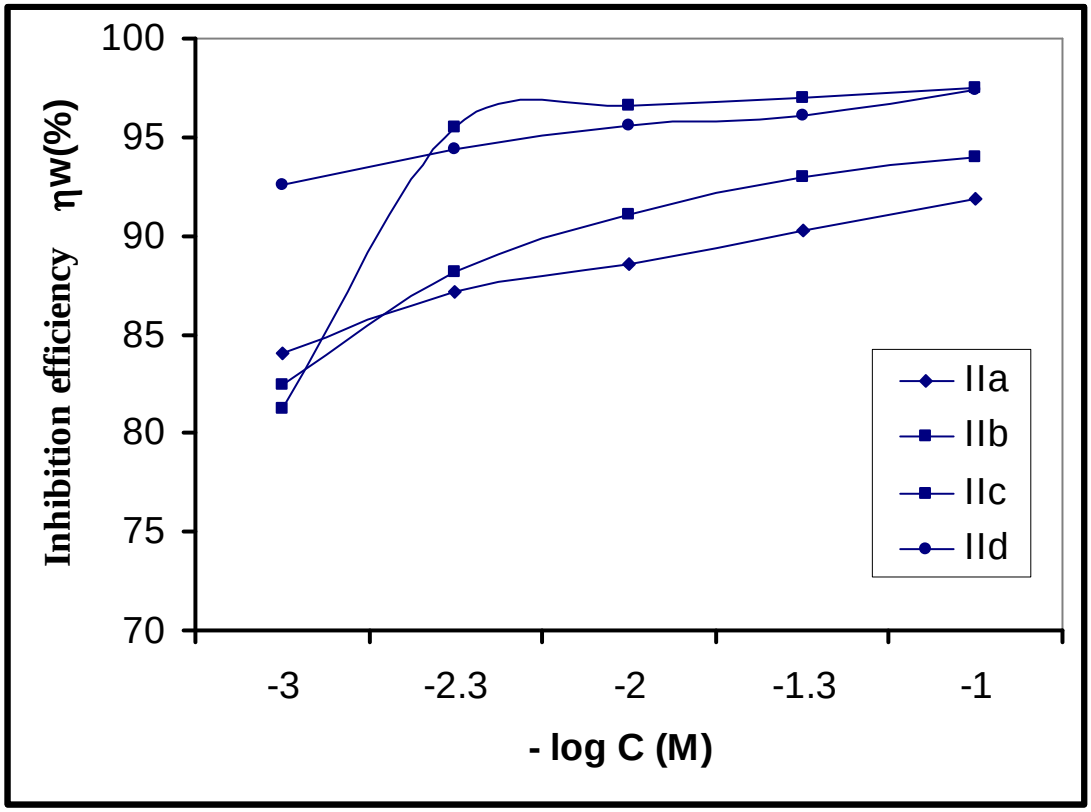


Fig. 5. Variation of the inhibition efficiency with concentration of the synthesized Gemini surfactants of (II_{a-d}) at 25°C.

Biological Activity

The synthesized Gemini surfactants were evaluated for their biocidal activities against different types of bacteria and Fungi. Tables 5-6 summarizes the results of the diffusion agar technique.

As shown in Table 5, compounds (I_{a-d}), are more effective biocides against Gm+ve bacteria and fungi but less with *P.aeruginosa* and *E.coli* Gm-ve bacteria.

Gram-negative bacteria were less sensetive than Gram-positive bacteria to the tested compounds probably because their outer membranes are less permeable to the amphiphilic compounds. Surfactants with 18 carbon atoms in the alkyl chain of the hydrophobic group are less active than those with 12 carbon atoms, the same results were recorded for the othe gemini surfactants[26].

The highest antibacterial activities were observed for the (dodecyl) derivatives $I_{a,c,d}$ which are characterized by the smallest substitutions (hydrogen and methyl groups).

Table 6 shows the MICs values (µg/ml) for the compounds $I_{a,c,d}$ exhibited the best performance in the preliminary screening. MICs values corroborated an antimicrobial potency dependent on the target microorganism (Gram+ve bacteria> fungi>Gram –ve bacteria).

Thus, the results showed that in general the compounds had a broad spectrum biocidal activity against the tested Gram+ve bacteria and fungi.

The compound $I_a$and I_d exhibited a good antibacterial potency against B.subtilis with MIC value of 39µg/ml while compound I_c exhibited a good antifungal potency against *P.italicum* with MIC value 19µg/ml. Also compound I_a was active toward Gm+ve bacteria with MIC value 39µ/ml.

Table 5. Antibacterial and Antifungal Activity (Inhibition zone (mm)) of Gemini surfactant using diffusion agar technique[a]

Tested Organism Compound	Gram positive bacteria		Gram negative bacteria		Fungi			
	B. Subtilis	*S. Aureus*	*E. Coli*	*P. Aeruginosa*	*C. Albicans*	*A. Fumigatus*	*P. Italicum*	*S. Racemosum*
I_a	13 17	14 17	0 18	0 0	5 8	9 14	6 9	8 12
I_b	9 11	5 7	5 7	0 0	7 9	3 14	10 13	8 14
I_c	7 9	9 10	5 8	0 5	8 11	17 19	10 14	9 15
I_d	5 8	7 9	7 11	0 0	4 5	8 10	7 9	5 6
II_a	7 10	5 9	0 0	0 0	7 11	3 5	0 0	0 3
II_b	7 10	5 8	0 0	0 0	3 7	6 11	4 6	6 9
II_c	5 8	5 8	0 0	0 0	2 6	9 14	3 6	8 12
II_d	11 15	9 12	0 0	0 0	7 12	9 12	0 7	0 0
St[b]	18 22	6 15	20 27	5 11	10 19	18 24	9 19	13 21

a: zone of growth of inhibition (mm) (concentration of tested of tested sample : 2.5; 5 mg/ml) respectively)
b: chloram phenicol was used as standard antibacterial agent and terbinafin as standard antifungal agent.

Table 6. Minimal Inhibitory concentration (MIC) (µg/ml) values of Gemini surfactants

Tested organism Compound	Gram positive bacteria		Gram negative bacteria	Fungi			
	B. Subtilis	*S. Aureus*	*E. Coli*	*C. Albicans*	*A. Fumigatus*	*P. Italicum*	*S. Racemosum*
Ia	39	39	5000	625	313	625	313
Ic	625	313	625	625	95	19	313
Id	39	313	313	625	313	313	625

Dissolved in methanol

CONCLUSION

New types of amphipathic compounds with two hydroxyl groups and two lipophilic alkyl chains studied in this work were found to possess excellent water-solubility, micelle forming property and ability to lower surface tension. The prepared compounds were exellent corrosion inhibitors due to the presence of atoms such as nitrogen and oxygen.

The biocidal results of these gemini surfactants imply that the chemical structure and the length of an alkyl chain had a significant effect on the antimicrobial activity, the results showed that compounds $I_{a,c,d}$had a broad spectrum for bacteria and fungi, the other two compounds I_c, II_c showed a higher inhibition efficiency.

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