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## Synthesis and properties of biodegradable cationic gemini

## surfactants with diester and flexible spacers

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## Abstract

A series of cationic gemini surfactants with diester and flexible spacers, namely  $C_{12}$ -PG- $C_{12}$ ,  $C_{14}$ -PG- $C_{14}$  and  $C_{16}$ -PG- $C_{16}$ , were synthesized, purified and characterized. The surface properties and aggregation behavior of the gemini surfactants were investigated by surface tension, electrical conductivity, fluorescence and krafft point. These gemini surfactants possess higher surface activity than the traditional monomeric surfactants. The thermodynamic parameters exhibited that the micellization was a spontaneous and exothermic process in environment. The micellization process became less favorable with the decrease of alkyl chain length and the increase of temperature. Steady-state fluorescence measurements revealed that the micropolarity and aggregation number of micelles decreased with the increase of hydrocarbon chain length. The Krafft points were taken as less than 0°C, which indicated the synthesized gemini surfactants had good water solubility. The biodegradability of the gemini surfactants were evaluated in river water using Closed Bottle tested and showed their high biodegradation ratio in the open environment due to the diester bond inserting in the flexible spacer of surfactant molecules.

Keywords Gemini surfactants, Diester and fexible sacers, Surface properties, Biodegradability

## **1** Introduction

Gemini or dimeric surfactants, consisting of two single alkyl tails and two polar head groups covalently linked by a spacer group [1-3], have attracted more and more research attentions because of the lower critical micellar concentration (CMC), the better adsorption behavior, the superior aqueous solution, and the tendency to form micelles of different shapes and dimensions even at low concentration compared to the corresponding monomeric surfactants [4-7]. Among them, cationic gemini surfactants have been widely developed because their synthetic route from readily available starting materials is straight-forward. In recent years, cationic gemini surfactants show their great potential as a next generation surfactant for biomedical and industrial applications such as effective corrosion inhibitors [8,9], bactericidal agents [10-12], gene delivery agents [13,14], drug entrapment and release [15], and detergents, etc. However, the applicability of cationic gemini surfactants is usually hampered by certain environmental concerns and toxicity

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issues [16]. Therefore, great efforts have been taken to overcome these popular problems that exist for cationic gemini surfactants. The main approach was to introduce an easily cleavable bond or readily biodegradable groups into the structure of cationic gemini surfactants.

Most recently, there have been several reports focus on the physical and chemical properties of cationic gemini surfactants with ester and flexible spacers in literatures [17-19]. It is due to ester and flexible spacers, cationic gemini surfactants can not only increase the biodegradation ratio, but also improve the overall performance of gemini surfactants and extend the potential application. For example, Tehrani-Bagha et al. presented a new type of cationic gemini surfactant with an ester bond inserted into a short space. The cationic gemini surfactant designed in this way was observed to be classified as readily biodegradable [17]. Bergström et al reported a novel type of cationic gemini surfactants containing an ester group and found that the growth behavior, geometrical shape and second CMC of micelles formed were conspicuously differ depending on the length of the gemini surfactant spacer group [18]. Parikh et al exploited two series (ester/amide and polymethylene spacers) of cationic gemini surfactants as potential plasmid DNA binding vectors, and the ester spacer based cationic gemini surfactants showed higher surface activity, readily biodegradable and lower toxicity to membranes among the synthesized gemini surfactants, which may become a potential vector for biomedical applications such as drug delivery or gene transfection/therapy [19]. In our previous work, we have synthesized a series of cationic gemini surfactants with rigid spacer, and investigated their surface and aggregation properties at different temperature in organic co-solvents. However, due to the poor solubility in aqueous solution, these gemini surfactants were difficult to degrade, which limited their potential application.

Enlightened by the advantages of inserting ester bonds in the structure of gemini surfactants, in this paper, we reported the design and synthesis of a group of cationic gemini surfactants with diester and flexible spacers containing different alkyl chains. The diester and flexible spacers were introduced to design our gemini surfactants with the expectation that the problem about hard degradation can be solved and the properties of gemini surfactants can be further improved. The gemini surfactants designed in this way were observed to exhibit good biodegradability. Furthermore, the surface properties of these gemini surfactants were studied, including their surface activity, thermodynamic parameters, and micropolarity. The chemical structure of the synthesized gemini surfactants is shown in Scheme 1.

### 2 Experiment

#### 2.1 Materials

1-bromododecane (>98%), 1-bromotetradecane (>98%), 1-bromohexadecane (>98%), acetone, dimethylamine (33% aqueous solution), chloroacetyl chloride ( $\geq$ 98%), ethyl acetate, ethanol were purchased from Sinopharm Chemical Reagent Corporation (Shanghai, China). Pyrene (99%) and 1,3-dihydroxypropane (98%) were purchased from Sigma-Aldrich and used as received without further purification. Ultrapure water was used in all experiments.

<sup>1</sup>H NMR spectra were recorded on a Bruker AV 400 NMR Spectrometer (Bruker Corporation, Switzerland, 400 MHz). Mass spectra were recorded on a GC-MS (Aglient, USA). Elemental analyses were carried out on a vario EL III Element Analyzer (Elementer Corporation, Germany). The infrared (IR) spectra were measured on a Japan FT/IR-430 spectrometer as KBr pallets.

#### 2.2 Synthesis

### 2.2.1 Propane-1,3-diylbis(chloroacetate) (1)

1,3-dihydroxypropane (0.10 mol, 7.61 g) in dichloromethane (20 mL) was added drop wise to a stirred dichloromethane (40 mL) solution of chloracetyl chloride (0.22 mol, 24.86 g) at 0°C. Then the mixture was stirred for 4 h at 40°C, and neutralized by saturated sodium bicarbonate solution. The organic layer was separated, washed with water, and dried over anhydrous magnesium sulfate. The solvent was removed under vacuum to give compound **1** as a colorless liquid (22.12 g, 98.56% content for GC-MS, 95.20% yield based on 1,3-dihydroxypropane). <sup>1</sup>H NMR (400 MHz CDCl<sub>3</sub>, TMS)  $\delta$  ppm: 2.05-2.09 (m, 2H), 4.06-4.12 (s, 4H), 4.27-4.31 (m, 4H); IR (KBr) cm<sup>-1</sup>: 2956, 1758, 1311, 1183, 789; GC-MS (m/z: 228.9 g mol<sup>-1</sup>), 135.0 (M-OOCCH<sub>2</sub>Cl), 107.0 (M-CH<sub>2</sub>CH<sub>2</sub>OOCCH<sub>2</sub>ClC<sub>11</sub>H<sub>23</sub>), 77.0 (M-OCH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>OOCCH<sub>2</sub>Cl).

#### 2.2.2 Compounds 2-4

A mixture of 1-bromoalkane (0.1 mol) and dimethylamine (33% aqueous solution, 0.5 mol, 5 equiv) in ethanol (40 mL) was placed in a dried 3-necked flask (150 mL). After stirring for 24 h at reflux, the reaction mixture was cooled to room temperature. The solvent was removed under vacuum, and the residue was poured into the saturated sodium bicarbonate solution (60 mL). The mixture was extracted with ethyl acetate, and the extract phase was washed with water, then dried over anhydrous magnesium sulfate. The solvent was removed to and the residue was purified by distillation to give compounds **2-4** as colorless oily products.

*N*,*N*-Dimethyldodecylamine (**2**, 20.15 g, 98.96% content for GC, 93.62% yield based on 1-bromododecane). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, TMS)  $\delta$  ppm: 0.86-0.90 (t, *J* = 8.0 Hz, 3H), 1.26-1.28 (d, *J* = 8.0 Hz, 18H), 1.47 (s, 2H), 2.23-2.30 (m, 8H); IR (KBr) cm<sup>-1</sup>: 2925, 2854, 1464, 721; GC-MS (m/z: 213.3 g mol<sup>-1</sup>), 58.2 (M-C<sub>11</sub>H<sub>23</sub>).

*N*,*N*-Dimethyltetradecylamine (**3**, 22.10 g, 99.32% content for GC, 91.08% yield based on 1-bromotetradecane). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, TMS)  $\delta$  ppm: 0.86-0.90 (t, *J* = 8.0 Hz, 3H), 1.26 (s, 22H), 1.47 (s, 2H), 2.23-2.30 (m, 8H); IR (KBr) cm<sup>-1</sup>: 2924, 2853, 1465, 721; GC-MS (m/z: 241.3 g mol<sup>-1</sup>), 58.2 (M-C<sub>13</sub>H<sub>27</sub>).

*N*,*N*-Dimethylhexadecylamine (**4**, 24.24 g, 99.42% content for GC, 89.59% yield based on 1-bromohexadecane). <sup>1</sup>H NMR (400 MHz CDCl<sub>3</sub>, TMS)  $\delta$  ppm: 0.86-0.90 (t, *J* = 8.0 Hz, 3H), 1.26 (s, 26H), 1.47 (s, 2H), 2.21-2.26 (m, 8H); IR (KBr) cm<sup>-1</sup>: 2924, 2853, 1463, 720; GC-MS (m/z: 269.3 g mol<sup>-1</sup>), 58.1 (M-C<sub>15</sub>H<sub>31</sub>).

### 2.2.3 Gemini surfactants

A mixture of propane-1,3-diylbis(chloroacetate) (10 mmol) and *N*,*N*-dimethylalkylamine (44 mmol, 2.2 equiv) in ethyl acetate (60 mL) was placed in a dried 3-necked flask (150 mL). After stirring for 24 h at reflux, the reaction mixture was cooled to room temperature. The precipitate was collected by filtration and washed with plenty of ethyl acetate, then dried under reduced pressure. The crude product was recrystallized for two times from acetone/acetonitrile (3:1) to afford the gemini surfactants as white crystals.

**C**<sub>12</sub>-**PG-C**<sub>12</sub> (4.93 g, 75.73% yield based on propane-1,3-diylbis(chloroacetate)). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, TMS)  $\delta$  ppm: 0.86-0.90 (t, *J* = 8.0 Hz, 6H), 1.25-1.33 (m, 36H), 1.75 (s, 4H), 2.07-2.11 (m, 2H), 3.54 (s, 12H), 3.75-3.80 (t, *J* = 8.0 Hz, 4H), 4.34-4.38 (t, *J* = 8.0 Hz, 4H), 5.32 (s, 4H); IR (KBr) cm<sup>-1</sup>: 2924, 2854, 1748, 1630, 1467, 1410, 1199, 1040, 898, 722, 602; Anal. Calcd. for C<sub>35</sub>H<sub>72</sub>N<sub>2</sub>O<sub>4</sub>Cl<sub>2</sub>%: C, 64.09; H, 11.07; N, 4.27. Found %: C, 63.88; H, 11.01; N, 4.31.

**C**<sub>14</sub>-**PG-C**<sub>14</sub> (5.85 g, 85.29% yield based on propane-1,3-diylbis(chloroacetate)). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, TMS)  $\delta$  ppm: 0.86-0.90 (t, *J* = 8.0 Hz, 6H), 1.25-1.34 (m, 44H), 1.75 (s, 4H), 2.07-2.10 (m, 2H), 3.54 (s, 12H), 3.75-3.80 (t, *J* = 8.0 Hz, 4H), 4.34-4.38 (t, *J* = 8.0 Hz, 4H), 5.32 (s, 4H); IR (KBr) cm<sup>-1</sup>: 2924, 2853, 1748, 1636, 1466, 1409, 1200, 1040, 904, 721; Anal. Calcd for C<sub>39</sub>H<sub>80</sub>N<sub>2</sub>O<sub>4</sub>Cl<sub>2</sub>%: C, 65.79; H, 11.33; N, 3.94. Found %: C, 65.53; H, 11.33; N, 3.99.

**C**<sub>16</sub>-**PG-C**<sub>16</sub> (7.60 g, 85.93% yield based on propane-1,3-diylbis(chloroacetate)). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, TMS) δ ppm: 0.84-0.88 (t, J = 8.0 Hz, 6H), 1.23-1.32 (m, 52H), 1.75 (s, 4H), 2.06-2.09 (m, 2H), 3.50 (s, 12H), 3.72-3.76 (m , J = 8.0 Hz, 4H), 4.33-4.38 (t, J = 10.0 Hz, 4H), 5.36 (s, 4H); IR (KBr) cm<sup>-1</sup>: 2920, 2850, 1666, 1648, 1540, 1492, 1467, 1326, 1291, 1159, 729; Anal. Calcd for C<sub>43</sub>H<sub>88</sub>N<sub>2</sub>O<sub>4</sub>Cl<sub>2</sub>%: C, 67.24; H, 11.55; N, 3.65. Found %: C, 66.92; H, 11.48; N, 3.69.



Scheme 1. Synthetic route of the gemini surfactants C12-PG-C12, C14-PG-C14 and C16-PG-C16.

### 2.3 Surface tension measurement

The surface tensions of the gemini surfactant solutions at water-air interface were investigated by using a Wilhelmy plate technique (Krüss K20 Tensiometer, Germany) [20] at 298.15  $\pm$  0.1 K, and the surface tension values were measured at least three times. The surface tension of pure water was obtained as being 71.99  $\pm$  0.05 mN m<sup>-1</sup> at 298.15 K. All solutions were prepared with ultrapure water.

### 2.4 Electrical conductivity measurement

The conductivity measurements were carried out using a direct reading conductometer, model S320 (Mettler-Toledo GmbH, Switzerland) at different temperatures, KCl solutions (0.1 M and 0.01 M) were used for calibration of conductivity cell. The conductivity was recorded when its value fluctuated less than 1% over a 5 min interval. The tested solution was added to a container kept in a thermostat (THD 0506, NingBo TianHeng Instrument Factory, China) with the temperature accuracy of  $\pm 0.01$  °C. The critical micelle concentration (CMC) of gemini surfactants was obtained at the break point of the specific conductivity *versus* concentration curve [21].

### 2.5 Fluorescence Measurement

Steady-state fluorescence measurements were performed using an F-4600 fluorescence spectrophotometer (Hitachi High-Technologies Corp, Tokyo Japan). Pyrene was used as a fluorescence probe and cetylpyridinium chloride (CPC) as a quencher. The excitation wavelength was 336 nm, the emission spectra were scanned over the spectrum range of 345-460 nm, and the slit widths of excitation and emission were fixed at 5.0 and 2.5 nm, respectively. The ratio of the

intensities of the first peak (around 373 nm) to the third peak (around 384 nm) was used as an index of the polarity of the pyrene-solubilizing medium [22]. The intensity ratio of the first peak to the third peak ( $I_1/I_3$ ) can be taken as a measure of the microenvironment polarity, which is high in polar media and low in hydrophobic environments.

An aliquot of the ethanolic pyrene solution was transferred into a volumetric flsk and the solvent was evaporated. The fixed concentration of gemini surfactant solution (20 CMC) was added and the pyrene concentration was kept at  $1 \times 10^{-5}$  M. The quencher concentration was varied from 0 to  $9 \times 10^{-5}$  M. The fluorescence intensities of the peaks decrease with the increase of the quencher concentration without appearance of any new peak.

### 2.6 Krafft Temperature Measurements

A clear aqueous solution of the gemini surfactant (0.5 wt %, above the CMC ) was prepared by dissolving surfactant in water and placed in a refrigerator at 273.15 K for at least 24 h, so that solid surfactant-hydrate crystals appear. The temperature of the cooled gemini surfactant solution was then raised at a heating rate of 0.1°C min<sup>-1</sup> under constant stirring in a thermostat with a temperature accuracy of  $\pm$  0.01°C. The conductance ( $\kappa$ ) was measured every few minutes by a S320 conductometer (Mettler-Toledo GmbH, Switzerland). The Krafft temperature was taken as the temperature at which the conductance versus temperature plot showed an abrupt change in slope [23].

### 2.7 Biodegradability

Biodegradability of the prepare gemini surfactants was measured by the Closed Bottle test. The test method (OECD 301D) has been given in detail in literatures [24,25] and will be described only briefly in this paper. The experiment adopted 3.0 mg L<sup>-1</sup> of test substance existing in river water spiked with mineral salts. Ammonium chloride was omitted from the mineral salts which were prescribed to prevent nitrification. The river water was aerated for 8-10 days before using and particles were removed by sedimentation. The experiments were carried out in 300 mL BOD (biological oxygen demand) bottles with glass stoppers, using 3 bottles containing only river water, and series of 3 bottles containing the respective test substances and river water. The bottles were incubated in the dark at a temperature of  $25 \pm 0.5$ °C. The biodegradation was measured by following the course of the dissolved oxygen decrease in the bottles [25]. The amount of dissolved oxygen was monitored with an oxygen electrode (InPro 6850i) and an oxygen meter. The biodegradability was evaluated as the percentage of the biological oxygen demand to the theoretical oxygen demand.

### **3** Results and Discussion

#### 3.1 Synthesis

The synthetic routes for cationic gemini surfactants with diester and flexible spacers ( $C_{12}$ -PG- $C_{12}$ ,  $C_{14}$ -PG- $C_{14}$ ,  $C_{16}$ -PG- $C_{16}$ ) in this work are shown in Scheme 1. They were easily synthesized through a three-step procedure from the starting materials. First, the commercially available 1,3-dihydroxypropane (1 equiv) was reacted with chloracetyl chloride (0.22 equiv) to generate the important intermediate propane-1,3-diyl bis(chloroacetate) (1). Then, the alkylation of 1-bromoalkane (1-bromododecane, 1-bromotetradecane, 1-bromohexadecane, 1 equiv) with an excess molar ratio of dimethylamine (5 equiv) generated the compounds 2, 3, and 4. Finally, the

gemini surfactants C<sub>12</sub>-PG-C<sub>12</sub>, C<sub>14</sub>-PG-C<sub>14</sub> and C<sub>16</sub>-PG-C<sub>16</sub> were prepared at a high yield of 75.73-85.93% by quaterisation of propane-1,3-diyl bis(chloroacetate) (1) with *N*,*N*-dimethylalkylamine (2, 3, 4), respectively. Their chemical structures were confirmed by <sup>1</sup>H NMR spectroscopy, infrared spectroscopy, and elemental analysis.

### 3.2 Surface activity of the gemini surfactants

The surface tension  $(\gamma)$  of the investigated gemini surfactant aqueous solutions to the logarithm of concentration (C) at 298.15 K have been plotted in Fig. 1. The surface tension of aqueous solutions initially decreased with an increase in the concentration of gemini surfactants and then reached a plateau. The intersection point of surface tension curve is usually described as the critical micelle concentration (CMC) of a gemini surfactant and the plateau always means the formation of micelles. The surface activity parameters of the gemini surfactants are listed in Table 1. The CMC values of C12-PG-C12, C14-PG-C14 and C16-PG-C16 are 1.649, 0.2689 and 0.0560 mmol L<sup>-1</sup> at 25 °C respectively. It can be found that the CMC value gradually decreases with increasing hydrophobic chain length from 12 to 16, due to the enhanced hydrophobic interaction between the longer alkyl chains. For comparison, the CMC values of two single-chain cationic surfactants, CTAB (hexadecyltrimethylammonium bromide) DTAB and (dodecyltrimethylammonium bromide), are also calculated as 0.846 and 15.31 mmol L<sup>-1</sup> under the same experimental conditions. Evidently, the CMC values for the gemini surfactants are much lower than the traditional single-chain surfactants with the same alkyl chain in the hydrophobic groups. It demonstrates that the surface activities of the synthesized gemini surfactants are superior to that of single-chain cationic surfactants, indicating an excellent micelle forming ability.

The important physicochemical parameters including the surface tension value at CMC ( $\gamma_{CMC}$ ), the minimum surface area ( $A_{min}$ ) occupied by the gemini surfactant molecule, and the surface excess concentration ( $\Gamma_{max}$ ), are summarized in Table 1. The surface area ( $A_{min}$ ) occupied by the gemini surfactant molecules at the air-water interface is a measure of their packing density [26]. The surface excess concentration ( $\Gamma_{max}$ ) and the area occupied by a surfactant molecule ( $A_{min}$ ) at the air-water interface were calculated using the Gibbs adsorption equations (1) and (2) [27,28] as following:

$$\Gamma_{\max} = -\left(\frac{1}{2.303nRT}\right)\left(\frac{d\gamma}{d\log C}\right)_{\mathrm{T}} \tag{1}$$

$$A_{\min} = \frac{10^{16}}{N_{\rm A} \Gamma_{\max}} \tag{2}$$

In the equation, *R* is the gas constant (8.314 J mol<sup>-1</sup> K<sup>-1</sup>), *T* is the absolute temperature (K), *C* is the surfactant concentration (mol/L),  $d\gamma/d\log C$  is the slope of the surface tension vs the logarithm of concentration curve when the concentration is near the CMC,  $N_A$  is Avogadro's number ( $6.02 \times 10^{23}$  mol<sup>-1</sup>). The values of n = 3 (the number of species at the interface whose concentration changes with the surfactant concentration) are used for calculating the  $\Gamma_{\text{max}}$  values [5,29,30]. As shown in Table 1, the values of  $\Gamma_{\text{max}}$  of these gemini surfactants decrease, but the  $A_{\text{min}}$  values increase with increasing the length of the hydrophobic chains from 12 to 16, which indicates that the gemini surfactant with the longer hydrophobic chains has lower packing densities at the air-water interface. A possible explanation is that the longer hydrophobic chains

are more prone to bend at the air-water surface and cause the  $A_{\min}$  value to become larger [31].

Other important surface active parameters, such as the adsorption efficiency (p $C_{20}$ ) and the effectiveness of surface tension reduction ( $\Pi_{CMC}$ ) for these gemini surfactants, can also be obtained from the surface tension curve. The former parameter is obtained by using the equation (3):

$$pC_{20} = -\log C_{20}$$
 (3)

In the equation, *C* is the molar concentration of gemini surfactant (mol/L), and  $C_{20}$  represents the value of logarithm surfactant concentration required to reduce the surface tension of pure water by 20 mN m<sup>-1</sup>. The p $C_{20}$  value indicates the adsorption efficiency of gemini surfactants molecules at the air-water interface. The larger the p $C_{20}$  value, the less gemini surfactant adsorbed at the air-water interface.  $\Pi_{CMC}$  is the surface pressure at CMC, which is defined by using the equation (4):

$$\Pi_{\rm cmc} = \gamma_0 - \gamma_{\rm cmc} \tag{4}$$

where  $\gamma_0$  is the surface tension of pure solvent and  $\gamma_{CMC}$  is the surface tension of gemini surfactant solution at CMC.  $\Pi_{CMC}$  represents the maximum reduction of surface tension which can be used to evaluate the effectiveness of gemini surfactant to reduce the surface tension of water [26]. So the larger the value of  $\Pi_{CMC}$  is, the higher effectiveness of gemini surfactant is. As shown in Table 1, the variation of p $C_{20}$  and  $\Pi_{CMC}$  for the gemini surfactants exhibited that both the p $C_{20}$  and  $\Pi_{CMC}$ increased with increasing length of the hydrophobic chain.

In addition, the ratio of CMC/ $C_{20}$  reflects the relative tendency to adsorption and micellization of a surfactant, the larger the values of the CMC/ $C_{20}$ , the greater the tendency of the surfactant to adsorb at the air/water interface, relative to its tendency to form micelles. As shown in Table 1, it can be seen that these gemini surfactants were easier to self-assemble than adsorb at the air-water interface in aqueous solution. The values of  $\gamma_{CMC}$  for the gemini surfactants are 47.87, 45.47 and 43.24 mN m<sup>-1</sup> at 298.15 K, respectively. The results showed that the  $\gamma_{CMC}$  values decreased from 47.87 to 43.24 mN m<sup>-1</sup> with increasing the number of carbon atom in the hydrophobic chain from 12 to 16.



Fig. 1. Surface tension ( $\gamma$ ) vs the concentration (C) plots for the gemini surfactants at 298.15 K.

Table 1

Compounds	CMC <sup>a</sup> (mM)	CMC <sup>b</sup> (mM)	үсмс (mN/m)	$\Gamma_{max}$ (µmol/m <sup>2</sup> )	A <sub>min</sub> (nm <sup>2</sup> )	pC <sub>20</sub>	П <sub>СМС</sub> (mN/m)	CMC/C <sub>20</sub>
C <sub>12</sub> -PG-C <sub>12</sub>	$1.649\pm0.04$	$1.858\pm0.02$	47.87	2.26	0.74	3.01	24.12	1.70
C14-PG-C14	$0.2689 \pm 0.02$	$0.3144 \pm 0.01$	45.47	1.34	1.24	3.55	26.52	0.95
C16-PG-C16	$0.0560 \pm 0.005$	$0.0676 \pm 0.004$	43.24	1.06	1.57	4.44	28.75	1.54

Surface active properties and parameters of the micellization for the gemini surfactants at 298.15 K.

<sup>a</sup>Measured by tensiometry, <sup>b</sup>Measured by conductometry.

#### 3.3 Thermodynamic Properties of Micellization

The electrical conductivity measurement was applied in order to get a further investigation on the micellization behavior of the gemini surfactants in aqueous solution at four different temperatures (298.15, 308.15, 318.15 and 328.15) K. As shown in Fig. 2, S1 and S2, the CMC values were determined as sharp break points in the plots of specific conductance ( $\kappa$ ) versus gemini surfactants concentration (*C*) [21], and the degree of counterion dissociation ( $\alpha$ ) was determined from the pre-micellar slope (S1) to the post-micellar slope (S2),  $\alpha = S_2/S_1$  [32, 33]. As shown in Table 1, the values of CMC for C<sub>12</sub>-PG-C<sub>12</sub>, C<sub>14</sub>-PG-C<sub>14</sub> and C<sub>16</sub>-PG-C<sub>16</sub> measured by the electrical conductivity measurement are 1.858, 0.3144 and 0.0708 mmol L<sup>-1</sup> at 298.15 K, which are slightly larger than the CMC values measured by surface tension measurements. The results show that the values of CMC follow the similar trend as those investigated by surface tension measurements. In addition, the  $\alpha$  values decrease significantly with increasing hydrophobic tail length for the gemini surfactants. The long hydrophobic tails are favorable to form micelles and result in decreases in CMC values.



Fig. 2. Electrical conductivity ( $\kappa$ ) versus the concentration (*C*) for C<sub>12</sub>-PG-C<sub>12</sub>.

The thermodynamic parameters of micellization ( $\Delta G^{o}_{mic}$  and  $\Delta G^{o}_{ads}$ ) for the gemini surfactants have also been listed in Table 2. The standard Gibbs free energy of the aggregation ( $\Delta G^{o}_{mic}$ ) was calculated by the following equation (5):

$$\Delta G_{\rm mic}^{\rm o} = RT(3 - 2\alpha) \ln x_{\rm cmc} \tag{5}$$

where  $x_{\text{CMC}}$  is the CMC in mole fraction, *R* is the gas constant, and *T* is temperature on the Kelvin scale. The  $x_{\text{CMC}}$  is calculated by using the equation of  $x_{\text{CMC}} = \text{CMC} / (\text{CMC} + \text{number of moles for the solvent})$ . The Gibbs free energy of adsorption ( $\Delta G^{o}_{\text{ads}}$ ), which represents the free energy of transfer of 1 mol of gemini surfactant in solution to the interface, is calculated by the following equation (6):

$$\Delta G_{\rm ads}^{\rm o} = \Delta G_{\rm mic}^{\rm o} - \frac{\Pi_{\rm cmc}}{\Gamma_{\rm max}} \tag{6}$$

As shown in Table 2, the negative values of  $\Delta G^{o}_{mic}$  indicate that the micellization is a spontaneous process and its calculated absolute values increase with the increase of alkyl chain length, which have been found to be hydrophobically driven force for the formation of micelles. Furthermore, as compared to  $\Delta G^{o}_{mic}$ , the higher negativity values of  $\Delta G^{o}_{ads}$  suggest that the process of adsorption at the air-water interface is more spontaneous than micellization process in the bulk because the preference of adsorption is governed by the thermodynamic stability of the molecules at the air-water interface for the gemini surfactants. By rising the temperature from 298.15 to 328.15 K, the absolute values of  $\Delta G^{o}_{mic}$  are increased due to the less stability of the micellized gemini surfactant molecules than the freely dispersed in the aqueous phase. The standard enthalpy change for micellization process ( $\Delta H^{o}_{mic}$ ) can be determined using the Gibbs-Helmholtz equation (7):

$$\Delta H_{\rm mic}^{\rm o} = -RT^2 (3 - 2\alpha) \left( \frac{\delta \ln x_{\rm cmc}}{\delta T} \right)_{\rm P}$$
<sup>(7)</sup>

The values of  $\ln x_{CMC}$  in aqueous solutions were plotted against the temperature and the slopes of these plots were taken as the values of  $d\ln x_{CMC}/dT$ . The calculated  $\Delta H^{o}_{mic}$  values at four temperatures in aqueous solutions are summarized in Table 2. As shown in Table 2, the values of standard enthalpy of micellization ( $\Delta H^{o}_{mic}$ ) are negative for all the systems. It means that the micellization process is exothermic in aqueous solutions. The value of the  $\Delta H^{o}_{mic}$  is mostly becoming more negative with increase in alkyl chain length of the gemini surfactants. It means that the micellization process in C<sub>16</sub>-PG-C<sub>16</sub> is more exothermic than C<sub>14</sub>-PG-C<sub>14</sub> and C<sub>12</sub>-PG-C<sub>12</sub> at the same temperature. In addition, the standard entropy of micelle formation ( $\Delta S^{o}_{mic}$ ) can be calculated by the following equation (8) and the values are listed in Table 2.

$$\Delta S_{\rm mic}^{\rm o} = \frac{(\Delta H_{\rm mic}^{\rm o} - \Delta G_{\rm mic}^{\rm o})}{T} \tag{8}$$

From the observed data, it is obviously that the  $\Delta S^{\circ}_{mic}$  values for the gemini surfactants are positive in all cases and decrease with the increasing temperature in range from 298.15 K to 328.15 K in aqueous solutions. The positive of  $\Delta S^{\circ}_{mic}$  can be attributed to the destruction of water structure around the hydrophobic chain of the surfactant molecules. With the decrease of temperature, the surrounding iceberg structures of surfactant molecules diminished in size or became less rigid as temperature increased, the formation of micelles is difficult at higher temperature. Therefore, the micelle formation process of this system is a thermodynamically spontaneous process driven by entropy.

#### Table 2

Critical micellar concentration (CMC), degree of counter ion dissociation ( $\alpha$ ), standard Gibbs energy of micellization ( $\Delta G^{o}_{mic}$ ), standard Gibbs free energy of adsorption ( $\Delta G^{o}_{ads}$ ), standard enthalpy of micellization

Surfactant	T/K	СМС	a	$\Delta G^{ m o}{}_{ m mic}$	$\Delta G^{ m o}_{ m ads}$	$\Delta H^{ m o}_{ m mic}$	$\Delta S^{ m o}{ m mic}$
		(mM)	a	(kJ mol <sup>-1</sup> )	(kJ mol <sup>-1</sup> )	(kJ mol <sup>-1</sup> )	(kJ K <sup>-1</sup> mol <sup>-1</sup> )
C <sub>12</sub> -PG-C <sub>12</sub>	298.15	$1.858\pm0.02$	0.5670	-47.66	-54.78	-6.819	0.1370
	308.15	$1.952\pm0.02$	0.5942	-47.57		-6.419	0.1335
	318.15	$2.028 \pm 0.02$	0.6528	-45.75		-6.399	0.1237
	328.15	$2.105\pm0.02$	0.7076	-43.96		-6.367	0.1146
C <sub>14</sub> -PG-C <sub>14</sub>	298.15	$0.3144\pm0.01$	0.5966	-54.10	-67.23	-24.90	0.0979
	308.15	$0.3464\pm0.01$	0.6358	-53.04		-25.45	0.0895
	318.15	$0.4326\pm0.01$	0.7011	-49.67		-25.08	0.0773
	328.15	$0.5371\pm0.01$	0.7680	-46.06		-24.44	0.0659
C16-PG-C16	298.15	$0.0676\pm0.004$	0.5604	-63.43	-81.51	-14.12	0.1654
	308.15	$0.0714 \pm 0.004$	0.5934	-62.98		-14.56	0.1571
	318.15	$0.0760\pm0.004$	0.6223	-62.65		-15.02	0.1497
	328.15	$0.0956 \pm 0.004$	0.6611	-60.69		-15.28	0.1384

 $(\Delta H^{\circ}_{\text{mic}})$  and standard entropy of micellization  $(\Delta S^{\circ}_{\text{mic}})$  of the gemini surfactants in aqueous solution at various temperatures (*T*).

3.4 Microenviroment and Aggregation



Fig. 3. Variation of the pyrene intensity ratio  $I_1/I_3$  vs the concentrations (C) for the gemini surfactants at 298.15 K.

The micellization for the gemini surfactants was also investigated by a pyrene fluorescence probe through the steady-state fluorescence technique, which is useful for monitoring the self-aggregation in aqueous solution [34]. The shape and intensity for the photoluminescence (PL) spectra of pyene is sensitive to its microenvironment at the site of fluorophore solubilization. When surfactants begin to form micelles in aqueous solutions, pyrene molecules will penetrate into the interior hydrophobic region of micelles from the water, which will cause an abrupt change in  $I_1/I_3$ . Then the  $I_1/I_3$  value keeps constant as the concentration of surfactant increases in aqueous solutions. Therefore, the values can be utilized to analyze the micropolarity of the micelle system in polar media, reflecting the compactness of aggregates. Fig. 3 shows the variations of the pyrene polarity ratio  $I_1/I_3$  with the change of the surfactant concentration. The values of  $I_1/I_3$  change slightly as the initial surfactant concentration increases, suggesting that pyrene has no interaction with surfactant at the outset. However, with increasing the gemini surfactant concentration close to

the CMC value, there is an obvious decrease in  $I_1/I_3$ , because a spot of micelles have formed. Then the  $I_1/I_3$  value keeps constant as the concentration of surfactant increases in aqueous solutions, which indicates that the aggregate structures are compact and the microenvironment does not change. The minimum  $I_1/I_3$  values are decreased with the increase of the alkyl chain length, indicating that the longer hydrophobic tail makes the palisade layer more compact and leads to the reduction of polarity.

Further, the aggregation number ( $N_{agg}$ ) of the gemini surfactant solutions was determined by steady-state fluorescence quenching method [35]. The relation between the fluorescence intensities at 373 nm of pyrene in the absence ( $I_0$ ) and presence (I) of the quencher CPC is determined by total gemini surfactant concentration ([S]) and the quencher concentration in micelles ([Q]) according to the following equation (9):

$$\ln\left(\frac{I_0}{I}\right) = \frac{N_{\text{agg}}[Q]}{[S] - \text{cmc}} \tag{9}$$

The plots for the logarithm of pyrene intensity  $(I_0/I)$  versus the concentration of quencher CPC [*Q*] at 298.15 K are shown in Fig. S3 in supplementary data. All plots are fitted straight lines and slops are obtained. Thus, using the slope of each straight line, the  $N_{agg}$  values can be obtained from Eq (9), and given in tabular form (Table 3). The aggregation numbers of C<sub>12</sub>-PG-C<sub>12</sub>, C<sub>14</sub>-PG-C<sub>14</sub> and C<sub>16</sub>-PG-C<sub>16</sub> are found to be 23, 21 and 14, respectively. Obviously, the  $N_{agg}$  values decreased with the increase of alkyl chain length, which can be attributed that the gemini surfactant with longer hydrocarbon chain was easier to absorb at air/water interface than to form bigger aggregation in aqueous solutions [36].

### Table 3

The aggregation number ( $N_{agg}$ ), correlation coefficient (R), krafft temperature ( $K_t$ ), and biodegradation ratio of the gemini surfactants at 298.15 K.

Surfactant	$N_{ m agg}$	R	$K_{\rm t}$	Biodegradation (%)			
			(°C)	10d	20d	28d	
C12-PG-C12	23	0.9957	< 0	37.28	64.32	76.54	
C14-PG-C14	21	0.9974	< 0	34.37	58.53	73.50	
C16-PG-C16	14	0.9977	< 0	29.39	49.63	71.83	

#### 3.5 Krafft temperature

The krafft temperature ( $K_t$ ) is considered as the minimum temperature at which surfactants form micelles. Below the krafft temperature, the conductance of surfactant solution would increase slowly while during the temperature transition stage, the conductance increases sharply. These phenomena are attributed to the large dissolution of surfactant [37]. The abrupt change in the conductance ( $\kappa$ ) versus temperature plots was not observed and the gemini surfactant solution did not show any sign of precipitation after standing in a refrigerator for 24 hours. The values of the krafft points for all the gemini surfactants with diester and flexible spacers are assigned to be below 0°C, which indicates the surfactants have good water solubility.

#### 3.6 Biodegradability

It is well know that cationic gemini surfactants have their toxicity to the cell membranes of microorganisms. Therefore, the Closed Bottle test, a standardized method (OECD 301D), was applied to evaluate the biodegradability of these cationic gemini surfactants. From the data in Table 3, it is obvious that the biodegradation ratio of all the gemini surfactants can reach more than 70% biodegradation by exposing to the microorganisms after 28 days, which are close to the data reported for gemini surfactants with similar molecular structures in literatures [17,38,39]. As compared to  $C_{16}$ -PG- $C_{16}$  at 71.83%, the higher biodegradation ratio is gained in case of  $C_{12}$ -PG- $C_{12}$  and  $C_{14}$ -PG- $C_{14}$  at 76.54% and 73.50%, respectively. According to OECD's guidelines 60% biodegradation, the theoretical value should be achieved in drain water within 28 days in order for a surfactant to be classified as readily biodegradable [40]. Therefore, all the three gemini surfactants can be classified as readily biodegradable, which should benefit from the ability to degrade by the action of the environmental microorganisms due to the presence of the diester and flexible spacers [17]. Furthermore, the biodegradation ratio of these gemini surfactants decreases with increasing the length of the alkyl chain from 12 to 16.

### **4** Conclusions

In summary, three cationic gemini surfactants with diester and flexible spacers were designed and synthesized. Interestingly, the surface and thermodynamic properties of these gemini surfactants can be influenced by the molecule structures and spacer chain length. They have much lower CMC values than the traditional single-chain surfactants. The CMC values decreased with increasing hydrophobic chain length from 12 to 16. From the thermodynamic point of view, micelle formation was a spontaneous and exothermic process. The micellization process became less favorable with the decrease of alkyl chain length and the increase of temperature. The fluorescence measurement demonstrated that the synthesized gemini surfactants formed into micelles, which changed the microenvironment in solution and formed loosely bound aggregates in aqueous solutions. Besides, the  $N_{agg}$  decreased with the increase of alkyl chain length. All the three gemini surfactants possess good water solubility and can be classified as readily biodegradable. This should benefit from the ability to degrade by the action of the environmental microorganisms due to the presence of the diester and flexible spacers.

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## **Research highlights**

- The gemini surfactants with diester and flexible spacers were designed and synthesized.
- The surface properties and aggregation behavior of surfactants were investigated.
- They have higher surface activity than the traditional monomeric surfactants.
- The micellization is a spontaneous and exothermic process in environment.
- They possess good water solubility and can be classified as readily biodegradable.