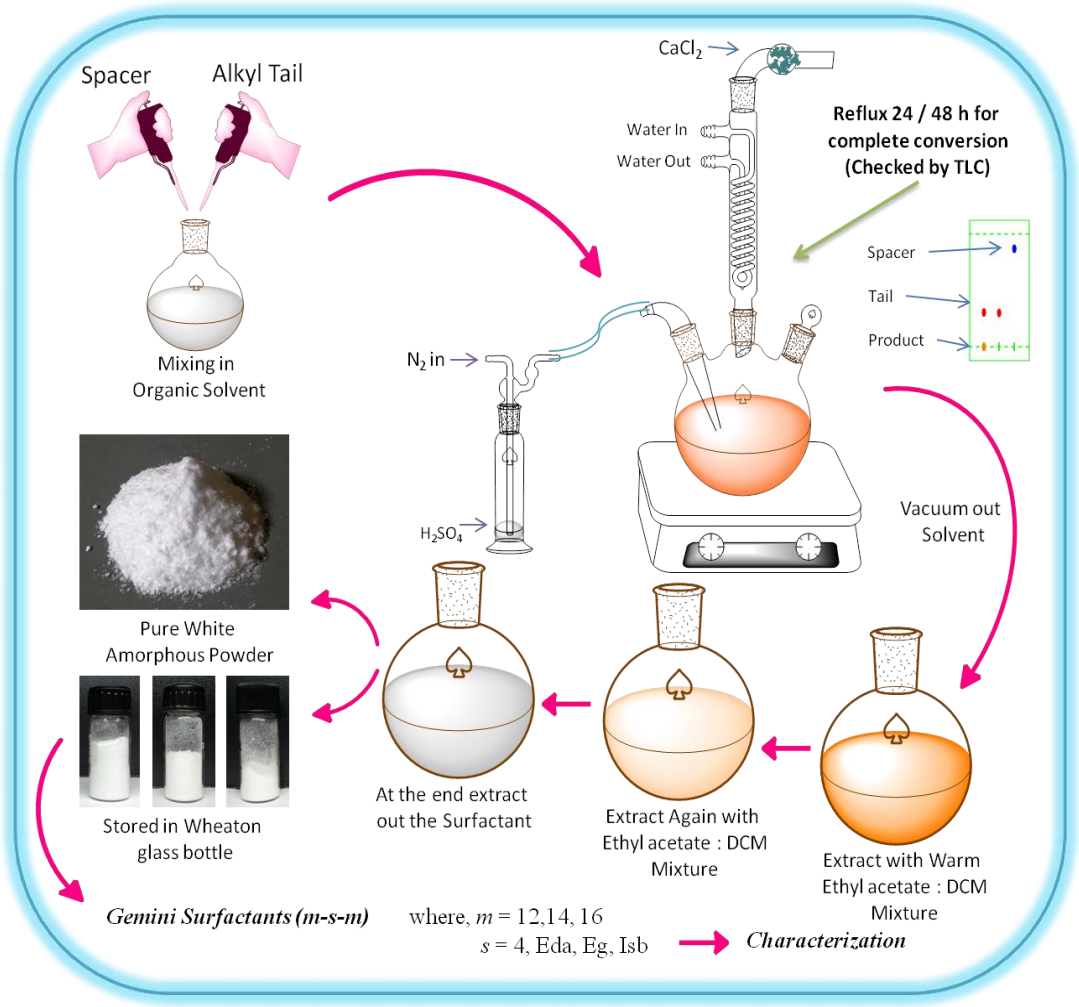
Chapter 2

Synthesis and Characterization of Gemini Surfactants



2.1. Materials and Methods

2.1.1. Materials

1,4-dibromobutance (99%, Sigma Aldrich), ethylene glycol (99%, Sigma Aldrich), ethylenediamine (99%, S.d.Fine Chemicals), D-Isosorbide (99%, Sigma Aldrich), chloroacetylchloride (CAC, 98%, S.d.Fine Chemicals, used after simple distillation), *N*,*N*-hexadecyldimethyl-1-amine (95%, Sigma Aldrich), *N*,*N*-tetradecyldimethyl-1-amine (95%, Sigma Aldrich) and *N*,*N*-dodecyldimethyl-1- amine (95%, TCI Chemicals), triethyl amine (99%, spectrochem), n-dodecenol (98%, SISCO), pyrophospheric acid ($\geq$90%, Fluka), 25% methanolic solution of tetramethylammonium hydroxide (Sigma Aldrich), sodium metal (95%, Loba), sodium hydroxide (99.5%, Merck), concentrated hydrochloric acid (Spectrochem) are used as received. All organic solvents (dichloromethane (DCM), toluene, acetonitrile, diethyl ether, chloroform, methanol, dry ethylacetate) were purchased as AR grade from spectro-chem and used as received. Absolute alcohol (99.5%) was provided by Department of chemistry, The Maharaja Sayajirao University of Baroda, India (Gujarat government approved). Absolute ethanol was dried by using of magnesium / iodine and stored on molecular sieves. De-ionized double distilled water (1-2 $\mu S \cdot cm^{-1}$) has been used for the reaction as well as for workup purposes throughout.

2.1.2. Methods

2.1.2.1. Spectroscopy Techniques

^{1}H NMR spectra was recorded on Bruker Avance II 400 NMR spectrometer (400 MHz) and were run in $CDCl_3$ or DMSO (D^6) at 298 K. Signal multiplicity

denoted as singlet (s), doublet (d), doublets of doublets (dd), triplets (t), quartered (q), multiplet (m). Electron mass spectra were recorded on Thermo-Fischer DCQ II GSMS instrument. Electron spray ionization mass (ESI-MS) was recorded on Waters, Q-TOF Micromass (LC-MS) at Sophisticated Analytical Instrumental Facility (SAIF), Punjab University, Chandigarh. Elemental (CHN) analysis was performed on Vario Micro Cube (elementar)s with acetanilide as reference standard at Central Salt & Marine Chemicals Research Institute (CSMCRI), Bhavnagar, India. The values of specific rotation $[\alpha]^{D}_{30}$ have been obtained from Kruss P8000 polarimeter (Germany) with an accuracy of $\pm$ 0.0003°.

2.1.2.2. Thermal stability Analysis

The thermal stability analyses of all gemini surfactants have been performed with NETZSCH STA 429C Thermal Gravimetric Analyzer (TGA). All samples were run in clean and dry aluminium pan under a closed N_2 atmosphere at flow rate of 100 mL/min. Gradual heating rate was maintained at 10ºC per minute. Before measurement, the sample was dried under a vacuum (20-30 mmHg) for 6-7 hrs for removing the moisture content.

2.2. Synthesis and Characterization of Gemini Surfactants

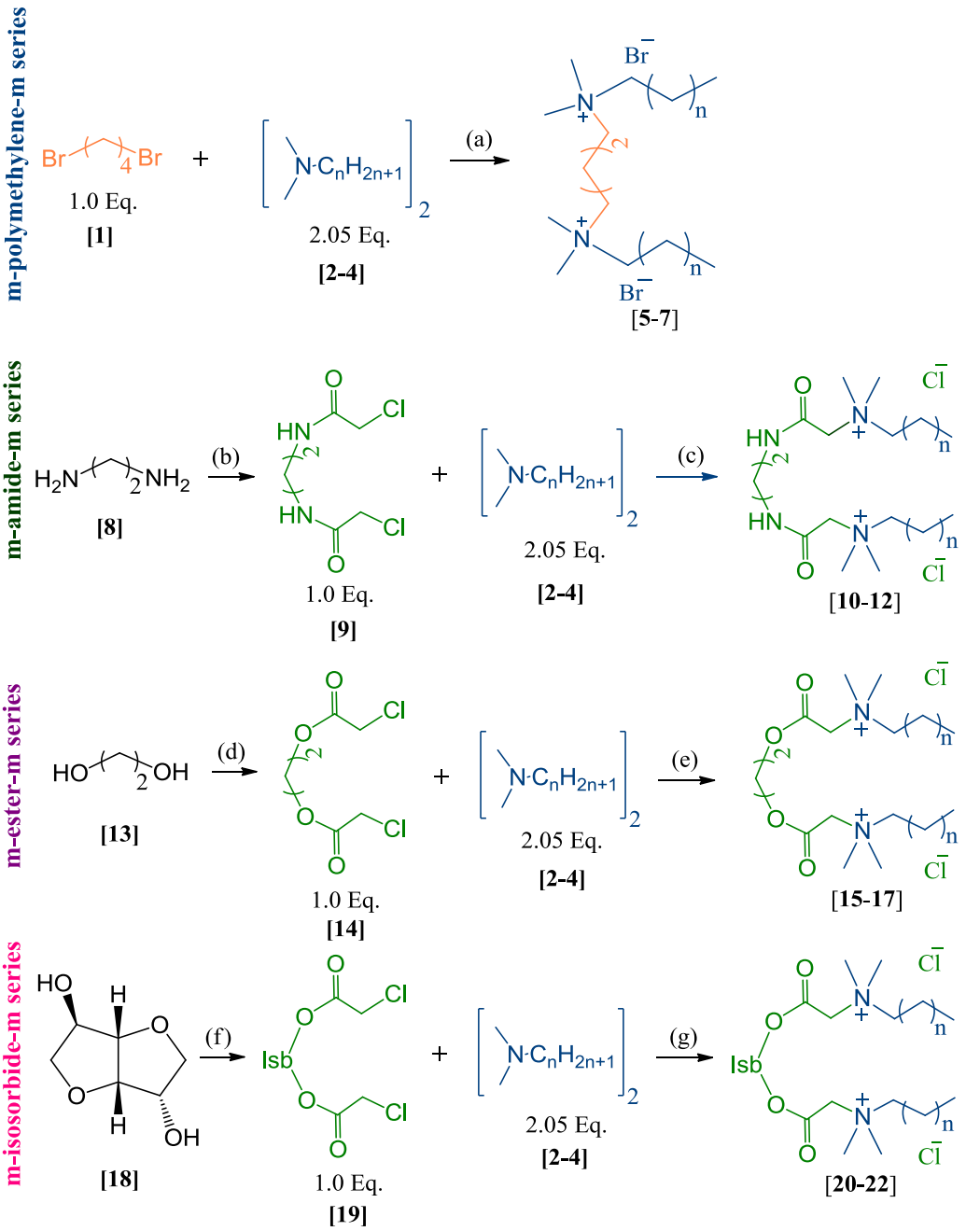
2.2.1. Cationic Gemini Surfactants

Nine new biocompatible / cleavable spacer based cationic gemini surfactants (CGS) with dodecyl, tetradecyl and hexadecyl alkyl chain (***m*** = 12, 14 or 16) have been synthesized and characterized. Polymethylene spacer based geminis (with similar ***m***) have also been synthesized for comparison purposes. In general, gemini surfactants are prepared by optimum mixing of the spacer and alkyl tail materials [1]. However, in the present case, biocompatible spacers have been synthesized, purified and characterized separately. Therefore, syntheses of biocompatible spacers are given in the beginning.

2.2.1.1. Synthesis and Characterization of Biocompatible (hydrophilic) Spacers

Three precursors (ethylene diamine, ethylene glycol, D-isosorbide) are reacted with acid chloride (chloroacetyl chloride) in an appropriate ratio to synthesized respective biocompatible spacer.

Spacer (1,2-bischloroacetylinediamine (**compound 9**), see Scheme 1) was obtained by adding a mixture of chloroacetyl chloride (CAC, 41.79 g, 0.37 mol) and chloroform ($CHCl_3$, 50 ml) drop by drop in to a cooled (0-5˚C) stirred mixture of ethylenediamine (**8**, 10.82 g, 0.18 mol), triethylamine (base, 54.64 g, 0.54 mol) and 50 ml $CHCl_3$ (with guard tubing) [2]. After addition, resulted mixture was stirred at room temperature for 4-8 h. After completion of the reaction, $CHCl_3$ was removed under vacuum to get solid mass which was solubilized and recrystallized by using dry ethanol (2-3 times) to obtain pure crystalline spacer (**9**, 15.72 g, 41% yield).



n = 12; [2]
n = 14; [3]
n = 16; [4]

12-4-12 (5), n = 10;	**14-4-14 (6)**, n= 12;	**16-4-16 (7)**, n = 14
12-Eda-12 (10), n = 10;	**14-Eda-14 (11)**, n= 12;	**16-Eda-16 (12)**, n = 14
12-Eg-12 (15), n = 10;	**14-Eg-14 (16)**, n= 12;	**16-Eg-16 (17)**, n = 14
12-Isb-12 (20), n = 10;	**14-Isb-14 (21)**, n = 12;	**16-Isb-16 (22)**, n = 14

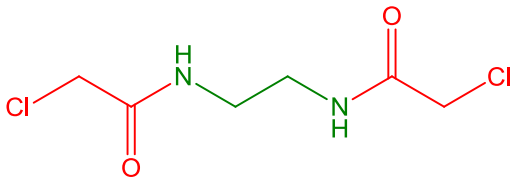
Scheme 1. Synthesis Route of Cationic Gemini Surfactants: (a, e & g) ethylacetate : DCM : ethanol (6:3.8:0.2), reflux under N_2 atm, 24-48 h; (b) $CHCl_3$, R.T. Stirring, 4-8 h; (c) ethanol, reflux under N_2 atm, 24-48 h; (d & f) DCM, reflux at 50°C, 4 h.

Spacers (1,2-bischloroacetoxyethane (**14**) and 1,4-bischloroacetoxy-D-isosorbate (**19**)) were obtained by the method given in the literature [3]. CAC (21.46

g, 0.19 mol) in DCM (50 ml) was added drop by drop in to a 250 ml round bottom flask contains solution of ethylene glycol (**13**, 5.59 g, 0.09 mol) or D-isosorbide (**18**, 10.23 g, 0.07 mol) in 25 ml DCM (under N_2 atm with screw top pressure tube). After complete addition, reaction mixture was stirred at 50˚C till completion of the reaction (for 4 h). This reaction mixture was neutralized with $NaHCO_3$ (aqueous solution) and washed with saturated NaCl solution. Solvent was removed under high vacuum and reaming mass was crystallized at lower temperature (≤ 10°C) to obtained spacers (1,2-bischloroacetoxyethane (**14**), 16.06 g, 83% yield) and (1,4-bischloroacetoxy-D-isosorbate (**19**), 18.63 g, 89% yield).

Characterization Data of Hydrophilic Spacers

1,2-bischloroacetylinediamine (**9**)

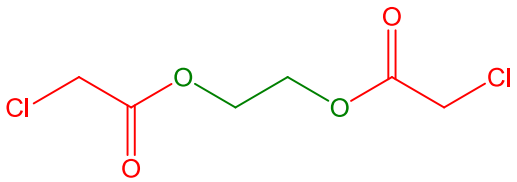


White colorless crystal, 15.72 g, 41% yield.

^{1}H NMR (400 MHz, Bruker, DMSO): δ 3.16-3.17 (t, 4H, $(CH_2)_2$), 4.06 (s, 4H, $(CH_2)_2$), 8.39 (s, 2H, $(NH)_2$).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 3302, 2068, 1667, 1537, 1266, 1066.

1,2-bischloroacetoxy ethane (**14**)



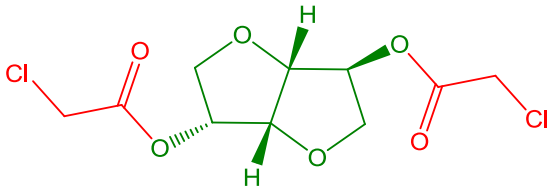
White colorless crystal, 16.06 g, 83% yield.

^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 4.11 (s, 4H), 4.44 (s, 4H).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2965 (CH), 1760 (C=O), 1459 (CH).

Mass (*m/z*, 215.03 gm/mol): 48.9 (29), 76.8 (100), 119.9 (20), 134.9 (15).

1,4-bischloroacetoxy-D-*isosorbate* (**19**)



White crystalline solid, 18.63 g, 89% yield.

SOP (specific optical rotation, $[\alpha]_D^{30}$): +137.12 $degcm^3g^{-1}dm^{-1}$ (c=0.1 in $CHCl_3$).

^{1}H NMR (400 MHz, Bruker; $CDCl_3$; TMS): δ 3.93-3.96 (m, 2H, CH_2), 4.03-4.04 (d, 2H, CH_2), 4.10 (s, 2H, CH_2), 4.15 (s, 2H, CH_2), 4.53-4.55 (d, 1H, CH), 4.91-4.94 (t, 1H, CH), 5.27-5.31 (m, 2H, CH).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}) neat: 2991 (CH), 2881 (CH), 1751 (C=O), 1462 (CH) and 1193 (C-O).

Mass (*m/z*, 299.10 gm/mol): 146.93 (M-$ClCH_2COOH$), 109.93 (stable compound of 2,5-dihydrofuro[3,2-b]furan), 76.89 (M-$ClCH_2CO^-$), 48.94 (M-$ClCH_2^+$).

2.2.1.2. General Procedure for Synthesis of Cationic Gemini Surfactant

Two series (polymethylene and biocompatible spacer) of gemini surfactants are synthesized by a modified methodology adopted earlier [4] (see Scheme 1). Spacers (1,4-dibromobutane (**1**, 4.32 g, 0.02 mol), 1,2-bischloroacetylinediamine (**9**, 4.26 g, 0.02 mol), 1,2-bischloroacetoxyethane (**14**, 4.30 g, 0.02 mol), 1,4-bischloroacetoxy-D-isosorbate (**19**, 5.98 g, 0.02 mol)) and various alkyl quaternary amines (*N*,*N*-dimethyldodecyl-1-amine (**2**, 8.75 g, 0.041 mol), *N*,*N*-dimethyltetradecyl-1-amine (**3**, 9.90 g, 0.041 mol), *N*,*N*-dimethylhexadecyl-1-amine

(**4**, 11.05 g, 0.041 mol)) are mixed (in an appropriate ratio) with dry ethylacetate:DCM or dry ethanol:ethylacetate or dry ethanol in 250 ml round bottom flask and refluxed for 24 to 48 hrs (under N_2 atmosphere with guard tubing).

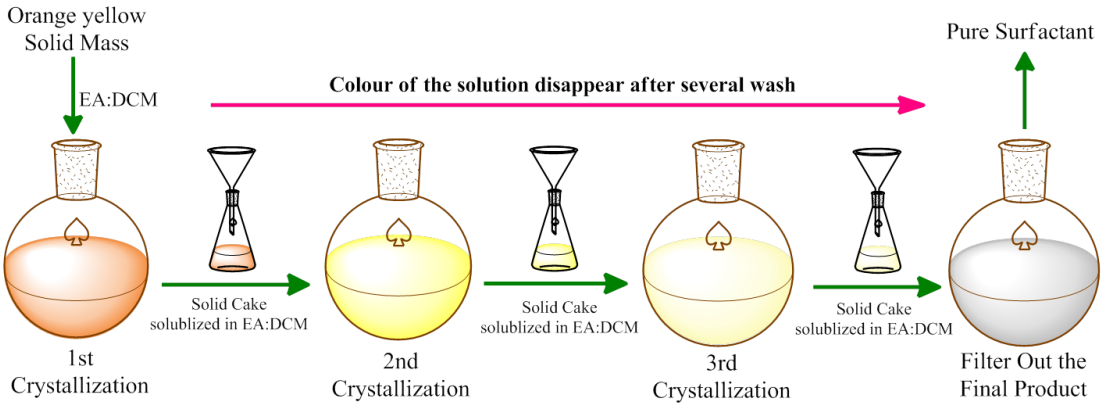
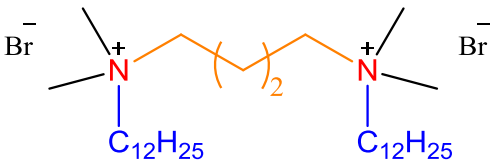


Figure 1. Schematic representation of purification of cationic gemini surfactants

Reaction completion was confirmed by disappearance of the spot of spacer from TLC [$CHCl_3$:MeOH, 9:1; Rf = 0.3 (**5-7**, **10-12**, **15-17**, **20-22**), 1.3-1.6 (**1**, **9**, **14**, **19**)]. After completion of the reaction, solvents were removed under low vacuum to get orange / yellowish mass. This was re-crystallized (See Figure 1) at least three times with appropriate solvent mixture of dry ethylacetate:DCM (8:2) to obtain the respective gemini surfactant in form of white amorphous powder (**5-7**, **10-12**, **15-17**, **20-22**).

Characterization Data of Cationic Gemini Surfactants

12-4-12 (5) (*butanediyl-1,4-bis(N,N-dimethyl-N-dodecyl-ammonium) dibromide)*



White amorphous powder, 10.41 g, 81% yield.

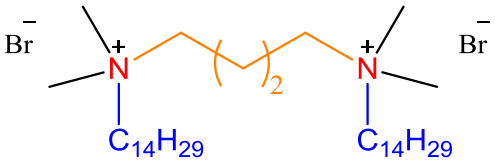
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.88-0.91 (t, 6H, $(CH_3)_2$), 1.27 (s, 28H, $(CH_2)_{14}$), 1.38 (s, 8H, $(CH_2)_4$), 1.78 (s, 4H, $(CH_2)_2$), 2.17 (s, 4H, $(CH_2)_2$), 3.29 (s, 12H, $(CH_3)_4$), 3.40-3.42 (t, 4H, $(CH_2)_2$), 3.96 (s, 4H, $(CH_2)_2$)

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2917, 2850, 2039, 1470, 1375, 1055.

ESI-MS (*m/z*, 642.720 gm/mole): 561.5 ($M-Br^-$), 527.6 ($M-Br^-$, $2CH_3$), 517.6 ($M-Br^-$, $3CH_3$), 241.3 ($M-C_{12}H_{25}N^+(CH_3)_4$, $2Br^-$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{32}H_{70}Br_2N_2 \cdot 2H_2O$: C, 56.62; H, 10.99; N, 4.12(%); Found C, 56.47; H, 11.18; N, 4.37(%).

14-4-14 (6) (*butanediyl-1,4-bis(N,N-dimethyl-N-tetradecyl-ammonium) dibromide)*



White amorphous powder, 10.06 g, 72% yield.

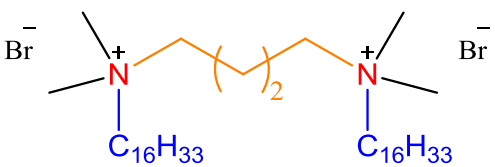
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.87-0.90 (t, 6H, $(CH_3)_2$), 1.26 (s, 36H, $(CH_2)_{18}$), 1.37 (s, 8H, $(CH_2)_2$), 1.78 (s, 4H, $(CH_2)_2$), 2.17 (s, 4H, $(CH_2)_2$), 3.30 (s, 12H, $(CH_3)_4$), 3.41-3.43 (t, 4H, $(CH_2)_2$), 3.98 (s, 4H, $(CH_2)_2$).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2917, 2849, 2040, 1471, 1379, 1280, 1178, 1048.

ESI-MS (*m/z*, 698.829 gm/mole): 619.6 ($M-Br^-$), 583.6 ($M-Br^-$, $2CH_3$), 573.6 ($M-Br^-$, $3CH_3$), 296.4 ($M-C_{14}H_{29}N^+(CH_3)_2$, $2Br^-$), 241.3 ($C_{14}H_{29}N^+(CH_3)_2$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{36}H_{78}Br_2N_2 \cdot 1H_2O$: C, 60.32; H, 11.25; N, 3.91(%); Found C, 60.12; H, 11.78; N, 4.96(%).

16-4-16 (7) (*butane-1,4-diyl bis(N,N-dimethyl-N-hexadecyl-ammonium) dibromide)*



White amorphous powder, 8.90 g, 59% yield

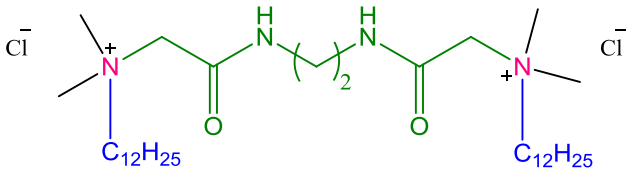
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.87-0.90 (t, 6H, $(CH_3)_2$), 1.26 (s, 44H, $(CH_2)_{22}$), 1.36 (s, 8H, $(CH_2)_2$), 1.76 (s, 4H, $(CH_2)_2$), 2.13 (s, 4H, $(CH_2)_2$), 3.30 (s, 12H, $(CH_3)_4$), 3.41-3.45 (t, 4H, $(CH_2)_2$), 3.91 (s, 4H, $(CH_2)_2$).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2917, 2850, 1629, 1433, 1472, 1285, 1187.

ESI-MS (*m/z*, 754.932 gm/mole): 675.4 ($M-Br^-$), 629.5 ($M-Br^-,3CH_3$), 370.6 ($M-C_{16}H_{33}$, $2Br^-$), 324.6 ($M-C_{16}H_{33}N^+(CH_3)_2$, $2Br^-$), 298 ($C_{16}H_{33}N^+(CH_3)_2CH_2CH_2$, $2Br^-$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{40}H_{86}Br_2N_2{\cdot}0.5H_2O$: C 62.89, H 11.47, N 3.67; Found C 62.96, H 11.54, N 3.07.

12-Eda-12 (10) (*ethane-1,2-diyl bis(N,N-dimethyl-N-dodecyl-ammoniumacetoamide) dichloride)*



White amorphous shining powder, 10.88 g, 85% yield

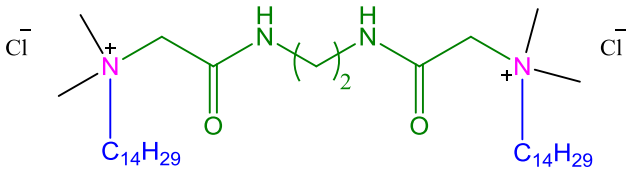
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.87-0.90 (t, 6H, $(CH_3)_2$), 1.26 (s, 28H, $(CH_2)_{14}$), 1.36 (s, 8H, $(CH_2)_4$), 1.78 (s, 4H, $(CH_2)_2$), 3.42 (s, 12H, $(CH_3)_4$), 3.46 (s, 4H, $(CH_2)_2$), 3.60-3.63 (t, 4H, $(CH_2)_2$), 4.63 (s, 4H, $(CH_2)_2$), 9.44 (s, 2H, 2NH).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 3176, 3005, 2921, 2851, 1679, 1464, 1268, 1226.

ESI-MS (*m/z*, 639.867gm/mole): 603.6 ($M-Cl^-$), 567.6 ($M-2Cl^-$), 399.4 ($M-C_{12}H_{25}$, $2Cl^-$), 284.3 ($M-C_{12}H_{25}N^+(CH_3)_2CH_2CONHCH_2$, $2Cl^-$), 200.2 ($M-C_{12}H_{25}NCH_3$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{34}H_{72}Cl_2N_4O_2{\cdot}0.25H_2O$: C, 63.38; H, 11.34; N, 8.69(%); Found C, 63.43; H, 11.44; N, 8.22(%).

14-Eda-14 (11) (*ethane-1,2-diyl bis(N,N-dimethyl-N-tetradecyl-ammoniumacetoamide) dichloride*).



White amorphous powder, 10.29g, 74% yield.

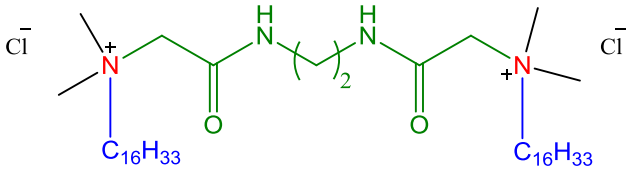
^{1}H NMR (400 MHz , Bruker, $CDCl_3$, TMS): δ 0.85-0.90 (t, 6H, $(CH_3)_2$), 1.24 (s, 36H, $(CH_2)_{18}$), 1.34 (s, 8H, $(CH_2)_4$), 1.76 (s, 4H, $(CH_2)_2$), 3.42 (s, 12H, $(CH_3)_4$), 3.44(s, 4H, $(CH_2)_2$), 3.59-3.63 (t, 4H, $(CH_2)_2$), 4.62 (s, 4H, $(CH_2)_2$), 9.41 (s, 2H, 2NH).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 3176, 3005, 2919, 2850, 1683, 1464, 1269, 1228.

ESI-MS (*m/z*, 695.973gm/mole): 659.7 ($M-Cl^-$), 623.7 ($M-2Cl^-$), 427.5 ($M-C_{14}H_{29}$, $2Cl^-$), 312.3 ($M-C_{14}H_{29}N^+(CH_3)_2CH_2CONHCH_2$, $2Cl^-$), 214.2 ($M-C_{14}H_{29}N^+$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{38}H_{80}Cl_2N_4O_2 \cdot 0.45H_2O$: C, 64.82; H, 11.58; N, 7.96(%); Found C, 64.90; H, 11.58; N, 7.90(%).

16-Eda-16 (12) (*ethane-1,2-diyl bis(N,N-dimethyl-N-hexadecyl-ammoniumacetoamide) dichloride*).



White amorphous powder, 9.18 g, 61% yield

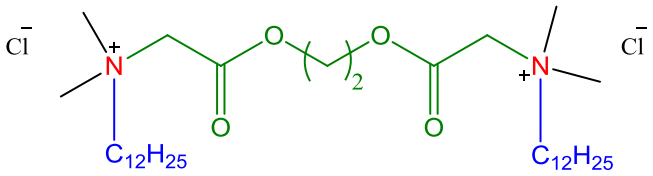
^{1}H NMR (400 MHz , Bruker, $CDCl_3$, TMS): δ 0.87-0.91 (t, 6H, $(CH_3)_2$), 1.26 (s, 44H, $(CH_2)_{22}$), 1.36 (s, 8H, $(CH_2)_4$), 1.78 (s, 4H, $(CH_2)_2$), 3.42 (s, 12H, $(CH_3)_4$), 3.46 (s, 4H, $(CH_2)_2$), 3.59-3.63 (t, 4H, $(CH_2)_2$), 4.63 (s, 4H, $(CH_2)_2$), 9.41 (s, 2H, 2NH).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 3173, 3005, 2918, 2848, 1678, 1460, 1271, 1228.

ESI-MS (*m/z*, 752.080gm/mole): 717.4 ($M-Cl^-$), 680.4 ($M-2Cl^-$), 410.5 ($M-C_{16}H_{33}N^+(CH_3)_2$, $2Cl^-$), 340.6 ($M-C_{16}H_{33}N^+(CH_3)_2CH_2CONHCH_2$, $2Cl^-$), 228.6 ($[CH_2NHCOCH_2N^+(CH_3)_2]_2$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{42}H_{88}N_4O_2Cl_2 \cdot 0.5H_2O$: C 66.28, H 11.79, N 7.36; Found C 66.33, H 12.19, N 6.80.

12-Eg-12 (15) (*ethane-1,2-diyl bis(N,N-dimethyl-N-dodecyl-ammoniumacetoxy) dichloride*).



Pale yellowish white sticky material (highly hygroscopic), 5.01 g, 39% yield.

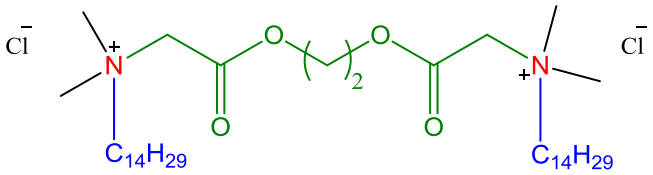
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.88-0.91 (t, 6H, $(CH_3)_2$), 1.26 (s, 28H, $(CH_2)_{14}$), 1.35 (s, 8H, $(CH_2)_4$), 1.78 (s, 4H, $(CH_2)_2$), 3.36 (s, 12H, $(CH_3)_4$), 3.79-3.81 (t, 4H, $(CH_2)_2$), 4.50 (s, 4H, $(CH_2)_2$), 5.45 (s, 4H, $(CH_2)_2$).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2919, 2852, 1745, 1466, 1254, 1213, 1129.

ESI-MS (*m/z*, 641.837gm/mole): 606.6 (M-Cl^-), 569.6 (M-$2Cl^-$), 401.4 ($C_{22}H_{46}N_2O_4$), 316.3 (M-$C_{18}H_{38}NO_3$), 272.3 (M-$C_{16}H_{34}NO_2$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{34}H_{70}Cl_2N_2O_4 \cdot 4.25H_2O$: C, 56.84; H, 11.01; N, 3.90(%); Found C, 56.75; H, 10.95; N, 3.77(%).

14-Eg-14 (16) (*ethane-1,2-diyl bis(N,N-dimethyl-N-tetradecyl-ammoniumacetoxy) dichloride*).



White amorphous powder, 6.56 g, 47% yield

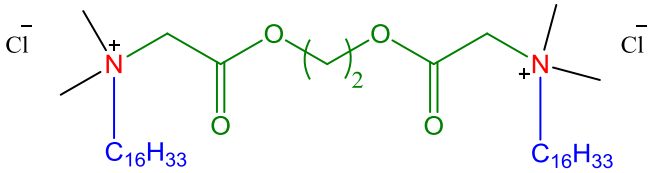
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.87-0.90 (t, 6H, $(CH_3)_2$), 1.25 (s, 36H, $(CH_2)_{18}$), 1.35 (s, 8H, $(CH_2)_4$), 1.78 (s, 4H, $(CH_2)_2$), 3.55 (s, 12H, $(CH_3)_4$), 3.80-3.84 (t, 4H, $(CH_2)_2$), 4.49 (s, 4H, $(CH_2)_2$), 5.51 (s, 4H, $(CH_2)_2$).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2918, 2849, 1746, 1468, 1256, 1213, 1129.

ESI-MS (*m/z*, 697.943gm/mole): 661.6 (M-Cl^-), 625.6 (M-$2Cl^-$), 429.4 ($C_{24}H_{49}N_2O_4$), 326.3 ($C_{20}H_{41}NO_2$), 313.3 (M-$C_{14}H_{29}N^+(CH_3)_2CH_2COOCH_2$, $2Cl^-$), 215.2 ($C_{15}H_{32}$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{36}H_{78}Cl_2N_2O_4 \cdot 2H_2O$: C, 62.18; H, 11.26; N, 3.82(%); Found C, 62.10; H, 11.37; N, 3.37(%).

16-Eg-16 (17) (*ethane-1,2-diyl bis(N,N-dimethyl-N-hexadecyl-ammoniumacetoxy) dichloride*).



White amorphous powder, 8.89 g, 59% yield

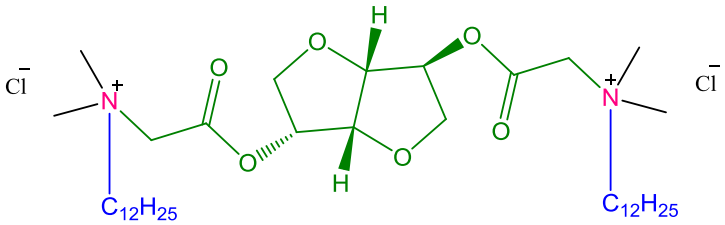
^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.87-0.90 (t, 6H, $(CH_3)_2$), 1.26 (s, 44H, $(CH_2)_{22}$), 1.35 (s, 8H, $(CH_2)_4$), 1.78 (s, 4H, $(CH_2)_2$), 3.56 (s, 12H, $(CH_3)_4$), 3.80-3.84 (t, 4H, $(CH_2)_2$), 4.49 (s, 4H, $(CH_2)_2$), 5.51 (s, 4H, $(CH_2)_2$).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 2920, 2853, 1751, 1636, 1472, 1187, 1048.

ESI-MS (*m/z*, 754.049gm/mole): 717.3 (M-Cl^-), 681.4 (M-$2Cl^-$), 667.4 (M-CH_3, $2Cl^-$), 372.6 (M-$C_{16}H_{33}N^+(CH_3)_2CH_2CO$, $2Cl^-$), 341.5 (M-$C_{16}H_{33}N^+(CH_3)_2CH_2COOCH_2$, $2Cl^-$), 229.5 ($C_{16}H_{33}$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{42}H_{86}N_2O_4Cl_2 \cdot 1H_2O$: C 65.32, H 11.49, N 3.63; Found C 65.63, H 11.87, N 3.12.

12-Isb-12 (20) (D-*isosorbate-1,4-diyl bis(N,N-dimethyl-N-dodecyl-ammoniumacetoxy) dichloride*).



Yellowish white sticky material (highly hygroscopic), 6.68 g, 46% yield

SOP (Specific Optical Rotation, $[\alpha]_D^{30}$): +30.08 $degcm^3g^{-1}dm^{-1}$ (c=0.1 in $CHCl_3$).

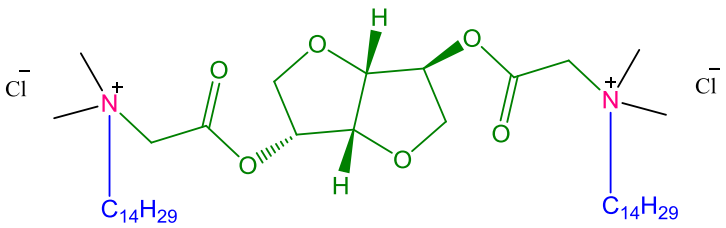
^{1}H NMR (400 MHz Bruker; $CDCl_3$; TMS): δ 0.91 (t, 6H, $(CH_3)_2$), 1.24 (s, 32H, $(CH_2)_{16}$), 1.36 (s, 4H, $(CH_2)_2$), 1.76 (s, 4H, $(CH_2)_2$), 3.53 (s, 6H, $(CH_3)_2$), 3.60-3.64 (d, 6H, $(CH_3)_2$), 3.77-3.99 (m, 6H, CH and CH_2), 4.08 (d, 1H, CH), 4.15 (s, 1H, CH), 4.62 (s, 1H, CH), 4.84-4.88 (d, 1H, CH), 5.03 (s, 1H, CH), 5.22-5.37 (m, 4H, $(CH_2)_2$), 5.47 (d, 1H, CH).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}): neat 2919 (CH), 2853 (CH), 1750 (C=O), 1469 (CH), 1243 (CN), 1203 (C-O) and 1092.

ESI-MS (*m/z*, 725.910 gm/mole): 689.6 (M-Cl^-), 653.6 (M-2Cl^-), 639.6 (M-2Cl^-, CH_3), 485.4 (M-$C_{12}H_{25}$, 2Cl^-), 400.4 (M-$C_{12}H_{25}N^+(CH_3)_2CH_2CO^-$, 2$Cl^-$).

Elemental (CHN) Analysis: Anal. Calculated for $C_{38}H_{74}Cl_2N_2O_6 \cdot 2H_2O$: C, 59.9; H, 10.3; N, 3.6(%); Found: C, 59.9; H, 10.4; N, 3.6.

14-Isb-14 (21) (D-*isosorbate-1,4-diyl bis(N,N-dimethyl-N-tetradecyl-ammoniumacetoxy) dichloride*).



White amorphous powder, 9.70 g, 62% yield

SOP ($[\alpha]_D^{30}$): +28.50 $degcm^3g^{-1}dm^{-1}$ (c=0.1 in $CHCl_3$).

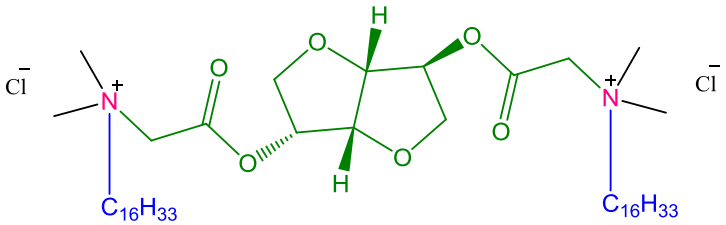
^{1}H NMR (400 MHz Bruker; $CDCl_3$; TMS): δ 0.86-0.88 (t, 6H, $(CH_3)_2$), 1.25 (s, 40H, $(CH_2)_{20}$), 1.34 (s, 4H, $(CH_2)_2$), 1.74 (s, 4H, $(CH_2)_2$), 3.52 (dd, 6H, $(CH_3)_2$), 3.59-3.63 (d, 6H, $(CH_3)_2$), 3.71-3.97 (m, 6H, CH and CH_2), 4.06-4.12 (q, 2H, CH_2), 4.59 (s, 1H, CH), 4.89-4.93 (d, 1H, CH), 4.99 (s, 1H, CH), 5.26-5.34 (m, 4H, CH_2), 5.51-5.55 (d, 1H, CH).

FT-IR (Shimadzu 8400S, KBr, cm^{-1}) neat: 2916 (CH), 2851 (CH), 1749 (C=O), 1470 (CH), 1257 (CN), 1204 (C-O) and 1095.

ESI-MS (*m/z*, 782.016 gm/mole): 745.7 (M-Cl^-), 709.7 (M-2Cl^-), 695.7 (M-2Cl^-, CH_3), 428.4 (M-$C_{14}H_{29}N^+(CH_3)_2CH_2CO$, 2$Cl^-$), 314.3 (M-[$C_{14}H_{29}$, Cl^-]$_2$), 257.2 (M-[$C_{14}H_{29}N^+(CH_3)_2$]$_2$, 2Cl^-).

Elemental (CHN) Analyses: Anal. Calculated for $C_{42}H_{82}Cl_2N_2O_6 \cdot 0.5H_2O$: C, 63.7; H, 10.6; N, 3.5(%); Found: C, 63.8; H, 10.7; N, 3.5.

16-Isb-16 (22) (D-*isosorbate-1,4-diyl bis(N,N-dimethyl-N-hexadecyl-ammoniumacetoxy) dichloride*).



White amorphous powder, 11.89 g, 71% yield.

SOP: $[\alpha]_D^{30}$ +26.16 $degcm^3g^{-1}dm^{-1}$ (c=0.1 in $CHCl_3$).

^{1}H NMR (400 MHz Bruker; $CDCl_3$; TMS): δ 0.87-0.90 (t, 6H, $(CH_3)_2$), 1.25 (s, 48H, $(CH_2)_{24}$), 1.35 (s, 4H, $(CH_2)_2$), 1.76 (s, 4H, $(CH_2)_2$), 3.52-3.53 (dd, 6H, $(CH_3)_2$), 3.60-3.64 (d, 6H, $(CH_3)_2$), 3.76-3.92 (m, 5H, $(CH_2)_2$ and CH), 3.96-3.99 (d, 1H, CH), 4.04-4.07 (d, 1H, CH), 4.12-4.15 (d, 1H, CH), 4.61-4.62 (d, 1H, CH), 4.86-4.90 (d, 1H, CH), 5.0-5.03 (t, 1H, CH), 5.25-5.36 (m, 4H, $(CH_2)_2$), 5.50-5.55 (d, 1H, CH).

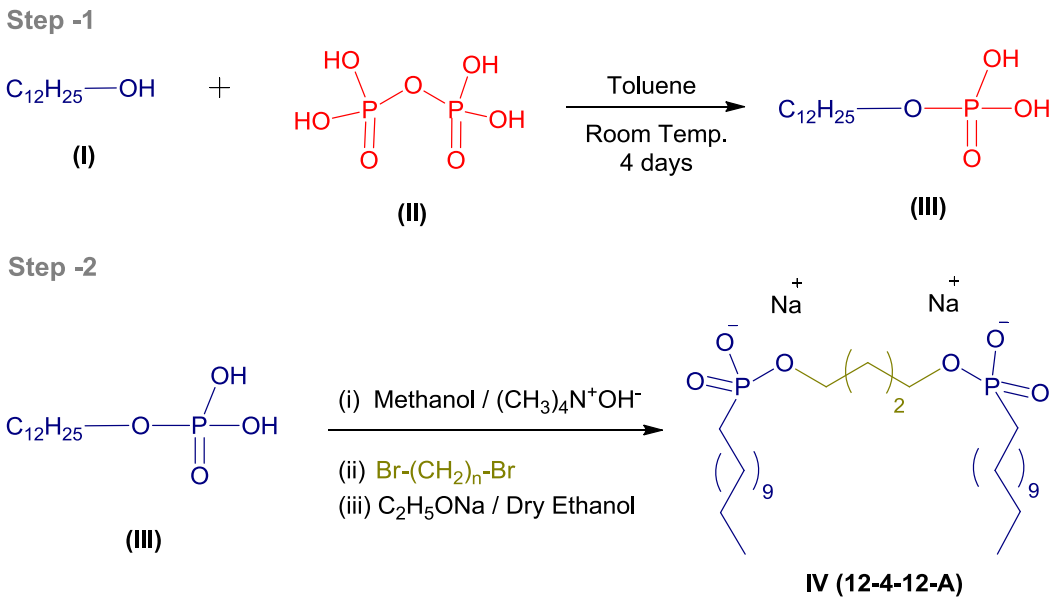
FT-IR (Shimadzu 8400S, KBr, cm^{-1}) neat: 2917 (CH), 2849 (CH), 1748 (C=O), 1470 (CH), 1256 (CN) and 1203 (C-O).

ESI-MS (*m/z*, 838.122 gm/mole): 801.2 (M-Cl^-), 765.3 (M-$2Cl^-$), 541.4 (M-$C_{16}H_{33}$, 2Cl), 328.6 ($C_{16}H_{33}N^+(CH_3)_2CH_2COOH$), 317.4 (M-$C_{32}H_{66}$, $2Cl^-$), 270.6 ($C_{16}H_{33}N(CH_3)_2$).

Elemental (CHN) Analyses: Anal. Calculated for $C_{46}H_{90}Cl_2N_2O_6$: C, 65.9; H, 10.8; N, 3.3(%); Found: C, 66.6 H, 10.8; N, 3.3.

2.2.2. Anionic Gemini Surfactant

Phosphate head group based anionic gemini surfactant (AGS) with dodecyl chain length have been synthesized for the comparison purpose with cationic gemini surfactants. The synthesis route of AGS (See Scheme 2) has been a slightly modified than the process reported [5].



Scheme 2. Synthesis route of Phosphate head group based anionic gemini surfactant with dodecyl chain length.

Dodecyl dihydorgenphosphate (**III**) have been prepared by mixing n-dodecanol (**I**, 14.91 g, 0.08 mol) and pyrophospheric acid (**II**, 17.80 g, 0.10 mol) in appropriate organic solvent (toluene, 10-20 ml). Stirring continued till a clear solution formed and then the reaction mixture was allowed to stand for 4 days. After completion of the reaction, mass is dissolved in diethtyl ether (50 ml) and then immediately washed with water (100 ml x 3). The ether rich layer was then added to dilute NaOH aqueous solution (50%) under continuous stirring. Once addition was completed, the ether rich layer was discarded (which contains unreacted **I**). The pH of the aqueous layer was adjusted (from basic (12.4) to acidic (0.5)) by concentrated

HCl. After acidification, the product was extracted with ether and aqueous layer has also been discarded. The ether-rich layer then washed with diute HCl (2 x 50 ml). This rich layer was vacuum desiccated for several hours till a floppy mass of dodecyl dihydorgenphosphate (**III**, 15.15 g, 57 yield) was obtained.

In a second step (Scheme 2), the dodecyl dihydrogen phosphate (**III**, 13.3 g. 0.05 mol) was mixed with methanolic solution of tertamethylammonium hydroxide (9.1 g, 0.1 mol) at room temperature. After removal of methanol (under reduced pressure), this tacky solid mass has been mixed with spacers (1, 4-dibormobutane, 5.4 g, 0.025 mol) in acetonitrile (50 ml) under continuous stirring followed by refluxing for 1-2 h. After removal of solvent (by applying vacuum), the tacky mass was acidified with dilute HCl solution (100 ml) followed by extraction with diethyl ether (3 x 50-100 ml). The ether layer was washed with water (3 x 50 ml). After removal of ether, the solid brownish mass was crystallized with a mixture of $CHCl_3$:ethyl acetate (40:60) to obtain pure hydroxyl form of AGS. The hydroxyl form was again reacted with sodium ethoxide (C_2H_5ONa) in dry ethanol. After removal of ethanol, the pure AGS (12-4-12-A, **IV)** was dried under the vacuum and then characterized.

Characterization Data of Anionic Gemini Surfactant

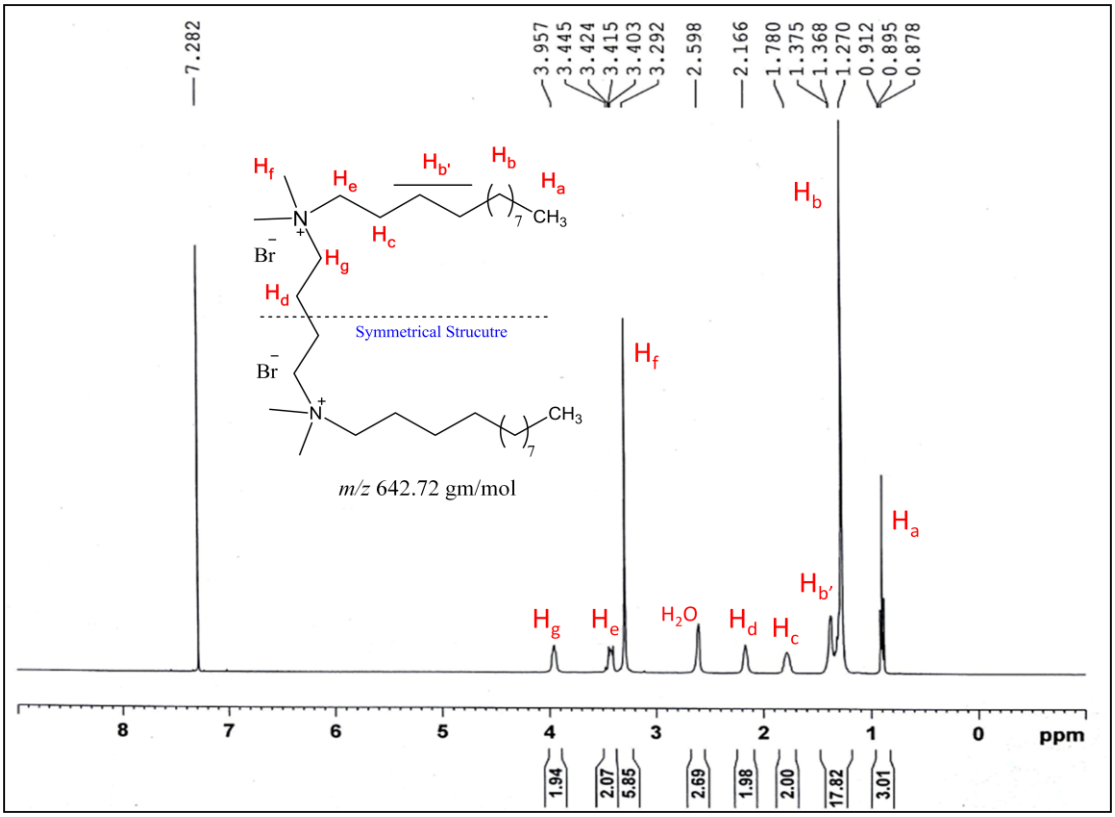
12-4-12-A (IV) (*phosphoric acid*, P,P′-*1,4-butanediyl* P,P′-*ditetradecyl ester, sodium salt)*. White amorphous powder, 8.02 gm, 51% yield

^{1}H NMR (400 MHz, Bruker, $CDCl_3$, TMS): δ 0.88-0.91 (t, 6H, $(CH_3)_2$), 1.27-1.37 (s, 36H, $(CH_2)_{18}$), 1.67-1.69 (t, 4H, $(CH_2)_2$), 1.87 (s, 4H, $(CH_2)_2$), 4.02-4.07 (q, 4H, $(CH_2)_2$), 4.13-4.15 (d, 4H, $(CH_2)_2$).

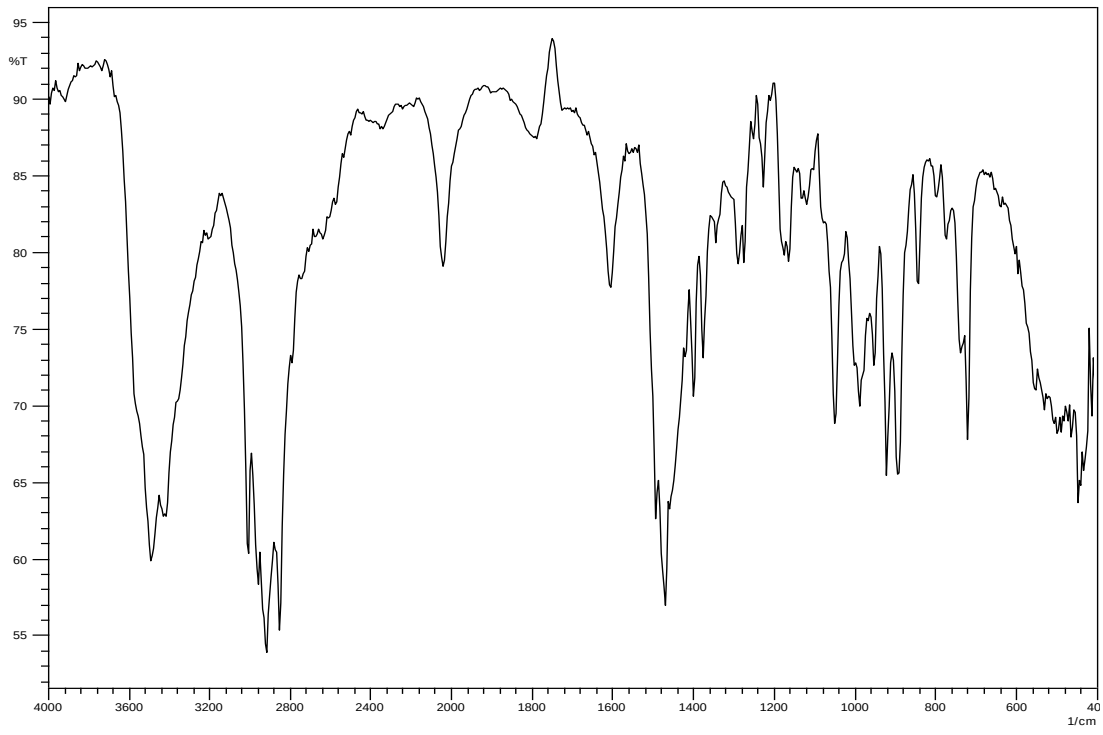
FT-IR (Shimadzu 8400S, KBr, cm^{-1}): 1056, 1111, 1261, 1470, 2354, 2853, 2922.

ESI-MS (*m/z*, 630.38 gm/mole): 653.4 (M with sodium), 631.5 (M), 609.5 (M-Na^+), 587.5 (M-$2Na^+$), 476.4 (M-$C_{11}H_{23}$), 338.4 (M-$C_{12}H_{25}PO_4^{-2}Na^+$).

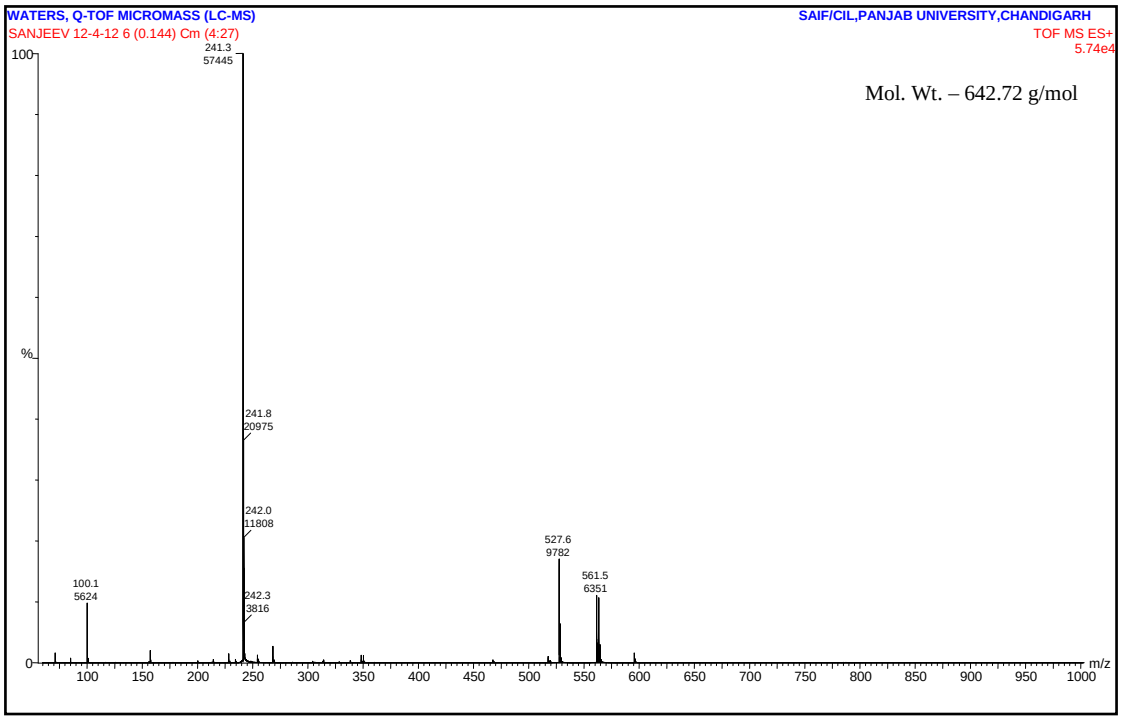
2.2.3. Spectral Data of Gemini Surfactants



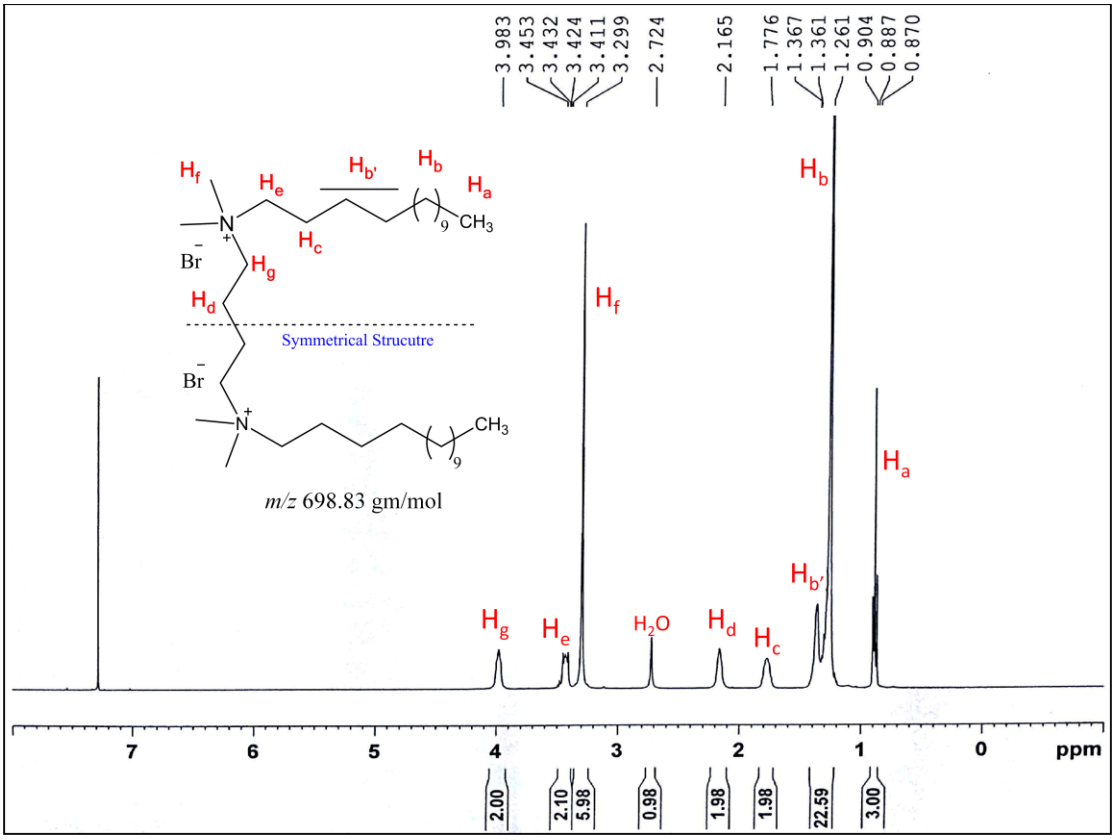
^{1}H NMR Spectra of Cationic Gemini Surfactant (12-4-12, Compound 5)



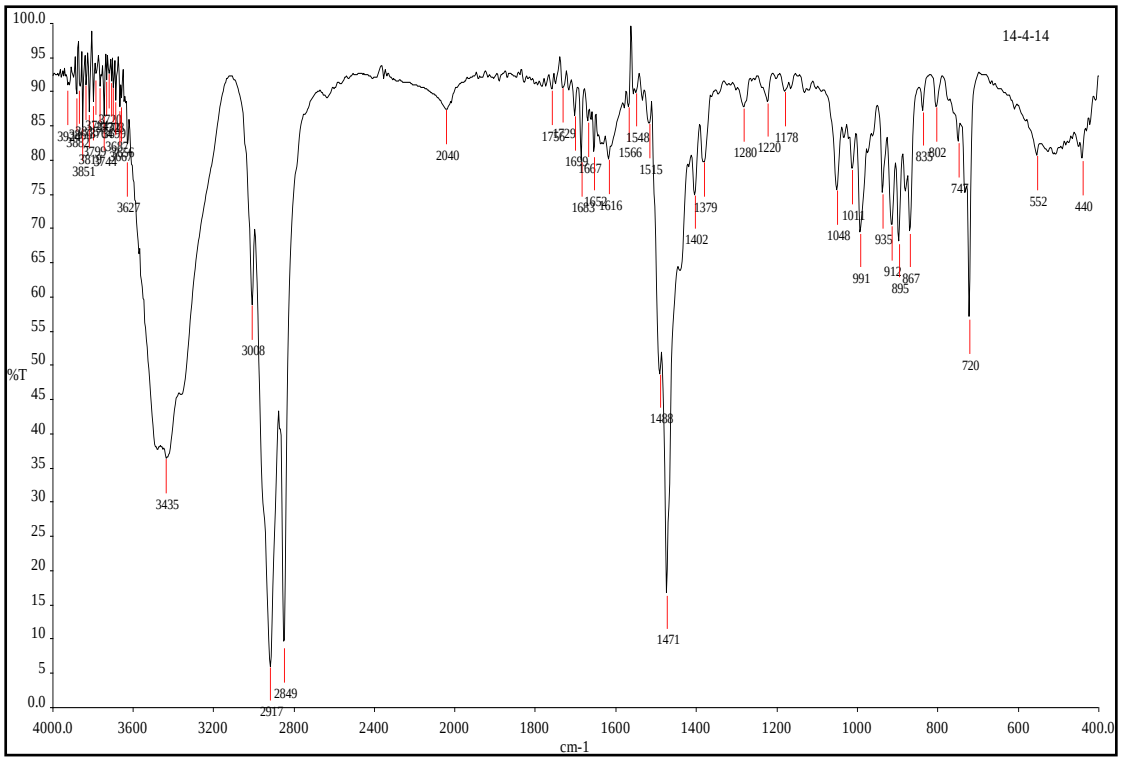
FT-IR Spectra of Cationic Gemini Surfactant (12-4-12, Compound 5)



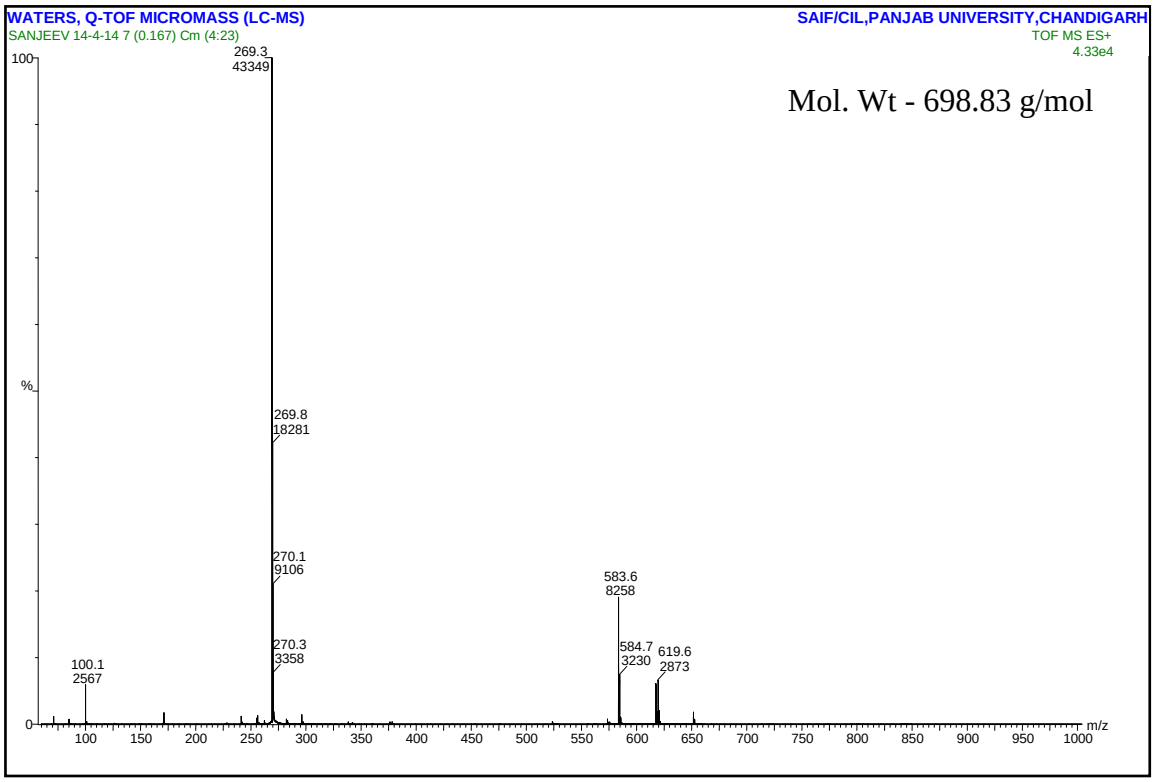
ESI-Mass Spectra of Cationic Gemini Surfactant (12-4-12, Compound 5)



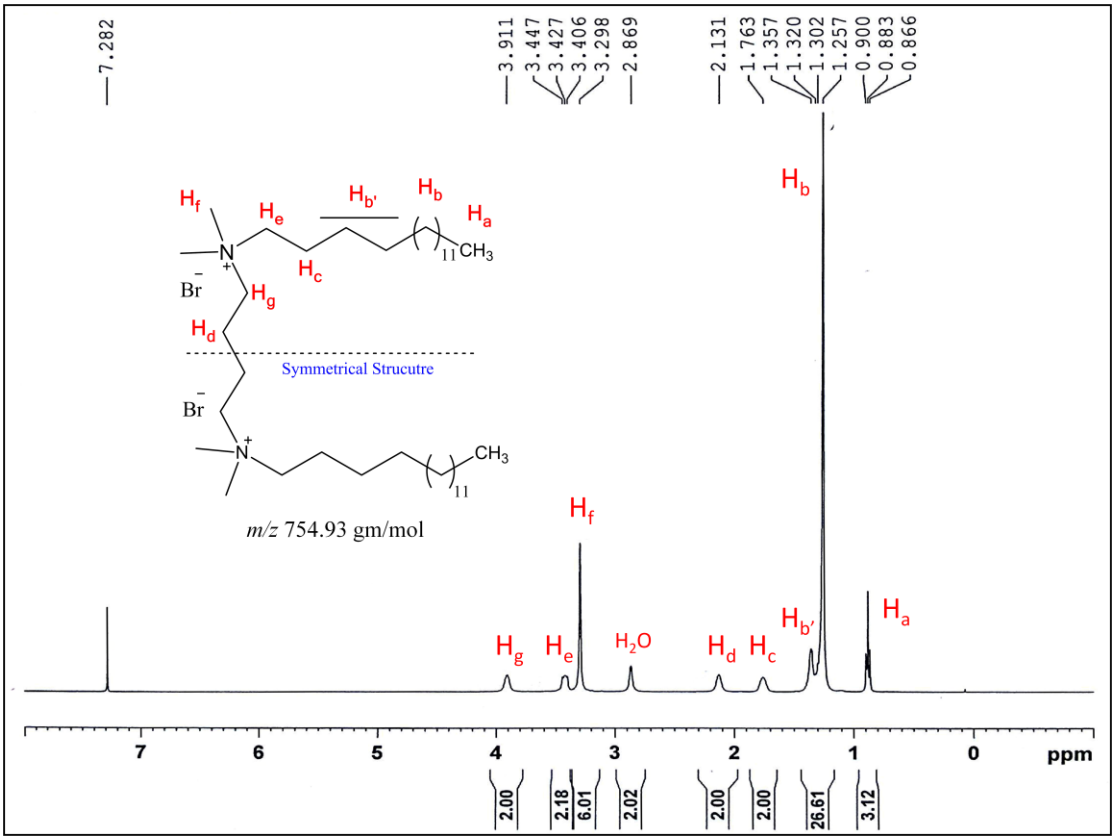
^{1}H NMR Spectra of Cationic Gemini Surfactant (14-4-14, Compound 6)



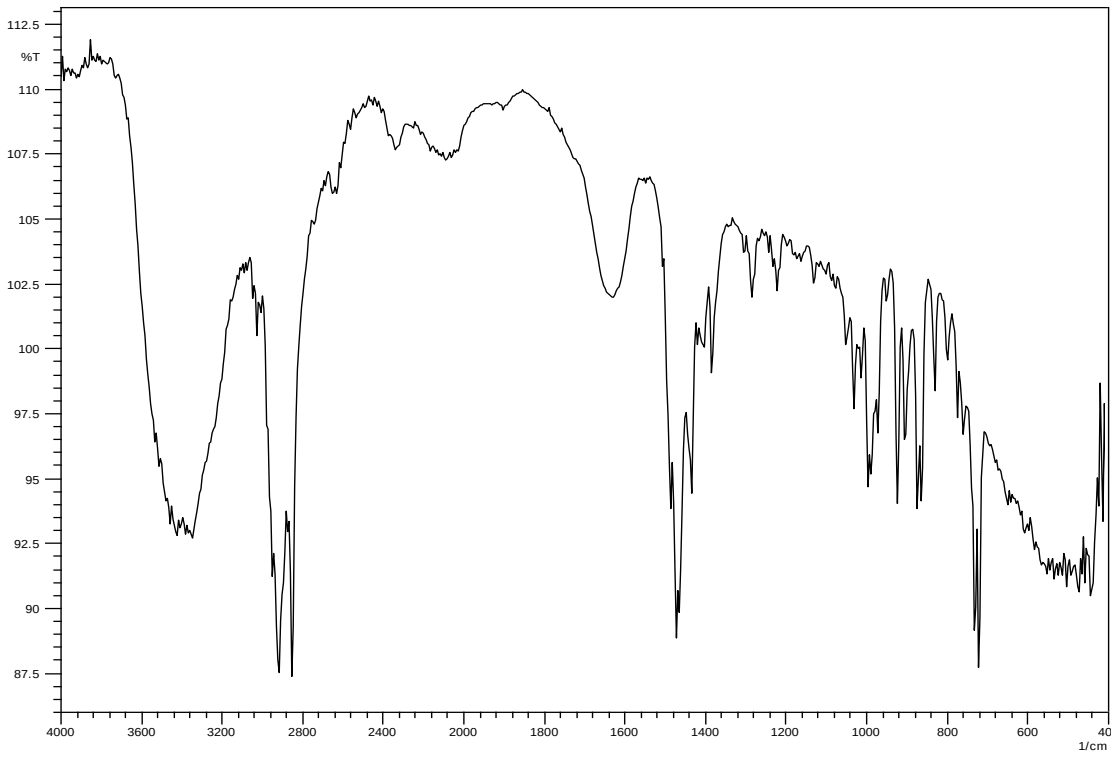
FT-IR Spectra of Cationic Gemini Surfactant (14-4-14, Compound 6)



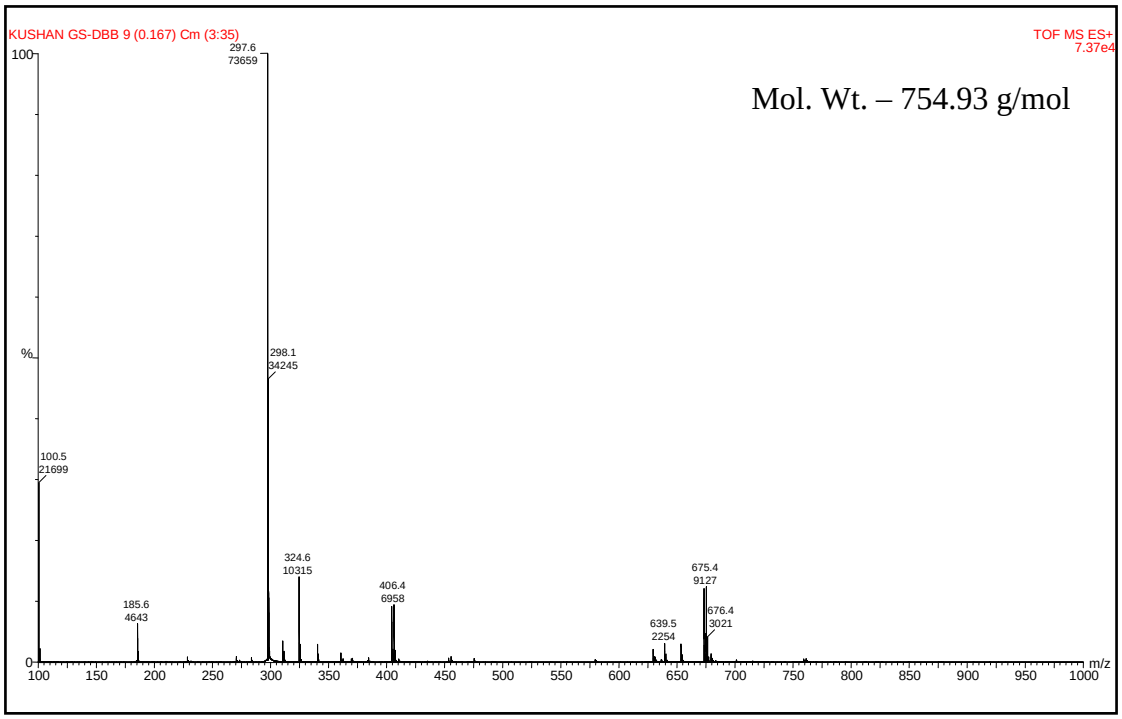
ESI-Mass Spectra of Cationic Gemini Surfactant (14-4-14, Compound 6)



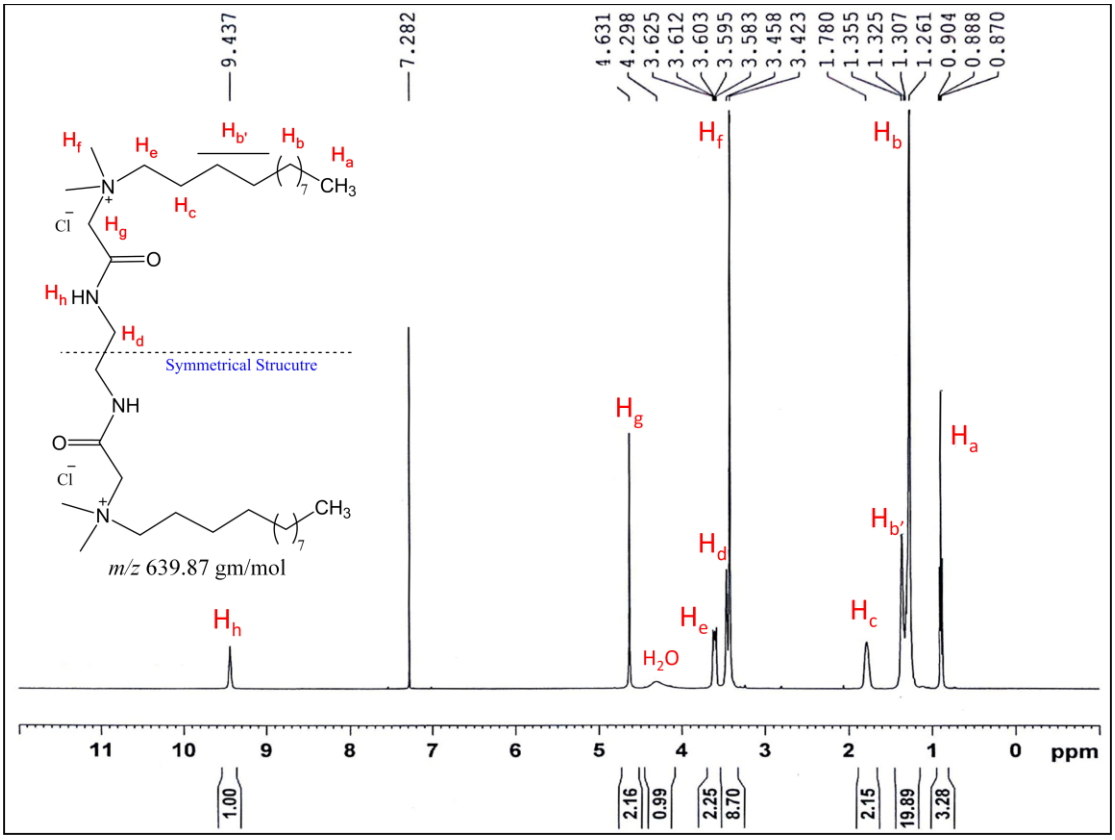
^{1}H NMR Spectra of Cationic Gemini Surfactant (16-4-16, Compound 7)



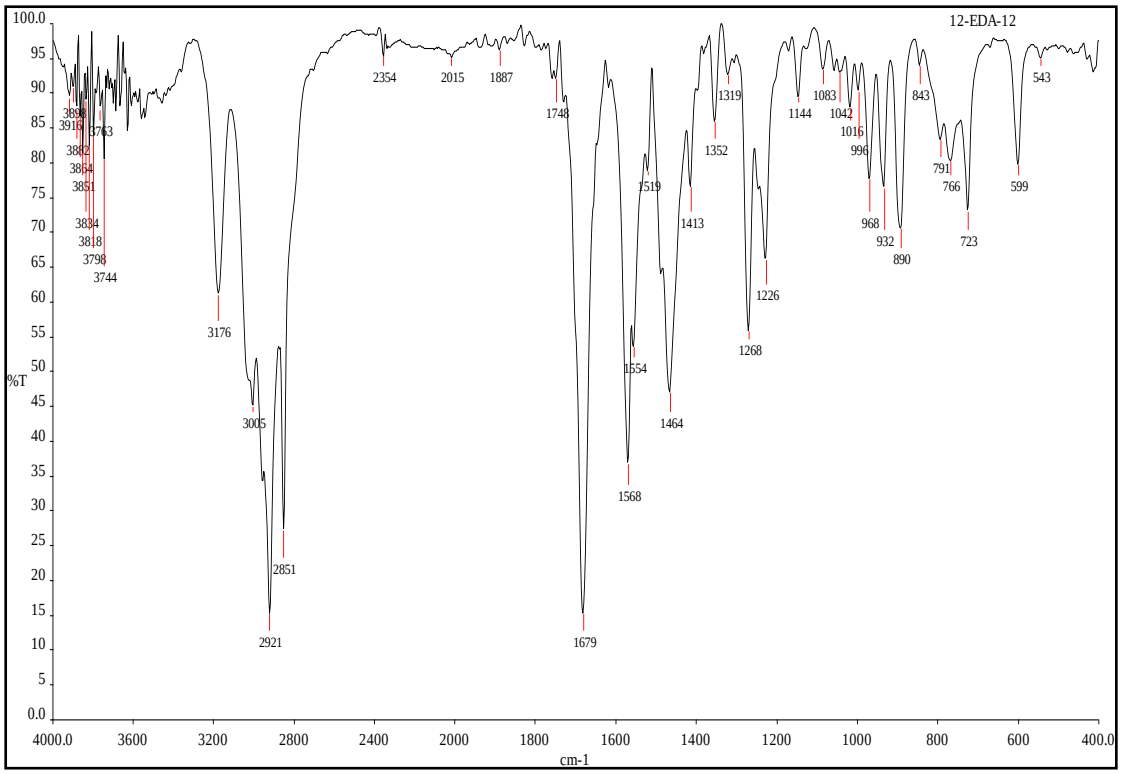
FT-IR Spectra of Cationic Gemini Surfactant (16-4-16, Compound 7)



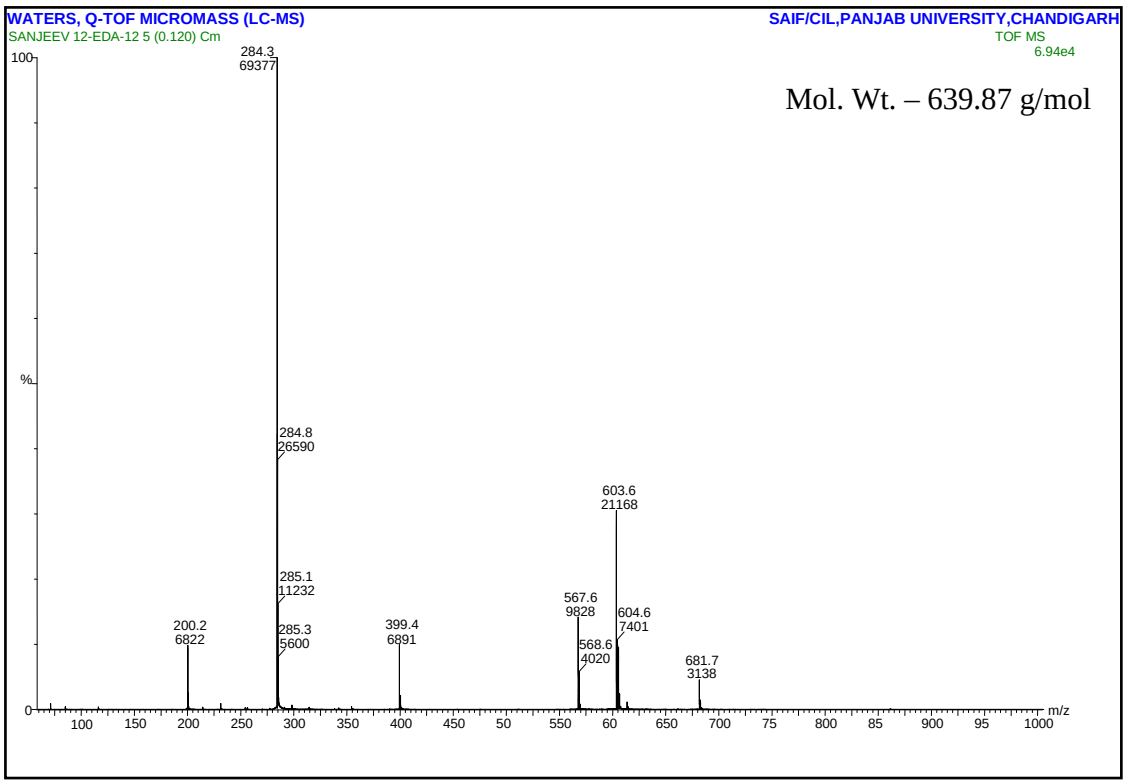
ESI-Mass Spectra of Cationic Gemini Surfactant (16-4-16, Compound 7)



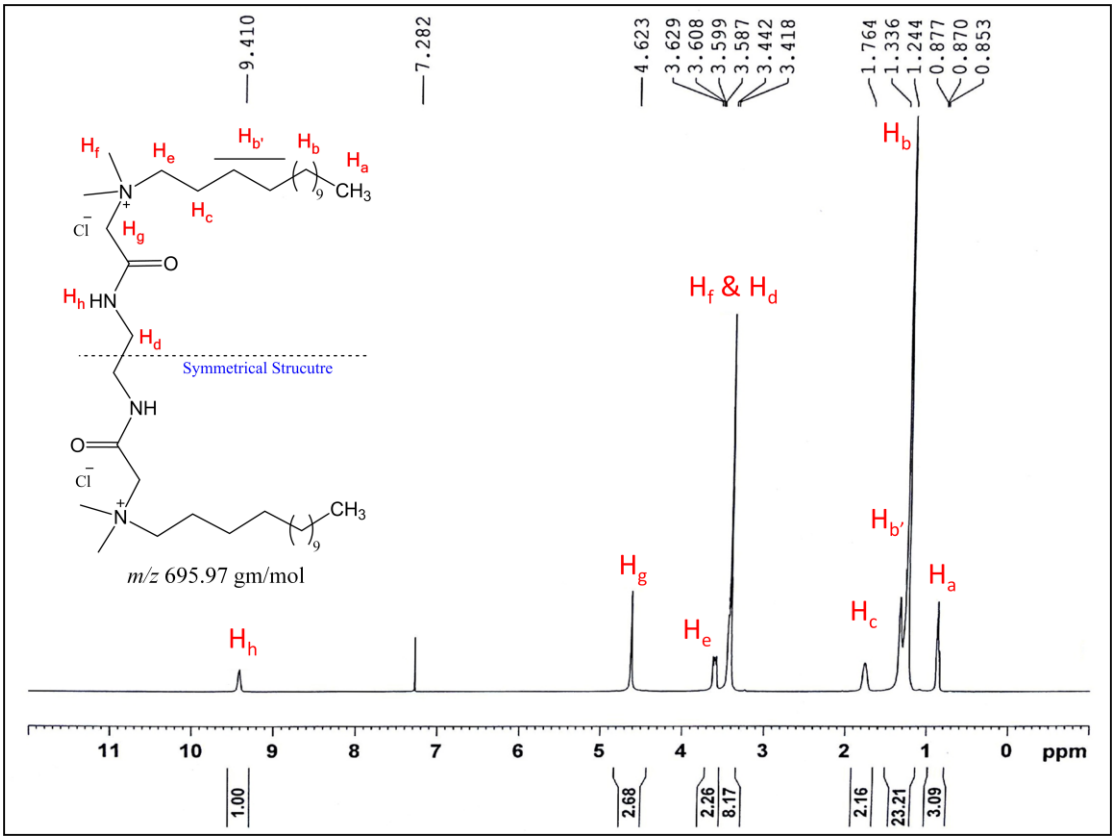
^{1}H NMR Spectra of Cationic Gemini Surfactant (12-Eda-12, Compound 10)



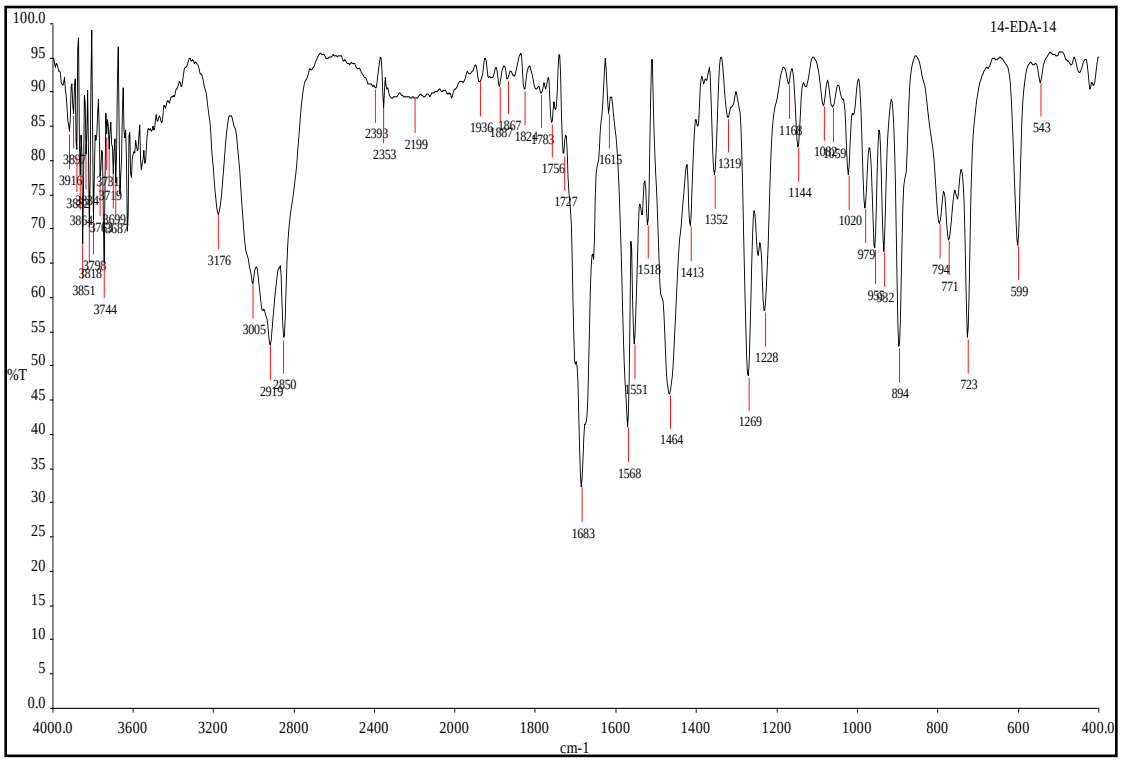
FT-IR Spectra of Cationic Gemini Surfactant (12-Eda-12, Compound 10)



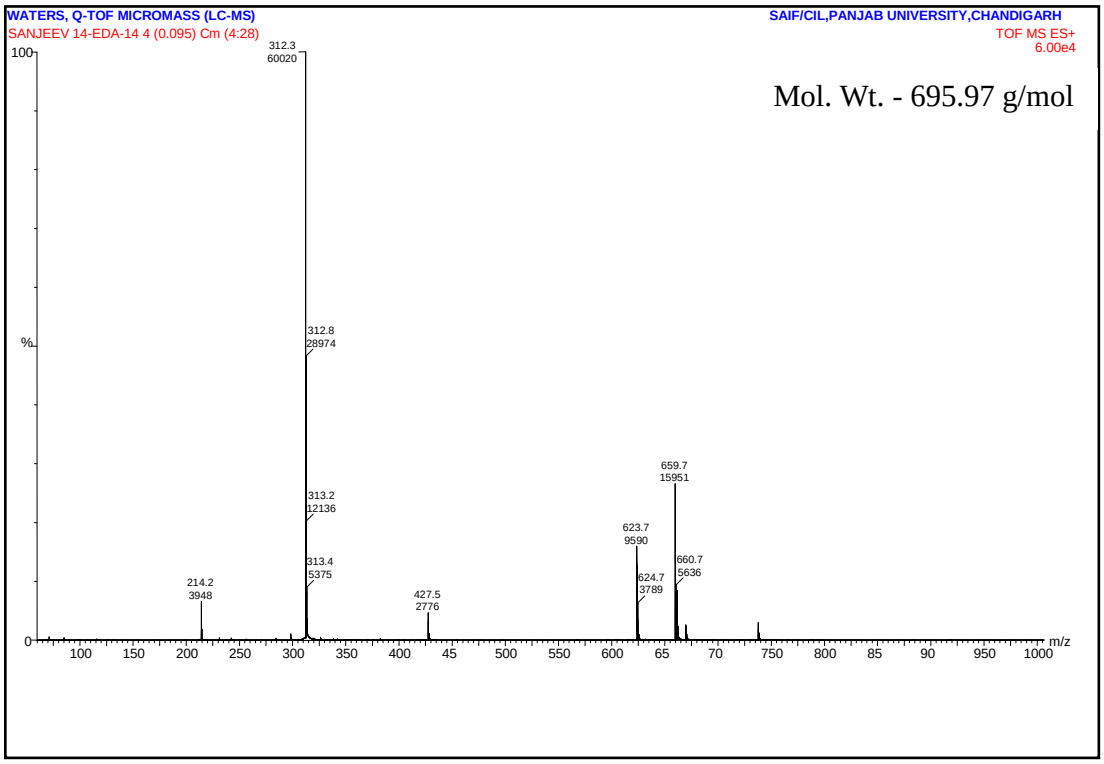
ESI-Mass Spectra of Cationic Gemini Surfactant (12-Eda-12, Compound 10)



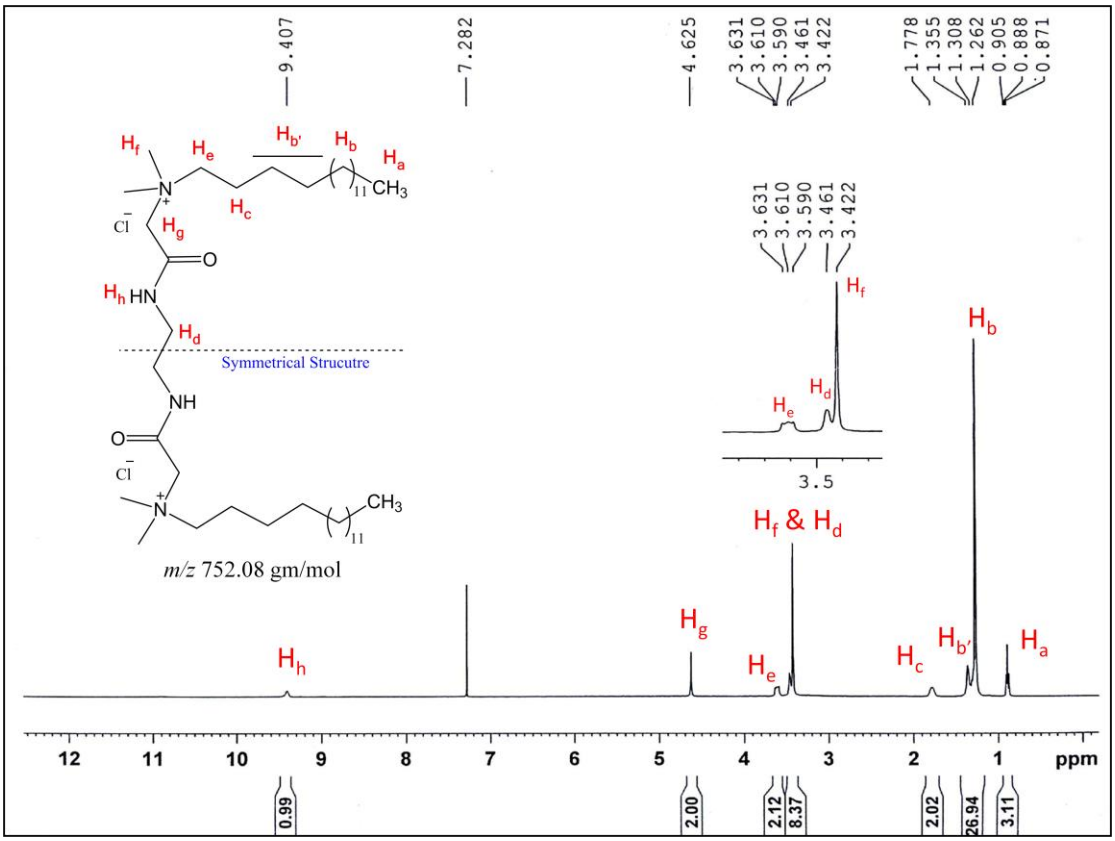
^{1}H NMR Spectra of Cationic Gemini Surfactant (14-Eda-14, Compound 11)



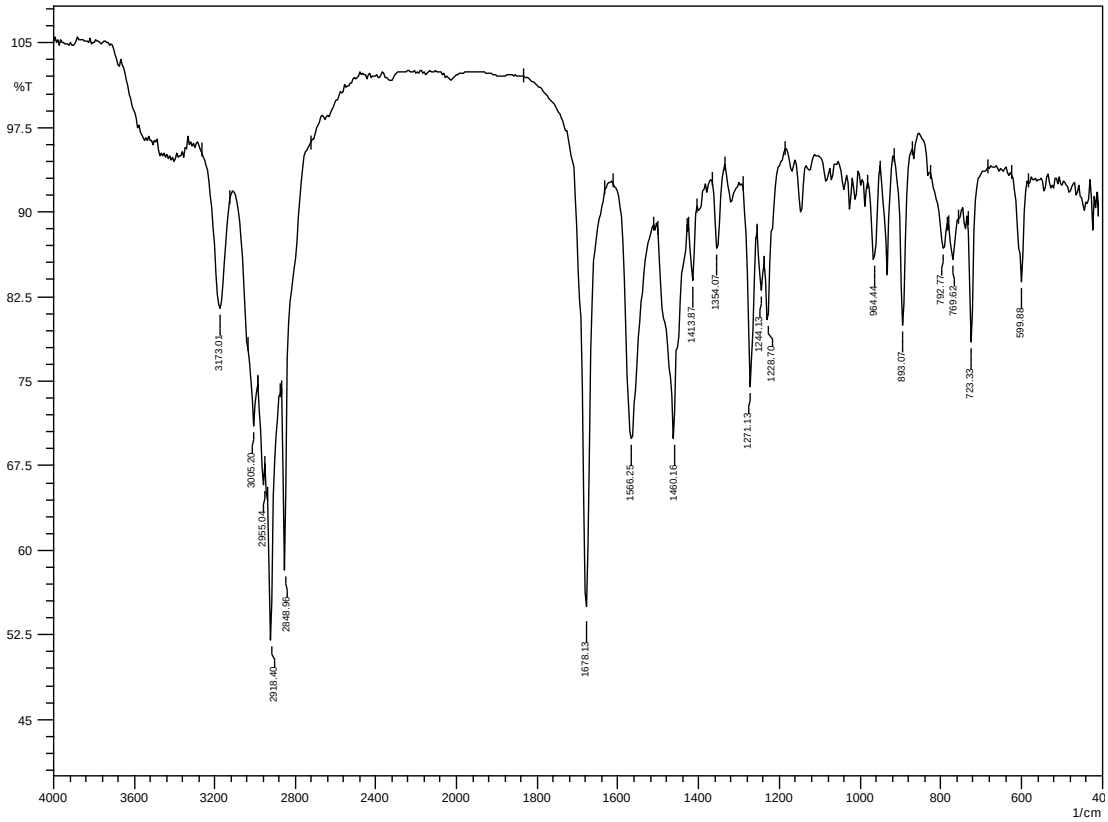
FT-IR Spectra of Cationic Gemini Surfactant (14-Eda-14, Compound 11)



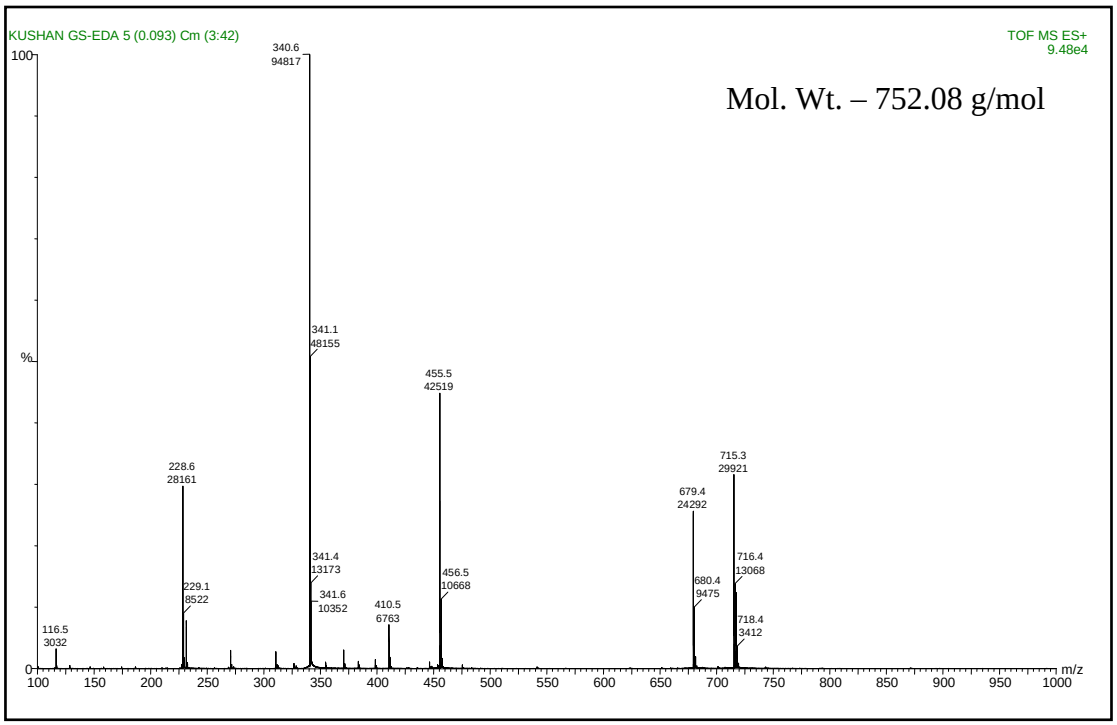
ESI-Mass Spectra of Cationic Gemini Surfactant (14-Eda-14, Compound 11)



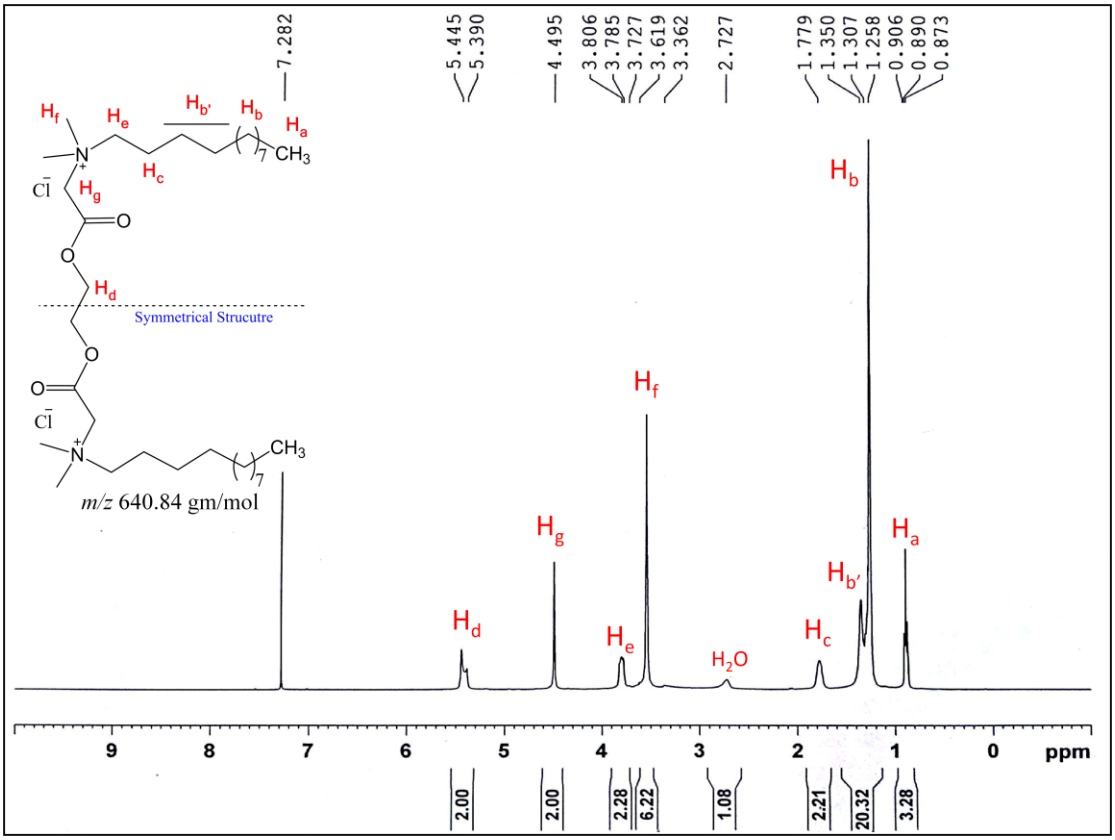
^{1}H NMR Spectra of Cationic Gemini Surfactant (16-Eda-16, Compound 12)



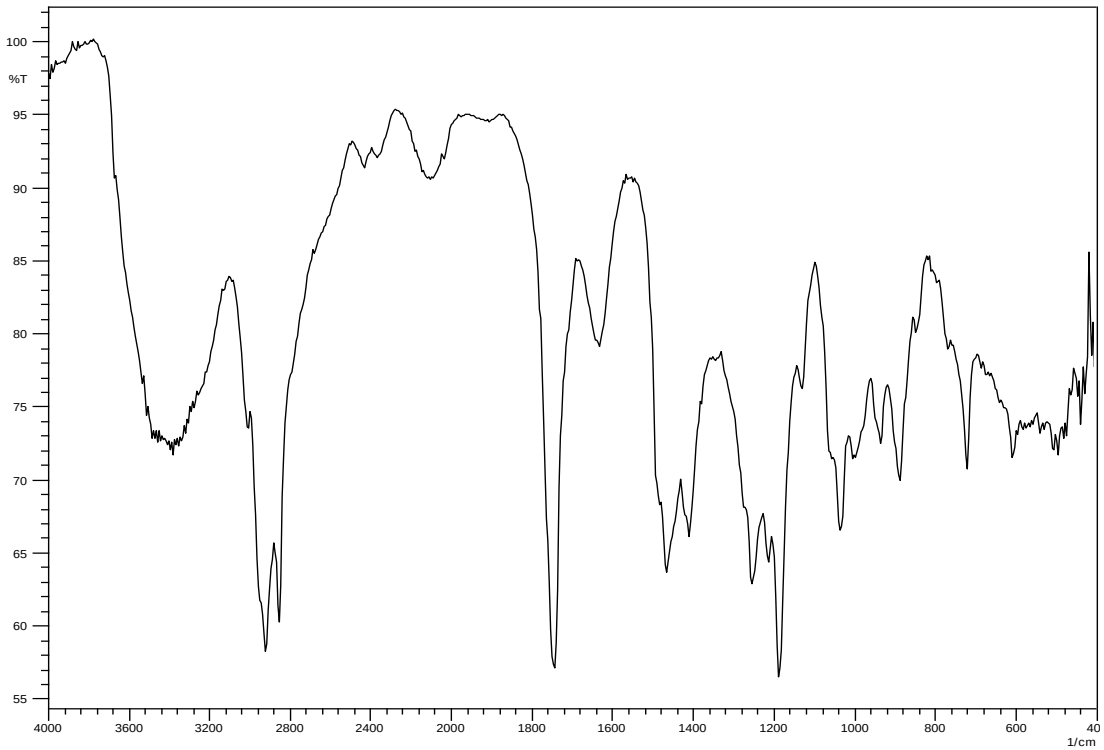
FT-IR Spectra of Cationic Gemini Surfactant (16-Eda-16, Compound 12)



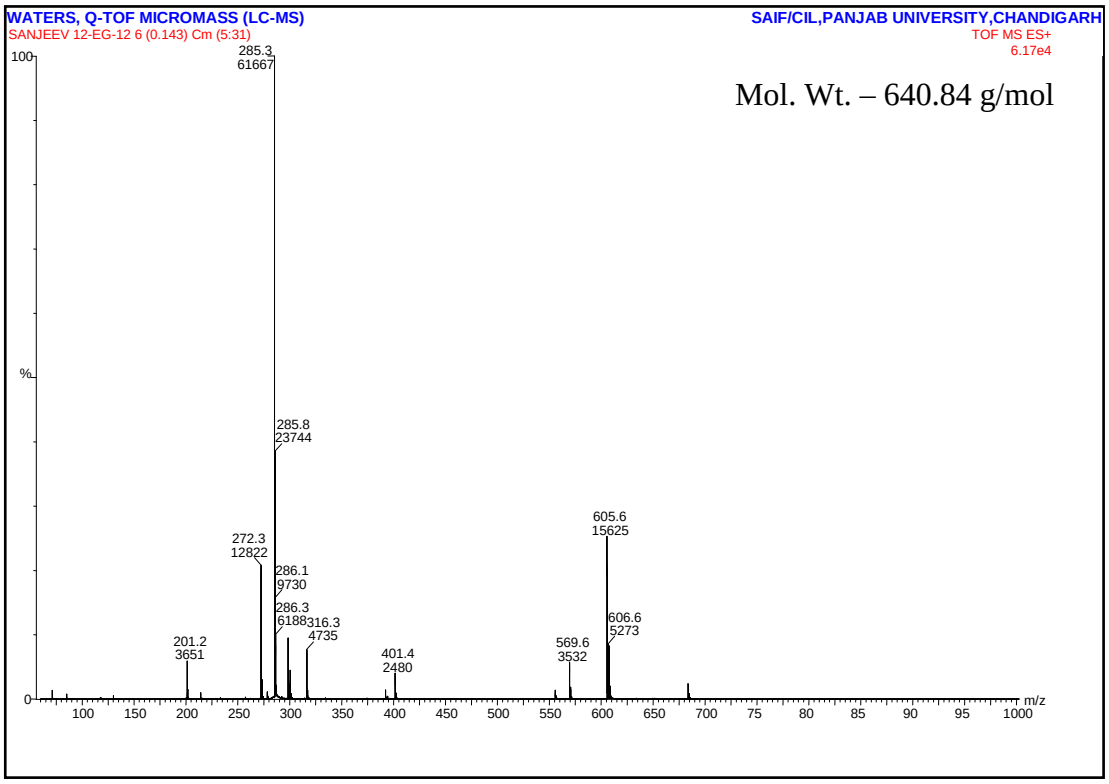
ESI-Mass Spectra of Cationic Gemini Surfactant (16-Eda-16, Compound 12)



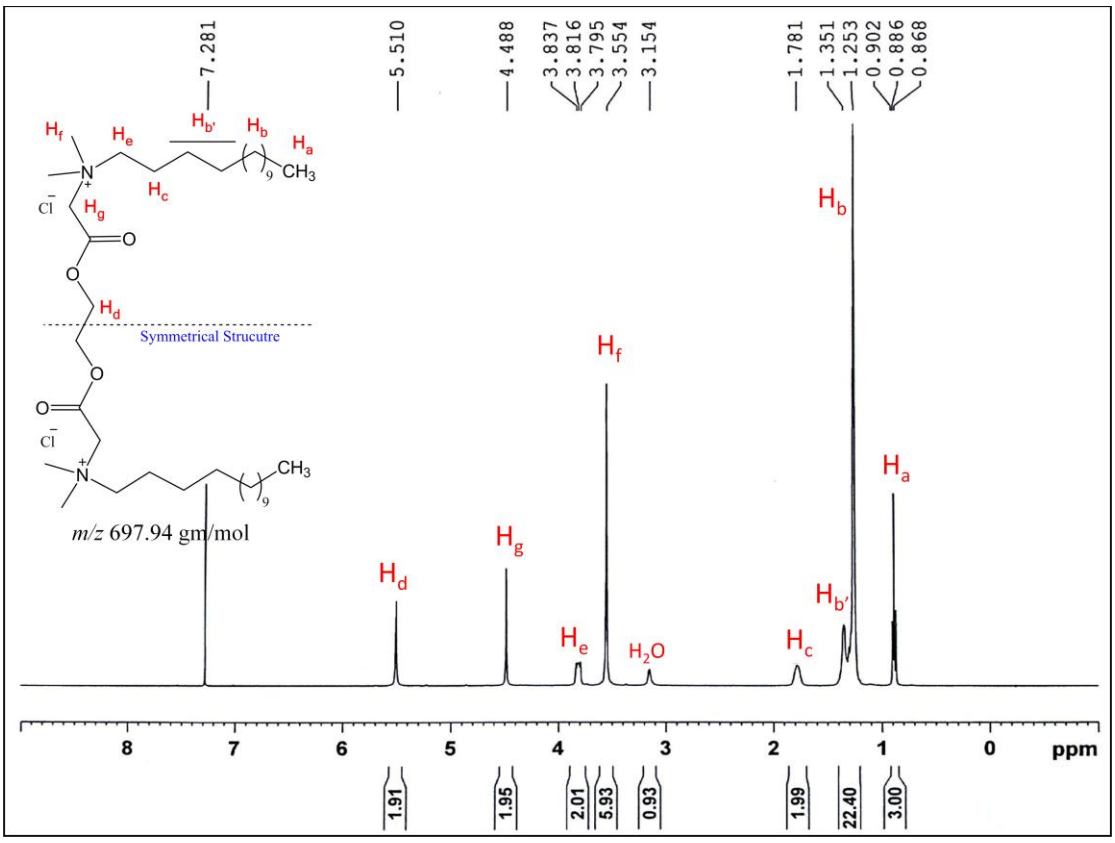
^{1}H NMR Spectra of Cationic Gemini Surfactant (12-Eg-12, Compound 15)



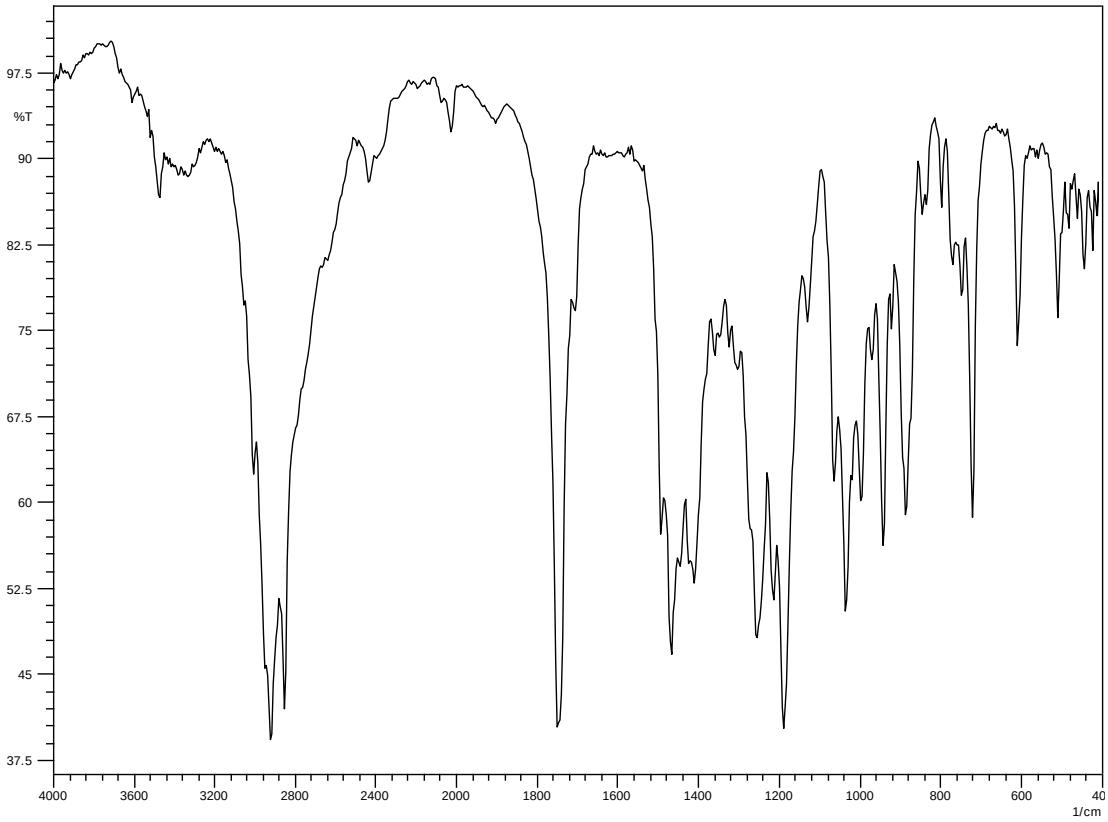
FT-IR Spectra of Cationic Gemini Surfactant (12-Eg-12, Compound 15)



ESI-Mass Spectra of Cationic Gemini Surfactant (12-Eg-12, Compound 15)



^{1}H NMR Spectra of Cationic Gemini Surfactant (14-Eg-14, Compound 16)



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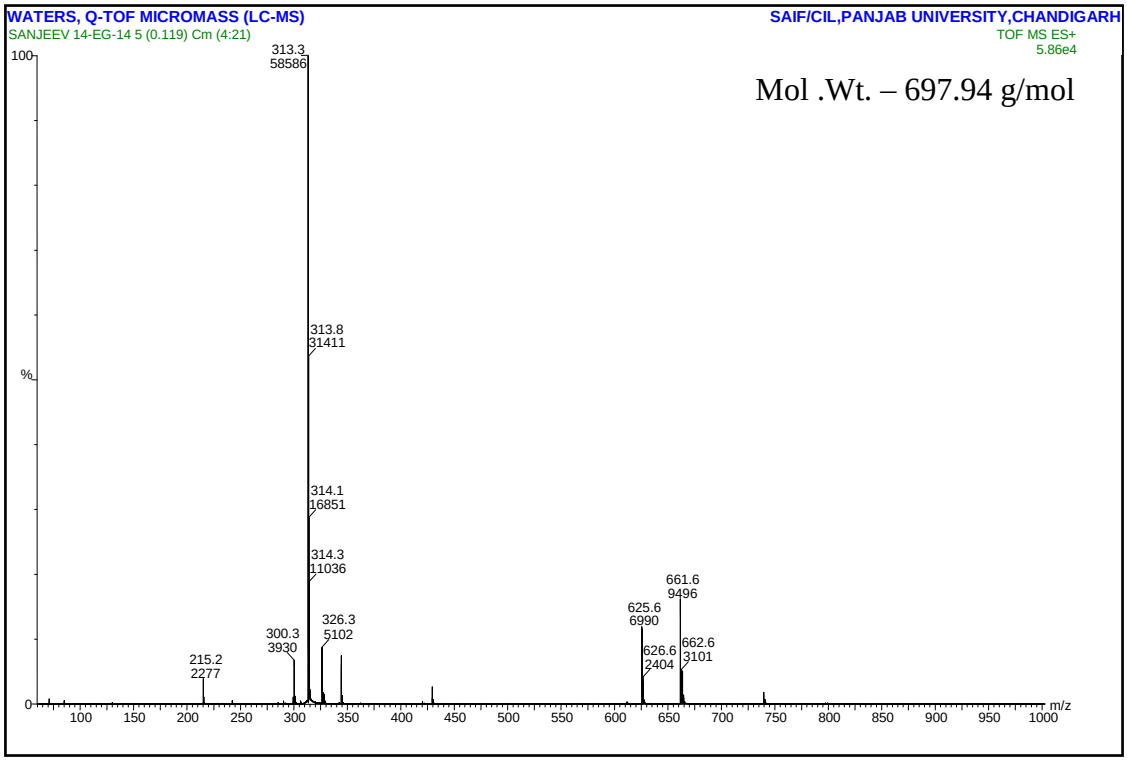
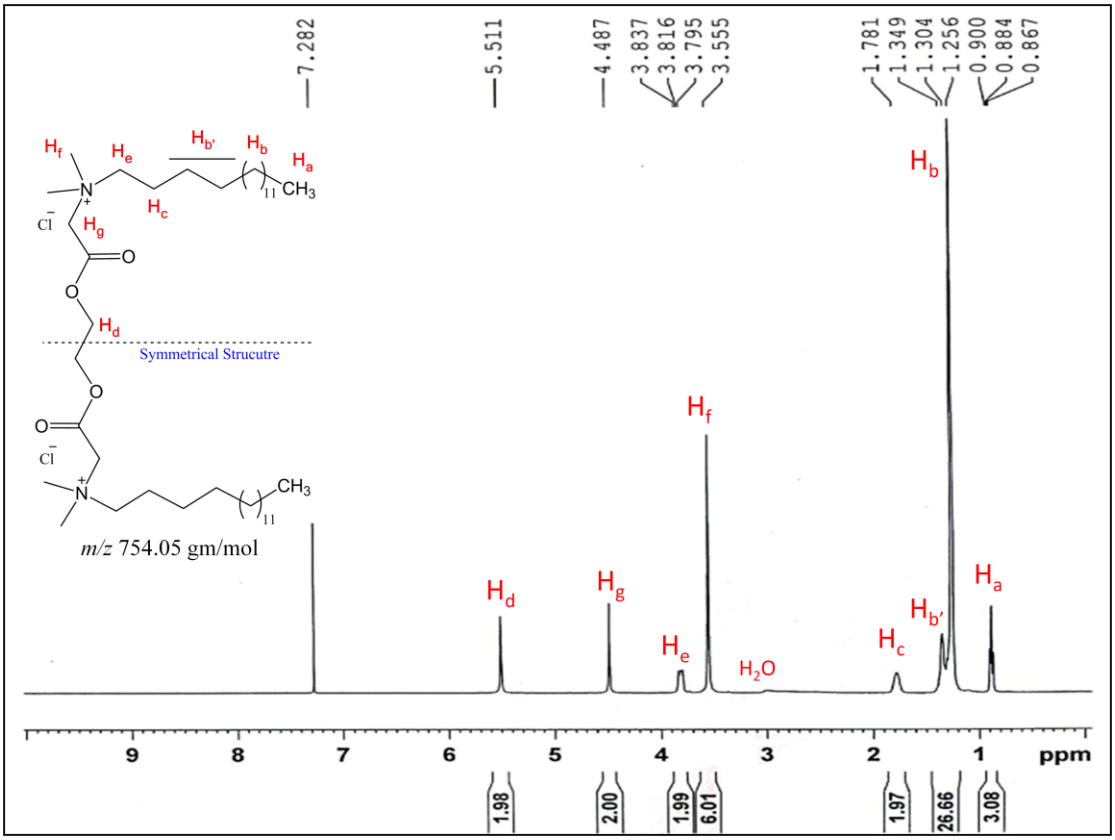


ESI-Mass Spectra of Cationic Gemini Surfactant (14-Eg-14, Compound 16)



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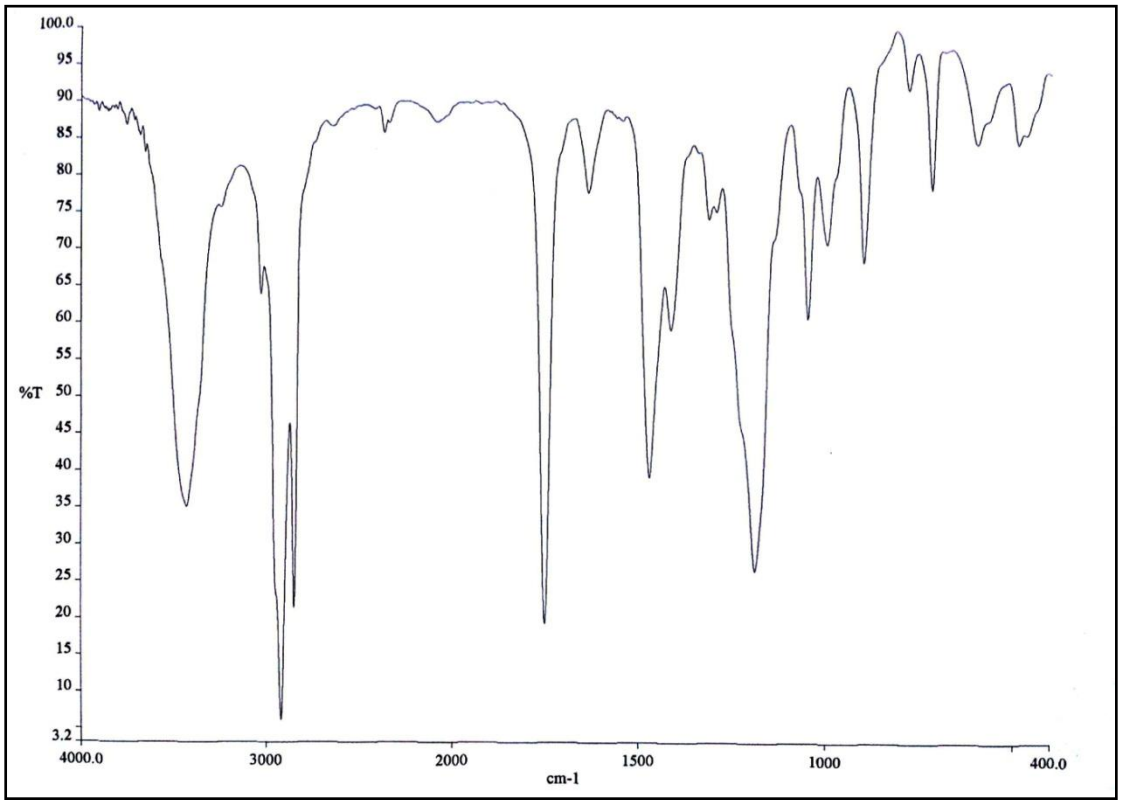

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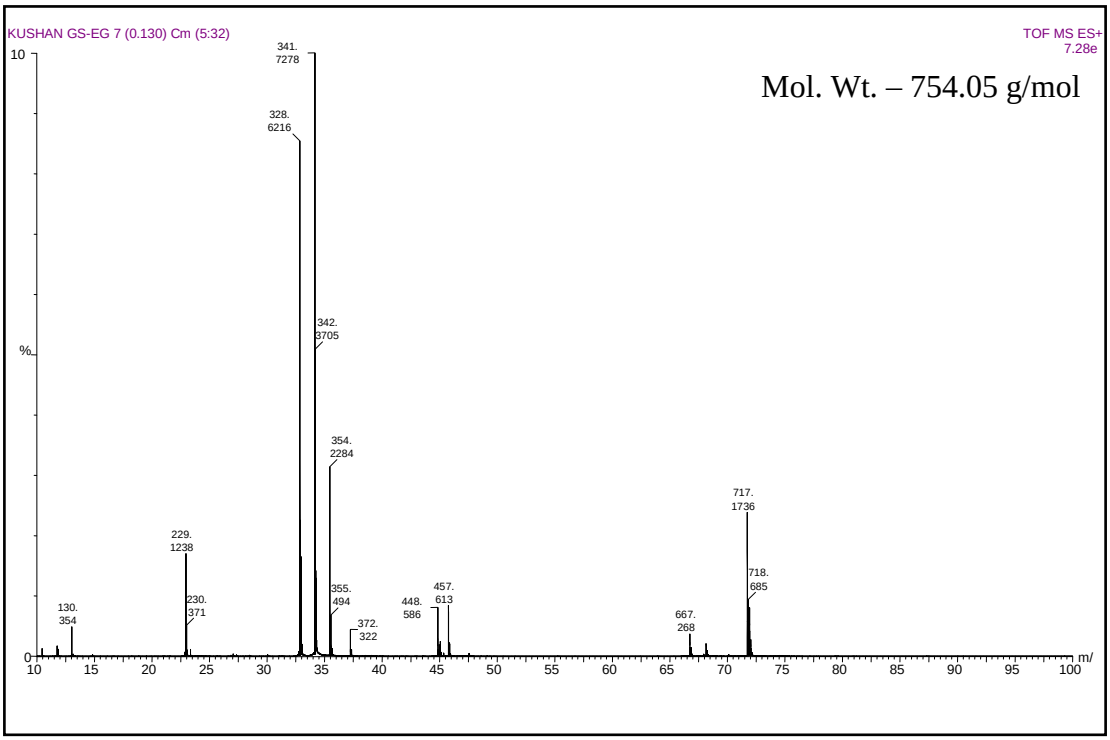

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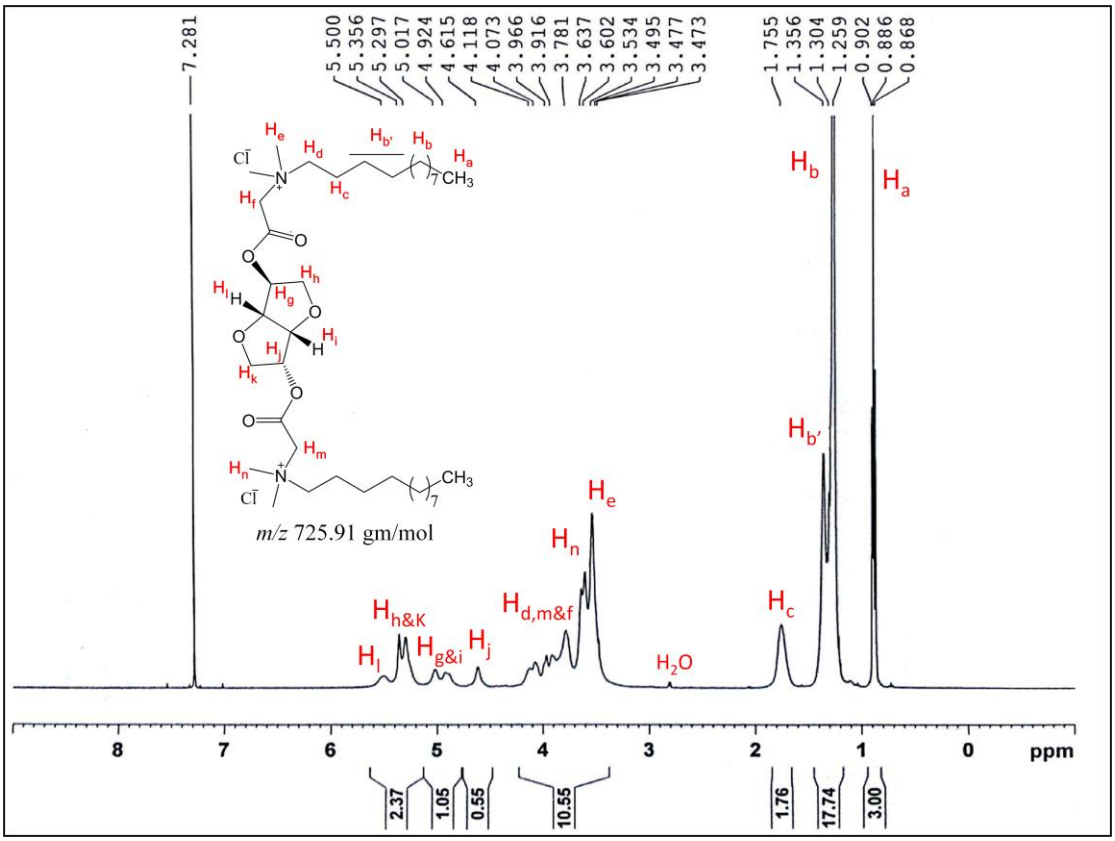
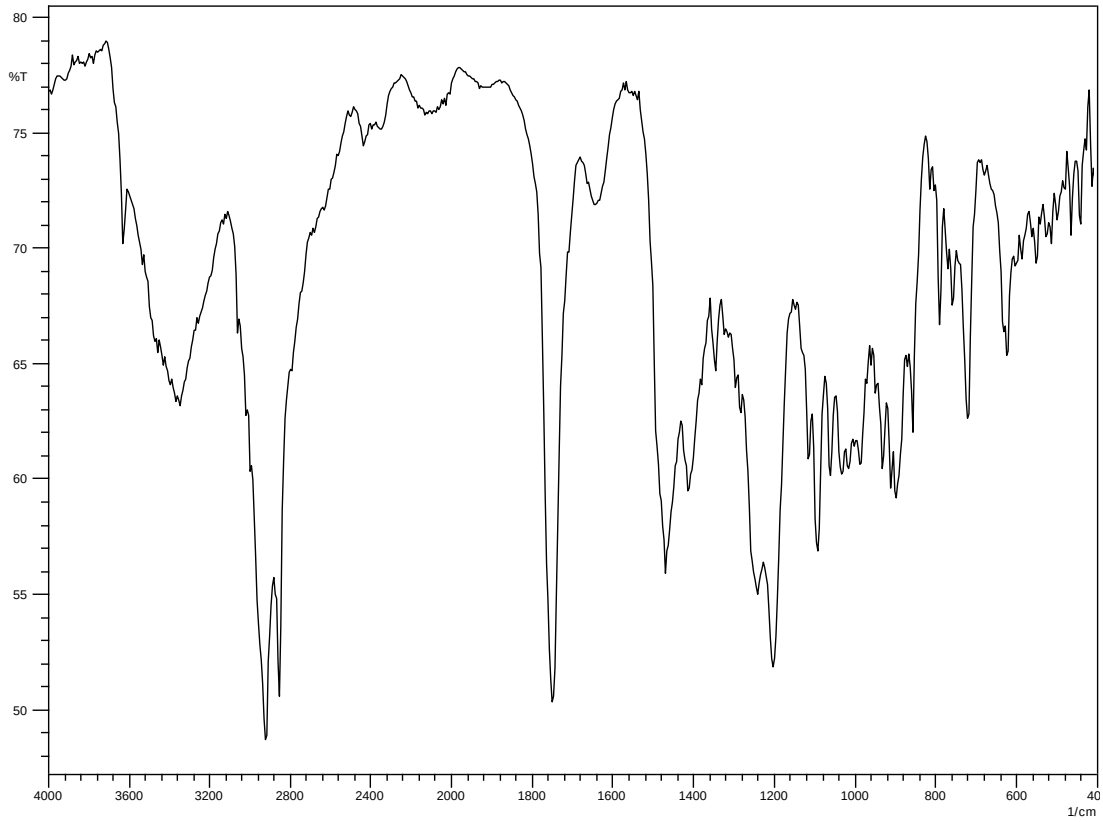


^{1}H NMR Spectra of Cationic Gemini Surfactant (12-Isb-12, Compound 20)



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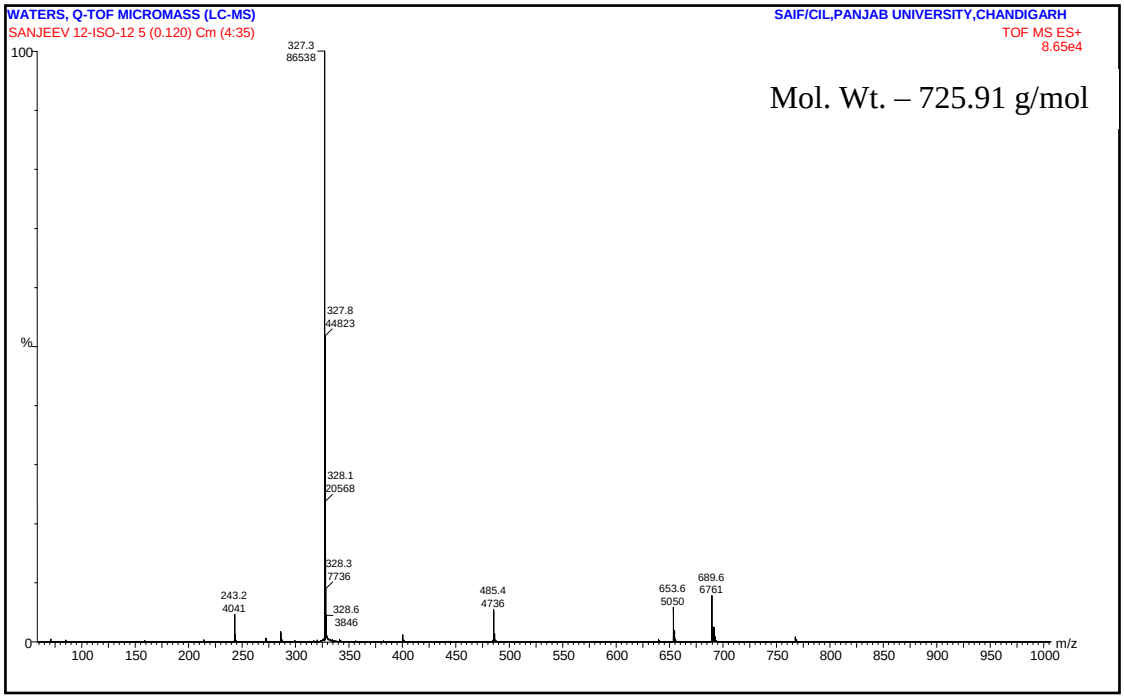

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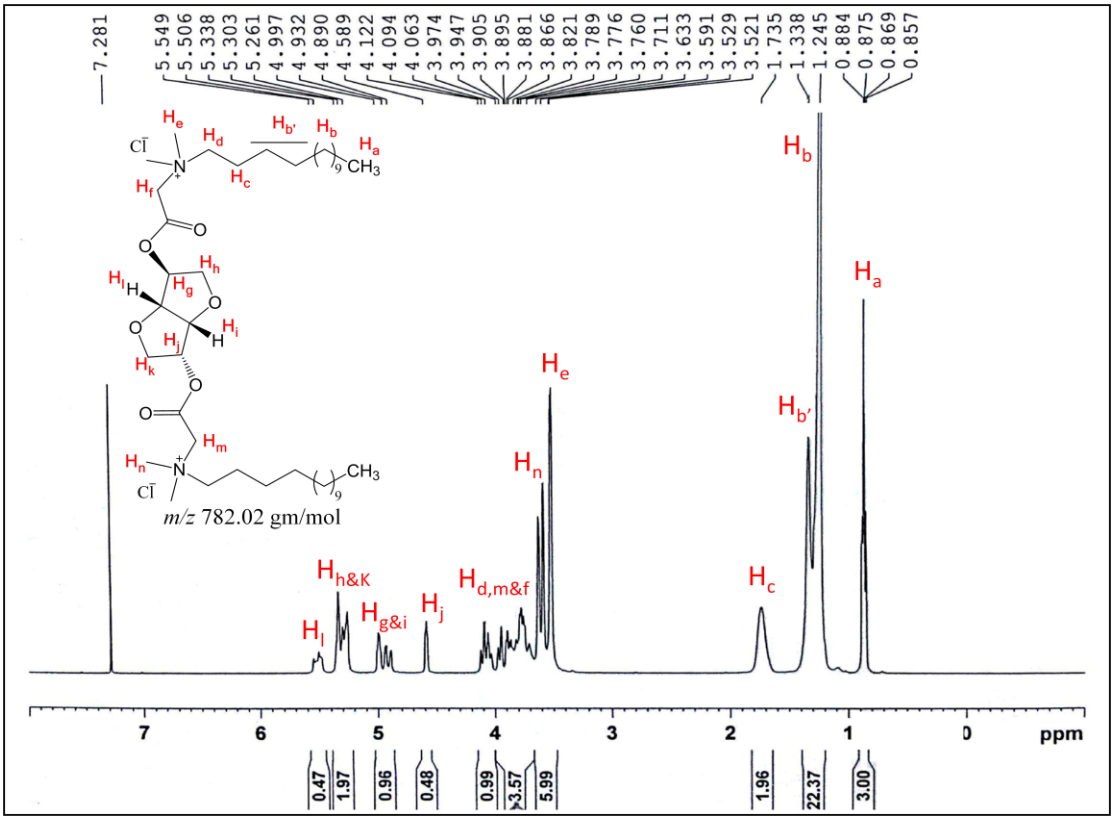

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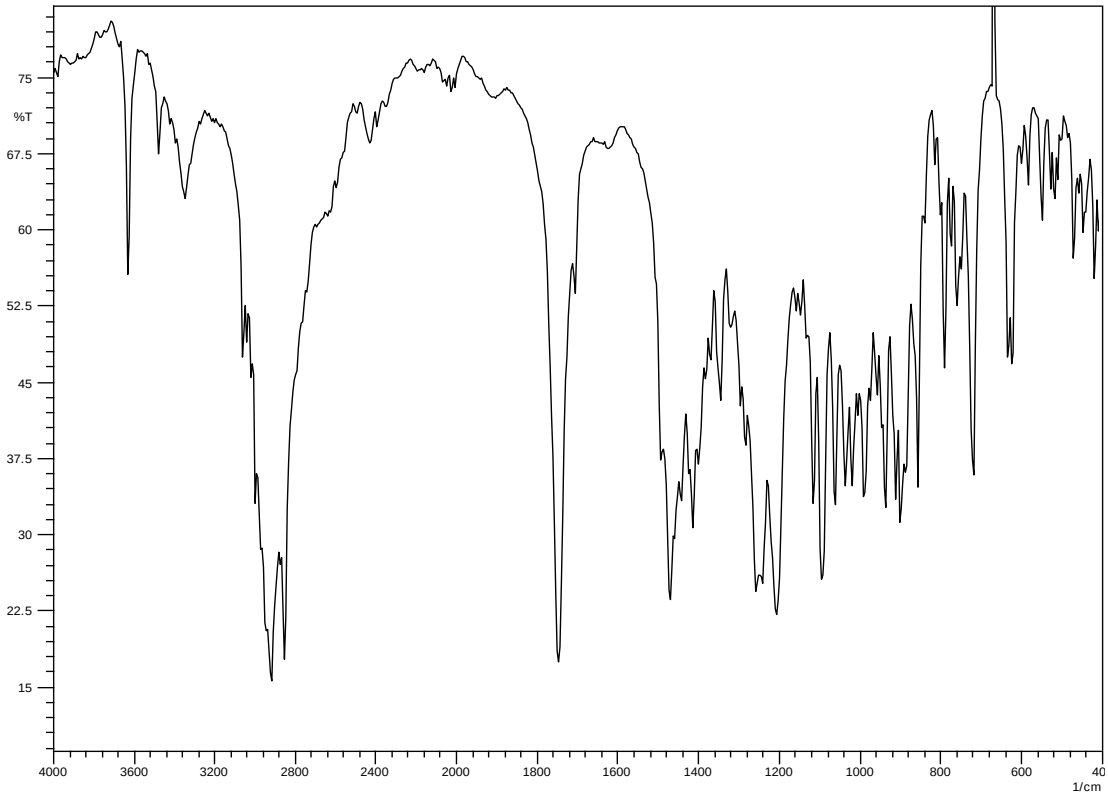

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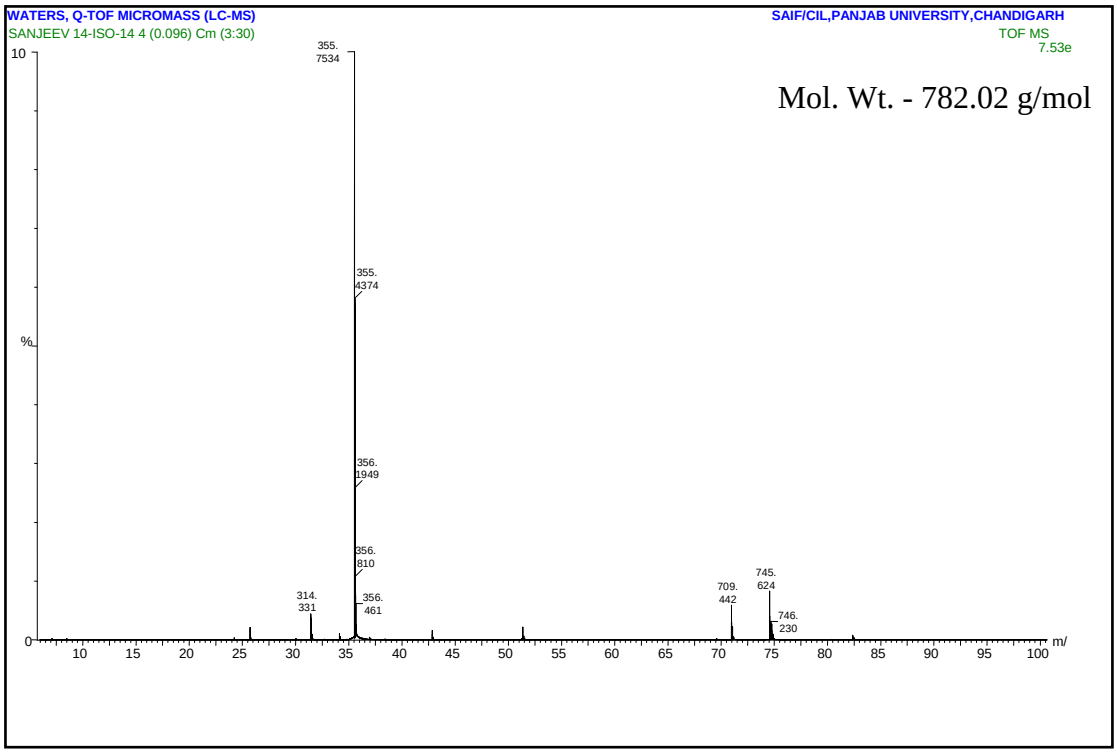

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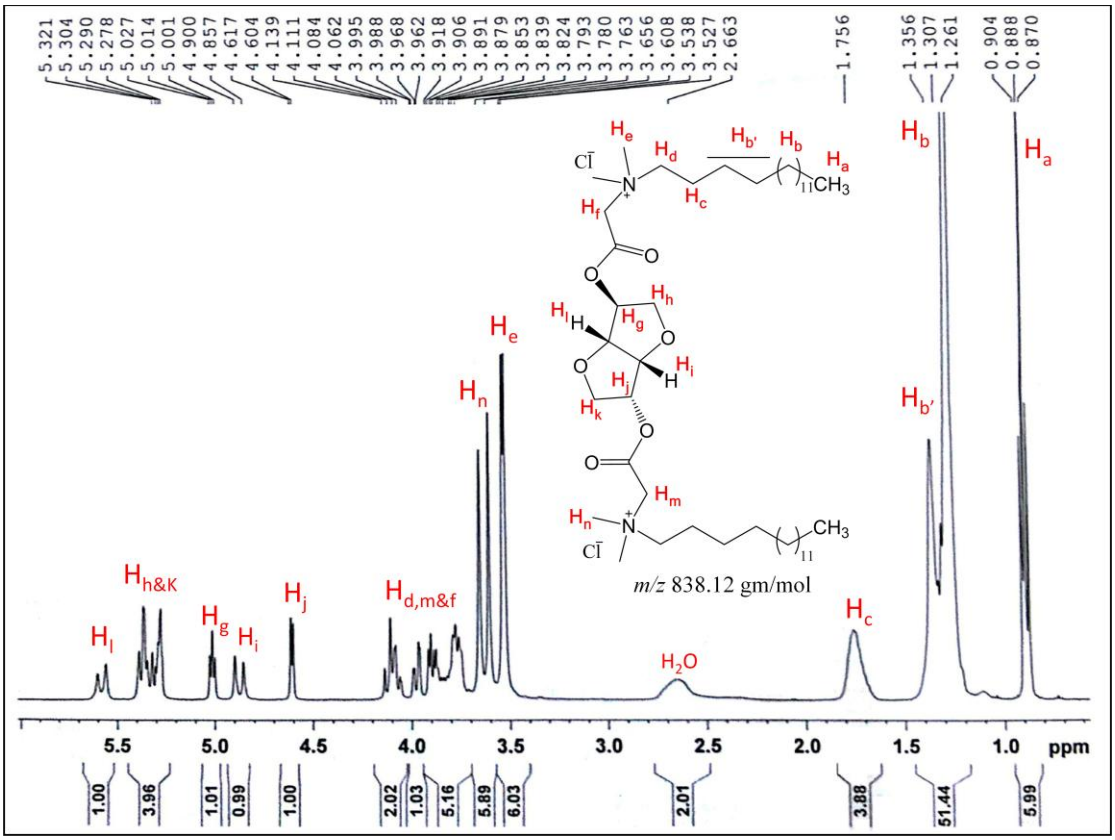
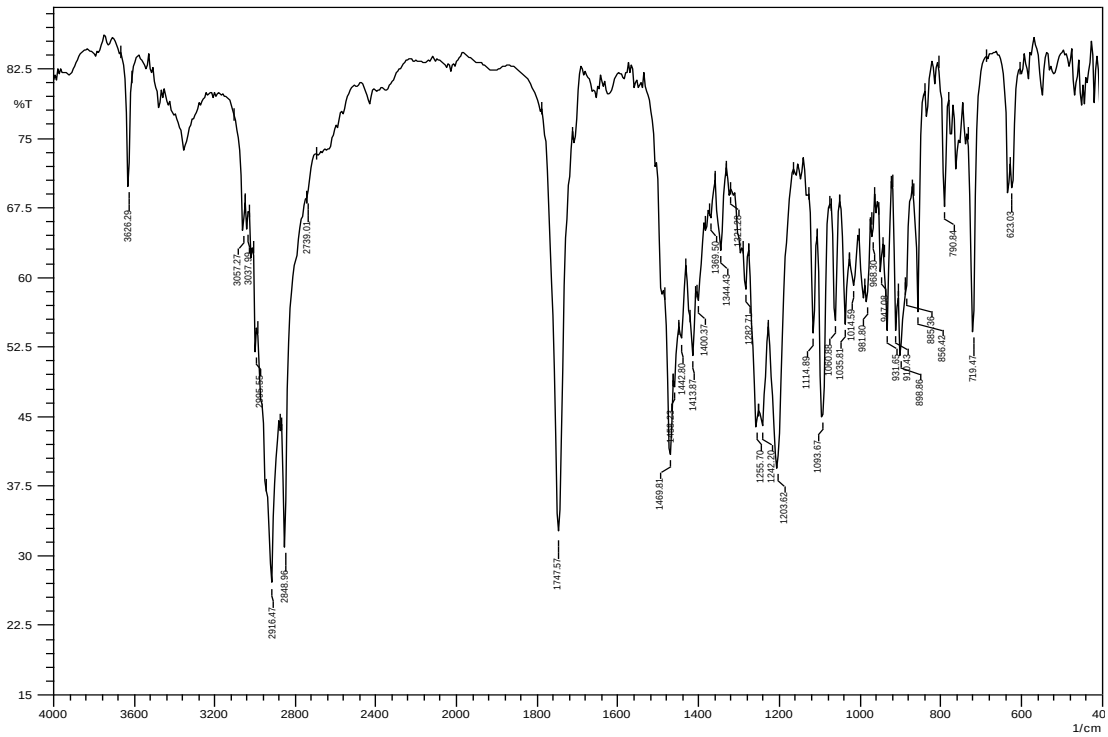


^{1}H NMR Spectra of Cationic Gemini Surfactant (16-Isb-16, Compound 22)



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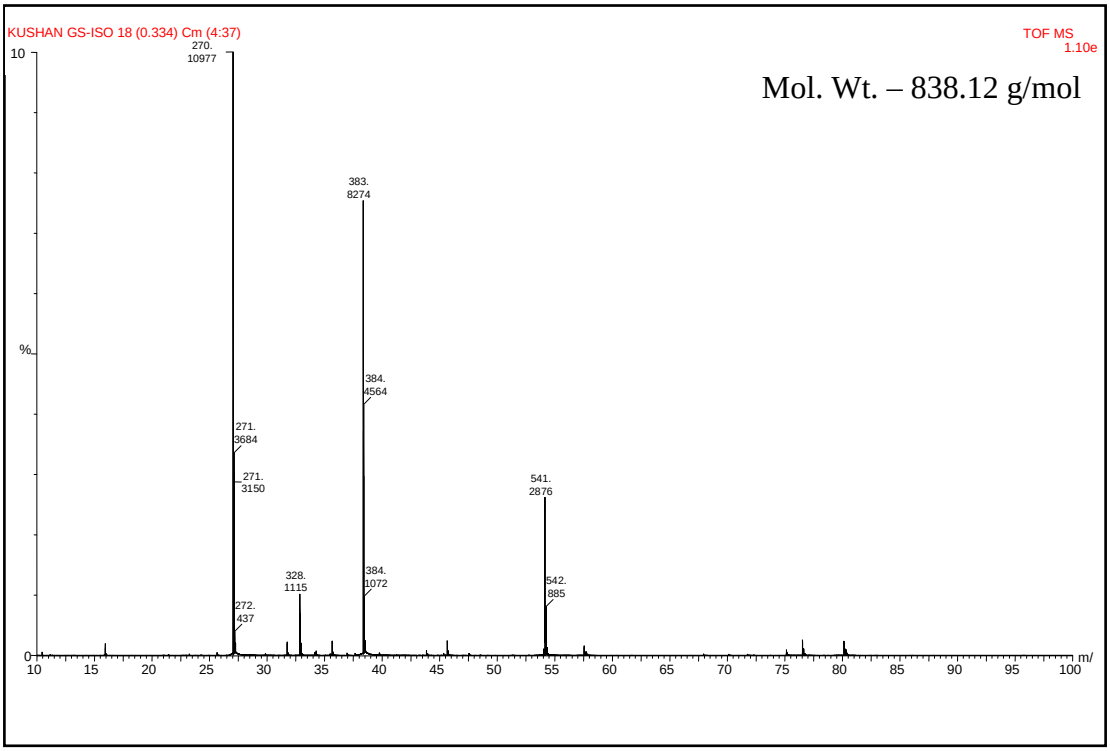

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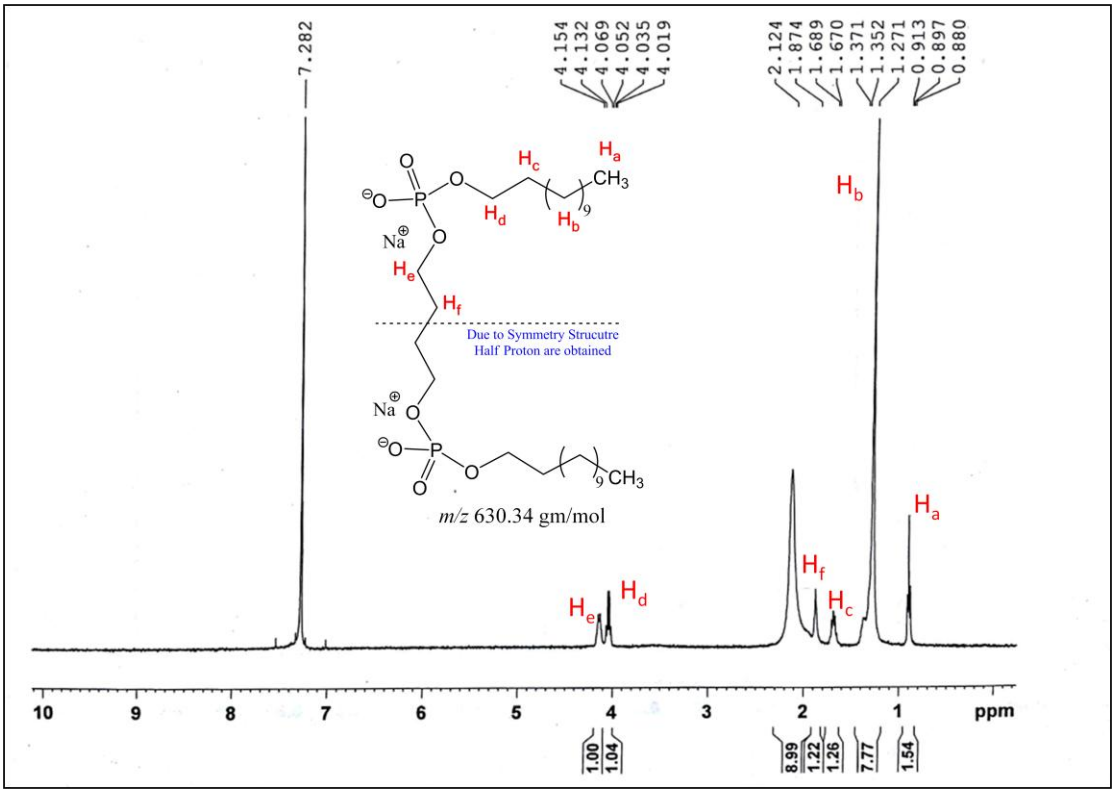
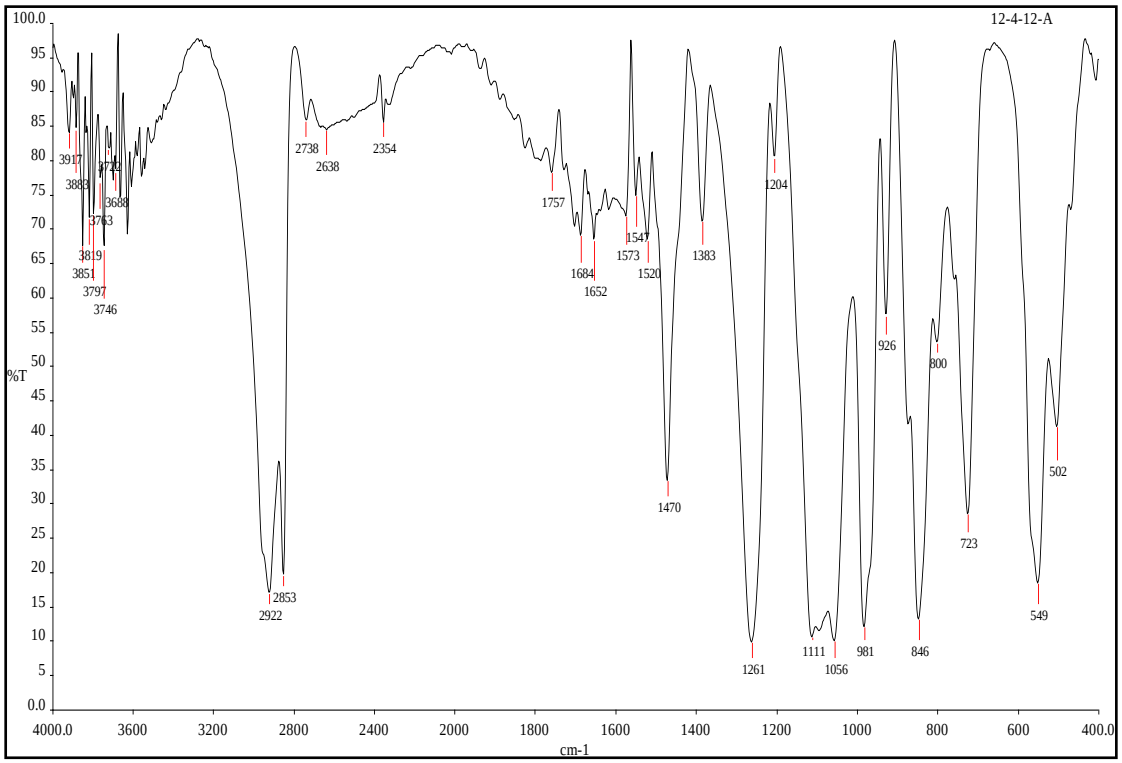
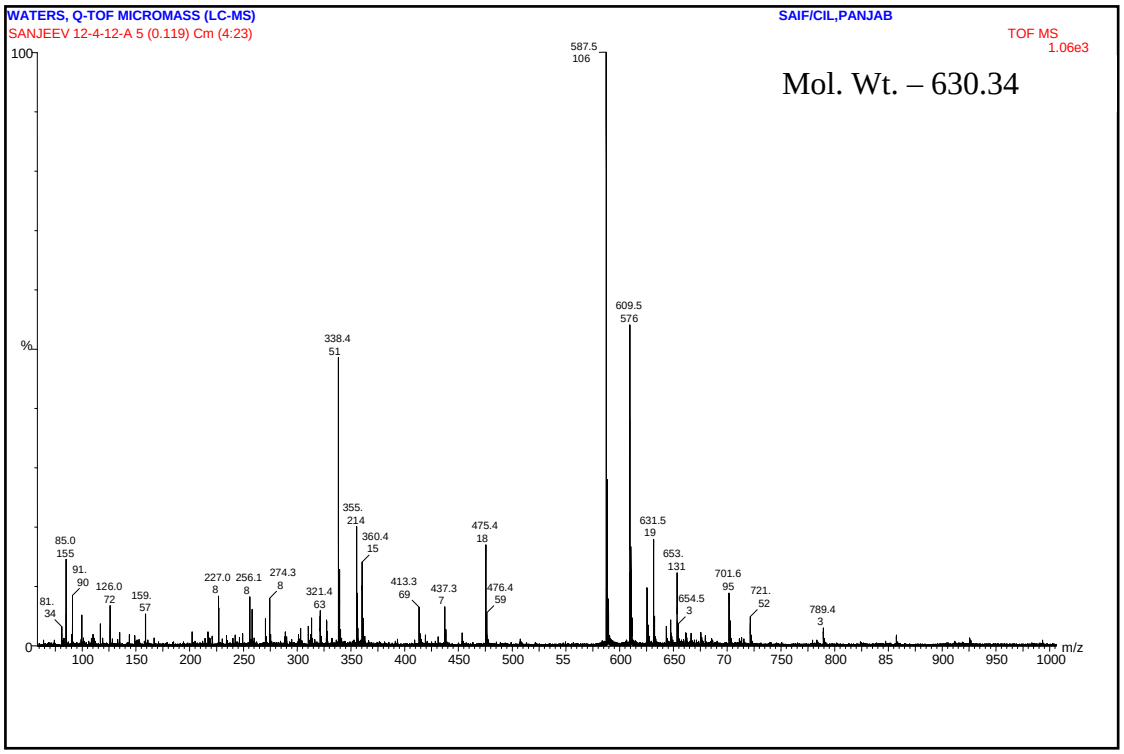


^{1}H NMR Spectra of Anionic Gemini Surfactant (12-4-12-A, Compound IV)



FT-IR Spectra of Anionic Gemini Surfactant (12-4-12-A, Compound IV)



ESI-Mass Spectra of Anionic Gemini Surfactant (12-4-12-A, Compound IV)

2.3. Thermal Stability of Gemini Surfactants

The synthesized cationic gemini surfactants are hygroscopic in nature. They may be in the form of monohydrates or dihydrates. These hydrated gemini surfactants have been used to check their surface and other properties. To maintain the accuracy in weighing in the preparation of stock solution, thermogravimetric analysis (TGA) has been used to determine the hydration of gemini surfactants. From expanded degradation curve of TGA (Figure 2a), it was observed that 12-4-12 gemini loss 0.174 mg of compound in the form of two water molecules and found in agreement with the elemental (CHN) analysis (See Section 2.2.1). The hydration of other cationic gemini surfactants were also matched by both techniques (TGA and CHN) and an appropriate correction were made for the preparation of aqueous stock solution.

Thermogravimetric technique has also been used to explore the thermal properties / stability of gemini surfactants by the characteristic curve of decomposition, which shows two temperatures of stability (Figure 2a). From the Figure 2, sharp degradation with a few intervals clearly indicate high purity of all the gemini surfactants.

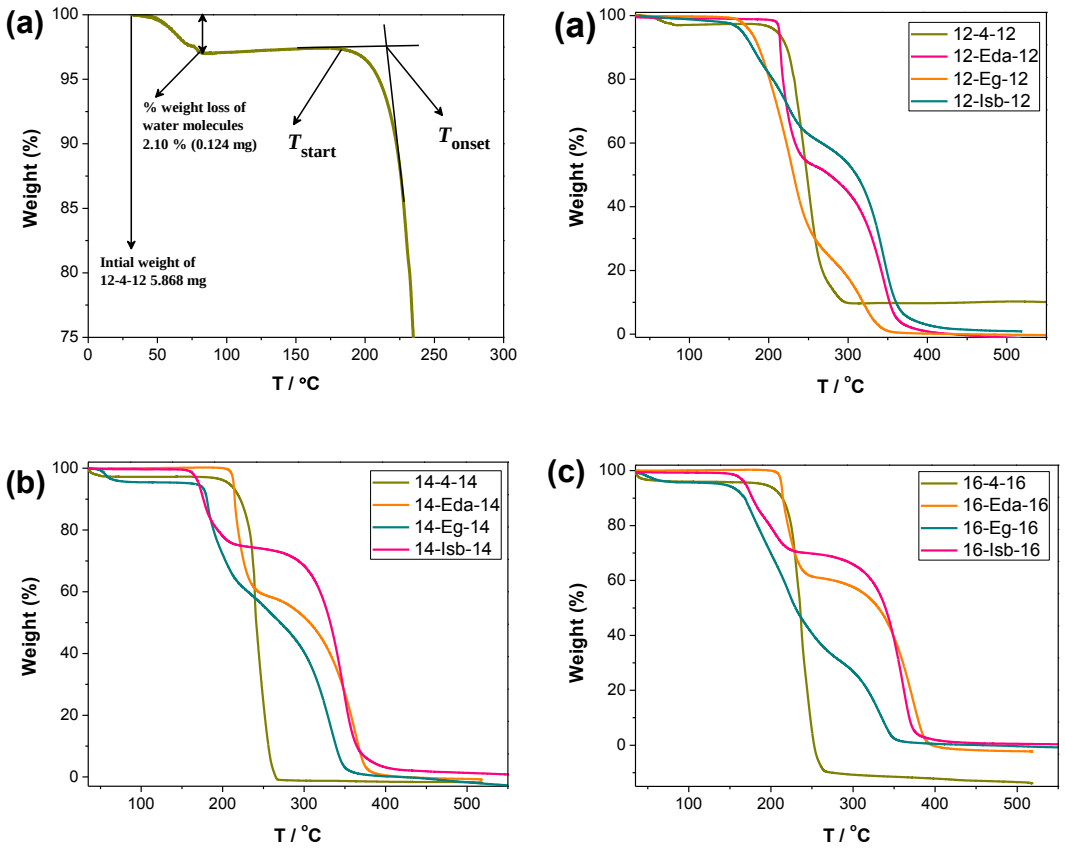


Figure 2. (*a*) Expanded thermogravimetry (TGA) graph shows the loss of apparent two water molecule from gemini surfactant (12-4-12) and indicating start (T_{start}) and onset degradation temperature (T_{onset}) and (*b-d*) representing thermal degradation curve of all gemini surfactants by TGA.

The onset temperature (T_{onset}) is the intersection of the baseline weight after the loss of the water of hydration and the tangent on the weight versus temperature curve where decomposition occurs. The start temperature (T_{start}) is the temperature at which the decomposition of the surfactant begins [6]. The T_{onset} and T_{start} of geminis are listed in Table 1. In the literature [7], it has been observed that the single

surfactant / ionic liquid system degrade sharply after T_{start}. Similar behavior was observed with polymethylene based geminis. However, rest of the gemini surfactants were degraded with several mass loss steps (visually observed, see Figure 2*b*, *c*, *d*). These mass loss steps represents the formation of stable intermediates (isosorbide spacer based geminis have stable intermediate between 213°C - 310°C). In all geminis (Table 1), amide spacer based geminis exhibits a higher thermal stability (due to higher T_{start} = ~170°C), whereas isosorbide spacer geminis exhibits lower thermal stability (lower T_{start} = ~ 135°C).

Table 1. Starting (T_{start}) and onset (T_{onset}) degradation temperatures (T) gemini surfactants (g1-g4) derived by decomposition curve of thermogravimetry analysis (TGA).

Gemini Surfactants	T_{onset} / °C	T_{start} / °C	Start to onsent ratio ($T_{s/o}$)
12-4-12	223.85	176.91	0.790
14-4-14	230.10	171.76	0.747
16-4-16	225.96	173.38	0.767
12-Eda-12	263.53	161.96	0.615
14-Eda-14	289.43	196.27	0.678
16-Eda-16	298.62	188.83	0.632
12-Eg-12	228.70	138.60	0.606
14-Eg-14	256.01	156.27	0.610
16-Eg-16	202.48	131.64	0.650
12-Isb-12	283.61	131.19	0.463
14-Isb-14	301.21	139.30	0.463
16-Isb-16	311.75	130.52	0.419

T_{start} / T_{onset} ratio indicates the temperature interval required for complete degradation (Table 1). Interestingly, degradation interval of geminis shows some dramatical observations where isosorbide spacer based geminis show maximum

degradation intermission ($T_{s/o}$ = ~0.44). However, polymethylene spacer samples have shown minimum degradation intermission ($T_{s/o}$ = 0.77). On this basis, one can say that the thermal degradation of geminis is dependent on the spacer group.

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