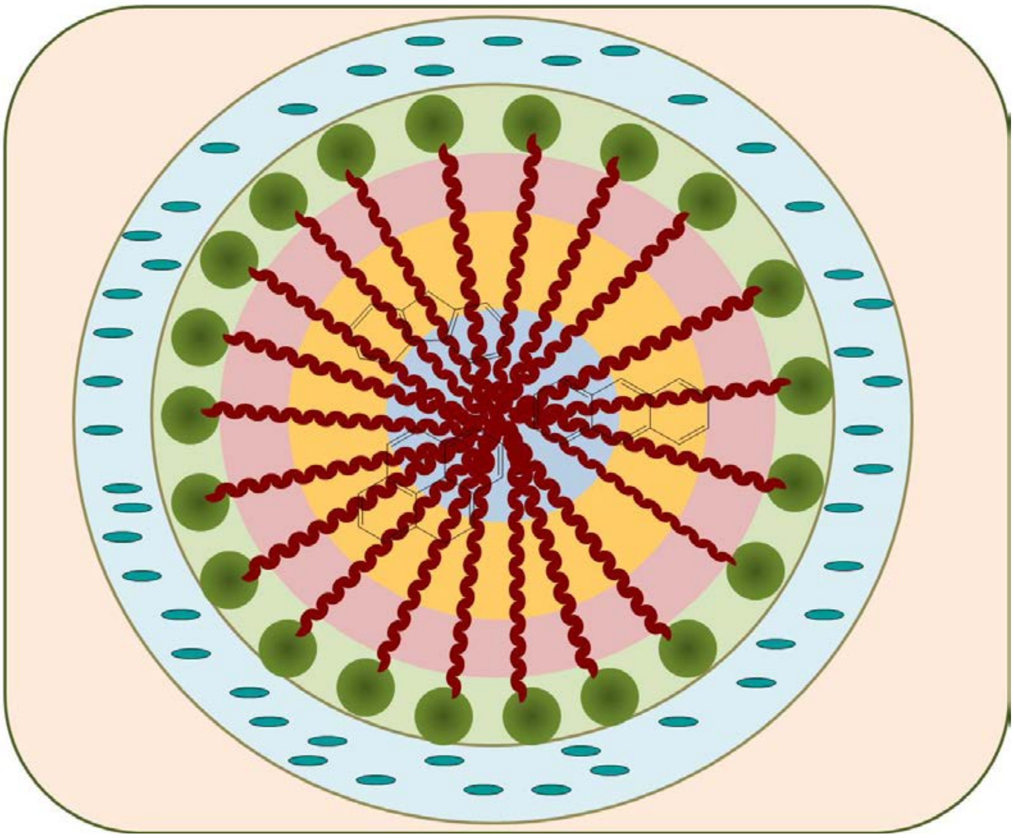
Chapter 5

Solubilization Potential of Mixed Cationic Gemini Surfactant with Anionic Gemini Surfactant/Bile Salt: A case of Polycyclic Aromatic Hydrocarbon



5.1. Introduction

Beyond cmc, an increased aqueous solubility of otherwise nearly insoluble organic compounds brought about. This phenomenon called *micellar solubilization*. Contamination of environment by hazardous organic compounds is one of the burning problems to be addressed by chemists, environmentalists, industrialists, policy makers among others. Surfactants can be beneficial for environment washing or in treatment technologies by performing solubilization of hydrophobic organic contaminants [1, 2].

From application point of view, selection of surfactant or surfactant mixture is required to optimize the desired treatment or formulation [3, 4]. Surfactant mixtures often show synergism towards surface activity, solubilization and lower cmc [5]. In the last two decades, cationic gemini surfactants have been proved much better candidates, over their monomeric counter part, in various emerging technologies due to better physicochemical properties, greater binding ability to negatively charged moiety (*e.g.* DNA or bovin serum albumin), as potential gene delivery agents, as templates for nano-particle synthesis among others [6, 7]. Efforts have been made to design surfactant mixtures to achieve optimum synergistic behavior [8, 9].

Anionic bio-surfactants, bile salts, are synthesized from cholesterol in the liver. They work as solubilizers and emulsifiers for various bio-molecules (cholesterol, bilirubin, lecithin and hydrophobic vitamins) in gastrointestinal tract [10]. Due to typical chemical structure [11] of bile salts, their solution properties are different from conventional anionic surfactant. The solution properties of bile salt are also exploited in drug permeation, cosmetics and models in pharmaceutical research [12, 13]. Bile salts mixed with steroids, phospholipids or surfactants associate into giant morphologies [14, 15]. This prompted for continuous attention on the mixed micellar systems containing bile salt and conventional surfactant/polymer/drug [16-23].

Recently, many surfactant mixtures have been used to increase the aqueous solubility of organic compounds [24, 25]. People are preferentially using a gemini surfactant as one of the components of a mixture to achieve the desired application such as solubilization, pollutant removal, higher surface activity or formulation [6, 26-28]. It has been observed that when cationic geminis are mixed with oppositely charged conventional anionic surfactants, combinations show better solubilization potential towards polycyclic aromatic hydrocarbons (PAHs) [29]. Most PAHs are chemically inert, hydrophobic, and insoluble in aqueous medium [30].

The system may enhance the solubility PAHs but at the same time it can be accumulated on soil (or water body) with poor biodegradation. Not much work is available on cationic gemini-anionic bile salt binary mixtures to predict the solubilization potential with respect to PAH. Y. Moroi *et.al* have reported micellar solubilization of PAHs in single bile salt [31]. They reported better solubilization of cholesterol over PAH. Further, interactions of biodegradable gemini surfactants with bile salts have also been investigated in recent time [32].

Limited number of studies have been attempted regarding mixed micellization of oppositely charged cationic and anionic gemini surfactants as discussed in **Chapter 3** [33, 34]. Moreover, not a single report is available regarding the solubilization potential of oppositely charged mixed gemini surfactants (or CG mixed with bile salt) towards PAHs solubilization. This study has been design to show solubilization of PAHs in (i) binary mixtures of gemini and conventional cationic surfactants, (ii) binary mixtures of oppositely charged gemini surfactants and (iii) binary mixture of cationic gemini (CG) with oppositely charged bile salt. This study exploits both the potential of the gemini surfactants and their mixing with oppositely charged gemini/bile salt. Effects of alkyl chain length and nature of the spacer (in cationic geminis) have also been checked in order to delineate the structure-property relationship.

5.2. Results and Discussion

5.2.1. Micellar Solubilization of PAHs in Oppositely Charged Gemini Surfactants

The interior of the surfactant micelle acts as an organic pseudo phases of different polarities from head group to core regions. Incorporation of different hydrophobic compounds takes place into the micelles according to their polar / non-polar character. Based on the aqueous solubility, the hydrophobic character of PAHs will be in the order: anthracene > pyrene > fluorine [35, 36]. Aqueous solubility of PAHs is expected to increase in micelles or mixed micelles which is discussed in following paragraphs.

The molar solubilization ratio (MSR) is the number of moles of organic compound solubilized per mole of surfactant present in the solution [37]. Mathematically, MSR can be represented by the eq. (1)

$$\mathrm{MSR} = (S_{\mathrm{t}} - S_{\mathrm{cmc}})/(C_{\mathrm{t}} - C_{\mathrm{cmc}}) \quad (1)$$

where S_{t} is the total PAH solubility in the individual surfactant solution at a particular total surfactant concentration C_{t}. S_{cmc} is the apparent solubility of the PAH at the cmc which can be taken equivalent to aqueous solubility. Gemini surfactants show better solubilization capacity (higher MSR) for all the PAHs except AG. Since AG micelles are negatively charged, they may provide electrostatic repulsion to PAHs (due to lone pair of electrons on the ring) and responsible for lower MSR (Table 1). Further, nearly no solubility has been found in SC and SDC.

Micelle–water partition coefficient (K_m = X_m/X_a) represents the solubilization by the micellar phase. X_m and X_a represent the mole fraction of the PAH in the micellar and aqueous phases, respectively. X_m and X_a can be written in terms of MSR as X_m = MSR/(1 + MSR) and X_a = $[S_{\mathrm{cmc}}]$ V_m. V_m is the molar volume of water (0.01807 L mol^{-1}) at 30 °C. K_m can be correlated with MSR by the eq. (2) [37]

$$K_m = \mathrm{MSR}/\{[S_{\mathrm{cmc}}]V_{\mathrm{m}}\,(1+\mathrm{MSR})\} \qquad (2)$$

Standard free energy change of solubilization (from aqueous to micellar phase) ΔG_s^0, by the eq.(3),

$$\Delta G_s^o = -RT \ln K_m \qquad (3)$$

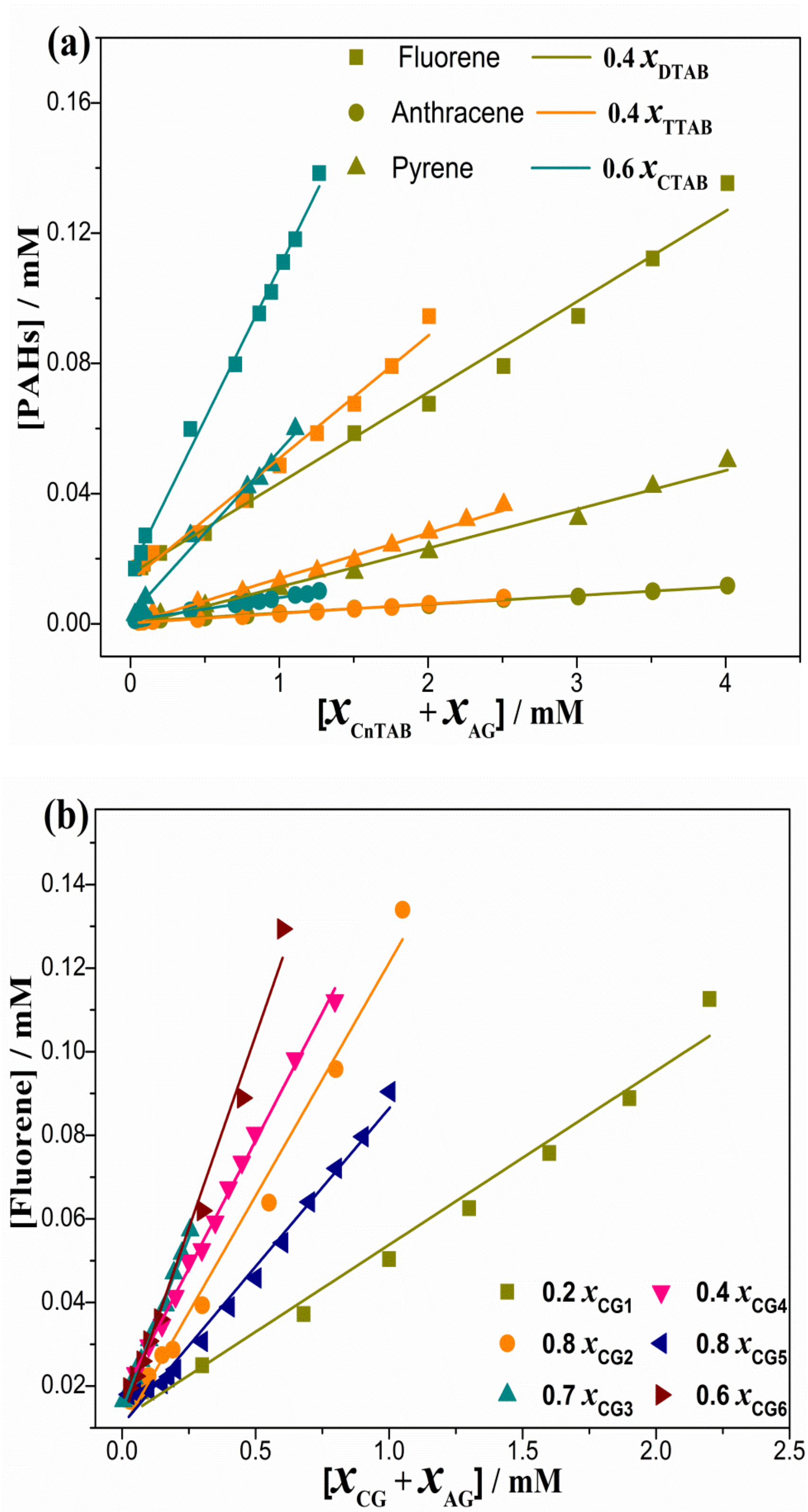
The values of K_m and ΔG_s^0 are also complied in Table 1

Amongst all the pure surfactant systems, CG3 has the maximum MSR value, which may be due to formation of micelles of lower polarity [38]. The lower MSR values with AG (or MSR ~ 0 with bile salt) are in consonance with the study reported recently [39].

For the purpose, binary systems with lowest cmc values were selected (from the study given in **Chapter 3**) and used for PAH solubilization. Variation of solubility of PAHs with surfactant mixture concentration ([$X_{\mathrm{CG/CnTAB}}$ + X_{AG}]), has been shown in Figure 1 and related data are compiled in Table 2. The composition of binary mixture is different for different systems. This is due to the fact that minimum cmc ($\mathrm{cmc_m}$) was found at different compositions (of the two surfactants of the binary mixture).

Table 1. PAH solubilization parameters (molar solubilization ratio, MSR; micelle-aqueous phase partition coefficient, ln K_m; Gibbs free energy, ΔG^o_s) of single (conventional or gemini) surfactant in aqueous solution at 303 K.

Surfactant	Fluorene			Anthracene			Pyrene		
	MSR	ln K_m	$-\Delta G^o_s$ kJ·mol^{-1}	MSR	ln K_m	$-\Delta G^o_s$ kJ·mol^{-1}	MSR	ln K_m	$-\Delta G^o_s$ kJ·mol^{-1}
DTAB	0.0241	10.27	25.44	0.0030	10.97	27.18	0.0154	11.04	27.35
TTAB	0.0357	11.66	28.89	0.0036	12.16	30.13	0.0189	12.76	31.62
CTAB	0.0698	12.01	29.75	0.0073	12.40	30.71	0.0450	12.41	30.76
CG1	0.0716	12.04	29.83	0.0088	12.76	31.63	0.0443	12.69	31.44
CG2	0.0955	12.21	30.26	0.0118	12.68	31.41	0.0635	12.82	31.75
CG3	0.1271	12.85	31.84	0.0155	13.46	33.35	0.0932	14.16	35.09
CG4	0.0479	11.59	28.71	0.0051	11.87	29.42	0.0210	12.23	30.30
CG5	0.0666	12.11	30.00	0.0071	12.68	31.40	0.0333	13.09	32.42
CG6	0.0972	12.60	31.22	0.0093	12.88	31.90	0.0463	13.94	34.53
AG	0.0203	11.21	27.78	0.0012	10.89	26.98	0.0061	11.81	29.26
SC	-	-	-	-	-	-	-	-	-
SDC	-	-	-	-	-	-	-	-	-


(a)
Fluorene
Anthracene
Pyrene
0.4 x_{DTAB}
0.4 x_{TTAB}
0.6 x_{CTAB}
[PAHs] / mM
0.00
0.04
0.08
0.12
0.16
0
1
2
3
4
$[x_{CnTAB} + x_{AG}]$ / mM
(b)
0.2 x_{CG1}
0.4 x_{CG4}
0.8 x_{CG2}
0.8 x_{CG5}
0.7 x_{CG3}
0.6 x_{CG6}
[Fluorene] / mM
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.0
0.5
1.0
1.5
2.0
2.5
$[x_{CG} + x_{AG}]$ / mM

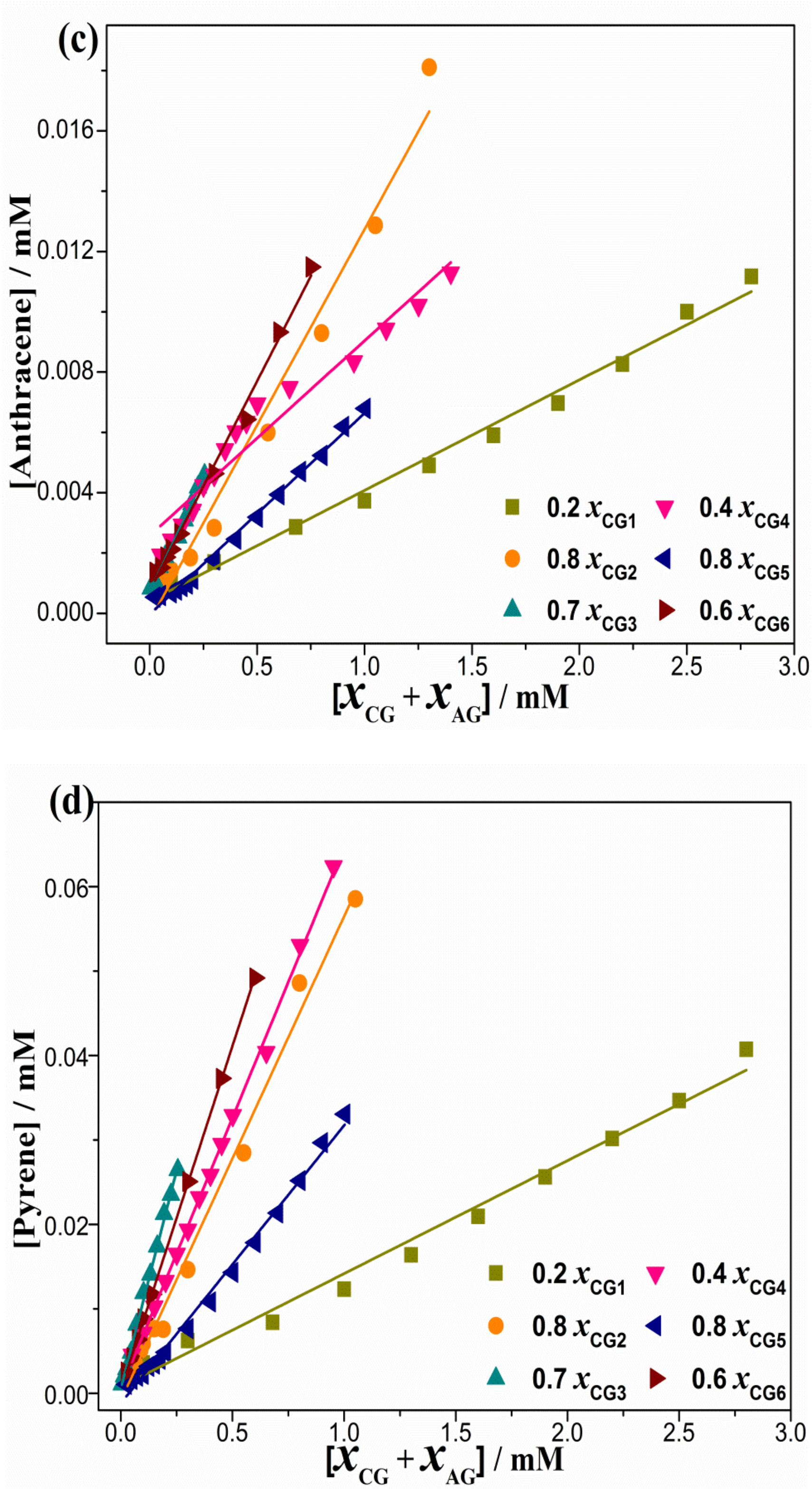


Figure 1. Variation of solubility of PAHs (fluorene, anthracene and pyrene) in binary (cationic + anionic) aqueous surfactant systems at 303 K.

Table 2. PAH Solubilization parameters (molar solubilisation ratio, MSR; micelle-aqueous phase partition coefficient, ln K_m; Gibbs free energy, $\Delta G^o{}_s$) of mixed (cationic + anionic) conventional and gemini surfactant systems in aqueous solution at 303 K.

Surfactant[a]	Fluorene			Anthracene			Pyrene		
	MSR	**lnK_m**	**-$\Delta G°_S$**	**MSR**	**lnK_m**	**-$\Delta G°_S$**	**MSR**	**lnK_m**	**-$\Delta G°_S$**
AG (0.6) + DTAB (0.4)	0.0289	10.619	26.311	0.0028	10.984	27.213	0.0124	11.362	28.150
AG (0.6) + TTAB (0.4)	0.0437	11.019	27.301	0.0032	11.227	27.816	0.0153	11.351	28.122
AG (0.4) + CTAB (0.6)	0.0899	10.957	27.146	0.0068	11.038	27.348	0.0504	11.054	27.387
AG (0.8) + CG1 (0.2)	0.0476	10.819	26.807	0.0039	10.981	27.206	0.0151	11.113	27.532
AG (0.2) + CG2 (0.8)	0.1211	11.932	29.563	0.0143	12.528	31.038	0.0611	12.292	30.454
AG (0.3) + CG3 (0.7)	**0.1687**	12.807	31.729	**0.0148**	13.164	32.615	**0.1023**	13.882	34.394
AG (0.6) + CG4 (0.4)	0.1224	11.226	27.813	0.0115	13.031	32.286	0.0643	11.529	28.566
AG (0.2) + CG5 (0.8)	0.0826	12.081	29.931	0.0072	12.763	31.620	0.0357	12.883	31.918
AG (0.4) + CG6 (0.6)	**0.1998**	11.911	29.512	**0.0147**	12.062	29.884	**0.0813**	12.020	29.781

[a] Mixed surfactants with mole fractions mentioned in parenthesis.

Comparing the MSR data obtained for single (Table 1) and binary (Table 2) system, higher MSR values were found with mixed surfactant systems with all the PAHs. It may be due to decreased electrostatic and increased hydrophobic interactions. Also, mixing may produce larger micelles with higher hydrophobic volumes. In a separate study, it has been shown that large micelles can be produced on mixing oppositely charged surfactants [40, 41]. Such type of mixed micelles provide higher hydrophobic volume and responsible for more effective solubilization and higher MSR values. The synergism is attributable to the increased hydrophobicity of the binary surfactant micelles and facilitation of the solubilization process. Among the gemini surfactant, AG + CG3 / CG6 systems were found more effective in solubilizing different PAHs (Table 2). Among the different PAHs, anthracene has been found less soluble in all the binary mixtures. Anthracene has less aqueous solubility and continues the same trend even with single or binary surfactant system.

There are various possible loci of solubilization, such as on the background water-micellar interface, between the polar head groups and the micellar interior [42]. The locus and content of solubilization depend on the structures of surfactant (s) and solubilized PAH. The MSR values (Table 2) of different mixed surfactant systems for various PAHs follow the order given as under:

fluorene - AG + DTAB < AG + TTAB < AG + CG1 < AG + CG5 < AG + CTAB < AG + CG2 < AG + CG3 < AG + CG6

anthracene - AG + DTAB < AG + TTAB < AG + CG1 < AG + CTAB < AG + CG5 < AG + CG4 < AG + CG6 < AG +CG3

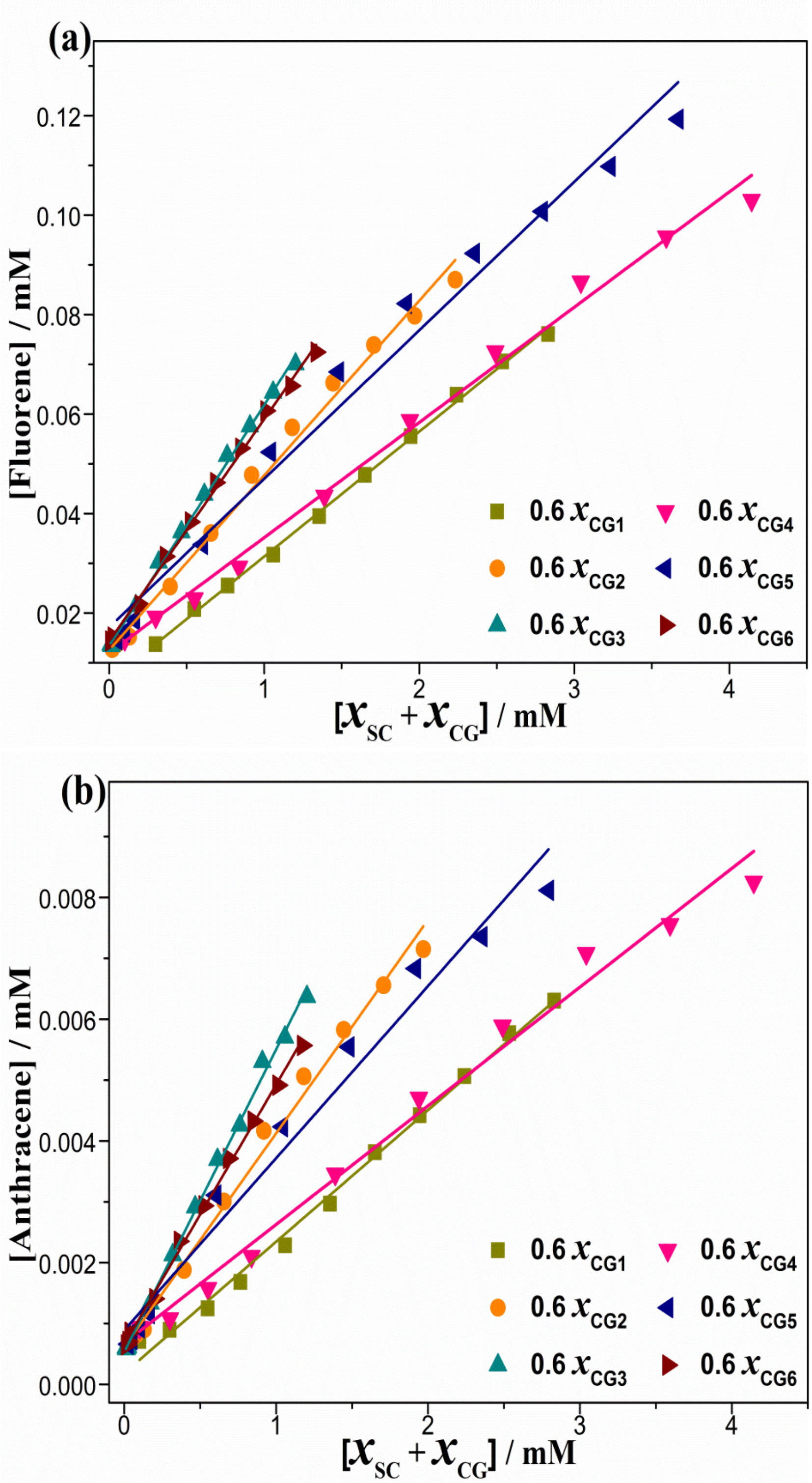
pyrene - AG + DTAB < AG +CG1 < AG + TTAB < AG + CG5 < AG + CTAB < AG +CG2 < AG + CG4 < AG + CG6 < AG + CG3

MSR data show that poor performing single surfactants remain poor even in mixed system. Solubilization capacity of the binary mixtures depends on the polarity and hydrophobic volume of an individual PAH which decides the final MSR. However, this is surprising to note that surfactants present at two ends of the ordering (with single surfactants) are found most effective in binary mixtures. This shows the synergistic effect of mixing two gemini surfactants of an appropriate spacer/chain length.

5.2.2. Micellar Solubilization of PAHs in Oppositely Charged Cationic Gemini and Anionic Bile Salt

As mentioned above (Table 1), no solubilization data could be collected with individual bile salt (SC or SDC). This may be due to low aggregation number and small hydrophobic volume of the bile salt micelle [43]. For the purpose, binary systems having CG mole fraction (x = 0.6) and bile salt (SC or SDC) mole fraction (x = 0.4) were selected and used for PAH solubilization (Figures 2 and 3). MSR data for such mixed systems are compiled in Table 3. Comparing the MSR data for binary system (with bile salt), it can be seen that higher MSR values are found with mixed systems with each PAHs in comparison to single CGs (or anionic surfactant). This can be understood in the light of the facts explained in the context of oppositely charged gemini mixture (*supravide*). The synergism is attributable to facilitation of the solubilization process. Among the various mixtures, bile salt + CG3 /CG6 system were found more effective in solubilizing different PAHs. Among the different PAHs, anthracene has been found again less soluble in all the binary mixtures.

Table 4 shows the comparative solubilization of PAHs (anthracene and pyrene) in various binary mixtures having oppositely charged surfactants. The bile salt containing binary systems show poor PAH solubilization than that of conventional anionic surfactant (SDS or SDBS) or AG containing binary systems. However, at the same time they can be accumulated at the site of application as slowly biodegradable material. If they can be partially replaced by some bio-surfactants like bile salts, lower damage can be achieved to the environment. Further, above bile salt containing system can be applied to biomedical applications such as drug delivery or cholesterol solubilization. Recent work has now been conducted towards greener ways of surfactant applications [17, 39, 43, 44, 45].


(a)
[Fluorene] / mM
0.02
0.04
0.06
0.08
0.10
0.12
0
1
2
3
4
[x_{SC} + x_{CG}] / mM
0.6 x_{CG1}
0.6 x_{CG2}
0.6 x_{CG3}
0.6 x_{CG4}
0.6 x_{CG5}
0.6 x_{CG6}
(b)
[Anthracene] / mM
0.000
0.002
0.004
0.006
0.008
0
1
2
3
4
[x_{SC} + x_{CG}] / mM
0.6 x_{CG1}
0.6 x_{CG2}
0.6 x_{CG3}
0.6 x_{CG4}
0.6 x_{CG5}
0.6 x_{CG6}

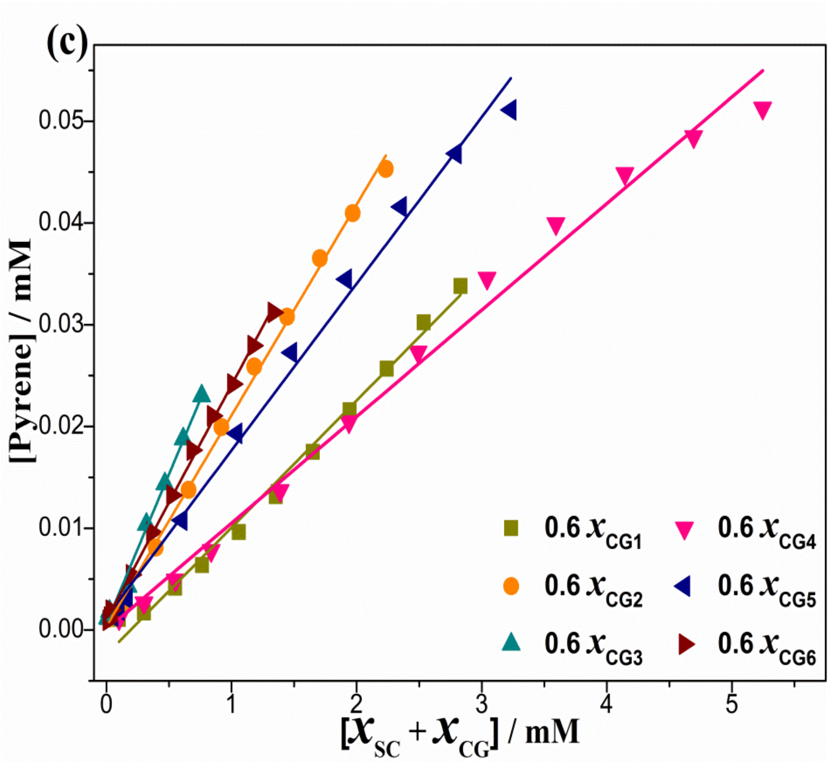
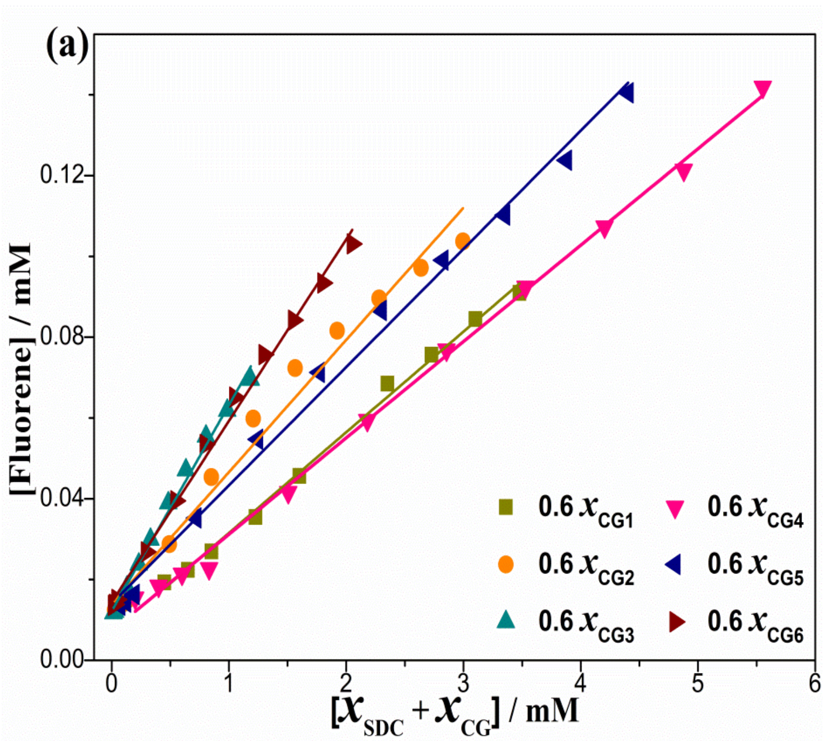


Figure 2. Variation of solubility of PAHs (fluorene, anthracene and pyrene) in binary mixture of CG with SC at 298 K.



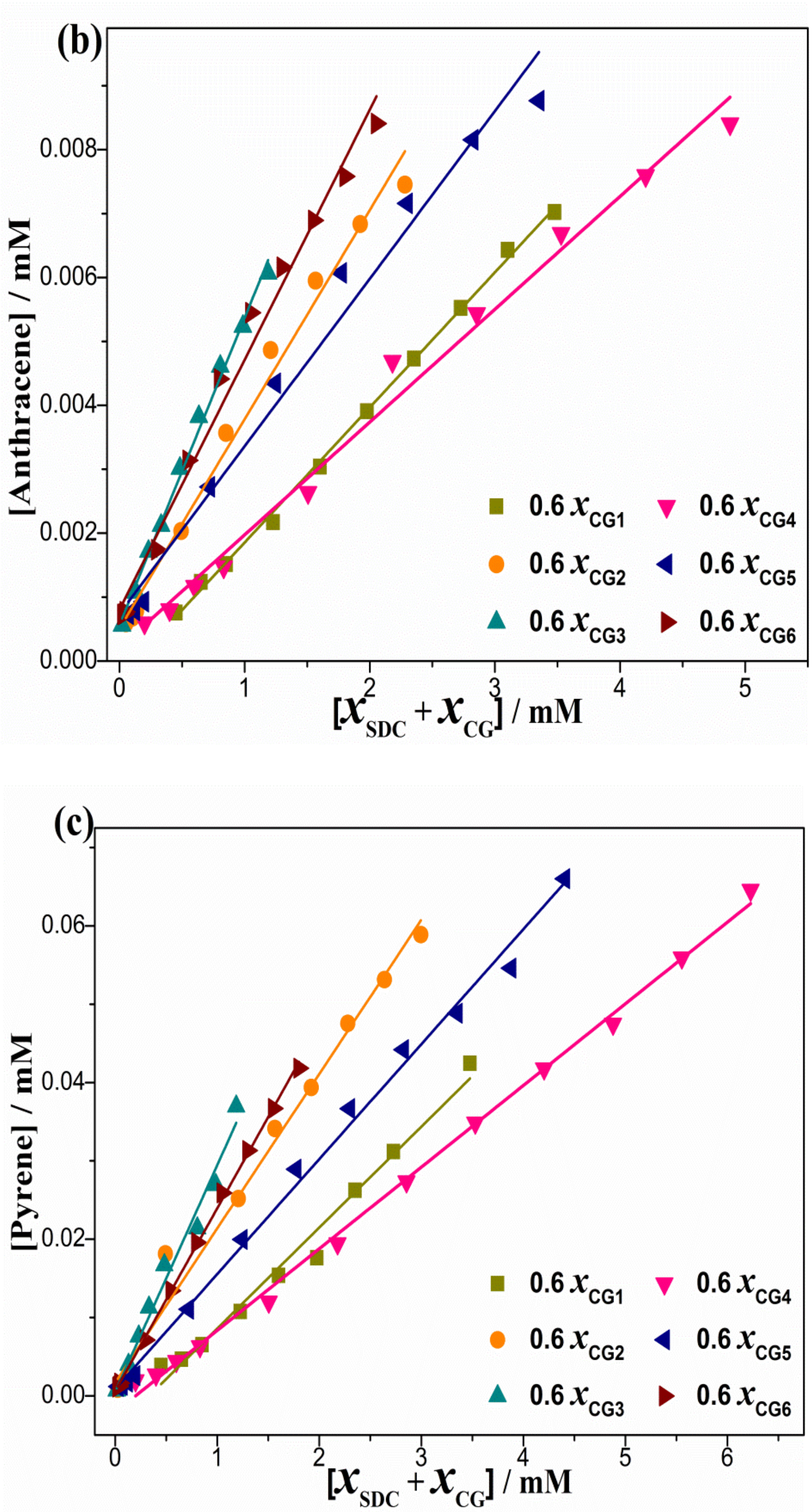


Figure 3. Variation of solubility of PAHs (fluorene, anthracene and pyrene) in binary mixture of CG with SDC at 298 K.

Table 3. Solubilization parameters (molar solubilization ratio, MSR; micelle-aqueous phase partition coefficient, ln K_m; Gibbs free energy, ΔG^o_s) of mixed (CG + anionic SC/SDC) system in aqueous solution at 298 K. Solubilization parameters of mixed surfactant system have been obtained at fixed mole fraction (0.6 x_{CG}) above their CMC.

Surfactant	System	Fluorene			Anthracene			Pyrene		
		MSR	lnK_m	$-\Delta G°_s$ kJ·mol^{-1}	MSR	lnK_m	$-\Delta G°_s$ kJ·mol^{-1}	MSR	lnK_m	$-\Delta G°_s$ kJ·mol^{-1}
CG1 + **SC**	Mixed	0.025	10.67	26.45	0.002	10.92	27.05	0.014	11.25	27.88
CG2 + **SC**	Mixed	0.035	11.21	27.78	0.004	11.54	28.60	0.021	11.84	29.33
CG3 + **SC**	Mixed	0.048	11.68	28.93	0.005	12.23	30.29	0.030	12.83	31.78
CG4 + **SC**	Mixed	0.023	10.27	25.44	0.002	10.35	25.64	0.011	10.64	26.37
CG5 + **SC**	Mixed	0.030	10.77	26.68	0.003	10.83	26.82	0.016	11.32	28.06
CG6 + **SC**	Mixed	0.045	11.61	28.76	0.004	12.01	29.76	0.023	12.34	30.56
CG1 + **SDC**	Mixed	0.025	10.55	26.13	0.002	10.89	26.98	0.013	11.09	27.48
CG2 + **SDC**	Mixed	0.033	11.62	27.30	0.003	11.39	28.23	0.020	10.66	26.41
CG3 + **SDC**	Mixed	0.049	11.88	29.43	0.005	12.42	30.76	0.029	12.88	31.90
CG4 + **SDC**	Mixed	0.025	10.37	25.70	0.002	10.52	26.06	0.011	10.80	26.77
CG5 + **SDC**	Mixed	0.029	10.71	26.83	0.003	10.88	26.96	0.015	11.19	27.73
CG6 + **SDC**	Mixed	0.045	11.39	28.23	0.004	11.73	29.06	0.023	12.08	29.94

Table 4. Comparison of MSR data observed in various studies for the solubilization of anthracene and pyrene

System[a]	MSR		Reference
	Anthracene	Pyrene	
16-E2-16+SDS	**0.025**	0.058	[39]
16-E2-16+SDBS	**0.024**	0.075	[39]
16-6-16+AOT	0.010	0.053	[47]
AG(0.3) + CG3(0.7)	**0.0148**	**0.1023**	**Present study**
AG(0.4) + CG5(0.6)	**0.0147**	**0.0813**	**Present study**
SC(0.4)+CG3(0.6)	**0.005**	**0.030**	**Present study**
SC(0.4)+CG6(0.6)	**0.004**	**0.023**	**Present study**
SDC(0.4)+CG3(0.6)	**0.005**	**0.029**	**Present study**
SDC(0.4)+CG6(0.6)	**0.004**	**0.023**	**Present study**

[a]Mixed surfactants with mole fraction 0.5 each (if different then mentioned in parenthesis).

Another approach for such applications requires information regarding the shape and size of the mixed aggregates present in the solution. In a recent study it has been reported that CG micelle (12-4-12) changes the shape on addition of SC or SDC [46]. However, due to lower concentration of the two components of the mixed micelle, it is reasonable to assume that no morphological change is expected before or after PAH solubilization. The absence of breaks in [PAH] *vs* [CG + SC or SDC] plots (Figures 2 and 3) are in conformity to the above proposition.

5.3. Conclusion

Investigation reveals that solubilization efficiency of oppositely charged mixed surfactant systems is better than that of constituting individual surfactant. The selected binary mixtures observably increase the aqueous solubility of PAHs in the order: fluorene > pyrene > anthracene. The present study clearly support the view that oppositely charged binary mixtures are better candidates over similarly charged binary mixtures [39]. Further, selected systems (Table 4) of AG + CG3 / CG6 are showing fair solubilization efficiencies with all the PAHs under study over CG + SC / SDC systems. However, if greener mixed surfactant system is required then bile salt can be preferred as one of the component of binary mixture with CG. The study yielded interesting method of selecting binary mixture for the surfactant based technologies (pollutant solubilization or surfactant based remediation of soil / water) [24, 48].

Reference

[1] D. A. Edwards, R. G. Luthy, Z. Liu, *Environ. Sci. Technol*. 25 (1991) 127.

[2] I. T. Yeom, M. M. Ghosh, C. D. Cox, K. G. Robinson, *Environ. Sci. Technol*. 29 (1995) 3015.

[3] R. M. Hill, Mixed surfactant systems. in: K. Ogino, M. Abe (Eds.), Surfactant Science Series, vol. 46, Marcel Dekker Inc, New York, 1993, pp. 317.

[4] T. Yadav, D. Tikariha, J. Lakra, M. L. Satnami, A. K. Tiwari, S. K. Saha, K. K. Ghosh. *J. Mol. Liq*. 204 (2015) 216.

[5] M. J. Rosen, T. J. Kunjappu. Molecular Interactions and Synergism in Mixtures of Two Surfactants, In Surfatants and Interfacial Phenomena. 4th ed.; John Wiley & Sons.: New York, 2012, pp. 421.

[6] R. Zana, *Adv. Colloid Interf. Sci*. 97 (2002) 205.

[7] K. Parikh, B. Mistry, S. Jana, S. Gupta, R. V. Devkar, S. Kumar, *J. Mol. Liq*. 206 (2015) 19.

[8] J. F. Scamehorn. Phenomena in Mixed Surfactant System; ACS Symposium Series No. 311; American Chemical Scociety: Washington, DC, 1986.

[9] M. H. Paul, N. R. Donn, Mixed Surfactant Systems. In Mixed Surfactant System; ACS Symposium Series; American Chemical Society: Washington, DC, 1992.

[10] K. Matsuoka, Y. Moroi, *Biochim. Biophys. Acta*. 1580 (2002) 189.

[11] P. Venkatesan, Y. Cheng. D. Kahne, *J. Am. Chem. Sco*. 116 (1994) 6955.

[12] J. Brajtburg, J. Bolard, J. Clin. *Microbiol. Rev*. 9 (1996) 512.

[13] P. Sharma, M. V. S. Verma, H. P. S. Chalwa, R. Panchagnula, *Farmaco* 60 (2005) 874.

[14] Y. V. Zastavker, N. Asherie, A. Lomakin, J. Pande, J. M. Donovan, J. M. Schnur, G. B. Benedek, Proceedings of the National Academy of Science 96 (1999) 7883.

[15] S. Kumar, H. Patel, *J. Mol. Liq*. 190 (2014) 74.

[16] L. Jiang, K. Wang, M. Deng, Y. Wang, J. Huang, *Langmuir* 24 (2008) 4600.

[17] J. Bhattacharjee, G. Verma, V. K. Aswal, A. A. Date, M. S. Nagarsenker, P. A. Hassan, *J. Phys. Chem*. B 114 (2010) 16414.

[18] A. C. Kumar, H. Erothu, H. B. Bohidar, A. K. Misra, *J. Phys. Chem*. B 115 (2011) 433.

[19] C. -W. Njauw, C. –Y. Cheng, V. A. Ivanov, A. R. Khokhlov, S. –H. Tung, *Langmuir* 29 (2013) 3879.

[20] V. Patel, B. Bharatiya, D. Ray, V. K. Aswal, P. Bahadur, *J. Colloid Interf. Sci*. 441 (2015) 106.

[21] C. M. Faustino, C. S. Serafim, I. N. Ferreira, M. A. Branco, A. R. Calado, L. Garcia-Rio, *Ind. Eng. Chem. Res*. 53 (2014) 10112.

[22] Kabir-ud-Din, M. A. Rub, A. Z. Naqvi, *Colloids Sirf*. B 84 (2011) 285.

[23] R. J. Hamill, *Drugs* 73 (2013) 919.

[24] J. Wei, G. Huang, C. An, H. Yu, *J. Hazard. Mater*.190 (2011) 840.

[25] A. A. Dar, G. M. Rather, A. R. Das, *J. Phys. Chem*. B. 111 (2007) 3122.

[26] F. M. Menger, J. S. Keiper, *Angew. Chem. Int. Ed*. 39 (2000) 1906.

[27] M. J. Rosen, *Chem. Technol*. 23 (1993) 30.

[28] M. R. Rosen, D. J. Tracy, *J. Surfact. Deterg*. 1 (1998) 547.

[29] T. Yoshimura, A. Ohno, K. Esumi, *J. Colloid Interface Sci*. 272 (2004) 191.

[30] J. H. Park, T. M. Penning In: Stadler RH, Lineback DR (eds) Process-induced Food Toxicants-Occurrence, Formation, Mitigation and Health Risks, Wiley Jersey, 2009, p 243.

[31] R. Ninomiya, K. Matsuoka, Y. Moroi, *Biochim. Biophys. Acta*. 1634 (2003) 116.

[32] M. Akram, I. A. Bhat, Z. Yaseen, Kabir-ud-Din, *Colloids Surf. A: Physicochemical Eng. Aspects* 335 (2009) 55.

[33] Z. Liu, Y. Fan, M. Tian, R. Wang, Y. Han, Y. Wang, *Langmuir* 30 (2014) 7968.

[34] X. Pei, J. Zhao, X. Wei, *J. colloid and Interface Sci*. 356 (2011) 176.

[35] D. Mackay, W. Y. Shiu, *J. Chem. Eng. Data* 22 (1977) 399.

[36] J. Lakra, D. Tikariha, T. Yadav, S. Das, S. Ghosh, M.L. Satnami, K.K. Ghosh, *Colloids Surf. A: Physicochemical Eng. Aspects* 451(2014) 56.

[37] D. A. Edwards, R. G. Luthy, Z. Liu, Environ. *Sci. Technol.* 25 (1991) 127.

[38] S. Kumar, K. Parikh, *J. Surf. Deterg*. 16 (2013) 739.

[39] W. H. Ansari, N. Fatma, M. Panda, Kabir-ud-Din, *Soft Matter* 9 (2013) 1478.

[40] S. Kumar, H. Patel, *J. Mol. Liq*. 190 (2014) 74.

[41] H. Yin, Z. Zhou, J. Huang, R. Zheng, Y. Zhang, *Angew. Chem*, 115 (2003) 2238.

[42] S. Kumar, D. Bansal, Kabir-ud-Din, *Langmuir* 15(1999) 4960.

[43] M. Akram, I. A. Bhat, Z. Yaseen, Kabir-ud-Din, *Colloids Surf. A Physicochem. Eng. Asp.* 444 (2014) 209.

[44] K. Matsuoka, Y. Kuranga, Y. Moroi, *Biochim. Biophys. Acta* 1580 (2002) 200.

[45] M. Mikov, J. P. Fawcett, Bile acids: chemistry, biosynthesis, analysis, chemical and metabolic transformations and pharmacology, Medishet Publisher, geneva, 2007.

[46] S. Padasala, V. Patel, d. Ray, K. Singh, V. K. Aswal, *RSC Adv*. 6 (2016) 96584.

[47] M. Panda, Kabir-ud-Din, *J. Mol. Liq*. 163 (2011) 93.

[48] Kabir-ud-Din, M. Shafi, P. A. Bhat, A. A. Dar, *J. Hazard. Mater*. 167 (2009) 575.