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Association of Amphiphilic Molecules in Various Solvent Systems

Solvents have the ability to dissolve, dilute, disperse, and extract relevant material from different states of matter. Solvents play a crucial role in various fields where organic solvents are utilized for manufacturing, purifying, or crystallizing compounds. Traditionally, water and volatile organic solvents (e.g., hydrocarbons) were two principal classes utilized for ages with no severe issues. On the other hand, these solvents face challenges at the nexus of the 20th and 21st centuries in terms of sustainability, usefulness, and greenness [1,2]. To overcome the challenges, other solvents like ionic liquids (ILs) and deep eutectic solvents (DESs) are used nowadays.

Ionic liquids are organic salts entirely made up of ions and have melting points lower than the boiling point of water. Due to the high lattice energies of salts, they often have a relatively high melting point. Salts' lattice energy reduces as the cation or anion radius becomes larger, and when large non-symmetric organic anions and cations are utilized, the melting point of the compounds can be in the ambient temperature range. The first ionic liquid, ethyl ammonium nitrate [EtNH3]-[NO3], which has a melting point of 12°C, was created by Walden in 1914 [3]. It is possible to modify the ionic components of an ionic liquid to alter its properties. In comparison to molecular solvents, ionic liquids typically possess lower volatility and stronger thermal stability. Ionic liquids are establishing a reputation for creating unique solvents for particular purposes, despite the fact that no class of solvent is ideal for all uses. Deep Eutectic Solvents are a subclass of these alternate liquids.

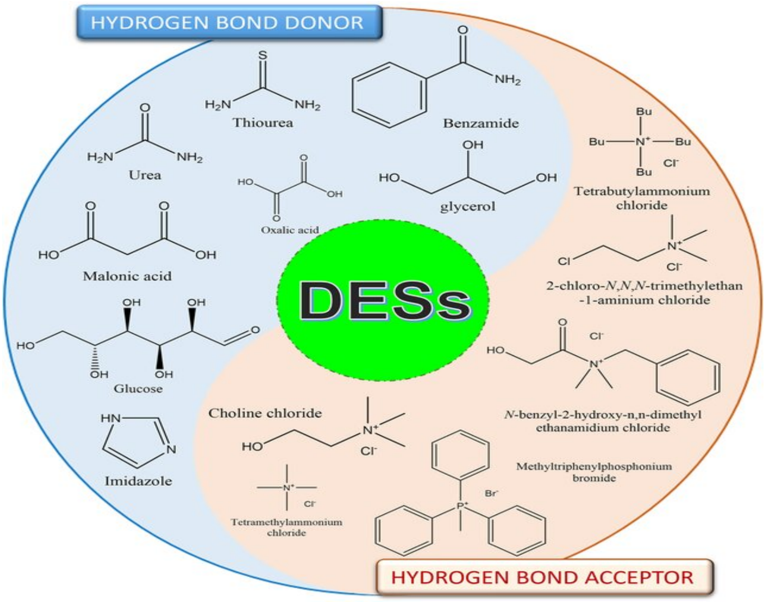
About two decades back, a new designer solvent (DES) was introduced in the scientific literature. The term DES has been used to define a liquid made up of eutectic mixes of quaternary ammonium salts and hydrogen bond donors (HBDs) including alcohols, amides, and carboxylic acids. Even though DESs have characteristics similar to ionic liquids, they are less expensive, easy to prepare, and biodegradable. They have been formed from not hazardous materials as well as from components that are suitable for human consumption, such as glycerol and glucose. Radosevic et al. [4] evaluated the toxicity and biodegradability of DESs and concluded that they "have a green profile and a good prospect for a wide use in the field of green technologies."

A surfactant is a molecule that lowers the surface tension of a liquid and improves the spreading and wetting characteristics of the liquid. Surfactants are employed in a wide range of products and technologies, including biotech and healthcare, the fossil fuel sector, nutraceuticals, hygiene products, stain removers, fire prevention, fuel additives, foaming agents, dyes, varnishes, and epoxy resins [5]. The nano-structure of DES, with or without water, can influence the aggregation/association behavior of surface-active agents (Surfactants). Surfactants, due to their solution behavior, are of immense importance in different applications of the colloidal field. The synergy between surfactants and DES can boost their application in different areas of biomedical sciences. An upward trend has been seen in recent times in studying the physicochemical/ association behavior of surfactants and their interconnection with DES [6,7].

There are seven chapters in the thesis, including i) General Introduction; ii) Materials and Methodologies; iii) Preparation, characterization, and physical properties of deep eutectic Solvents; iv) Micellization of various surfactants in DESs; v) Clouding phenomenon of ionic surfactant (+TBAB) in DES; vi) Solubilization of curcumin with and without additives in DES and vii) Overall Conclusion and future

Chapter-1: General Introduction

This chapter provides a comprehensive review of the literature on solvent systems and the behavior of surfactants in them. Ionic liquids (ILs) and deep eutectic solvents (DESs) have become prominent research topics in the quest for greener solvents. Paul Walden introduced ILs in 1914, which are a group of low-melting ion compounds. ILs are classified depending on their cation segment, which includes alkyl ammonium, dialkyl imidazolium, phosphonium, and N-alkyl pyridinium. They are also classified as protic and aprotic ionic liquids. It was formerly considered that deep eutectic solvents (DESs) are an analog of IL. However, based on recent research, it has been suggested that DES could be a viable solution for a solvent needed in the current days [8,9]. DESs having a lower melting point than their constituents are less toxic, more conductive, non-flammable, environmentally friendly, and biodegradable [10–12]. DES can be synthesized by judicious mixing of hydrogen bond donor (HBD) and hydrogen bond acceptor (HBA) [13]. The library of various HBDs and HBAs [14] is given in Scheme 1. Due to its benefits (easier preparation, a wider variety of liquids, cost-effectiveness, etc.) over other conventional solvents, research in the field of DES has increased significantly over the past two decades. Based on the constituent parts, different types of DESs (Type I, Type II, Type III, Type IV, and Type V) are reported in the literature [15].



Scheme 1: A Library of commonly used HBDs and HBAs

A well-known DES (reline) of type III, which has been applied in a variety of industrial applications, is constituted of urea (HBD) and choline chloride (ChCl, HBA) in a eutectic composition (1:2) [16]. Reline has an issue with its extremely high viscosity, which can be somewhat solved by substituting alternative HBDs (ethylene glycol, glycerol, amino acids, etc.) for urea [17]. A certain amount of water was also added (until it maintained the DES network) to obtain low-viscosity DESs. Water can serve as another HBD in this case. Later, people considered employing water as an exclusive HBD (so-called aquoline) to produce low viscous DESs [18,19].

Studying the self-assembly behavior of amphiphiles in such environmentally friendly solvents may pave the way for novel applications. In the present work, we have synthesized a variety of DES from hydrophilic to hydrophobic. We have also determined various physiochemical properties of solvents that are used for association of surfactants. This thesis work is related to the solution behavior of surfactants in DES containing various degrees of water content (the lower content side).

Surface Active Agent, commonly referred to as a surfactant, was introduced by Antara Products in 1950 [20]. Surfactants are amphipathic organic compounds made up of at least one "lyophilic/hydrophilic" group that loves solvents/water and one "lyophobic/hydrophobic" group that hates solvents/water. In the simplest terms, a surfactant is made up of a minimum of one hydrophobic tail and a hydrophilic head portion and it is represented in Figure 1.

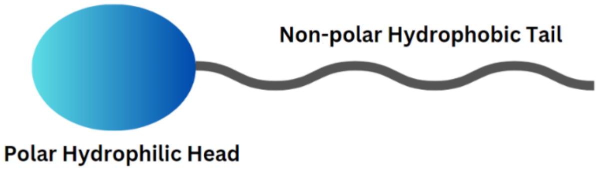


Figure 1: Representative structure of a typical surfactant molecule

The hydrophobic portion is a straight or branched alkyl or fluorocarbon chain with 8-18 carbon atoms, whereas the hydrophilic portion contains charge. Based on the charge present on a head group, a surfactant can be classified as cationic, anionic, non-ionic, and zwitterionic (amphoteric) [21]. The graphical representation of types of surfactants is given in Scheme 2.

- Cationic surfactant: CTAB, TTAB, DTAB

- Anionic surfactant: SDS, SDBS

- Zwitterionic surfactant: Lauryl betaine, Cocamidopropyl betaine

- Non-ionic surfactant: Triton X-100, Tween 80

Scheme 2: Graphical representation of types of surfactants

Cationic surfactant carries a positive charge on the hydrophilic head group. Cationic surfactants include cetyltrimethylammonium bromide (CTAB), benzalkonium chloride, and cetyl pyridinium chloride. Anionic surfactant carries a negative charge on the hydrophilic head group. Most of anionic surfactants are easily synthesized and used in detergent formulations [22]. Examples are sodium dodecyl sulfate (SDS), sodium dodecyl benzene sulphonate (SDBS), dioctyl sodium sulfosuccinate, etc. Non-ionic surfactant refers to the surfactant molecules, which do not undergo ionization when being dissolved in water. It has an uncharged hydrophilic head group. They can be classified as polyol esters, polyoxyethylene esters, and poloxamers. Some examples include Triton X-100, Sorbitan, Polysorbate 20, etc. The hydrophilic component of amphoteric surfactants consists of both positive and negative charges. Depending on the pH of a solution, the charge may be negative, positive, or none. The positively charged amphoteric surfactants are generally based on ammonium cations, while the negatively charged ones are typically based on carboxylate, sulfate, or sulphonate [23].

Surfactant solutions exhibit unique properties in aqueous solutions due to the presence of a hydrophilic head group and a hydrophobic chain in its structure [24]. There are various phenomena in aqueous surfactant solution which is represented in Figure 2.

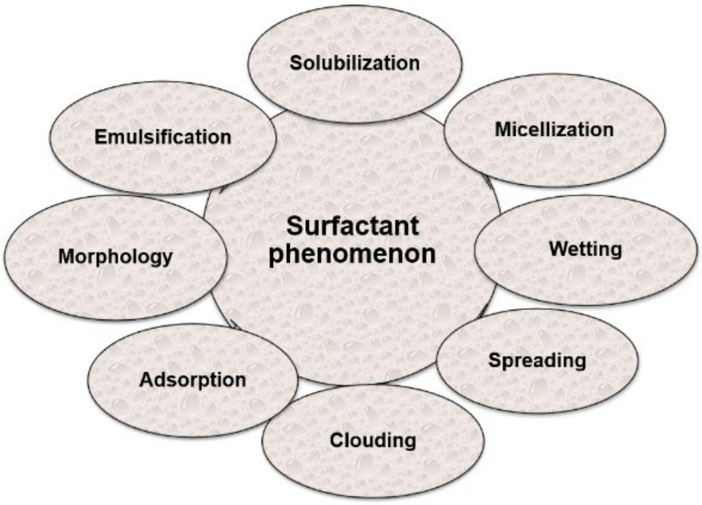


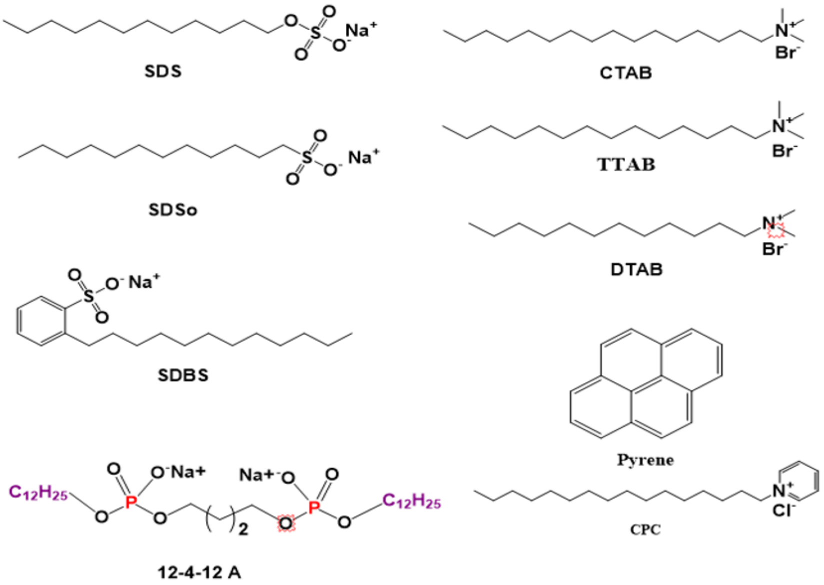
Figure 2: Various phenomena in aqueous surfactant solution

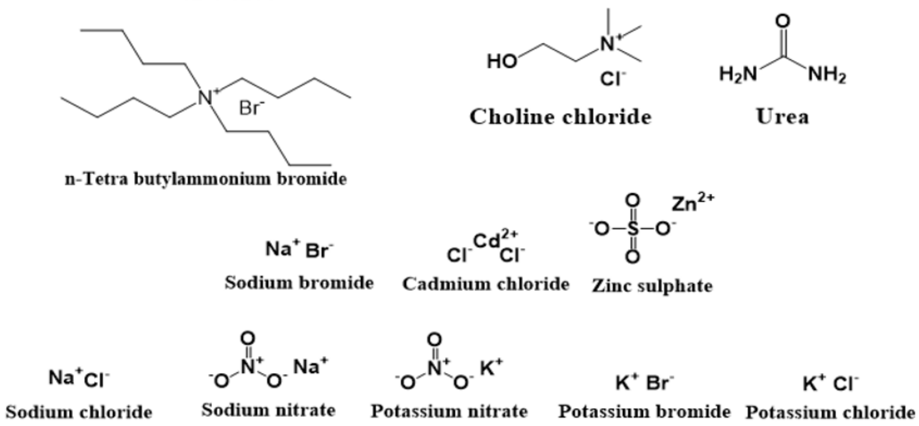
However, in this thesis work, we have mainly been concerned with micellization, aggregation, and clouding behavior of some ionic surfactants in the presence of quaternary ammonium salt namely TBAB.

Chapter-2: Materials and Methods

2.1. Materials

ChCl (99%) is a TCI, India product used after vacuum drying (at 40oC). SDS, SDSo, SDBS, CTAB, DTAB, and pyrene were high-purity chemicals obtained from Sigma Aldrich, St Louis, MO, USA (99%) and used as received. Urea, SDS, pyrene, and TBAB were high-purity chemicals (99 %) obtained from Sigma Aldrich and used without further purification. ZnSO4 and CdCl2 are procured from ACS chemicals and used after drying. Thymol, menthol, and camphor (99%) are purchased from loba chem. 12-4-12A was the same as used earlier [25]. Aquoline (of compositions 1:2, 1:3, 1:4, and 1:5) and all the reline-water mixtures have been prepared with pure distilled water (κ~1.0 µS.cm-1). The chemical structures of the material used are shown in Scheme 2.





Scheme 2: Chemical structures of the material used

2.2. Methods

2.2.1. Characterization of synthesized DESs

The formation of DESs was confirmed by FT-IR (FTIR–8400S Shimadzu Japan IR Spectrophotometer) using potassium bromide (KBr) pallets in the frequency range of 400-4000 cm-1. DESs were further characterized by 1H and 13C NMR (Bruker Avance 400 MHz NMR spectrometer) in a deuterated solvent. Tetramethylsilane (TMS) was used as an internal standard.

2.2.2. Preparation of reline-water mixtures

Various reline-water mixtures were obtained by mixing proportionate amounts of reline and water and used for measurements of various physical properties. The above mixtures (water in reline or reline in water) were also used to study micellization and clouding behaviors.

2.2.3. Physico-chemical properties measurements

Shear viscosity (η_s) was measured using HAAKE MARS (Modular Advanced Rheometer System) Thermo fisher scientific, Karlsurhe, Germany, and η_s vs shear stress plots were obtained, which were used to acquire zero shear viscosity (η_0) by using inbuilt computer software of rheometer. This experiment was performed for all aquolines and different reline-water mixtures (water in reline and reline in water).

The specific conductance (κ) of DESs and reline-water mixtures was measured using EUTECH cyber scan CON510 conductometer, Singapore (cell constant 1 cm^{-1}). We used AQUASOL digital calibration solution (κ~2764 µS.cm−1), Rakiro Biotech Sys Pvt to calibrate the conductometer. Ltd, India. All measurements were performed at constant temperature (in a water thermo state having temperature controlling accuracy within ± 0.1 K). The sample was equilibrated for 30 m at a constant temperature before acquiring conductivity data. The measurement process was repeated for each composition.

pH measurements on various aquoline systems have been performed using pH meter CL 54+, Ajmer, India. Precalibration of pH instrument was performed using various standard buffer solutions (4,7 and 11). Before measurement, each sample was pre thermostated (30 m) at 303 K.

The Du Nouy ring method [26] (using a platinum-iridium ring) was used to measure the surface tensions of all the DESs and reline-water mixtures. Deionized water was used to calibrate the tensiometer.

The densities of the synthesized aqulines were measured at the corresponding temperatures (303K, 313K, and 323K) using a 10 mL specific gravity bottle with a core diameter of 1 mm. The mass measurements were performed on a digital electronic balance (CP225D Sartorius AG, Germany) with an uncertainty of 0.01 mg. The uncertainty in the density measurement was ±10^{-4} g/cm^3.

The contact angle of aqulines has been measured on Krüss DSA100, Germany, contact angle goniometer at 30 ± 0.1°C. 5L of each aquoline has been delivered using a microlitre syringe (durasil) to form a sessile drop on the surface of the glass slide. Contact angle has been taken in triplicate and an average has been reported as the final value.

2.2.4. Fluorescence measurement

Fluorescence measurements (micro polarity, apparent dielectric constant, and quenching) have been carried out (using pyrene as a probe) on the RF-6000, Japan Spectro fluorophotometer (having a 1 cm quartz cell). Different concentrations of surfactants were used to get fluorescence data in various compositions of aqulines and water in reline/reline in water. Data were acquired with constant excitation at 337 nm, and the slit widths of excitation and emission were also fixed at 3 and 3 nm, respectively. The ratio of I^{st} and III^{rd} vibration maxima (I_1/I_3) in the fluorescence spectra of pyrene was used to obtain CMCs of various surfactants. The uncertainty in the measured CMC was ±0.1 mM L^{-1}.

2.2.5. Acquisition of CP data

CP data were collected (using the previously reported method [27]) by placing a sample bottle containing SDS + TBAB (in reline-water mixtures) into a temperature-controlled water bath. The temperature was ramped with an accuracy of ± 0.1 K. The appearance of turbidity (or LLPS) was noted visually. Temperatures of appearance and disappearance of turbidity were very close to each other and hence the appearance of turbidity has been taken as the CP. The measurements were repeated thrice to get a precise CP value (within ± 0.1 K). The effect of adding metal salts ($CdCl_2$ or $ZnSO_4$) has also been seen on the CP variation of 0.1 M SDS + 0.1 M TBAB (in water in reline containing 40 wt% of water).

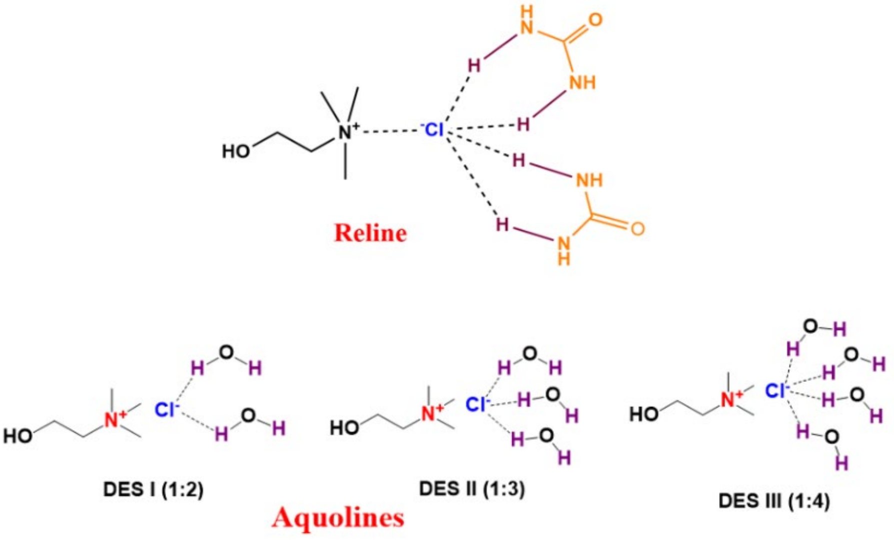
2.2.6. Solubilization experiment

The solubility of curcumin has been determined in DESs by adding a definite amount of curcumin into DESs. A mixture has been equilibrated for 24h before the solubilization experiment. The absorption spectra were acquired (at respective λmax and with an uncertainty of ± 0.5 nm) using a Shimadzu, Japan, UV–vis. spectrophotometer (UV-1800) having a quartz cell with a path length of 1 cm at 303 K.

Chapter-3: Preparation, Characterization, And Physical Properties of Deep Eutectic Solvents

3.1. Preparation of various DESs

Reline has been synthesized by adopting a reported procedure [28]. For this purpose, dried choline chloride and urea (1:2 M ratio) were mixed and heated at 80^{0}C with continuous stirring (2h) till the appearance of clear fluid. This fluid was equilibrated for 24 h (in an electric oven) at 40^{0}C. The so-obtained reline was characterized by proton NMR and IR spectroscopies. Aquoline was formed by following a reported procedure [29] in which dried choline chloride and water ($\kappa \sim 1.0\ \mu S.cm^{-1}$) were mixed in different compositions (1:2 (DES I), 1:3 (DES II), 1:4 (DES III), and 1:5 (DES IV)) followed by stirring under ambient conditions for 30 min. Transparent homogenous fluid so obtained was equilibrated for 1 h in a paraffin-sealed bottle and later on, stored in a desiccator. Ternary DES (Chcl: urea: glycerol (1:1:1), CUG I and Chcl: urea: glycerol (1:1.5:0.5), CUG II) and hydrophobic DESs (thymol, menthol, and camphor) were formed by mixing appropriate components in a eutectic ratio. The mixture was heated at 60^{o}C with continuous stirring. The possible interactions among synthesized DESs are given in Scheme 3.



Scheme 3: The chemical structure of DESs

3.2. Characterization of prepared DESs

The formation of DESs was confirmed by FT-IR. Some of the FTIR spectra are given in Figure 3. Hydrogen bonding assists in remarkable changes to the frequency shift in IR bands and the intensity of the vibrational mode of the functional group participating in H-bonding. The H-bond also leads to band broadening. DESs are formed by mixing Chcl with different molar ratios of HBDs. Figure 3a represents the IR spectra of aquoline in which the presence of water molecules in the network of ChCl (in a typical DES) leads to distinct changes in the frequency shift in the IR bands owing to hydrogen bonding interactions. Figures 3b represent the IR spectra of hydrophobic DESs.

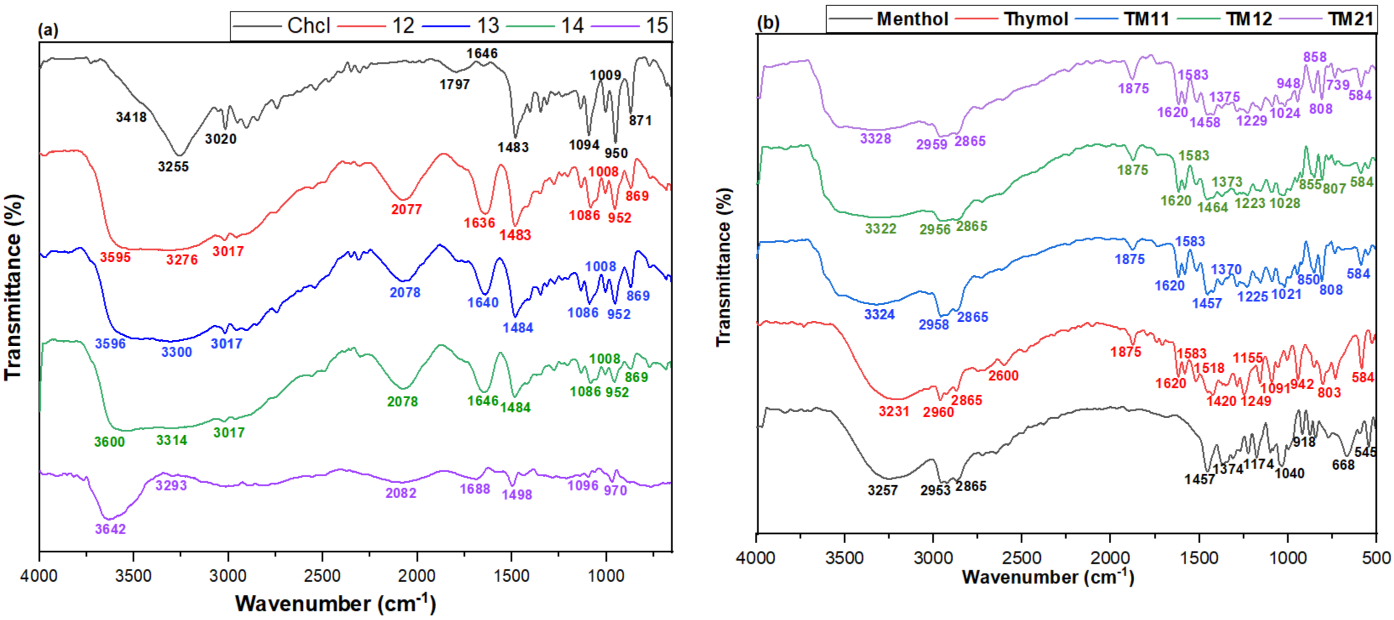


Figure 3: FTIR spectra of a) aqulines b) hydrophobic DESs

3.3. Physical properties of prepared DESs and DES-water mixture

Various physical properties of DESs and DESs-water are compiled in Table 1 and Table 2.

Table 1. Compilation of physical properties (zero shear viscosity (η0), specific conductance (κ), pH, contact angle and surface tension of various DESs

DESs	Molar ratio	Viscosity η0	Specific conductance κ	pH	Contact angle	Surface tension
		(mPa.s)	mS cm^{-1}			Dyne/cm
DES I	1:2	176.64	18.30	6.93	63.80	62
DES II	1:3	175.50	42.20	6.90	53.04	70
DES III	1:4	160.83	55.90	6.98	48.54	66
DES IV	1:5	155.29	69.20	7.08	29.17	67
Reline	1:2	279	0.68	10.38	76.40	76
TM	1:1	136.01	0.00083	6.05	-	-
TM	1:2	187.16	0.00084	6.40	-	-
TM	2:1	137.70	0.00084	7.20	-	-
CTM	1:1:1	207.44	0.00081	6.46	-	-

Table 2: Compilation of physical properties (zero shear viscosity (η0), specific conductance (κ), surface tension, density, and pH) of reline-water mixture in water in reline and reline in water region.

Wt.% of Water	Viscosity η_0	Specific conductance κ	Surface tension	Density	pH
	(mPa.s)	mS cm^{-1}	Dyne cm^{-1}	gm cm^{-3}	
100	-	-	67	0.995	7.02
90	149.77	-	50	1.016	9.09
80	148.86	-	49	1.039	9.32
70	156.45	-	48	1.060	9.41
60	163.64	-	54	1.080	9.48
50	172.94	-	56	1.099	9.55
40	177.98	56.5	61	1.118	9.67
33.3	165.72	44.8	60	1.132	9.79
30	170.17	41.7	62	1.138	9.86
20	188.27	15.52	64	1.158	10.06
10	230.14	4.45	72	1.175	10.33
0	279	0.682	76	1.190	10.38

Chapter-4: Micellization of Various Surfactants in DESs

4.1. Micellization of ionic surfactants in DESs and DES-water mixture

The association behavior of various surfactants in different DESs and DES-water mixture has been studied by fluorescence measurements and representative plots for surfactant-DES are given in Figure 4a. Similar such plots (not shown) are obtained with other DES systems and other surfactants. These plots are used to obtain a ratio of intensities of the Ist vibronic peak to the IIIrd vibronic peak (I_1/I_3). Later, I_1/I_3 vs [surfactant] curves are plotted (Figure 4b) to obtain the CMC of particular surfactant-DES combinations.

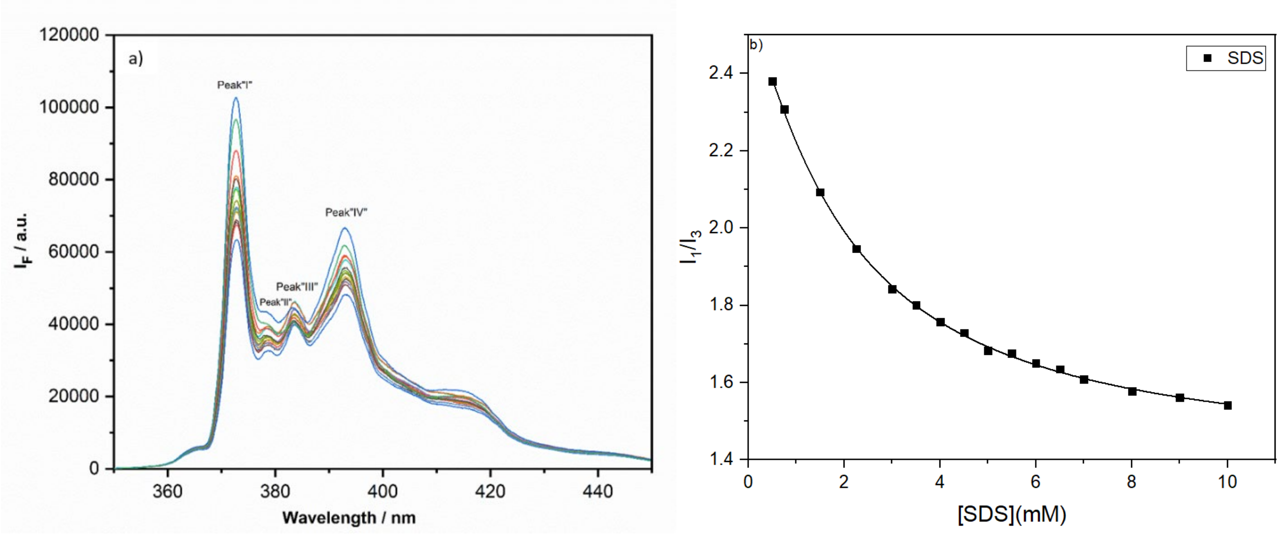


Figure 4: a) Fluorescence (emission) spectra (intensity vs wavelength) of pyrene in various concentrations of surfactant in DES b) Variation of I1/I3 (for pyrene) against surfactant concentration

CMC data for various surfactants in DESs are compiled in Table 3. From the CMC data, it has been observed that the CMC value is lower in DESs as compared to water. A similar trend of lower CMC value in comparison to other DESs or water can be seen for cationic CTAB [30,31].

Table 3. CMC data of various conventional and gemini surfactants in different DESs

Surfactants	CMCs (mM L^{-1})				
	Water	**Aquoline**		**Reline-water mixture**	
		Molar ratio ChCl: H_2O		**Molar ratio ChCl-urea: water**	
SDS	7.90^{b} 8.60^{e}	1:2	3.08	1:0.64	13.9^{a}
		1:3	4.69	1:2.13	9.01
		1:4	3.75	1:4	5.72
		1:5	2.98	1:6	2.90
				1:8	4.03
				1:12.1	3.8^{a}
				1:28.4	1.81
				1:230	1.02
SDBS	2.30^{b}	1:2	3.31	-	
		1:3	2.73		
		1:4	2.48		
SDSo	10.65^{b}	1:4	5.0	-	
12-4-12A	0.55^{c}	1:4	1.40	-	
CTAB	0.87^{d} 1.04^{e}	1:4	0.82	-	
DTAB	14.7^{d}	1:2	8.385	-	
		1:3	6.071		
		1:4	5.261		

[a] Ref. [6], [b] Ref. [33], [c] Ref. [25], [d] Ref. [30] and [e] Ref. [31].

4.2. Aggregation number and micellar environment

The quenching experiment in the presence of an appropriate quencher (e.g., CPC) can use to draw information regarding aggregation number (Nm) and environment experienced by the probe pyrene. With an increase of [CPC], the fluorescence intensity of the Ist vibronic peak gradually reduces without the emergence of any new peak. The data relating to the Stern-Volmer constant (Ksv), aggregation number (Nm), micro polarity (I1/I3), and apparent dielectric constant (e) for various surfactants are compiled in Table 4.

Table 4. Stern-Volmer constant (Ksv), aggregation number (Nm), micro polarity (I_1/I_3) and apparent dielectric constant (ε) for various surfactants

Surfactants	Aggregation Number Nm	K_{sv} 10^4	Micro polarity I_1/I_3	Apparent dielectric constant ε
SDS	34	0.671	1.53	41.97
SDSo	57	2.14	1.80	63.75
SDBS	168	7.15	1.69	55.00
12-4-12 A	4	1.72	1.98	78.01
CTAB	37	10.07	2.26	100.54
DTAB	27	1.55	1.54	43.33

Chapter-5: Clouding Phenomenon of Ionic Surfactant (+TBAB) In DES

5.1. Clouding of SDS in water in reline and reline in water

Clouding behavior (or LLPS) in aqueous SDS solutions has been reported with TBAB in the last two decades. It is known that organic counter ions (e.g., TBA+) interact with the sulphate head group via close ion pair interaction. TBA+ (having four n-butyl alkyl chains together with an N atom having a positive charge) can interact solvophobically (via butyl chains) and electrostatically (due to opposite charges) with the anionic micellar surface. This causes an increase in the surfactant packing parameter (P) [32,33] and the formation of larger aggregates. These aggregates of higher hydrophobicity are sufficient to produce clouding followed by phase separation (on standing, LLPS) [34]. The formation of various micellar architectural structures in an aqueous solution was reported and interpreted in terms of increasing.

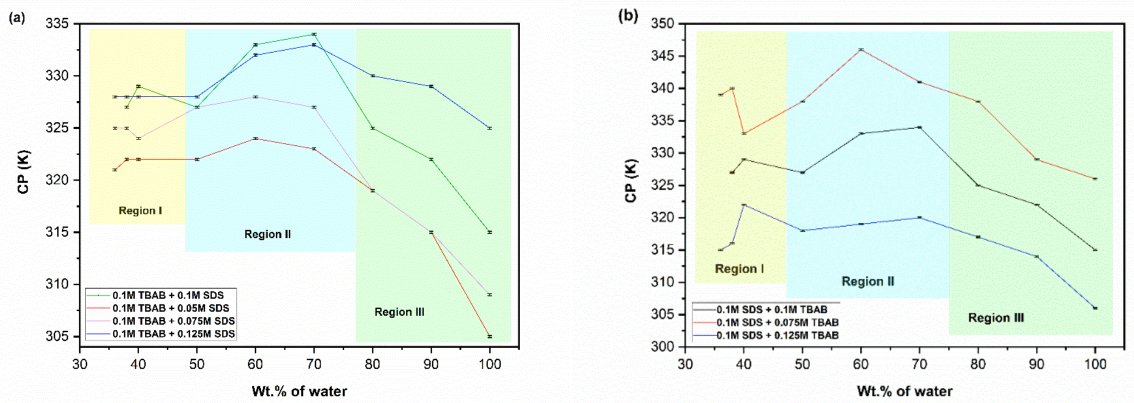


Figure 5: Variation of cloud point (CP) of SDS+TBAB against wt.% of water:(a) effect of [SDS], (b) effect of [TBAB]

In the present study, SDS showed clouding behavior with TBAB both in water in reline and reline in the water region (Figure 5). It may be mentioned here that clouding was not observed above 66 % of reline in the reline-water mixture in water in reline. Further, SDS + TBAB was not soluble in higher reline content in the water in reline region which restricted the CP studies below this composition. A perusal of data shown in Figure 5 dictates that the dependence of CP in DES (reline-water mixtures) shows a similar trend as observed in the aqueous system (i.e., CP a [SDS] and CP a 1/[TBAB]). However, CP values are found to be higher than the values obtained in an aqueous solution.

5.2. CP variation with ZnCl2/CdCl2 for 0.1 M SDS + 0.1 M TBAB in water in reline

The effect of the addition of $ZnCl_2$ and $CdCl_2$ on the CP behavior has been depicted in Figure 6.

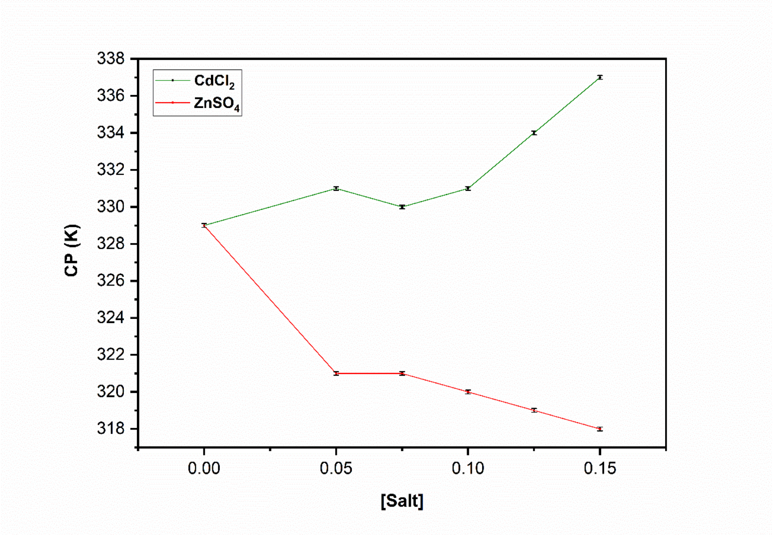


Fig. 6: Variation of cloud point (CP) against [metal salt] for 0.1M SDS+ 0.1M TBAB in 40 wt.% water in water in reline region: 🟩 $CdCl_2$, ●$ZnSO_4$

Chapter-6: Solubilization of Curcumin with And Without Additives in DESs

6.1. UV measurements

Figure 7 ((a) without surfactant and (b) with surfactants) shows the absorbance spectra of curcumin in different conventional solvents and DESs. Curcumin has an absorption maximum of around 425 nm in water and 420 in ethanol. In the case of aqulines blue shift was observed (433-443 nm). By adding ionic surfactant, the intensity increases in the water and again the maximum shifted towards the blue. In the case of the aqulines-surfactant system, there is a decrease in intensity (DES I), and absorption maxima are at around the same wavelength.

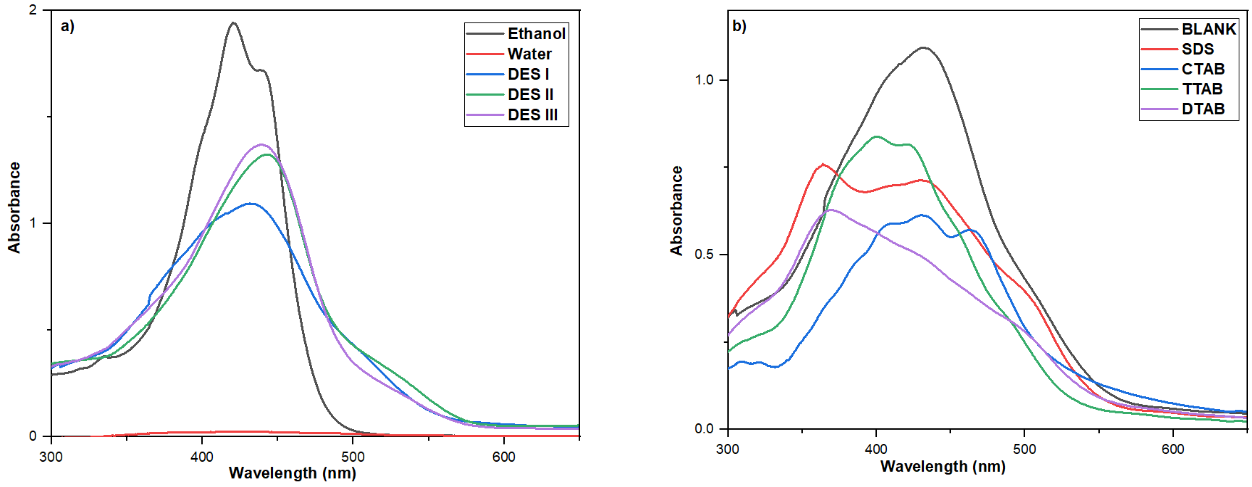


Figure 7: Absorption spectra of curcumin in conventional solvent and DESs: a)without surfactant; b) with surfactant (in DES I)

6.2. Fluorescence measurements

Figure 8 ((a) without surfactant and (b) with surfactants) shows the steady-state fluorescence spectra of curcumin stimulated at its absorption maxima at 303 K in various DESs and components of DESs. Single peaks for water (540 nm), ethanol (520 nm), DES I (562 nm), DES II (564 nm), DES III (568 nm), glyceline (550nm), reline (507), CUG I (515 nm), CUG II (528 nm), water + ChCl (489nm), and water + urea (550nm) was found. The spectra demonstrated the distinctive properties of the solvents on curcumin emission.

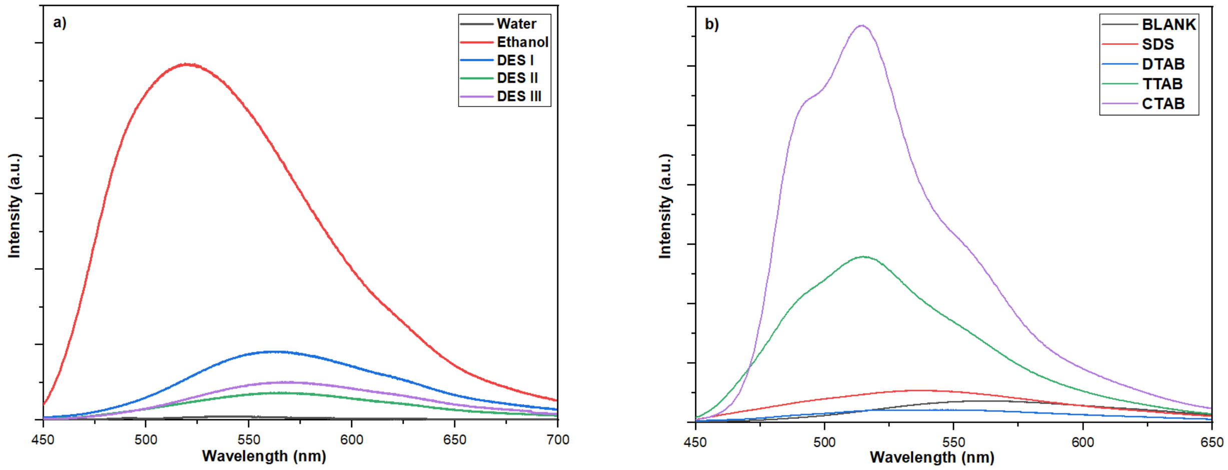


Figure 8: Fluorescence spectra of curcumin in conventional solvent and DESs: a) without surfactant; b) with surfactant (in DES I)

Chapter-7: Overall Conclusion and Future Work

This chapter outlines and summarizes the most significant findings and prospective applications of this thesis study. The scope and future prospects of research in the area of self-assemblies in DESs are also addressed in this chapter. Hydrophilic DESs were prepared using quaternary ammonium salt (choline chloride) and HBD (*e.g.,* urea, water), and hydrophobic DESs were prepared using thymol, menthol, and camphor at varying molar ratios. The physical properties like shear viscosity, conductivity, surface tension, contact angle, pH, and density were investigated. DESs were used to study surfactant aggregation. It was shown that surfactants are able to self-assemble in DESs which was surprising due to the high ionic strength. The micellization and clouding phenomenon can be observed in the reline-water mixtures as in an aqueous solution. The association behavior of ionic surfactants was also studied in aqualines (water-based DESs). An important area of research from the perspective of using a naturally occurring substance of biological and medicinal value is the solubilizing study of curcumin in various solution environments. We have measured the UV-visible and steady-state fluorescence spectra of the curcumin in various DESs.

Reline, reline-water mixtures, and aquoline has been found as Newtonian, electrically conducting, and highly polar fluids. The addition of water in reline causes non-Newtonian behavior of reline, which changes into Newtonian under the influence of shear. CMC decrease in water in reline region via formation/breaking of H-bonded structures in ChCl-urea-water motifs. However, CMC decreased in region III (in reline in water) due to the molecular solution of choline chloride, which furnished a Ch+ counter ion. This Ch+ ion can interact with the head groups of the micelle and is responsible for lowering CMC in region III. Data obtained from the fluorescence study concluded that the micellization process, of a variety of surfactants, can be observed in aquoline (ChCl + water) as seen in pure water. CMC decreases with an increasing number of water molecules per mole of ChCl in a typical aquoline. Further, CMC values are lower in most cases when compared with water. Micelles show a lower aggregation number (Nm) and higher polar environment experienced by the probe (pyrene). However, Gemini (12-4-12A) shows higher CMC and lower aggregation numbers than in water. This can be understood in light of architectural differences between Gemini and conventional surfactants. The study demonstrates that micellization phenomenon can occur with both types of ionic surfactants (anionic and cationic) in aquoline which is rare for other DESs (e.g., reline, ethaline, or glyceline) as observed in pure water and data can be used to have association processes are in demand without using water as the polar solvent. CP values have been found dependent on [SDS] and [TBAB] in reverse fashion, respectively. Further, CP values were consistently higher than observed in pure water. In a selective system effect of the addition of CdCl2 and ZnSO4 shows opposite CP variation, which can be correlated with hydrated and crystal radii of metal ions. From the solubilization of curcumin in various DESs, it is observed that curcumin is more soluble in DESs as compared to aqueous solution.

Future research in this area may concentrate on a variety of topics. The study of surfactant interactions and curcumin solubilization in deep eutectic solvents (DES) has great potential for improving drug delivery systems. The optimized surfactant-DES systems could enhance the solubility, stability, and delivery of poorly soluble drugs and bioactive compounds, opening new possibilities for pharmaceutical, nutraceutical, and cosmetic applications. Additionally, the exploration of environmentally friendly and sustainable surfactants within DES can pave the way for greener technologies. The development of robust and effective drug delivery systems can be facilitated by a greater comprehension of surfactant micellization and clouding activities. Clouding phenomena can lead to the development of tailored DES-based formulations with unique thermo-responsive properties. Understanding the factors influencing cloud point transitions will enable the design of smart materials for temperature-controlled drug delivery, cosmetics, and separations. Investigating the effect of different surfactant structures on clouding behavior may help in the development of improved and environmentally friendly surfactant systems for a variety of applications. The studies on the bioavailability and pharmacokinetics of the curcumin-DES system may unlock its full therapeutic potential, addressing various health conditions. The future impact of this work may revolutionize diverse sectors by providing efficient and eco-friendly solutions to complex challenges and pave the way for innovative and effective curcumin-based treatments, enhancing healthcare outcomes worldwide.

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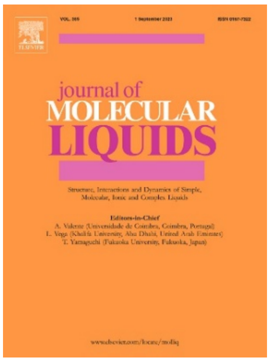
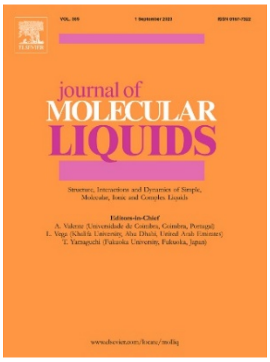
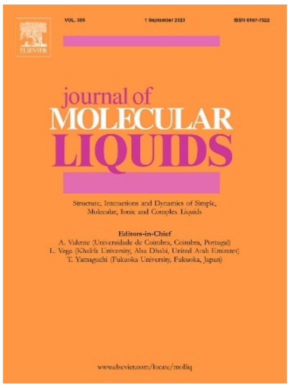
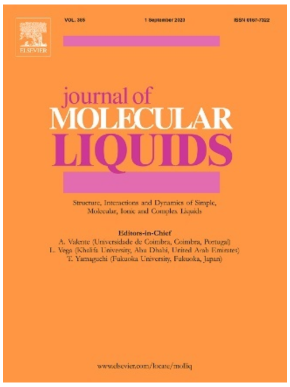
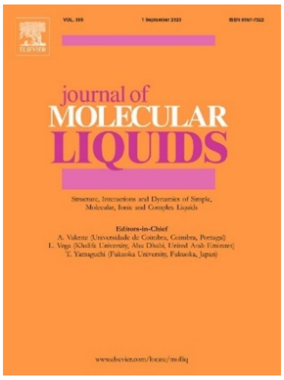
❖ List of Publications (Related to Thesis)

1.		**Title: Micellization of conventional and gemini surfactants in aquoline: A case of exclusively water based deep eutectic solvent** **Darshna Hirpara**, Brijesh Patel, Vishwajit Chavda, Sanjeev Kumar **Journal of Molecular Liquids**, Volume 362, p. 119672 **Available Online:** 24 June 2022 **DOI:** https://doi.org/10.1016/j.molliq.2022.119672
2.		**Title: Micellization and clouding behaviour of an ionic surfactant in a deep eutectic solvent: A case of the reline-water mixture** **Darshna Hirpara**, Brijesh Patel, Vishwajit Chavda, Arpita Desai, Sanjeev Kumar **Journal of Molecular Liquids**, Volume 364, p. 119991 **Available Online:** 2 August 2022 **DOI:** https://doi.org/10.1016/j.molliq.2022.119991
3.		**Title: Influence of salt counter ion on aggregation behavior of cationic surfactant in aquoline (ChCl + water): A case of deep eutectic solvent** **(Manuscript under preparation)**
4.		**Title: Photophysical analysis of curcumin solubility in Various conventional and deep eutectic solvents** **(Manuscript under preparation)**

5.		**Title: Physical Properties and molecular interaction in reline-water Mixture at different compositions/temperatures: Rheology and Refractometry measurements** **(Manuscript under preparation)**

❖ List of Publications (Non-related to Thesis)

1.		**Title: Composition triggered Aggregation/Solubilization behaviour of mixed counter charged Gemini Surfactants: A Multi-technique investigations** Brijesh Patel, Sneha Singh, Kushan Parikh, Vishwajit Chavda, **Darshna Hirpara,** Debes Ray, Vinod K. Aswal, Sanjeev Kumar **Journal of Molecular Liquids**, Volume 359, p. 119242 **Available Online:** 28 April 2022 **DOI:** https://doi.org/10.1016/j.molliq.2022.119242
2.		**Title: GO/Ionic Surfactant Inspired Photophysical Modulation of Rhodamine B in Reline with or without Additives** Vishwajit Chavda, **Darshna Hirpara**, Sanjeev Kumar **Journal of Molecular Liquids**, Volume 368, p. 120614 **Available Online:** 18 October 2022 **DOI:** https://doi.org/10.1016/j.molliq.2022.120614

3.		**Title: A Sustainable Approach for the Adsorption of Methylene Blue from Aqueous Background: Adsorbent Based On DES/CGS Modified GO@ZrO$_2$** Vishwajit Chavda, Brijesh Patel, Sneha Singh, **Darshna Hirpara**, V. Devi Rajeswari, Sanjeev Kumar **RSC Sustainability,** Under review **Manuscript ID:** SU-ART-07-2023-000236
1.		**Review** **Title: Exploring the potential of deep eutectic solvents in pharmaceuticals: Challenges and opportunities** Priyanka A. Shah, Vishwajit Chavda, **Darshna Hirpara**, Vinay S. Sharma, Pranav S. Shrivastav, Sanjeev Kumar **Journal of Molecular Liquids,** Under review **Manuscript ID:** MOLLIQ-D-23-04707

❖ Work presented in Conferences/ Seminars/ Workshops

Conferences		
1.	GUJARAT UNIVERSITY Estd. 1949	**Title:** **Micellization and Clouding Phenomenon in Reline-Water Mixture: A case of Anionic surfactant** **Darshna Hirpara,** Sanjeev Kumar **National Conference** on *Recent Advances and Future Trends in Biological, Chemical and Physical Science 2021 (RAFTBCPS-2021)*, **30th -31st July 2021**. **Presented Session: POSTER**
2.		**Title:** **Clouding and Liquid-Liquid phase Separation in Deep Eutectic Solvent: A case of an Anionic Surfactant** **Darshna Hirpara,** Sanjeev Kumar **International Conference** on *Complex Fluids and Soft Matter 2021 (Compflu-2021)*, **13th -15th December 2021**. **Presented Session: ORAL**
3.		**Title:** **Micellization Behavior of An Anionic Surfactant in a "Designer Solvent": A Case of Deep Eutectic Solvent** **Darshna Hirpara,** Sanjeev Kumar **International Conference** on *Molecules to Materials (MTM – 2021)*, **17th -18th December 2021.** **Presented Session: POSTER**
4.		**Title:** **Physico-chemical Studies on Deep Eutectic Solvent: A Case of Reline-water System** **Darshna Hirpara,** A.N. Prajapati, Sanjeev Kumar **International Conference** on *Advanced Materials and Applications (ISAMA-2022)*, **18th July 2022.** **Presented Session: ORAL**

Received 1st Rank for best oral presentation

5.		Title: **Association Behaviour of an Ionic Surfactants in Deep Eutectic Solvent and its Components** **Darshna Hirpara,** Sanjeev Kumar **National Conference** on *Modern material and chemical sciences (MEMCS-23),* **6th -7th January 2023.** **Presented Session:** ORAL
6.		Title: **Curcumin and its precursor (Curcuma Longa) solubilization in Conventional and Deep Eutectic Solvents with and without ionic surfactants** **Darshna Hirpara,** Sanjeev Kumar *30th CRSI-NSC & 16th CRSI-RSC* **Symposium Series** *in Chemistry,* **2nd-6th February 2023.** **Presented Session:** **POSTER**
7.		**PARTICIPATED** **Darshna Hirpara,** Sanjeev Kumar **International Conference** *on Surface Chemistry: Colloids and Interface Aspects with Applications (SCCIA-2022),* **3rd-7th January 2022.**
Workshops		
8.		**Darshna Hirpara** **5-Day Faculty Development Programme** *Accelerating Innovations in Material Science - Surface Characterization,* **18th to 22nd May 2021.**

9.		**Darshna Hirpara** **7-Day Training program** *Synergistic Training program Utilizing the Scientific and Technological Infrastructure* ***(STUTI)*** on Modern Spectroscopic, Thermal and Microscopic Techniques,**21st -27th September 2022.**
10.		**Darshna Hirpara** **One-Day workshop** Early Career Researchers by Inspiring India in Research, Innovation, and STEM Education (iRISE*) on* *IP and Knowledge Management*, **28th September 2022.**

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