

Research Article

An Interaction of Anionic- and Cationic-Rich Mixed Surfactants in Aqueous Medium through Physicochemical Properties at Three Different Temperatures

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The mixed micellization of aqueous binary mixtures of DTAB-rich and SDS-rich surfactants, comprising sodium dodecyl sulfate (SDS) and dodecyltrimethylammonium bromide (DTAB) is studied in aqueous solution by using the physicochemical properties (PCPs) at three different temperatures ($T = 293.15, 298.15, \text{ and } 303.15 \text{ K}$) and $P = 0.1 \text{ MPa}$. The DTAB concentration is varied from 0.0001 to $0.03 \text{ M/mol}\cdot\text{L}^{-1}$ in the $\sim 0.01 \text{ M/mol}\cdot\text{L}^{-1}$ SDS solution, while the concentration of SDS is varied from 0.001 to $0.015 \text{ M/mol}\cdot\text{L}^{-1}$ in the $\sim 0.005 \text{ M/mol}\cdot\text{L}^{-1}$ DTAB. The stable formulations have been obtained by employing the DTAB-rich and SDS-rich surfactants solutions in 3 : 1 ratio. Therefore, different phases and aggregated states formed in the ternary combinations of DTAB/SDS/H₂O have been identified and described. The calculated PCPs have been utilized for determining the nature of the solute-solvent interaction ($S_T S_0 I$). With increasing surfactants concentration, the polarisation of the solution also increases along with an increase in relative viscosity (η_r), viscous relaxation time (τ), and surface excess concentration (Γ_{max}). However, the surface area of the molecule (A_{min}), hydrodynamic volume (V_h), and hydrodynamic radius (R_h) decrease along with an increase in surfactants concentration.

1. Introduction

The role of mixed surfactants is very crucial in our daily life. It has widespread applications in the various households and industrial processes such as usages in the chemical purification, targeted drug delivery, synthesis of advanced nanomaterials [1–4], cosmetics, wastewater treatment, food industries, detergency, and oil recovery enhancement [5–8].

With the advantages of high biodegradability, greater surface activity, high biocompatibility, and application in various separation techniques, utilization in drug formulation and related biomedical applications makes the studies of the mixed surfactant system inevitable [9]. Due to the opposite charge, the surfactant induces several remarkable properties. However, cationic and anionic mixed surfactants in an aqueous medium show numerous noble features that arise from the strong electrostatic interactions between the oppositely charged head groups [10]. It has been already reported that several types of the binary surfactant systems,

cationic and anionic, show the strongest synergisms in the formation of mixed micelle and surface tension reduction of the solution [11].

The PCPs of surfactants, such as critical micellar concentration (CMC), the degree of ionization, and thermodynamics of micellization depend on the nature of the hydrophobic tail, hydrophilic head group, and the counterion species [12]. Mixed surfactants are also used in a personal cleaning product, laundry aids, shampoo, fabric softeners, and solubilizers for water-insoluble or sparingly soluble bio-inspired molecules like polyphenolic compound, ionic liquid, and anticorrosive agents for steel and plastics and used as a catalyst for some industrially significant reactions, flotation collectors for mineral ores, and leveling agents for improving the dyeing processes [13–17]. Because it has an amphiphilic nature, the study of the interaction of mixed surfactants in an aqueous medium helps to decode functional and diverse information about the system and assist in harnessing their potential in technical applications [18–20].

Hence, the ternary system (DTAB/SDS/H₂O) can demonstrate arrays of self-assembled microstructures, viz, micelles, vesicles, planar bilayers, and bicontinuous structures. Earlier studies have been focused mostly on two critical facts which influence the interaction activities: (a) the type of the interactions involved during the formation of the micelles (b) and the resultant structure of the formed aggregates [21]. The SDS and DTAB surfactants (Figure 1) actively interact with each other due to opposite charge species. However, above the CMC, surfactants form aggregates into the micelle [22]. Maiti et al. [23] have been investigated on oppositely charged single-tailed surfactants that could associate through electrostatic, ion-dipole, and van der Waals force attraction under specific conditions. Thus, the various aggregated microstructures (micelles, vesicles, and lamellar phases) of cationic surfactants have attracted the attention of researchers for their multifaceted potential application in the field of drug delivery and nanoparticle synthesis. The structure of the surfactants plays an essential role in their aggregation behavior. The critical packing parameters infer the type of possible assemblies in the solution. Due to these potentials, the mixed surfactants solution has remarkable properties such as lower surface tension with higher surface activities and critical aggregation concentrations (CACs) which are essential for detergency and pharmaceutical applications [24, 25]. The cationic surfactants can form many supramolecular structures, at the specific mole ratios and concentrations; they have formed a remarkable micelles structure [26, 27] and vesicles [28, 29]. Bakshi et al. studied single and mixed micellization of surfactants by using conductivity, turbidity, and NMR measurements [30, 31]. Therefore, anionic and cationic mixed surfactants can form a numerous type of aggregated microstructures like lamellar phases, vesicles, spheres, precipitates, and rod shape structures [32, 33]. Moreover, mixing of surfactants is also used in drug formulation, lowering the Krafft temperature, and with increasing the cloud point [34], and some studies have been reported on the electrical conductance of cationic and anionic mixed surfactants [35]. Recently, many researchers have been focused on the aggregation and micelles formation process in the aqueous and mixed solvent system [36, 37]. Earlier researchers have been focused mostly on spectroscopic and thermodynamic studies of single and mixed surfactants through UV-visible, CMC, CAC, entropy, enthalpy, Gibbs free energy, micelle ionization degree, Krafft temperature, dissociation constant, and the pre-slope and post-slope values of single and mixed surfactants in an aqueous medium and mixed solvent system at different temperatures [38–45].

There is a little work on PCPs of SDS-rich and DTAB-rich mixed surfactants in an aqueous medium at $T = 293.15$, 298.15 , and 303.15 K [46]. In this research article, we are studying the various PCPs, which include relative viscosity, viscous relaxation time, acoustic impedance, hydrodynamic volume, hydrodynamic radius, intrinsic viscosity, friccohesity shift coefficient, surface excess concentration, and area of a molecule of the SDS-rich and DTAB-rich mixed surfactants in an aqueous medium at three different temperatures ($T = 293.15$, 298.15 , and 303.15 K) at 0.1 MPa. This type of study on the mixed surfactant system could assist in

harnessing their potential in the household and industrial applications.

2. Materials and Methods

2.1. Materials. All chemicals were purchased from Sigma-Aldrich, and their details are given in Table 1. Dodecyltrimethylammonium bromide and sodium dodecyl sulfate surfactants were stored in the P₂O₅-filled vacuum desiccator due to their hygroscopic nature.

2.2. Solution Preparation. All solutions, water + SDS (aq-SDS) and water + DTAB (aq-DTAB), were prepared separately by dissolving 0.005 M/mol·L⁻¹ and 0.01 M/mol·L⁻¹ of DTAB and SDS surfactants separately into Milli-Q water and used as a stock solution. The 0.005 M/mol·L⁻¹ DTAB and 0.01 M/mol·L⁻¹ SDS solutions were used as a solvent for 0.000096 to 0.012 M/mol·L⁻¹ SDS and 0.000864 to 0.00504 M/mol·L⁻¹ DTAB, respectively. These solutions were kept for ~ 10 min sonication at 30 MHz for better homogenization. All solutions were prepared at the temperature 298.15 K and pressure 0.1 MPa using Milli-Q water at pH 7 and conductivity 0.71 μ S·cm⁻¹. For weighing, Mettler Toledo NewClassic MS was used with $\pm 0.1 \cdot 10^{-6}$ kg repeatability. To avoid evaporation and contamination, all solutions were kept in an airtight volumetric flask at the temperature of 298.15 K.

Anton Paar DSA 5000M density meter was used for measurements of their densities (ρ) and sound velocity (u) data with $\pm 5 \cdot 10^{-6}$ g·cm⁻³ uncertainty, and the temperature was controlled by a built-in Peltier (PT100) device with $\pm 1 \cdot 10^{-3}$ K accuracy. Repeatability of the instrument corresponds to precision in ρ and u data with $1 \cdot 10^{-3}$ kg·m⁻³ and 0.10 m·s⁻¹, respectively.

The instrument was calibrated with Milli-Q water at the temperature of 298.15 K, while aq-NaCl (1 M/mol·kg⁻¹) and 10% aq-DMSO were also used to check the performance of the instrument, and the values were in agreement with the literature within the experimental uncertainties (Table S1) [47, 48]. Reported densities were an average of three repeated measurements with $\pm 3 \cdot 10^{-6}$ g·cm⁻³ repeatability. The ρ and u at 3 MHz frequency of uncertainties were $\pm 5 \times 10^{-3}$ kg·m³ and ± 0.5 m·s⁻¹, respectively. All experiments were carried out at the three different temperatures ($T = 293.15$, 298.15 , and 303.15 K) with ± 0.01 K accuracy [49]. Sound velocity work based on oscillation periods of quartz U-tube with air, solvent, and solutions [50]. After each measurement, the tube was cleaned with acetone and dried by passing dried through the U-tube by using an air pump. A process of drying continued till a constant oscillation period for air was obtained and noted as an initial calibration. Viscosity, surface tension, and friccohesity data were measured by Borosil Mansingh Survisometer [51] (Cal no. 06070582/1.01/C-0395, NPL, India) through viscous flow time (VFT) and pendant drop number (PDN) methods, respectively. Lauda Alpha RA 8 thermostat was used for controlling the temperature with ± 0.05 K accuracy. After attaining a thermal equilibrium, the VFT was recorded by using an electronic timer with ± 0.01 s accuracy, while the PDN counted with an electronic counter. The Survisometer was

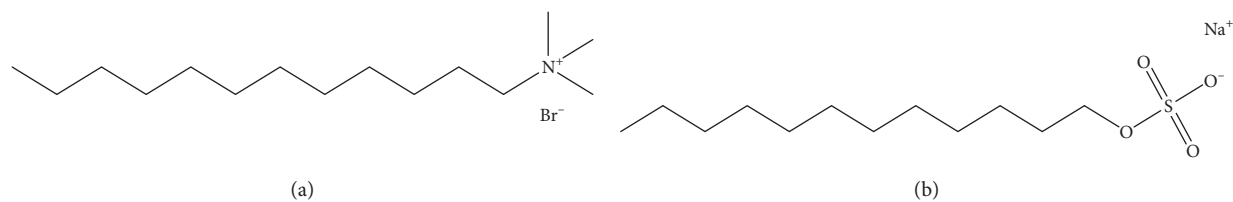


FIGURE 1: Molecular structure of dodecyltrimethylammonium bromide (DTAB) (a) and sodium dodecyl sulfate (SDS) (b) surfactant.

TABLE 1: Specification of chemicals used in this work.

Name of chemicals	Purity ^a (%)	Mw	Source	CAS no.
DTAB	~99	308.34	Sigma-Aldrich	1119-94-4
SDS	98	288.37	Sigma-Aldrich	151-21-3

^aPurity as provided by suppliers; DTAB, dodecyltrimethylammonium bromide; SDS, sodium dodecyl sulfate.

washed with Milli-Q water, followed by acetone, and absolutely dried before measurements and 5, 10, 15, and 20% (w/w) aq-DMSO (AR grade, Rankem) solutions were used to check the performance of the Survimeter, and the values are in obedience to that of the literature values, given in Table S2 (supplementary material) [48, 52, 53]. The reported surface tension and viscosities are an average of three repeated measurements with $\pm 2 \times 10^{-6} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ and $\pm 0.03 \text{ mN}\cdot\text{m}^{-1}$ uncertainties, respectively.

3. Results and Discussion

3.1. Viscometric Study. Viscosity (η) values of SDS-rich and DTAB-rich mixed surfactants were measured at the three different temperatures ($T = 293.15, 298.15,$ and 303.15 K) and at 0.1 MPa , and the same data are summarized in Table 2. Viscosity is a flowing, transporting property of the liquid mixture, and it is affected by molecular orientation and the nature of interaction ability of the solute and solvent interaction. And viscosity also gives the information about the interaction affinity of ionic species with the solvent system [54]. Table 2 shows that the aq-DTAB shows a higher η value than aq-SDS (Table S3). It indicates that the DTAB and SDS have the same hydrophobic part, except by only the head part (hydrophilic part). Due to the addition of DTAB into the aqueous system, the hydrophobic portion could be disrupted by the hydrogen bonding (HB) of the solvent system. Probably, it could also repel the solvent molecules to the surface site.

It could induce the weak CF with decreases in the surface tension (γ) value. DTAB has three methyl ($-\text{CH}_3$) groups in its head part which could also be developed by higher hydrophobicity; with stronger hydrophobic interaction, the γ value decreases with an increase in the η value. Generally, surfactants have a structure-breaking nature tendency of the solvent molecules which is present at the surface and strong electrostatic interaction with an increase in the η value. On increasing the concentration of surfactants, the η value increases with stronger IMF. SDS shows weaker hydrophobicity than DTAB because SDS has oxygen atoms in its head part. So, it could show weak hydrophobic interaction, and the η

TABLE 2: Relative viscosity (η_r) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T = 293.15, 298.15,$ and 303.15 K and at 0.1 MPa .

$M \text{ (mol}\cdot\text{L}^{-1})$	293.15 K	298.15 K SDS-rich	303.15 K
0.005000	1.0245	1.0828	0.6281
0.000096	1.4596	0.9800	2.7704
0.000240	1.3026	1.0026	1.1631
0.000480	1.7872	0.9961	1.9515
0.000672	1.2815	0.8303	1.3448
0.000792	1.0601	1.2297	1.2073
0.000960	1.1046	1.0402	0.7981
0.006011	1.0234	1.1561	0.7698
0.007200	1.2651	1.1661	0.8053
0.007920	1.3315	1.4613	0.8415
0.009000	1.2510	1.4196	0.7796
0.010800	1.3326	1.1678	1.3417
0.012000	1.2202	2.4387	0.8836
		DTAB-rich	
0.010000	1.0858	0.4814	1.1978
0.000864	2.4619	1.6787	0.7013
0.000960	2.8325	2.2650	0.7551
0.001536	2.8749	1.8171	0.7718
0.002016	2.8246	2.8142	0.7288
0.002496	3.6614	4.6162	0.7161
0.002976	6.8520	5.8893	0.7620
0.003264	2.3537	8.9771	0.7392
0.003600	1.1194	1.0365	0.8286
0.005040	3.2060	1.7780	1.0040

$M \text{ (mol}\cdot\text{L}^{-1})$ is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$) and standard uncertainties u are $u(m) = 0.00001 \text{ mol}\cdot\text{L}^{-1}$, $u(T) = \pm 0.01 \text{ K}$, and $u(p) = \pm 0.01 \text{ MPa}$.

values decrease. Thus, the aq-DTAB shows the highest η value with stronger van der Waals interactions and inducing stronger IMI affinities with solvent molecules. So, the DTAB shows lower γ values as the aq-DTAB could induce much solvent engagement. Addition of DTAB into the aq-SDS solution could form micelles at the air-liquid interfaces (ALIs). This study could be used for the preparation of drug formulation in the aqueous medium.

Table 2 shows increasing SDS and DTAB concentration due to stronger hydrophobic-hydrophobic interactions (HbHbI), stronger London dispersive force (LDF), and intermolecular force (IMF); then, the viscosity is increased. With increasing surfactants concentration, the population of the surface charges is increased in the solution, which could be induced by stronger interaction. The viscosity infers linkages of DTAB-rich and SDS-rich with a solvent system to determine fluid dynamics within the capillary with uniform water supply, contrary to static data like density. With

increasing temperature, the kinetic energy increases as well as oscillation (rotational, vibrational, and transition) could be developed which shows weaker IMF and electrostatic interaction; then, the viscosity is decreased. The measurement of η data has been carried out in accordance with relative viscosity (η_r) as in [27]:

$$\eta_r = \frac{\eta}{\eta_0}, \quad (1)$$

where η_0 and η are the viscosity of the solvent and solution, respectively. The η_r value has been summarized in Table 2. The behavior of η_r versus M of SDS-rich and DTAB-rich is qualitatively the same as commonly observed in surfactant solutions [55, 56].

The η_r values of DTAB and SDS with the solvent systems follow the order: SDS > DTAB. This order inferred that the interaction affinity of the SDS molecule is stronger as compared to DTAB. However, SDS and DTAB both have the same tail part but different head groups. SDS contains oxygen atoms in its head part while $-\text{CH}_3$ groups in the DTAB could disrupt the HB of the solvent system, and DTAB could develop stronger ion-hydrophobic interaction (IH_bI). Due to the inclusion of 0.000864 to 0.00504 M/mol·L⁻¹ DTAB into aq-SDS solution, the η_r value is more increased. It depicted that DTAB shows stronger hydrophobic interaction and maximum solvent molecules could repel with increase in the micelles formation rate. Similarly, 0.000096 to 0.012 M/mol·L⁻¹ SDS was added into aq-DTAB. Hence, increasing rate of the η_r value decreases than the aq-DTAB system while decrement is higher compared to the DTAB-rich solution. Therefore, SDS shows the stronger ion-hydrophilic interaction (IHI) with a solvent system. On increasing the concentration of DTAB and SDS, the η_r value increases at a certain concentration, and after that, the η_r value decreases and further significantly increases. It indicates that, on increasing the concentration of surfactants, the micellization and aggregation processes could be occurred.

In our study, the trends of SDS-rich and DTAB-rich surfactants do not follow the regular trend. It means that the surfactant has a long alkyl chain (AC) which could trapped the air bubble, and so the graph trend of SDS-rich and DTAB-rich surfactants are obtained in the zic-zac order.

Chakraborty et al. [57] have reported that DTAB shows more interaction affinity towards the protein. The protein also has both hydrophilic and hydrophobic domains with the polar peptide bond in its molecular structure, due to stronger IH_bI dominant over IHI with increases in the η_r value. And the similar reason may be possible in the η_r value of the DTAB-rich mixed surfactant system. The η values have been further used to calculate viscous relaxation time (τ) using the following equation [58]:

$$\tau = \frac{4\eta}{3u^2\rho}, \quad (2)$$

where ρ is the density of the solution (Table S4), η is the viscosity of the solution (Table S3), and u is the sound velocity (Table S5) used for τ measurement.

The τ values are summarized in Table 3 and represented in Figures 2 and 3. The τ value is depending on the concentration, and interaction affinity of the solute with the

TABLE 3: Viscous relaxation time (τ /ps) of SDS-rich and DTAB-rich surfactants in the aqueous medium at three different temperatures $T = 293.15, 298.15,$ and 303.15 K and at 0.1 MPa.

M (mol·L ⁻¹)	293.15 K	298.15 K	303.15 K
	SDS-rich		
0.005000	6.22E-07	5.74E-07	2.95E-07
0.000096	9.08E-07	5.53E-07	8.14E-07
0.000240	8.10E-07	5.66E-07	3.42E-07
0.000480	1.11E-06	5.62E-07	5.73E-07
0.000672	7.97E-07	4.76E-07	3.95E-07
0.000792	6.59E-07	7.05E-07	3.55E-07
0.000960	6.87E-07	5.97E-07	2.35E-07
0.006011	6.37E-07	6.64E-07	2.26E-07
0.007200	7.87E-07	6.70E-07	2.37E-07
0.007920	8.29E-07	8.40E-07	2.48E-07
0.009000	7.78E-07	8.15E-07	2.29E-07
0.010800	8.29E-07	6.71E-07	3.94E-07
0.012000	7.58E-07	1.40E-06	2.60E-07
		DTAB-rich	
0.010000	6.58E-07	6.34E-07	2.25E-07
0.000864	4.54E-07	3.79E-07	1.62E-06
0.000960	4.79E-07	5.09E-07	1.87E-06
0.001536	4.90E-07	4.09E-07	1.89E-06
0.002016	4.63E-07	6.34E-07	1.86E-06
0.002496	4.55E-07	1.04E-06	2.41E-06
0.002976	4.84E-07	1.33E-06	4.52E-06
0.003264	4.70E-07	2.02E-06	1.55E-06
0.003600	5.26E-07	2.34E-07	7.38E-07
0.005040	6.38E-07	4.01E-07	2.11E-06

M (mol·L⁻¹) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ mol·L⁻¹) and standard uncertainties u are $u(m) = 0.00001$ mol·L⁻¹, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa, and the expanded uncertainties, U_c (0.95 confidence level), is $U_c(\tau) = \pm 0.003$ ps (0.95 level of confidence).

solvent systems and temperature may be related to the structural relaxation processes occurring due to the rearrangement and reorientation of the molecules [59].

With an increase in the temperature, the τ value decreases with the increasing KE and weakening of electrostatic and binding forces. The τ value order of solvent is SDS > DTAB. This τ value order is also supported for η_r and ρ data. It infers that the SDS strongly interacts with the solvent medium by multiple intermolecular interactions (MIMI), and due to the strong interaction between solute and solvent, the solution could slowly pass through the capillary with an increase in the τ value. By increasing the concentrations of DTAB and SDS, the τ value increases with the weakening of CF and stronger electrostatic interaction, IMF, van der Waal forces. An inclusion of SDS into the aqueous system, the τ value is increased, while with DTAB, the τ value slightly decreases due to the stronger IHI domination over IH_bI . On increasing 0.000096 to 0.0012 M/mol·L⁻¹ SDS, the τ value drastically increased with higher polarization, strong compactness, and the mobility of the micelles could be decreased. Similarly, with DTAB 0.000864 to 0.00504 M/mol·L⁻¹ into aq-SDS, the τ value is less increased compared to the DTAB-rich surfactant solution. It infers that, due to the stronger IHI, the flow rate of the solution is decreased with increase in the τ value, while with DTAB-rich surfactant solution, because of stronger IH_bI and with the weakening of CF, the solution quickly passes and the τ value is decreased.

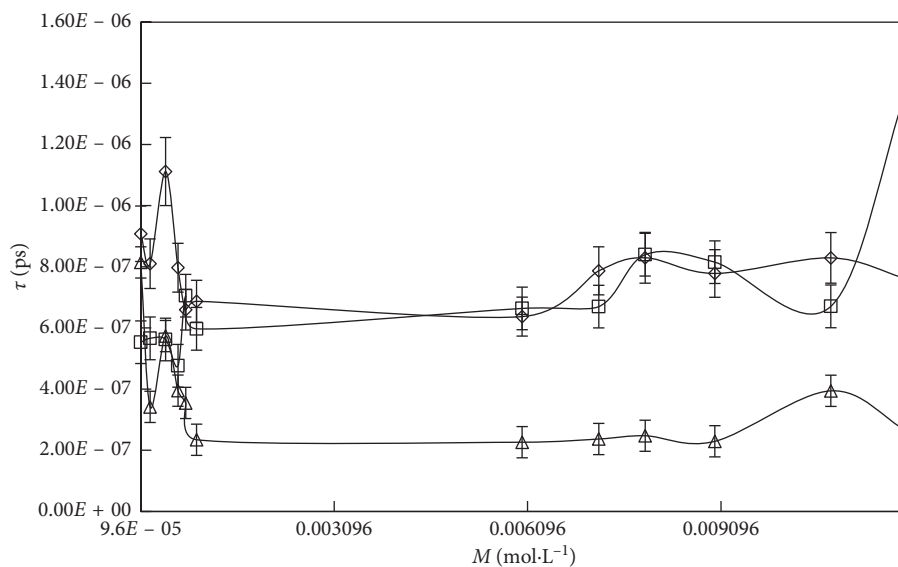


FIGURE 2: The τ value of the SDS-rich surfactant at the three different temperatures = 293.15 (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

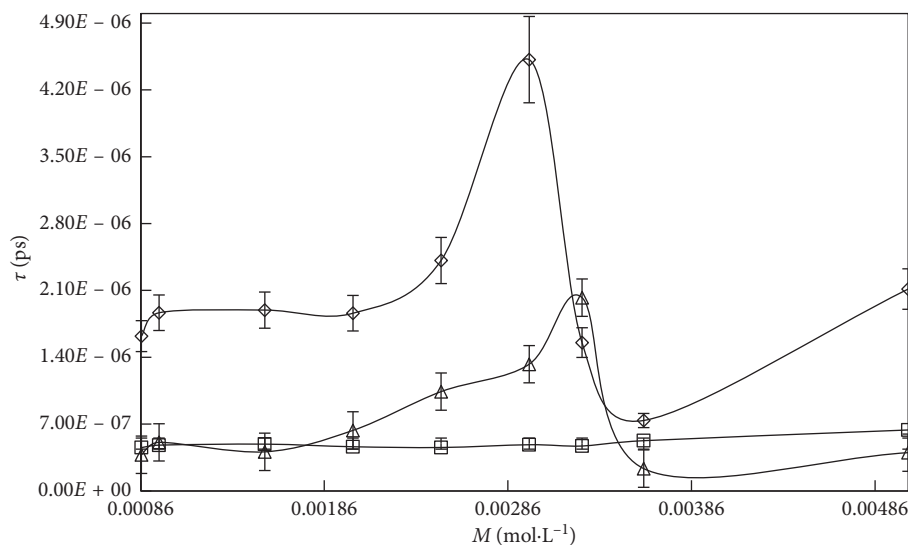


FIGURE 3: The τ value of the DTAB-rich surfactant at the three different temperatures $T=293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

3.2. *Acoustic Impedance (Z)*. Initially, an inclusion of DTAB into the aqueous system, the acoustic impedance (Z) value decreases, while with SDS, the Z value is increased. Furthermore, on increasing the concentration of SDS and DTAB, the Z value (Table 4) increases. To measure a sound velocity, which is generated by the vibration due to $S_L S_O I$, the Z value was calculated by using the following equation:

$$Z = \rho \cdot u, \quad (3)$$

where ρ is the density and u is the sound velocity (u) of the solution.

The Z value infers an increase in the u value at a fixed composition and temperature. However, on increasing the temperature, the Z value is increased. It indicates that the Z property is directly proportional to the u value (Table S5) because of the heat which is a kind of KE.

On increasing the temperature, the molecules could gain energy which could induce rotational, electronic, transformational, and vibrational transitions and because of these transitions, the sound waves could travel quickly and the Z value is increased. The Z value (Figures 4 and 5) of the solvent systems follows the order: SDS > DTAB. The Z value also supported the ρ , η_r , and τ data. This order reflected that aq-SDS shows the higher Z value than aq-DTAB. SDS has a higher hydrophilic nature and stronger interaction abilities with an increase in the compactness of the solution. Thus, the aq-DTAB shows the higher hydrophobic nature which could induce stronger IH_bI repelling the solvent molecules to the surface site and weakening the CFs with decreases in the γ value and with stronger IMI, the compactness and internal pressure (IP) increases, so the Z value is increased.

TABLE 4: Acoustic impedance ($Z/\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T=293.15$, 298.15 , and 303.15 K and at 0.1 MPa.

M ($\text{mol}\cdot\text{L}^{-1}$)	293.15 K	298.15 K SDS-rich	303.15 K
0.005000	1481.77	1493.79	1498.87
0.000096	1481.90	1507.06	1504.04
0.000240	1482.03	1507.14	1504.12
0.000480	1482.02	1507.23	1504.21
0.000672	1481.93	1495.07	1504.28
0.000792	1481.94	1495.15	1504.31
0.000960	1481.89	1494.30	1503.99
0.006011	1481.31	1494.34	1503.56
0.007200	1482.11	1493.99	1502.86
0.007920	1480.60	1493.54	1503.57
0.009000	1481.86	1494.32	1503.72
0.010800	1481.76	1494.17	1504.16
0.012000	1482.45	1494.74	1504.81
		DTAB-rich	
0.010000	1483.00	1495.30	1504.82
0.000864	1482.79	1480.63	1502.52
0.000960	1482.62	1494.48	1506.18
0.001536	1482.50	1494.53	1504.13
0.002016	1482.53	1494.60	1504.22
0.002496	1482.13	1494.52	1504.29
0.002976	1482.16	1494.48	1504.26
0.003264	1480.20	1492.06	1503.21
0.003600	1482.23	1494.31	1503.82
0.005040	1481.90	1493.87	1503.56

M ($\text{mol}\cdot\text{L}^{-1}$) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ $\text{mol}\cdot\text{L}^{-1}$) and standard uncertainties u are $u(m) = 0.00001$ $\text{mol}\cdot\text{L}^{-1}$, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa.

All parameters are supporting each other on the basis of these interlink (coordinative) properties.

On increasing 0.000096 to 0.012 $\text{M}/\text{mol}\cdot\text{L}^{-1}$ SDS and 0.000864 to 0.00504 $\text{M}/\text{mol}\cdot\text{L}^{-1}$ DTAB concentration with aq-DTAB and aq-SDS, respectively, the Z value increases. However, in the case of DTAB-rich surfactant, the increasing rate of the Z value is higher than the SDS-rich surfactant at the three different temperatures ($T=293.15$, 298.15 , and 303.15 K).

Both surfactants have the same hydrophobicity spacer (tail region) except the hydrophilic spacer (head region). The higher Z value of aq-SDS infers that the aq-SDS could strongly interact by stronger IHI and ion-dipole interaction (IDI) forms small size micelles of the aq-SDS solution while with aq-DTAB, by stronger IH_bI forms large size micelles with weaker compactness in the solution, and the Z value is decreased. However, with increasing SDS concentration, the Z value increases with stronger IHI dominant over IH_bI and stronger electrostatic, van der Waals interaction with higher compactness occurring in the solution. For the DTAB-rich system, the Z value decreases with stronger IH_bI dominant over IHI.

3.3. Surface Property. The DTAB-rich and SDS-rich systems have been applied in several technological applications because of the formation of micelles during the aggregation method under certain functioning conditions. Several

physical properties of surfactants have been reported in the literature because of their ability of characterizing different physical properties that have been analysed in the literature and due to their ability of describing the aggregation processes by using electrical conductivity (κ) and surface tension (γ) values [30, 31].

Table S6 shows that the γ value of SDS-rich and DTAB-rich decreases with increases in surfactants concentration in an aqueous system at the three different temperatures ($T=293.15$, 298.15 , and 303.15 K). It is evident from Table S6 that the γ value initially decreases with increasing concentration of SDS and then reaches a minimum. It indicates that micelles could form and the concentration of the break point is CMC, whereas for DTAB-rich, the surface tension reduced by adsorption of the surfactant at the interface, and a sigmoidal curve between surface tension (γ) and \log (surfactant) is produced by the distinct break after which the γ value remains almost unchanged. Due to the presence of DTAB and SDS, surfactants produce a decrease in the γ value. Nevertheless, this decrease in surface tension reaches a constant γ value at a certain surfactant concentration. It depicted that the surface tension is a physical property influenced by the aggregation phenomenon due to a change in the surface concentration of the surfactant. Due to this reason, the surface tension has been used to determine the colloidal dynamics of numerous systems [60]. Thus, the aggregation process creates the concentration of SDS and DTAB remains constant due to the addition of different surfactants that are engaged in the formation of micelles. However, it could not effect on the surfactant concentration in the free liquid surface. Hence, the surface tensions remain with a constant value.

3.4. Interfacial Behavior. The packing symmetry of the solvent spread monolayer of the ion-pair amphiphiles at the air-water interface depends on the stoichiometry and the magnitude of the charged head groups and the symmetry and the dissymmetry in the precursors' hydrophobic spear (the alkyl chain). The alkyl chains packed them in a way to maximize their van der Waals interaction, LDF, and electrostatic interaction in the bulk site. However, molecular packing at the air-water interfaces (AWI) to be more compact results in the lower molecular lift-off area [61].

The surface excess concentration (Γ_{\max}) and the minimum surface area of the molecule (A_{\min}) are two important parameters which determine the adsorption behavior and packing density of the micelles at the air/water interface [60, 62]. Γ_{\max} is the concentration difference between the interface and a virtual interface in the interior of the volume phase, while A_{\min} describes the minimum area of the amphiphile molecules at the surfactant-saturated monolayer at the air/solution interface [58, 60].

A reverse result is observed with A_{\min} . The solvent system follows the order: aq-SDS > aq-DTAB and aq-DTAB > aq-SDS, the surface excess concentration and area of molecules, respectively. The very low A_{\min} and the high Γ_{\max} values for pure aq-SDS suggest that it is a poor self-assembly behavior presumably owing to the planar head group which could not provide an appropriate packing at the interface.

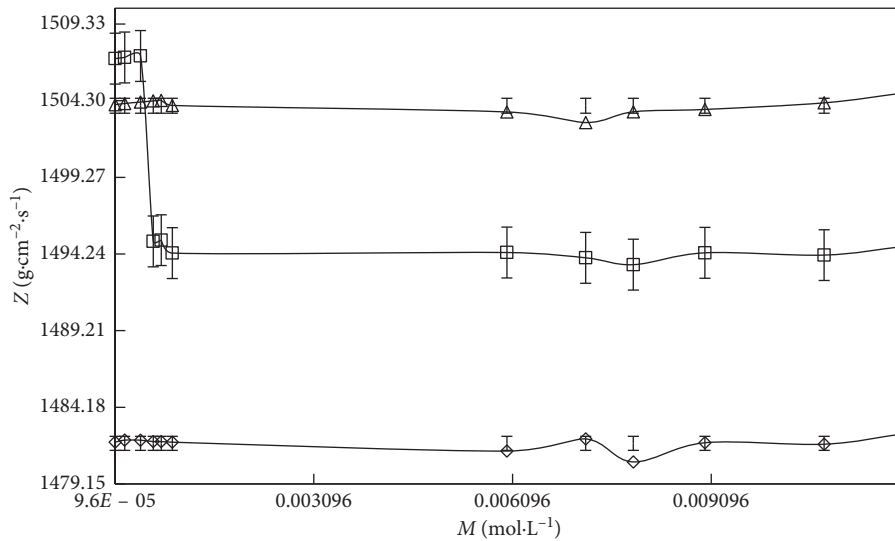


FIGURE 4: The Z value of the SDS-rich surfactant at the three different temperatures $T = 293.15$ (◇), 298.15 (□), and 303.15 K (△), respectively.

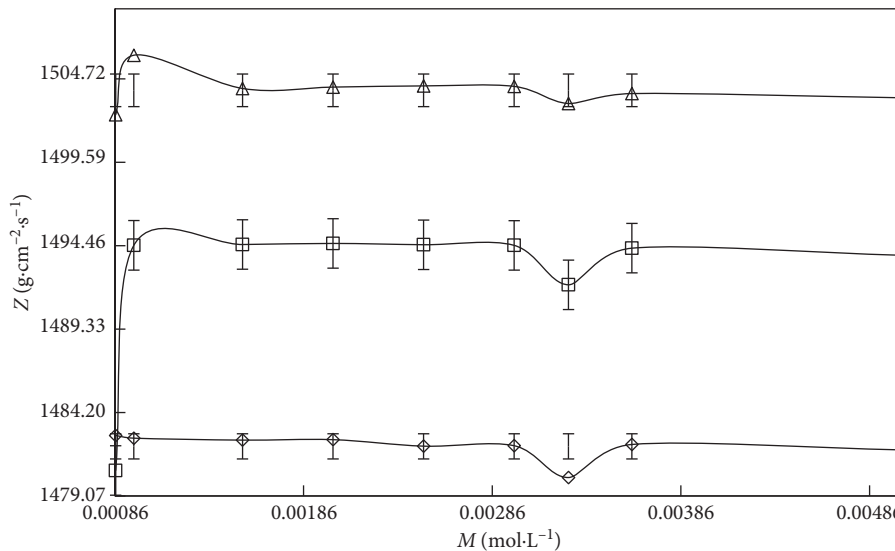


FIGURE 5: The Z value of the DTAB-rich surfactant at the three different temperatures $T = 293.15$ (◇), 298.15 (□), and 303.15 K (△), respectively.

The sudden change in the interfacial parameters by adding DTAB may presumably be connected to the efficient self-assembly behavior of DTAB, which favors the self-assembly process even at this low doping. With further increases in the concentration of DTAB and SDS in the aq-SDS and aq-DTAB, respectively, the total Γ_{\max} increased indicating an antagonistic effect by the doping of aq-SDS in the DTAB system in this concentration range. A reverse effect is observed for the A_{\min} value (in this concentration range) which is decreased with the increase in the concentration of DTAB. The increase in Γ_{\max} and decrease in A_{\min} with an increase in the DTAB content indicate that the packing density of surfactant molecules at the interface decreases with an increase in the SDS content. The surface excess concentration (Γ_{\max}) value for 0.00096 to 0.012 M/mol·L⁻¹ SDS and 0.000864 to 0.00504 M/mol·L⁻¹ DTAB in aq-DTAB and aq-SDS solution is summarized in Table 5, and the area of molecules (A_{\min}) is

calculated according to the following Gibbs adsorption equation [63], given in Table 6:

$$\Gamma_{\max} = -\frac{c}{2RT} \cdot \frac{d\gamma}{dc}, \quad (4)$$

$$A_{\min} = \frac{1 \times 10^{18}}{\Gamma_{\max} N_A}, \quad (5)$$

where N_A is the Avogadro number, Γ_{\max} is the surface excess concentration, A_{\min} is area of molecules, R is the gas constant, T is the temperature in Kelvin, $d\gamma$ is the difference in the surface tension value, and c is the surfactant concentration. For Γ_{\max} calculation, the 0.012 M/mol·L⁻¹ and 0.00504 M/mol·L⁻¹ as the limiting SDS and DTAB concentration is written in equation (4) contrary to CMC reported [64]. Furthermore, Γ_{\max} is calculated, and surface pressure (π) is noted as follows:

TABLE 5: Surface excess concentration ($\Gamma_{\max}/\text{mol}\cdot\text{m}^{-2}$) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T=293.15, 298.15,$ and 303.15 K and at 0.1 MPa .

M ($\text{mol}\cdot\text{L}^{-1}$)	293.15 K	298.15 K SDS-rich	303.15 K
0.000096	104.57	32.32	40.87
0.000240	8903.09	6826.05	9244.40
0.000480	1983.06	3906.60	2792.54
0.000672	-4771.73	-4278.36	-3228.07
0.000792	14396.98	15220.63	7270.84
0.000960	-4249.40	10801.67	-8857.06
0.006011	-7020.87	-6358.77	-5015.42
0.007200	-35875.12	36095.19	30640.08
0.007920	-6680.42	-7485.56	11272.62
0.009000	-4131.37	-1995.31	-4163.18
0.010800	-2974.58	-1587.85	-1767.75
0.012000	-1611.23	-5292.82	-1280.98
		DTAB-rich	
0.000864	96550.00	40830.30	54441.63
0.000960	2148.31	14651.86	16499.02
0.001536	-1561.66	2858.12	-3389.47
0.002016	21654.96	15465.11	13188.97
0.002496	-11603.35	27424.35	18028.51
0.002976	125576.98	129682.4	105979.7
0.003264	-60686.80	42126.50	52703.16
0.003600	-6723.80	14731.67	15019.49
0.005040	96550.00	40830.30	54441.63

M ($\text{mol}\cdot\text{L}^{-1}$) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$) and standard uncertainties u are $u(m) = 0.00001 \text{ mol}\cdot\text{L}^{-1}$, $u(T) = \pm 0.01 \text{ K}$, and $u(p) = \pm 0.01 \text{ MPa}$.

TABLE 6: Area of the molecule ($A_{\min}/\text{nm}^2\cdot\text{mol}^{-1}$) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T=293.15, 298.15,$ and 303.15 K and at 0.1 MPa .

M ($\text{mol}\cdot\text{L}^{-1}$)	293.15 K	298.15 K SDS-rich	303.15 K
0.000096	$1.59E-08$	$5.14E-08$	$4.06E-08$
0.000240	$1.86E-10$	$2.43E-10$	$1.80E-10$
0.000480	$8.37E-10$	$4.25E-10$	$5.95E-10$
0.000672	$-3.48E-10$	$-3.88E-10$	$-5.14E-10$
0.000792	$1.15E-10$	$1.09E-10$	$2.28E-10$
0.000960	$-3.91E-10$	$-1.54E-10$	$-1.87E-10$
0.006011	$-2.36E-10$	$-2.61E-10$	$-3.31E-10$
0.007200	$-4.63E-11$	$-4.60E-11$	$-5.42E-11$
0.007920	$-2.49E-10$	$-2.22E-10$	$-1.47E-10$
0.009000	$-4.02E-10$	$-8.32E-10$	$-3.99E-10$
0.010800	$-5.58E-10$	$-1.05E-09$	$-9.39E-10$
0.012000	$-1.03E-09$	$-3.14E-10$	$-1.30E-09$
		DTAB-rich	
0.000864	$2.68E-09$	$1.02E-08$	$1.08E-08$
0.000960	$1.72E-11$	$4.07E-11$	$3.05E-11$
0.001536	$7.73E-10$	$1.13E-10$	$1.01E-10$
0.002016	$-1.06E-09$	$5.81E-10$	$-4.90E-10$
0.002496	$7.67E-11$	$1.07E-10$	$1.26E-10$
0.002976	$-1.43E-10$	$-6.05E-11$	$-9.21E-11$
0.003264	$-1.32E-11$	$-1.28E-11$	$-1.57E-11$
0.003600	$-2.74E-11$	$-3.94E-11$	$-3.15E-11$
0.005040	$-2.47E-10$	$-1.13E-10$	$-1.11E-10$

M ($\text{mol}\cdot\text{L}^{-1}$) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4} \text{ mol}\cdot\text{L}^{-1}$) and standard uncertainties u are $u(m) = 0.00001 \text{ mol}\cdot\text{L}^{-1}$, $u(T) = \pm 0.01 \text{ K}$, and $u(p) = \pm 0.01 \text{ MPa}$.

$$\pi_{\text{binary}} = \gamma_{\text{W}} - \gamma_{\text{DTAB}} (\text{aq} - \text{DTAB}),$$

$$\gamma_{\text{binary}} = \gamma_{\text{water}} - \gamma_{\text{SDS}} (\text{aq} - \text{SDS}), \quad (6)$$

$$\pi_{\text{ter}} = \gamma_{\text{W+DTAB}} - \gamma_{\text{SDS}} (\text{anionic rich}),$$

$$\pi_{\text{ter}} = \gamma_{\text{W+SDS}} - \gamma_{\text{DTAB}} (\text{cationic rich}).$$

An inclusion of SDS into the water, the Γ_{\max} value (Figures 6 and 7) is more increased. It indicates that the SDS has oxygen atoms in the head part which is small in size. So, the maximum number of SDS molecules could go to the surface site. Similarly, an addition of DTAB into the aqueous system, the Γ_{\max} value is decreased than the aq-SDS system. It indicates that the larger size of DTAB has three $-\text{CH}_3$ groups in its structure which could induce a hindrance for a move to the surface site. So, the less number of DTAB molecules could move to the surface, and the Γ_{\max} value decreases. On increasing the concentration from 0.000096 to $0.012\text{ M/mol}\cdot\text{L}^{-1}$ SDS and 0.000864 to $0.00504\text{ M/mol}\cdot\text{L}^{-1}$ DTAB, the maximum surfactant molecules move to the surface site with surfactant molecules occupying a less area with stronger $\text{H}_b\text{H}_b\text{I}$ and stronger LDF due to a more considerable difference in the chemical potential of the surface and in the bulk phase. Due to the stronger LDF occurrence with stronger BF and stronger IMF, A_{\min} is decreased. On increasing the temperature, A_{\min} expands due to increased KE and weakening of BF. Due to the increase in the temperature, Γ_{\max} value decreases with increasing area of molecules with the weakening of BF and IMI, and the least number of surfactant molecules could go to the surface with the increased A_{\min} value (Figures 8 and 9).

3.5. Friccohesity Shift Coefficient (FSC). Friccohesity predicts working or functional ability of solution where the residual molecular forces remain in a reversible mode. Fundamentally, the ability of the medium or the solvent and the constituent molecules to promote the $\text{S}_1\text{S}_0\text{I}$ rather than self-binding individually is a fundamental need for sparing the molecular surface area. The disruption of the self-binding state could be attained by the weakening of the CF on increasing friccohesity attracting other molecules like drugs or others for binding. The self-binding state could have stronger homomolecular potential noted as an anti-dispersion activity. Hence, the potentializing homomolecular intramolecular potential to trap other molecules is an essential need to weaken CF and to develop intermolecular or the heteromolecular forces to get stuck to the solution. The shear stress and strains lead to velocity gradients and interlayer distance. The interlayer distance directly reflects the strength of the IMF when the solute molecules could align along with line subjected to the interlayer thickness. The intermolecular strength is determined with HB and also the weakening of the solvent structures and tends to form a structure with the solute. It becomes an urgent need that the status of CF and IMF is measured simultaneously which is rightly and logically determined by friccohesity data.

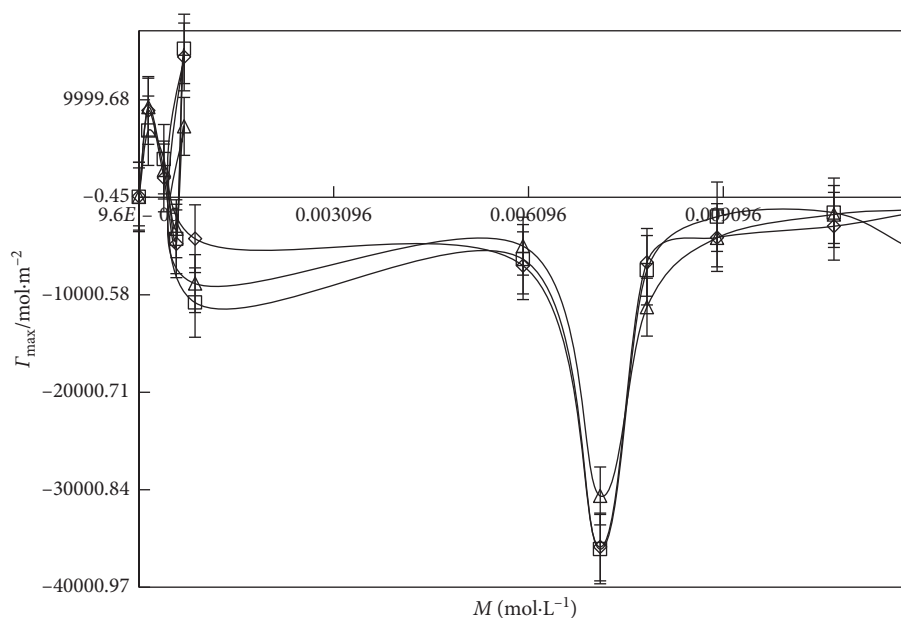


FIGURE 6: The Γ_{\max} value of the SDS-rich surfactant at the three different temperatures $T = 293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

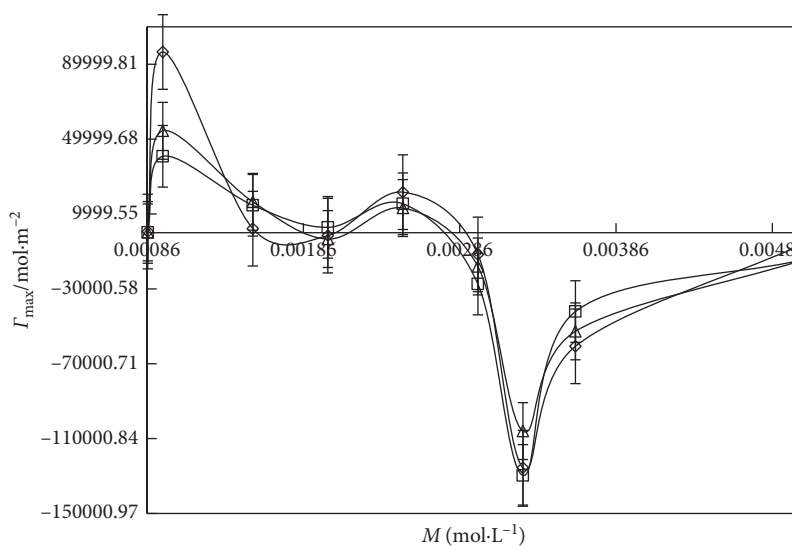


FIGURE 7: The Γ_{\max} value of the DTAB-rich surfactant at the three different temperatures $T = 293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

The η measurements deal with intra- and intermolecular networking of electronic forces materialized through electrostatic forces, and γ (Table S6) tracks damages of IMF or the molecular forces working within the similar molecules through HB and another interaction mechanism. The molecular forces have two separate domains where one of them remains operational at the surface, causing a continuous thin film where even air could not enter. Therefore, an aqueous electrolyte or surfactants in aqueous solutions even on shaking do not develop bubble. So, such engineering is confined to the surface force which is tracked by the surface tension. Another interaction between the two forces remains defunct because the force factors counterbalance

the linear elements of molecular interactions. The σ data have higher resolution and reproducibility and illustrate the interfaces of CFs and frictional forces (FFs) where these forces are the core theories of γ and η measurements, respectively. Therefore, σ of DTAB-rich and SDS-rich is given Table S7 and is calculated by using the following Man Singh equation [51]:

$$\sigma = \frac{\eta_0}{\gamma_0} \left[\left(\frac{t}{t_0} \right) \left(\frac{n}{n_0} \right) \right], \quad (7)$$

where η_0 , γ_0 , t_0 , and n_0 and η , γ , t , and n are viscosity, surface tension, viscous flow time, and pendant drop numbers of the solvent and solution, respectively.

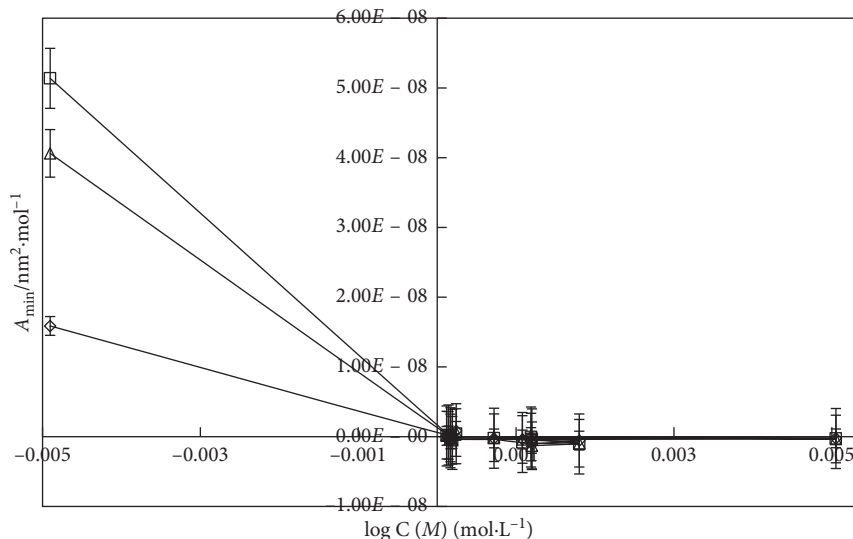


FIGURE 8: The A_{\min} value of the SDS-rich surfactant at the three different temperatures $T = 293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

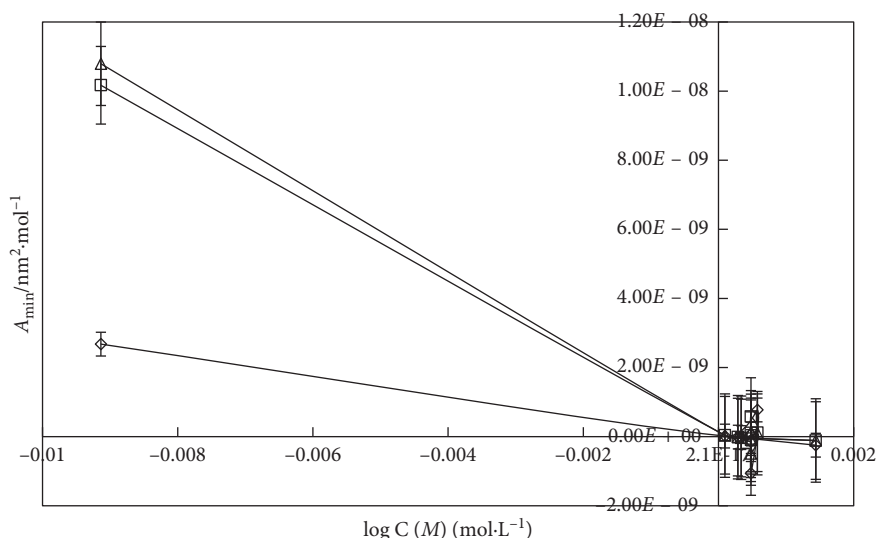


FIGURE 9: The A_{\min} value of the DTAB-rich surfactant at the three different temperatures $T = 293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

The friccohesity shift coefficient (σ_C) is calculated by using the following equation:

$$\text{Friccohesity shift coefficient } (\sigma_C) = \frac{1}{\sigma \cdot \gamma}, \quad (8)$$

where σ_C is the friccohesity shift coefficient, σ is the friccohesity, and γ is the surface tension of the solution.

The solvent systems follow the order in the aqueous medium: SDS > DTAB. This order infers that the σ_C value increased the aq-SDS (Table 7) than aq-DTAB due to SDS which could develop weak CFs with stronger FFs and IMF; the γ value decreases with the higher ρ value. While with aq-DTAB, the σ_C value is decreased. The σ_C value of aq-DTAB is more decreased than aq-SDS solutions because both surfactants have the same tail part, except the only head part, and so the stronger IH_bI and weak CFs with

stronger FFs. On increasing 0.000096 to 0.012 M/mol·L⁻¹ SDS and 0.000864 to 0.00504 M/mol·L⁻¹ DTAB concentration, the σ_C value increases due to stronger IMI with the weakening of CFs.

This parameter reveals the mechanism of S_LS₀I and S_LS₁I of surfactants [65]. Such parameters determined a critical and comparative study of γ (Figures 10 and 11) and friccohesity of the SDS-rich and DTAB-rich surfactant solution summarized in Table S7. It also infers the efficacy of interacting activity of SDS and DTAB with the solvent system, its fluidity and absorptivity. We obtained a conversion relation between γ and η , and the aq-DTAB shows higher η and lower γ compared to the aq-SDS solution due to stronger hydrophobic interaction. The η value is increased because of the interaction with dissimilar molecules. Due to the inclusion of SDS and DTAB in aq-DTAB and aq-SDS

TABLE 7: Friccohesity shift coefficient (FSC) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T=293.15$, 298.15 , and 303.15 K and at 0.1 MPa.

M (mol·L ⁻¹)	293.15 K	298.15 K SDS-rich	303.15 K
0.005000	1.997570	0.988696	1.126186
0.000096	0.472963	0.992845	1.524808
0.000240	1.229149	1.181705	0.751272
0.000480	0.722956	0.870212	1.363012
0.000672	1.056841	1.252171	1.983979
0.000792	1.226570	1.526528	0.629227
0.000960	1.478152	1.467933	1.274735
0.006011	0.795106	1.402486	0.608560
0.007200	0.878679	1.052150	0.702083
0.007920	0.999447	0.772808	0.630889
0.009000	1.021779	0.884746	0.853029
0.010800	0.780298	0.823337	0.546062
0.012000	0.625146	0.758690	0.391575
		DTAB-rich	
0.010000	2.606188	1.205797	1.135148
0.000864	2.752721	1.536592	0.719237
0.000960	2.556441	1.138905	0.625152
0.001536	3.491674	1.419604	0.615893
0.002016	2.648554	0.916497	0.626744
0.002496	3.554227	0.558781	0.483651
0.002976	2.533495	0.437935	0.258442
0.003264	2.444864	0.251481	0.772786
0.003600	2.074703	2.167979	1.686891
0.005040	1.490789	1.431129	0.440847

M (mol·L⁻¹) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ mol·L⁻¹) and standard uncertainties u are $u(m) = 0.00001$ mol·L⁻¹, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa.

solution, the friccohesity shift coefficient decreases with stronger FFs and weak CFs. On increasing the concentration of surfactants, the σ_C value is decreased. On increasing the temperature, the σ_C value is decreased due to the weakening of FF, electrostatic interaction, IDI, and binding forces.

3.6. Hydrodynamic Volume (V_h). Hydrodynamic values are a significant factor in determining a magnitude to the volume change of the hydrated molecules with increasing solute concentration. On increasing the temperature, the SDS-rich and DTAB-rich have negative V_h values which decrease as the size of the KE increases. The V_h values in this study (Table 8) shows negative at the temperatures $T=298.15$ and 303.15 K. Thus, the sign of the V_h values reflects the nature of the $S_L S_0 I$; then, we can conclude that, at different temperatures ($T=298.15$ and 303.15 K), the DTAB-rich and SDS-rich mixed surfactants have structure-making effects on water, whereas temperature 293.15 K in this study shows structure-breaking effects [66].

The hydrodynamic volume (V_h) reflected the $S_L S_0 I$ and solute-solute interaction ($S_L S_L I$). V_h is calculated with the following equation and summarized in Table 9:

$$V_h = \frac{\phi M}{N_A c}, \quad (9)$$

where ϕ is the fractional volume (Table 8), M is a molar mass of the solute, N_A is the Avogadro number, and c is the concentration.

Fractional volume (ϕ) is calculated by the following equation:

$$\phi = \frac{4}{3\pi r^3 N_A c}, \quad (10)$$

where r is the particles size, N_A is Avogadro's number, and c is the solute concentration.

The V_h values for solvent follow the order: SDS > DTAB. This order indicates that the interaction activity of SDS with H^+ ions of solvent molecules is stronger than DTAB because SDS could be strongly towards H^+ ions of water by the O^- ion which is present at the head region in the SDS. So, the interaction affinity of SDS with H^+ ions is higher, while with DTAB is the lower because DTAB has $-CH_3$ groups in its head region, which could repel the water molecules. Thus, the V_h value of DTAB is lesser than SDS in an aqueous medium. An inclusion of SDS into aq-DTAB, the V_h value drastically increased due to a higher concentration of SDS, it has more O^- ions which could show the stronger interaction affinity with the IHI domain over $IH_b I$, and SDS could form a more hydrogen sphere compared to the DTAB, while with DTAB into aq-SDS solution, the V_h value is decreased as compared to SDS-rich surfactants. It depicted that the stronger hydrophobic interaction and DTAB could show weak interaction ability with water molecules with decreases the V_h value. On increasing the surfactants concentration, the V_h values decrease with stronger $S_L S_L I$ and weaker $S_L S_0 I$. On increasing the temperature, the V_h value increases due to the weakening of electrostatic interaction and binding forces.

3.7. Hydrodynamic Radius (R_h). Hydrodynamic radius (R_h) depicts the basic activities of solute and solvent interaction. So, micelles of SDS and DTAB with solvent systems could change in R_h along with other amphiphilic solutes which could reflect various modes of interactions. Hydrophobicity and structural constituents of surfactants could develop stronger molecular networking with an effect of the solvent cage, and R_h is calculated using the following equation (Table 10):

$$R_h = \frac{\kappa T}{6\pi\eta D}, \quad (11)$$

where κ is the Boltzmann constant, D is the diffusion coefficient of the medium, and the R_h value is as DTAB > SDS in the aqueous medium. Due to the inclusion of DTAB in the aqueous system, the R_h value is increased while with SDS, the R_h value decreases. It indicates that the DTAB having $-CH_3$ groups could be repelled by the solvent molecules, so the size of the radius is increased, while SDS contains hydrophilic atoms in its head part which could strongly interact, so the value of hydrodynamic radius is decreased. Due to the addition of SDS into the aq-DTAB solution, the R_h value is decreased and with DTAB in the aq-SDS, the R_h value is also decreased. It depicted that the dominance of IHI over $IH_b I$. On increasing the concentration of 0.000096 to 0.012 M/mol·L⁻¹ SDS and 0.000864 to 0.00504 M/mol·L⁻¹ DTAB into aq-DTAB and aq-SDS solution, the R_h value decreases due to the stronger IMI, electrostatic interaction, van der Waals interactions, and IDI. On increasing the

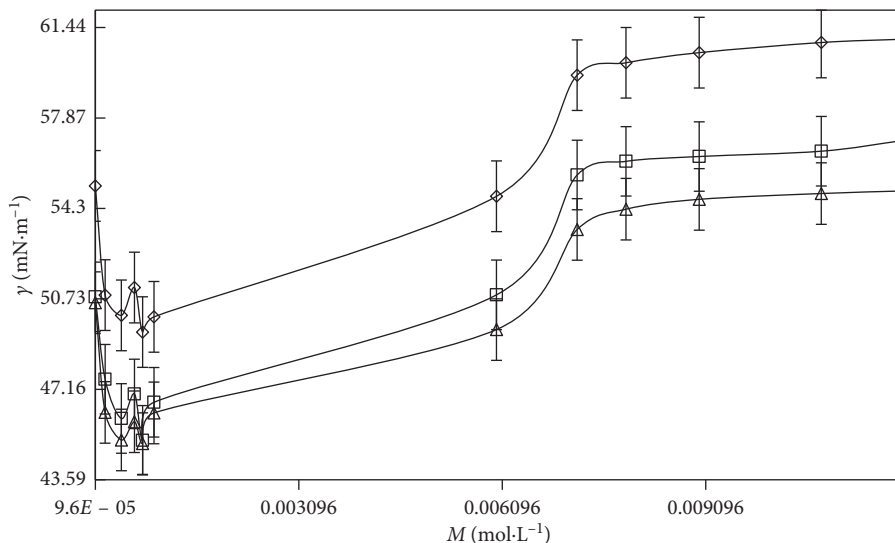


FIGURE 10: The γ value of the SDS-rich surfactant at the three different temperatures $T=293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

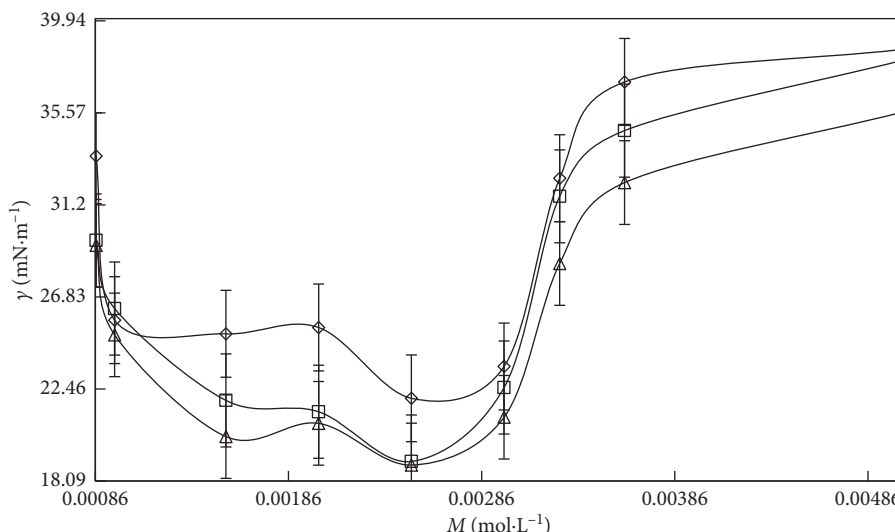


FIGURE 11: The γ value of the DTAB-rich surfactant at the three different temperatures $T=293.15$ (\diamond), 298.15 (\square), and 303.15 K (\triangle), respectively.

temperature, the R_h values are increased due to the weakening of BFs and IMF with increased kinetic expansion. Their R_h values depict a solvent entangling around the surfactants that affect a mutual contact of solvent molecules.

3.8. Viscosity B -Coefficient (B). Viscosity B -coefficient (B) of SDS-rich and DTAB-rich is calculated by using the following Jones-Dole equation:

$$\left(\frac{\eta_r - 1}{M}\right) = B + Dm + D'm^2. \quad (12)$$

$[\eta]$ is obtained from $(\eta_r - 1)/M$ versus M .

$$\left(\frac{\eta_r - 1}{M}\right) = [\eta], \quad (13)$$

where $[\eta]$ is the intrinsic viscosity, η_r is the relative viscosity; M is the molarity; B is the viscosity B -coefficient, and D and D' are Falkenhagen's coefficients. D illustrates $S_{L_1S_1I}$, while B illustrates $S_{L_1S_0I}$ [54, 66] at the three different temperatures ($T=293.15$, 298.15 , and 303.15 K), respectively. The positive B values depict stronger $S_{L_1S_0I}$ with stronger IMF (Table 11). The higher and positive B values for SDS-rich and DTAB-rich describe stronger IHI, IDI, and IMI. The B value predicts solute solvation and their effect on the structure of solvent in the vicinity of the solute molecule having either negative or positive magnitude. The B coefficient measures structural modifications induced by $S_{L_1S_0I}$. Thus, Table 11 reveals that DTAB has higher positive B values at $T=293.15$ K compared to SDS. Initially, surfactants in water could

TABLE 8: Fractional volume (ϕ) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T = 293.15, 298.15,$ and 303.15 K and at 0.1 MPa.

M (mol·L ⁻¹)	293.15 K	298.15 K SDS-rich	303.15 K
0.005000	0.0098	0.0331	-0.1488
0.000096	0.1838	-0.0080	0.7081
0.000240	0.1210	0.0010	0.0653
0.000480	0.3149	-0.0016	0.3806
0.000672	0.1126	-0.0679	0.1379
0.000792	0.0241	0.0919	0.0829
0.000960	0.0418	0.0161	-0.0808
0.006011	0.0094	0.0624	-0.0921
0.007200	0.1060	0.0664	-0.0779
0.007920	0.1326	0.1845	-0.0634
0.009000	0.1004	0.1678	-0.0882
0.010800	0.1330	0.0671	0.1367
0.012000	0.0881	0.5755	-0.0466
		DTAB-rich	
0.010000	0.0343	0.0791	-0.2075
0.000864	0.5848	-0.1195	0.2715
0.000960	0.7330	-0.0980	0.5060
0.001536	0.7499	-0.0913	0.3268
0.002016	0.7299	-0.1085	0.7257
0.002496	1.0646	-0.1136	1.4465
0.002976	2.3408	-0.0952	1.9557
0.003264	0.5415	-0.1043	3.1908
0.003600	0.0477	-0.0686	0.0146
0.005040	0.8824	0.0016	0.3112

M (mol·L⁻¹) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ mol·L⁻¹) and standard uncertainties u are $u(m) = 0.00001$ mol·L⁻¹, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa.

repel out the hydrophobic part of the surfactants to surface which results in a decrease of γ at the surface. Furthermore, the inclusion of SDS and DTAB to aq-DTAB and aq-SDS, the hydrophilic part accommodates in the bulk solution instead of the surface because surfactants being hydrophobic could not go to the surface site which is already occupied by the hydrophobic region of the SDS and DTAB. So, hydrophobicity increases in the bulk solution. Also, this mechanism leads to a stable formulation out of such solution mixtures. Thus, the DTAB-rich at $T = 298.15$ K could be induced hydrophobicity to a maximum extent and behaves as a structure maker at this temperature because $-CH_3$ could be heat sensitive. Positive B value supports the structure, making tendency of SDS-rich and DTAB-rich at the three different temperatures ($T = 293.15, 298.15,$ and 303.15 K).

The stronger H_bHI is decreased the B value with a tendency to behave as a structural breaker [54]. The surfactants induced stronger hydrophilic and hydrophobic interactions with the water system. The B values reflect the structure, making or breaking effects noted as $(\eta_{r-1}/m) > 1$. It indicates an ability of a solute to interact with the medium via the IMF and HB.

4. Conclusion

In this study, the relative viscosity, viscous relaxation time, and acoustic impedance values increase with

TABLE 9: Hydrodynamic volume (V_h/nm^3) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T = 293.15, 298.15,$ and 303.15 K and at 0.1 MPa.

M (mol·L ⁻¹)	293.15 K	298.15 K SDS-rich	303.15 K
0.005000	1.00	3.39	-15.23
0.000096	916.87	-39.94	3531.75
0.000240	241.47	2.07	130.18
0.000480	314.06	-1.57	379.62
0.000672	80.21	-48.37	98.28
0.000792	14.54	55.54	50.12
0.000960	20.86	8.03	-40.27
0.006011	0.75	4.97	-7.34
0.007200	7.05	4.42	-5.18
0.007920	8.02	11.15	-3.83
0.009000	5.34	8.93	-4.69
0.010800	5.90	2.98	6.06
0.012000	3.51	22.96	-1.86
		DTAB-rich	
0.010000	1.64	3.79	-10.62
0.000864	346.48	-70.79	160.87
0.000960	390.88	-52.25	269.83
0.001536	249.95	-30.43	108.93
0.002016	185.34	-27.55	184.28
0.002496	218.35	-23.30	296.68
0.002976	402.67	-16.38	336.42
0.003264	84.93	-16.36	500.46
0.003600	6.79	-9.75	2.07
0.005040	89.63	0.16	31.61

M (mol·L⁻¹) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ mol·L⁻¹) and standard uncertainties u are $u(m) = 0.00001$ mol·L⁻¹, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa.

increasing of concentration of the surfactants due to stronger ion-hydrophobic interaction with the weakening of cohesive forces with stronger frictional forces. By the addition of SDS and DTAB into water, the surface tension value decreases while the viscosity and friccohesity value increase due to weakening of cohesive forces and stronger intermolecular forces. These properties are correlated to each other. Mixed surfactants form self-assembly which could be applicable in the industry, pharmaceuticals, and drug formulation. Therefore, friccohesity determined the surface and bulk properties of the solution. With increasing concentration of the surfactant, surface excess concentration values are increased with stronger hydrophobicity pushing larger DTAB and SDS amount to the surface with more Brownian motion and stronger LDF. A less volume because of stronger H_bH_bI , bringing together the stronger LDF, and stronger LDF causes stronger binding forces have produced a greater internal pressure and lower surface area. On increasing the temperature, the area of the molecule increases because of weak intermolecular interaction and bond forces. SDS and DTAB mixed surfactant could be applicable in industrial and pharmaceutical for the formation of the drug, drug delivery, drug loading, enhanced solubility, and dispersion of drug. We have calculated the surface and bulk properties of the mixed surfactant which can be used in these applications.

TABLE 10: Hydrodynamic radius (R_h /nm) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T=293.15$, 298.15 , and 303.15 K and at 0.1 MPa.

M (mol·L ⁻¹)	293.15 K	298.15 K SDS-rich	303.15 K
0.005000	59.38	60.97	76.27
0.000096	52.35	61.38	54.30
0.000240	54.37	60.92	72.52
0.000480	48.93	61.05	61.03
0.000672	54.67	64.87	69.09
0.000792	58.24	56.91	71.63
0.000960	57.44	60.17	82.22
0.006011	58.92	58.09	83.22
0.007200	54.90	57.93	81.98
0.007920	53.97	53.73	80.78
0.009000	55.11	54.25	82.87
0.010800	53.96	57.90	69.15
0.012000	55.57	45.30	79.48
		DTAB-rich	
0.010000	58.24	58.95	83.34
0.000864	43.13	66.35	70.12
0.000960	41.16	64.74	63.46
0.001536	40.96	64.27	68.30
0.002016	41.20	65.51	59.03
0.002496	37.79	65.90	50.05
0.002976	30.66	64.54	46.15
0.003264	43.78	65.20	40.10
0.003600	56.09	62.77	82.35
0.005040	39.50	58.87	68.79

M (mol·L⁻¹) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ mol·L⁻¹) and standard uncertainties u are $u(m) = 0.00001$ mol·L⁻¹, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa.

TABLE 11: Intrinsic viscosity (η) of SDS-rich and DTAB-rich surfactants in the aqueous medium at the three different temperatures $T = 293.15$, 298.15 , and 303.15 K and at 0.1 MPa.

T/K	SDS-rich
293.15	1.3689
298.15	1.0474
303.15	1.7095
T/K	DTAB-rich
293.15	2.5019
298.15	0.6706
303.15	1.2427

M (mol·L⁻¹) is SDS and DTAB molarity in solvents ($\pm 3 \times 10^{-4}$ mol·L⁻¹) and standard uncertainties u are $u(m) = 0.00001$ mol·L⁻¹, $u(T) = \pm 0.01$ K, and $u(p) = \pm 0.01$ MPa.

Data Availability

The authors share the data underlying the findings of the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

Table S1 compares the measured densities values at $\pm 5 \cdot 10^{-6}$ g·cm⁻³ uncertainty by controlling the temperature by the help of the Peltier (PT100) device in $\pm 1 \cdot 10^{-3}$ K accuracy obtained from the Anton Paar DSA 5000M density meter with the literature values. Repeatability of the instrument corresponds to precision in ρ and u with 1.10^{-3} kg·m⁻³ and 0.10 m·s⁻¹, respectively, in 1.0 M/mol·kg⁻¹ sodium chloride and 10% (w/w) DMSO in aqueous solutions and were used for instrument calibration at $T = 298.15$ K. Table S2 compares the experimental data of surface tension and viscosity which were measured by Borosil Mansingh Survisometer through the viscous flow time (VFT) and pendant drop number (PDN) methods, respectively, with the literature values in 5 , 10 , 15 , and 20% (w/w) aq-DMSO. Viscosity and surface tension both have been an average of three replicate measurements with $\pm 2 \times 10^{-6}$ kg·m⁻¹·s⁻¹ and ± 0.03 mN·m⁻¹ uncertainties, respectively. There is also the difference in density measured with the Anton Paar DSA 5000M density meter with the literature values for 5 , 10 , 15 , and 20% (w/w) aq-DMSO. Table S3 compares the experimental data of viscosity at three different temperatures (293.15 , 298.15 , and 303.15 K) which were measured by Borosil Mansingh Survisometer. In all investigated concentrations of SDS-rich and DTAB-rich surfactants in the aqueous medium, there is an increase of viscosity from 293.15 K to 298.15 K, whereas in the case of DTAB-rich, there is a decrease in viscosity in all investigated concentrations from 298.15 K to 303.15 K. But there is not a regular pattern of viscosity change for SDS-rich in the increment of the temperature from 298.15 K to 303.15 K. Table S4 confers the density value is higher in the aq-DTAB solution which is used as a stock solution for SDS-rich surfactant solution. However, due to addition of SDS in the aqueous DTAB solution, the ρ value decreases. It depicted that the SDS and DTAB both have a same hydrophobic tail part, except the head part (counterpart). DTAB has three methyl (-CH₃) which could develop stronger hydrophobic interaction with the weakening of CF and stronger intermolecular interaction with the increase in the ρ value. Due to addition of SDS into aq-DTAB, the ρ value is decreased. It indicates that the SDS is less hydrophobic compared to DTAB, so it could induce less weak CFs than DTAB. With increasing the concentration of SDS, the ρ value increases due to stronger van der Waals interaction, electrostatic interaction, and intermolecular interaction. But at the particular concentration, the ρ value drastically decreased. However, at the particular concentration, the density value drastically decreased; it means that the concentration leading to CMC generates maximum assembly in a particular shape which is influenced by the nature of the surfactant and surrounding environment. The similar kind of trend is observed in the case of DTAB-rich surfactant. With increasing the temperature, the ρ value decreases due to increase in KE with weakening of binding forces (BF) and electrostatic interaction. Table S5

compares the sound velocity of the DTAB-rich surfactant and SDS-rich surfactant solutions. The sound velocities of the solvent follow the order: aq-SDS > aq-DTAB. The order indicates that the number of interacting molecules per unit volume increases, and the molecules become tightly packed in the presence of SDS, resulting in faster sound wave propagation. The u values were observed to increase with increasing temperature. This suggests that the molecules upon gaining the KE oscillate very strongly, weakening the S_0S_0I . The sound velocity is increased with increasing DTAB and SDS concentration and temperature. With increasing the surfactant concentration, the IMF strengthens, and the hydrophilic sites of DTAB and SDS become closer to greater KE transfer, thereby increasing u with higher density. On increasing the temperature, the interacting groups of DTAB and SDS with a solvent system obtain more energy with greater vibration, causing faster sound wave circulation. This subsequently increases the u while decreasing the ρ values (Table 2). The slopes for ρ is steeper than those for u (Tables S4 and S5) which mutually supports the first order of interaction with increasing surfactants concentration. Table S6 compares the surface tension data and the γ value of aq-DTAB is lower than the SDS-rich surfactant because of the weakening of CFs with stronger ion-hydrophobic interaction. The surface tension (γ) or surface activities define the involvement of solvent with surfactants activities where the CFs or surface energy of the solvent decreases to interact with SDS and DTAB. Stronger surfactants-solvent interactions reflect weaker CFs with disruption of the HB network with lower γ values and vice versa. The hydrophobic alkyl chain of the surfactants accumulates on the solvent surface, thereby decreasing the γ value. However, the aq-SDS γ value is lower than aq-DTAB due to stronger hydrophobic-hydrophobic interaction. With increasing the concentration of the surfactants, the γ value decreases with disruption of HB with weakening of CFs of the solution. Table S7 compares the data of friccohesity of SDS-rich and DTAB-rich surfactant solution at three different temperatures. In all investigated concentrations of DTAB-rich surfactants in the aqueous medium, there is increase of friccohesity from 293.15 K to 298.15 K, whereas in the case of $0.003264 \text{ mol}\cdot\text{L}^{-1}$, there is decrease in friccohesity. It is found that there is decrease in friccohesity from 298.15 K to 303.15 K in all investigated concentrations of DTAB-rich surfactants in the aqueous medium, while in the concentration $0.01 \text{ mol}\cdot\text{L}^{-1}$, there is an opposite trend. But there is not a regular pattern of friccohesity change for SDS-rich in the increment of temperature from 293.15 K to 303.15 K. (*Supplementary Materials*)

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