Research article

Effect of 2-Propanol on surface properties and wetting behavior of surfactants on the glass surface

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ABSTRACT

This study investigates the effects of 2-Propanol (2-PrOH) on the surface and wetting properties of anionic - Sodium bis(2-ethyl hexyl) sulfosuccinate, also known as Aerosol AT (AOT), Sodium Dodecyl Sulfate (SDS) – and cationic – Cetylpyridinium Chloride (CPC) and Cetyl-trimethylammonium Bromide (CTAB) surfactants on a glass surface. Key surface properties including surface tension(γ), critical micelle concentration (CMC), surface excess concentration (Γ_{max}), and minimum surface area per molecule (A_{min}), were determined in water and varying parts by volume (0.10, 0.20, and 0.30) 2-PrOH at 298.15 K. Additionally, Contact angle (CA), Adhesion tension (A_T) and Work of Adhesion (W_A) were analyzed to assess the impact of 2-PrOH on the wettability of the surfactant solutions. The results show that adding 2-PrOH significantly reduces the γ and CA, enhancing the wetting properties of all surfactants. Γ_{max} decreases, while A_{min} increases, indicating a more dispersed arrangement of surfactant molecules at the air/solution interface in the presence of 2-PrOH. This leads to improved spreading and adhesion on the glass surface, as demonstrated by increased A_T and W_A with increasing 2-PrOH parts by volume. The study concludes that 2-PrOH acts as an effective co-surfactant optimizing surfactant performance by lowering the γ and enhancing liquid/solid interactions, making these systems more effective in applications requiring strong wetting and adhesion. These findings provide valuable insights for designing surfactant formulations for industrial applications such as coatings, detergents, and surface treatments.

1. Introduction

Surfactants are amphiphilic molecules [1] that play a critical role in various industrial and scientific applications due to their ability to reduce surface tension (γ). They have many uses, including detergency, emulsification, wetting, and dispersing, which rely on their capacity to alter surface properties when adsorbed at interfaces [2]. The hydrophilic group has polar head groups based on functional groups such as carboxy, sulphonate, ammonium, hydroxyl, amide, etc. Hydrophobic groups are non-polar tails that can be linear or branched, such as a hydrocarbon chain with eight to eighteen carbon atoms. The hydrocarbon chain in aqueous solution is known as hydrophobic. It does not like water, whereas the polar head group is known as hydrophilic because it does like water [3]. Surfactants can generate stable integrated structures higher than a definite concentration, termed CMC [4]. A Swiss botanist, Karl Wilhelm Von Nageli, established the term micelle for that integrated structure in 1858. Micelle was derived from the Latin word Mica, which means crumb (a small particle of bread). McBain introduced the term micelle, which gets dispersed in an aqueous solution [5]. Although McBain's model had many flaws, it was a significant advancement in colloid and interface science [5]. Micelles are molecular

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aggregations; ionic surfactants form limited micelles in low ionic concentration solutions due to electrostatic repulsion between head groups and the entropic consequence of bounding counter ions close to the micelles. The radius of the micelle is approximately equal to the length of the hydrocarbon tail. Based on the temperature and the characteristic magnitude of the tail and head group, an ionic surfactant can form spherical micelles as well as different micelle shapes [6]. The performance of surfactants in these applications is greatly influenced by their interaction with solvents and the solid surface they contact. Understanding these interactions is essential for optimizing surfactant performance in formulations and applications involving surface wetting and spreading.

Surfactant behavior is largely affected by additives such as water-miscible organic solvents, electrolytes, and non-electrolytes [7–15]. Short-chain alcohols are more favorable for the researchers because they are miscible with water and tune the polarity and hydrophobicity of the medium. Alcohol is frequently used to modify the physiochemical properties of surfactant solutions. They can act as co-surfactants, enhancing the surface activity of primary surfactants by altering γ, adsorption characteristics, and interfacial behavior. Niraula et al. showed that methanol can affect γ and the viscosity of sodium dodecyl sulfate at temperatures ranging from 298.15 to 323.15 K. The CMC of sodium dodecyl sulfate (SDS) in water and methanol-water mixtures increases with increasing temperature. The addition of methanol raises the CMC of SDS [16]. The CMC and physiochemical properties of DTAB [17] and CTAB [18] were influenced by increasing methanol volume fractions and temperature. Bhattarai et al. investigated the interactions of SDS and DTAB. γ and conductivity measurements at 293.15 K were used to examine the micellar properties of DTAB and SDS. The cohesive force and dielectric constant decreased as methanol concentration increased, affecting micellization [19].

Additionally, understanding wettability is crucial for applications where the spreading of liquids on a solid surface is required. Wettability is typically measured through the contact angle (CA), which reflects the degree to which a liquid spreads on the surface. A lower CA indicates better wetting, which is desirable in many applications, such as coating, cleaning, and lubrication. The presence of co-solvent-like alcohol can influence the CA, thereby affecting the overall wetting behavior of surfactants on the surface [20–22].

Measurement of CA and γ of SDS mixed varying concentrations of propanol on poly tetra fluoro ethylene (PTFE) – water interface showed that the value of CA considerably decreases with an increase in the content of propanol. Similarly, the CA of an aqueous solution of CTAB with propanol on PTFE – the water surface resulted that change in CA is higher in lower concentration range of propanol. CA decreases with increasing Cetyltrimethylammonium Bromide (CTAB) concentration at low propanol concentrations [23]. At constant TX100, the wetting ability of TX100 and propanol mixture on PTFE and polymethylmethacrylate (PMMA) depends on propanol concentration and increases with it [22].

Iionescu et al. studied the formation of micelles of CTAB in water-DMSO solutions at 25°C and 40°C using tensiometry. A temperature rise inhibits micelle formation. In addition, DMSO was found to have an arbitrary effect on the formation of micelles of CTAB. As the mole fraction of DMSO approaches 0.33, the effect becomes more significant [24].

While previous studies have explored the effects of short-chain alcohols like methanol, and ethanol on surfactant behavior, few have systematically investigated the unique role of 2-PrOH as a co-surfactant. Our study not only broadens this scope by examining both anionic and cationic surfactants but also provides a novel perspective on how 2-PrOH enhances wettability and adhesion on hydrophilic surfaces, critical for industrial applications.

2. Material and method

2.1. Material

SDS (99 %) and AOT (99 %) were purchased from Merck Pvt. Ltd. Mumbai, India. CTAB (99 %) and CPC (99 %) were purchased in Loba Chemi, India. All the surfactants were used after drying in the oven for 1 h at 100 °C. 2-PrOH was procured from Thermo–Fischer Scientific India Pvt. Ltd. and was used without further treatment. Double distilled water (specific conductance 1–2 μScm^{-1}) was used to make mixed solvent media with varying parts by volume of 2-PrOH. A series of solutions were prepared by internal dilution method from the stock solutions of different surfactants for the measurement of γ. While concentrations in the post micellar region were used for the measurement of contact angle.

2.2. Surface tension measurement

γ was measured with a calibrated (by double distilled water, $\gamma = 72.3$ (± 0.2) mNm^{-1} at 298.15 $\pm$ 0.5 K) du Nouy tensiometer (Kruss K20, Germany). The ring was washed in ethanol and burnt to red hot to make it dry in the blue flame of the Bunsen burner. A digital balance (Afcoset - ERI 20 A) purchased in India was used to obtain precise (± 0.00001) weights of various surfactants to make solutions. The working concentration ranges for measurement of γ were 1.23×10^{-2} M to 1.42×10^{-4} M for CTAB, 1.26×10^{-2} M to 1.67×10^{-4} M for SDS, 4.86×10^{-3} M to 8.08×10^{-5} M for CPC and 8.13×10^{-3} M to 1.66×10^{-5} M for AOT.

2.3. Contact angle measurement

Drop Shape Analyzer (DSA 25E) Kruss, Germany was used to measure contact angle on quartz glass surface by sessile drop method at 298.15 $\pm$ 0.5K as described in earlier works [25–28]. Microscope glass slides (borosilicate glass) were used for CA measurements. Before use, the slides were cleaned with a chromic acid solution, thoroughly rinsed with double-distilled water, and dried. To prevent moisture absorption, the cleaned slides were stored in a desiccator containing a dehydrating agent until required for the experiment. Different concentrations above CMC (1.00×10^{-3} M to 1.00×10^{-2} M for CTAB, 1.10×10^{-2} M to 3.67×10^{-2} M for SDS, $1.00 \times$

10^{-3} M to 4.80×10^{-3} M for CPC and 1.00×10^{-3} M to 8.00×10^{-3} M for AOT) were prepared using the stock solution and loaded in the syringe in DSA. A liquid drop of 2 μL of surfactant solution was formed and the contact angle was measured immediately on the cleaned and dried surface of the glass slide. The syringe of DSA was rinsed after every change in concentration of surfactant solution with doubled distilled water at least three times in a row. The standard deviation of CA after 60 ± 2 sec of the water drop settled on the glass surface was $\pm 1.1^0$. The results obtained were reviewed, evaluated, and exported by Kruss Advanced Software (version 1.9.0.8).

3. Results and discussion

3.1. Surface tension and surface properties

Surface tension (γ) of two anionic (AOT and SDS) and two cationic (CPC and CTAB) surfactants were measured in water and 0.10, 0.20, and 0.30 parts by volume of 2-PrOH – water mixtures at 298.15 K. A graph is plotted with γ and logarithm of concentration (log C) for a series of surfactant concentrations. As the concentration increases, γ decreases because the surfactant accumulates at the air/solution interface, reducing the intermolecular forces. Eventually, the γ shows a breakpoint – this point is called CMC as shown in Fig. 1. Surfactant molecules become saturated at CMC, and further surfactant added forms micelles in solution rather than affecting γ [29].

The premicellar slope of the graph, $\frac{d\gamma}{d \log C}$, represents the pattern of γ decrease with the log C. This slope is useful in determining surface properties such as $\Gamma_{\max}$ using equation (1) [30]

$$\Gamma_{\max} = -\frac{1}{2.303 nRT}\left[\frac{d\gamma}{d \log C}\right]_{T,P} \tag{1}$$

R = the universal gas constant, T = the absolute temperature, and C = the molar concentration of surfactant. $n = 2$.

$A_{\min}$ represents the smallest surface area occupied by a single molecule at the air/solution interface. It is determined by using equation (2)

$$A_{\min} = 1/N_A \Gamma_{\max} \tag{2}$$

Where N_A denotes Avogadro Number.

3.1.1. Influence of 2-PrOH on adsorption properties

The adsorption of surfactants at the air/solution interface is significantly influenced by the addition of 2-PrOH. Surface excess concentration ($\Gamma_{\max}$) decreases consistently with increasing 2-PrOH volume fractions for all surfactants studied (Table 1). This reduction suggests that the presence of 2-PrOH disrupts the adsorption of surfactant molecules at the interface. The key mechanism underlying this behavior is the reduction in solvent polarity caused by 2-PrOH. Pure water, with its high dielectric constant ($\epsilon = 80$),
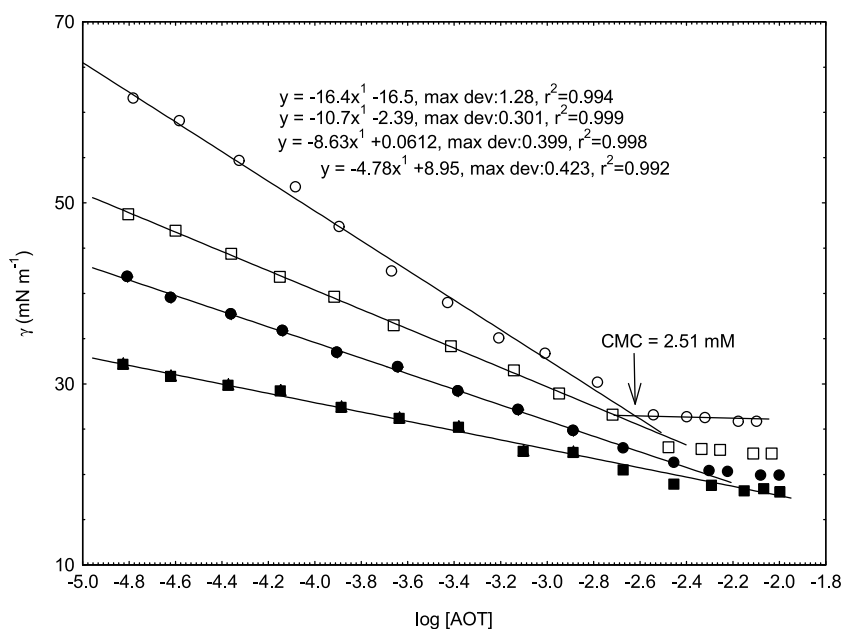
Fig. 1. Plot of γ vs log C, showing CMC and premicellar slope, of AOT in water (o) and various parts by volume (0.1 (□), 0.20 (●), 0.30 (■)) of 2-PrOH at 298.15 K.

Table 1

CMC, Premicellar slope ($\frac{d\gamma}{d \log C}$), Γ_{max}, and A_{min} of AOT, SDS, CPC, and CTAB in water and various parts by volume (0.10, 0.20, and 0.30) of 2-PrOH.

Volume fraction of 2-PrOH	CMC (mM)	$(\frac{d\gamma}{d \log C})$	$\Gamma_{max}10^6$ (mol m^{-2})	A_{min} (Å^2 molecule^{-1})
AOT				
0.00	2.51	−16.4	1.43	115.60
0.10	4.31	−10.7	0.93	177.19
0.20	5.01	−8.6	0.75	219.69
0.30	7.24	−6.5	0.41	396.64
SDS				
0.00	7.94	−23.4	2.04	81.02
0.10	9.98	−16.6	1.44	114.90
0.20	14.79	−10.1	0.88	187.71
0.30	21.23	−5.6	0.48	339.16
CPC				
0.00	1.01	−19.6	1.71	96.73
0.10	1.32	−13.7	1.19	138.39
0.20	1.67	−9.5	0.83	199.78
0.30	3.98	−6.5	0.57	289.01
CTAB				
0.00	0.98	−31.0	2.71	61.15
0.10	1.37	−22.1	1.93	85.78
0.20	1.79	−19.3	1.69	98.23
0.30	3.01	−7.4	0.64	257.60

*Uncertainties in CMC, $\frac{d\gamma}{d \log C}$, Γ_{max}, and A_{min} are ±2, ±4, ±4, ±4 % respectively.

promotes strong hydrophobic effects, driving surfactant molecules to adsorb at the interface. However, as 2-PrOH is introduced ($\epsilon = 18.62$) [31], the overall polarity of the medium decreases [32], weakening these hydrophobic interactions and making surfactants less prone to accumulate at the interface. 2-PrOH molecules interact with both the hydrophilic head and hydrophobic tail of surfactants, leading to a more dispersed arrangement of surfactant molecules in solution. This disruption increases the minimum surface area (A_{min}) occupied by surfactant molecules at the interface. Previous studies, such as those by Zdziennicka et al. [11,33], reported reduced surface tension and enhanced adsorption in alcohol-water mixtures. However, our findings uniquely show that 2-PrOH increases the A_{min} more significantly than methanol. Anionic surfactants, such as AOT and SDS, exhibit a more pronounced decrease in Γ_{max} compared to cationic surfactants like CPC and CTAB. This difference may be attributed to stronger stabilization of the negatively
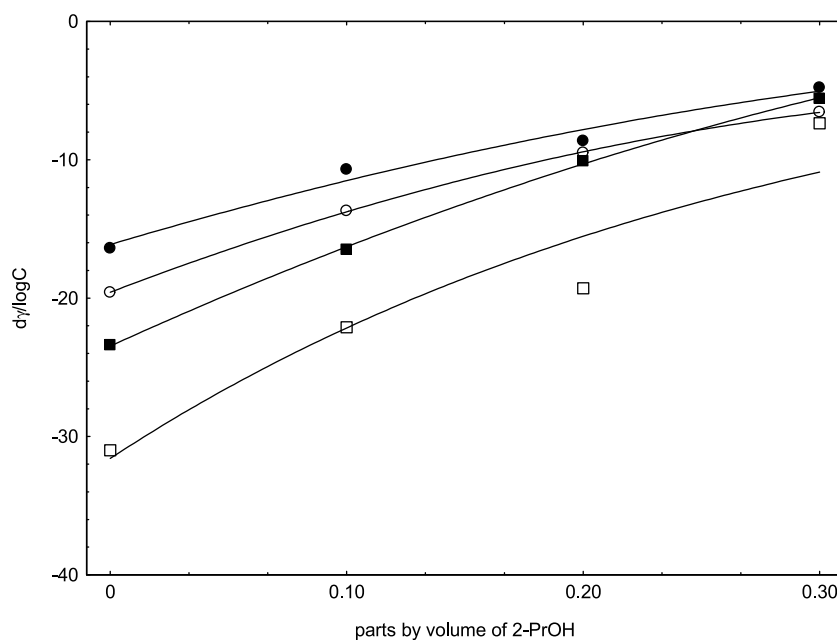
Fig. 2. Variation of the premicellar slope with parts by volume of 2-PrOH in water (●) and 0.10 (o), 0.20 (■), and 0.30 (□) parts by volume of 2-PrOH.

charged head groups of anionic surfactants in the less polar 2-PrOH-water mixtures, further reducing their tendency to adsorb the interface.

3.1.2. Influence of 2-PrOH on aggregation properties

The addition of 2-PrOH significantly affects the micellization of surfactants, as reflected by an increase in the CMC across all studied surfactants (Table 1). This trend indicates that 2-PrOH disrupts the self-assembly of surfactant molecules into micelles. The driving force for micellization in aqueous solutions is the hydrophobic effect, which minimizes contact between hydrophobic surfactant tails and water. However, the addition of 2-PrOH reduces solvent polarity, weakening hydrophobic interactions and requiring higher surfactant concentrations for micelle formation. 2-PrOH interacts with both hydrophobic tails and hydrophobic heads of surfactant molecules. Interacting with the tails, decreases their tendency to aggregate, while interaction with the heads alters hydration and reduces their affinity for the bulk aqueous phase. These effects collectively delay micellization. Additionally, the reduced polarity of the 2-PrOH-water mixture makes surfactants more soluble, decreasing the driving force for micelle formation. Anionic surfactants exhibit a greater increase in CMC compared to cationic surfactants. This difference likely arises from the stabilization of negatively charged head groups in the less polar 2-PrOH-water mixture. For cationic surfactants, the interaction between positively charged head groups and the modified solvent environment is different, but they also show increased CMC values due to weakened hydrophobic interactions.

3.2. Effect of 2-PrOH on premicellar slope

The premicellar slope $\left(\frac{d\gamma}{d \log C}\right)$ is a vital parameter in understanding how the γ of surfactant solution changes with increasing surfactant concentration in the region below CMC. It provides insight into the behavior of surfactant molecules as they accumulate at the air/solution interface before reaching CMC, where micelle formation begins. The steeper the premicellar slope, the more effectively the surfactant reduces γ as its concentration increases.

From Fig. 2, it is evident that the premicellar slope decreases as the parts by volume of 2-PrOH in the aqueous solution increases for all surfactants studied. In the presence of 2-PrOH, the premicellar slope decreases, reflecting a reduction in the surfactant's ability to lower γ. This is due to the reduced polarity of the solvent, weaker hydrophobic effects, disruption of water structure, and altered solvent–surfactant interactions Our finding is aligned with the previous work on the effect of short-chain alcohols (methanol and ethanol) on the premicellar slope of cationic surfactants. The point of difference is that 2-PrOH shows a pronounced effect being co-surfactant.

3.3. Relation between Γ_{max} and A_{min}

Surface properties such as Γ_{max} and A_{min} at the air/solution interface were calculated for the surfactants in different 2-PrOH – water mixtures. Table 1 contains the values of Γ_{max} and A_{min}. Surface excess concentrations represent the amount of surfactant molecules
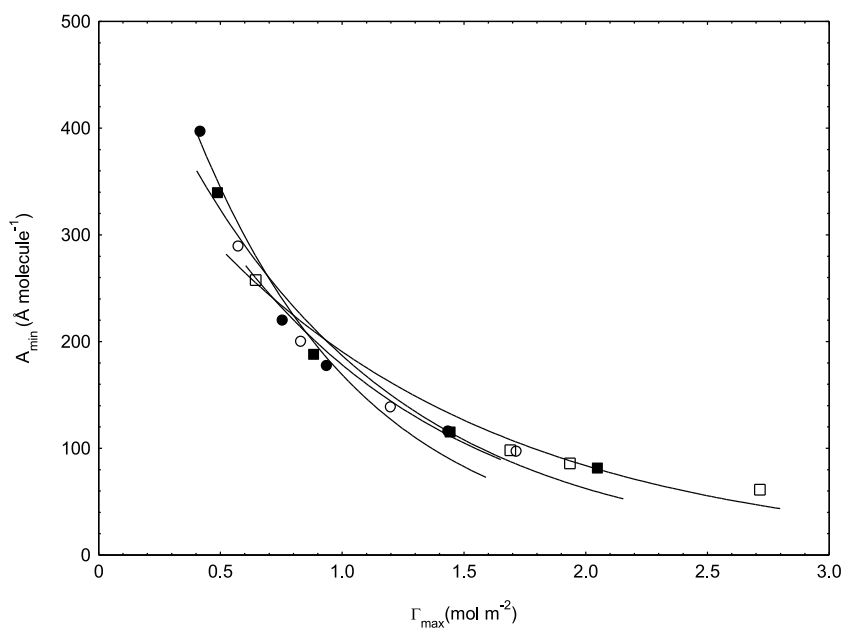

Fig. 3. Correlation between A_{min} and Γ_{max}

adsorbed at the air/solution interface. A higher Γ_{max} indicates that more surfactant molecules are present at the interface, leading to a more significant reduction in γ [34]. The data show a consistent decrease in Γ_{max} as the volume fraction of 2-PrOH increases. This decrement is attributed to weaker adsorption at the interface. The addition of 2-PrOH reduces the polarity of the solvent, making it less favorable for surfactants to accumulate at the interface. Additionally, 2-PrOH disrupts the structured water layer at the interface, weakening the hydrophobic force and thus driving force for surfactant adsorption. Specific observations for different surfactants illustrate anionic surfactants (AOT and SDS) show a significant drop in Γ_{max} with increasing 2-PrOH, likely due to their negatively charged head groups being more stabilized in the less polar 2-PrOH – water mixture.

A_{min} represents the single surfactant molecules that occupy the smallest amount of surface area at the air/solution interface. As seen in Table 1, A_{min} increases with the addition of 2-PrOH. The introduction of 2-PrOH reduces the polarity of the solvent, leading to less efficient packing of surfactant molecules at the interface. Surfactant molecules tend to spread out more in the mixed solvent, increasing the area they occupy. In pure water, strong intermolecular forces drive the tight packing of surfactant molecules at the interface. With the addition of 2-PrOH, these forces weaken, allowing the molecules to occupy a larger area. Alcohol may interact with the hydrophobic tails and hydrophilic heads of surfactants. This interaction disrupts the tight alignment of molecules at the interface. This is consistent with the observed increase in A_{min} [35]. Anionic surfactants, AOT and SDS, exhibit a larger increase in A_{min} compared to cationic surfactants. Fig. 3 provides a clear illustration of the inverse correlation between Γ_{max} and A_{min} in the presence of 2-PrOH. As 2-PrOH parts by volume increase Γ_{max} decreases, and A_{min} increases, highlighting the disruptive effect of 2-PrOH on surfactant adsorption and packing behavior at the interface. This relationship underscores the impact of mixed solvents on surfactant efficiency and surface activity.

3.4. Contact angle and wettability

The spreading of liquid over a solid surface is described as wetting. Liquid can also penetrate porous media in certain situations. Quantitatively, the wettability is calculated using the measurement of contact angle (CA) denoted by θ. Geometrically it is defined as the angle between the liquid phase and the solid phase when these phases are in contact with the gaseous phase, the values of which let us know the extent of wettability [36].

Surfactants are also used as wetting agents as they lower the γ of a liquid through adsorption at the air/liquid interface while simultaneously adsorbing at the solid/liquid interface. Mathematically, CA on the solid surface is related to interfacial tension by Young's equation [28],

$$Cos\,\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}} \tag{3}$$

Where γ_{SG}, γ_{SL}, and γ_{LG} are interfacial tensions between the solid/gas, solid/liquid, and liquid/gas interfaces respectively.

Surface excess concentration at the gas/liquid interface is calculated (analogous to equation (1)) using equation (4)

$$\Gamma_{LG} = -\frac{1}{20303nRT}\left[\frac{d\,\gamma_{LG}}{d\log C}\right]_{T,P} \tag{4}$$

Lucassen – Reynolds equation [37] is used to show the relation of surface excess concentrations in three interfaces (Γ_{LG}, Γ_{SL}, and Γ_{SG}) with their respective interfacial tensions as shown below.

$$\frac{\Gamma_{SG} - \Gamma_{SL}}{\Gamma_{LG}} = \frac{d(\gamma_{SG} - \gamma_{SL})}{d\gamma_{LG}} = \frac{d\gamma_{LG}\,Cos\,\theta}{d\gamma_{LG}} \tag{5}$$

Assuming $\Gamma_{SG} = 0$, the ratio of Γ_{SL} and Γ_{LG} can be obtained from the slope of a plot of $\gamma_{LG}\,Cos\,\theta$ (known as Adhesion Tension) (A_T), and γ_{LG}.

Work of Adhesion (W_A) is defined as the reversible work required to separate a unit area of liquid from a solid surface. It measures the interactive forces between the two different phases (solid and liquid). It can be obtained from CA using equation (6)

$$W_A = \gamma_{LG}(1 + Cos\,\theta) \tag{6}$$

For $\theta = 0^o$, $W_A = 2\gamma_{LG}$. It indicates that the attraction between liquid and solid is at least as strong as that between liquid and liquid.

In this study, the wettability of various surfactants (AOT, SDS, CPC, and CTAB) on the glass surface (hydrophilic surface) was analyzed by measuring CA followed by calculation of A_T, W_A, and ΔG_{wet} in different mixtures of water and 2-PrOH at 298.15 K (Table 2). Figs. 4–6 illustrate a representation of CPC, showing how the CA, A_T, and W_A change with surfactant concentration and 2-PrOH content.

3.4.1. Influence of 2-PrOH on wetting properties

The wetting properties of surfactant solutions, assessed through CA measurements [38], improved significantly with the addition of 2-PrOH (Table 2). CA decreases consistently as the 2-PrOH content increases, indicating enhanced wettability on the hydrophilic glass surface. This improvement is primarily due to a reduction in γ caused by 2-PrOH, which facilitates liquid spreading on the solid surface. As a co-surfactant [39], 2-PrOH disrupts the water structure and enhances surfactant molecule distribution at the air/liquid interface. Additionally, adhesion tension (A_T) and work of adhesion (W_A) increase with rising 2-PrOH content, reflecting stronger liquid/solid

Table 2

CA (*Cos* θ), A_T, W_A, and ΔG_{wet} of AOT, SDS, CPC, and CTAB in water, 0.10, 0.20, and 0.30 vol fractions of 2-PrOH – water mixed solvent at 298.15 K.

Volume fraction of 2-PrOH	Log C(M)	Cos θ	A_T (mNm^{-1})	W_A (mJ m^{-2})
AOT				
0.00	−2.0960	0.9109	23.48	49.27
	−2.1752	0.9109	23.57	49.46
	−2.3182	0.9055	23.75	49.97
	−2.3974	0.9042	23.83	50.19
	−2.5404	0.9015	23.93	50.48
	−2.7809	0.8970	24.24	51.27
0.10	−2.0916	0.9284	20.70	43.01
	−2.1806	0.9223	20.57	42.87
	−2.3172	0.9150	20.77	43.48
	−2.3953	0.9115	20.78	43.59
	−2.5427	0.9076	20.88	43.88
	−2.7584	0.9029	21.13	44.53
0.20	−2.0788	0.9376	18.64	38.51
	−2.1846	0.9311	18.51	38.38
	−2.3085	0.9255	18.76	39.04
	−2.3914	0.9219	18.78	39.16
	−2.5124	0.9184	19.56	40.85
	−2.7465	0.9141	20.91	43.79
0.30	−2.0750	0.9430	16.99	35.00
	−2.1758	0.9375	17.23	35.61
	−2.2979	0.9314	16.89	35.03
	−2.3888	0.9286	17.41	36.15
	−2.5090	0.9253	17.46	36.32
	−2.7436	0.9209	18.83	39.27
SDS				
0.00	−1.4322	0.9077	30.95	65.05
	−1.5571	0.9063	31.81	66.91
	−1.6821	0.9070	32.20	67.70
	−1.8070	0.9097	32.38	67.98
	−1.9319	0.9069	32.38	68.08
	−2.0569	0.9073	32.48	68.28
0.10	−1.5142	0.9113	26.53	55.64
	−1.6308	0.9084	25.56	53.70
	−1.7729	0.9116	24.65	51.70
	−1.9175	0.9118	23.46	49.19
	−2.0342	0.9118	23.20	48.65
	−2.1534	0.9110	24.86	52.15
0.20	−1.4595	0.9147	20.03	41.94
	−1.6029	0.9133	20.00	41.91
	−1.7142	0.9148	20.04	41.94
	−1.8342	0.9152	19.92	41.68
	−2.0566	0.9139	21.83	45.72
	−2.3024	0.9143	23.39	48.98
0.30	−1.4010	0.9173	17.23	36.02
	−1.5291	0.9170	17.11	35.76
	−1.6234	0.9178	17.11	35.76
	−1.7229	0.9183	17.12	35.76
	−1.8517	0.9184	17.64	36.85
	−2.0683	0.9170	18.40	38.46
CPC				
0.00	−2.3140	0.7226	27.60	65.80
	−2.4648	0.7157	27.73	66.48
	−2.6204	0.7083	27.82	67.10
	−2.7453	0.7056	27.86	67.34
	−2.8703	0.7018	27.99	67.87
	−2.9952	0.6982	28.12	68.40
0.10	−2.2520	0.7248	23.88	56.84
	−2.4262	0.7169	23.99	57.45
	−2.5564	0.7105	23.84	57.39
	−2.7027	0.7065	24.00	57.96
	−2.8789	0.7041	24.27	58.75
	−3.0244	0.7005	25.14	61.03
0.20	−2.2462	0.7262	21.28	50.58
	−2.3729	0.7190	21.29	50.91
	−2.5081	0.7119	21.37	51.39
	−2.6556	0.7083	21.41	51.63
	−2.7703	0.7053	21.53	52.06

Table 2 (*continued*)

Volume fraction of 2-PrOH	Log C(M)	Cos θ	A_T (mNm^{-1})	W_A (mJ m^{-2})
	−2.9056	0.7019	22.07	53.50
0.30	−2.2090	0.7266	18.06	42.92
	−2.3070	0.7197	17.78	42.48
	−2.4016	0.7130	17.65	42.41
	−2.5204	0.7097	17.43	41.98
	−2.6310	0.7067	17.92	43.29
	−2.7499	0.7032	18.41	44.58
CTAB				
0.00	−1.9981	0.7125	27.00	64.90
	−2.2199	0.7118	27.05	65.05
	−2.4418	0.7040	27.11	65.61
	−2.6636	0.6994	27.21	66.11
	−2.8855	0.6939	27.27	66.57
	−3.0087	0.6825	27.47	67.71
0.10	−1.9824	0.7149	22.37	53.67
	−2.1971	0.7134	22.93	55.08
	−2.4267	0.7055	23.54	56.90
	−2.6564	0.7018	23.50	56.98
	−2.8624	0.6964	23.82	58.03
	−3.1222	0.6850	27.18	66.86
0.20	−1.9965	0.7165	21.85	52.35
	−2.2219	0.7154	21.75	52.15
	−2.4031	0.7081	21.74	52.44
	−2.6199	0.7021	21.72	52.65
	−2.7723	0.6970	21.75	52.95
	−2.9569	0.6876	22.77	55.89
0.30	−1.9889	0.7180	19.85	47.50
	−2.1574	0.7168	19.93	47.73
	−2.3409	0.7096	19.53	47.07
	−2.5233	0.7049	19.66	47.56
	−2.6328	0.6996	19.60	47.62
	−2.7122	0.6908	19.35	47.37

*Uncertainties for CA, A_T, and W_A are ±4, ±5, and ±5 % respectively.
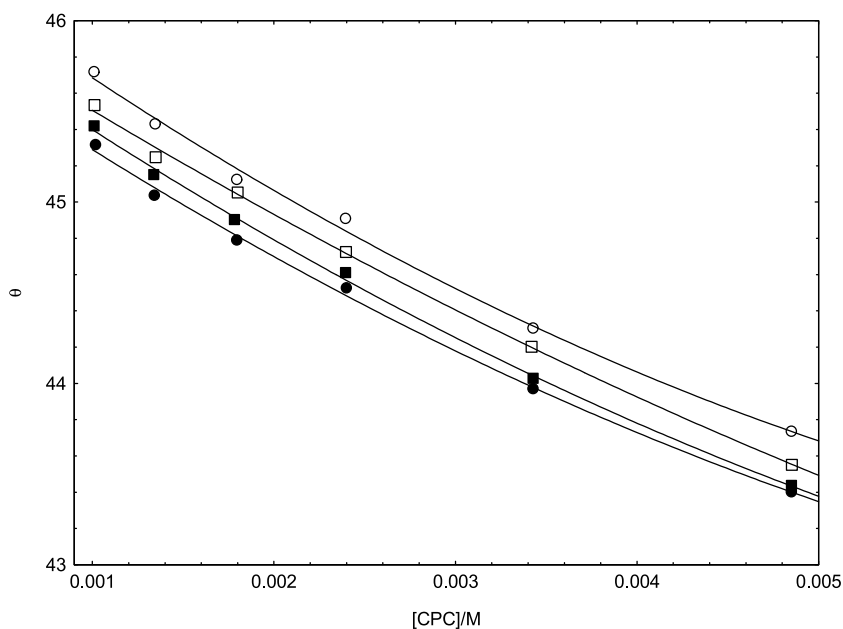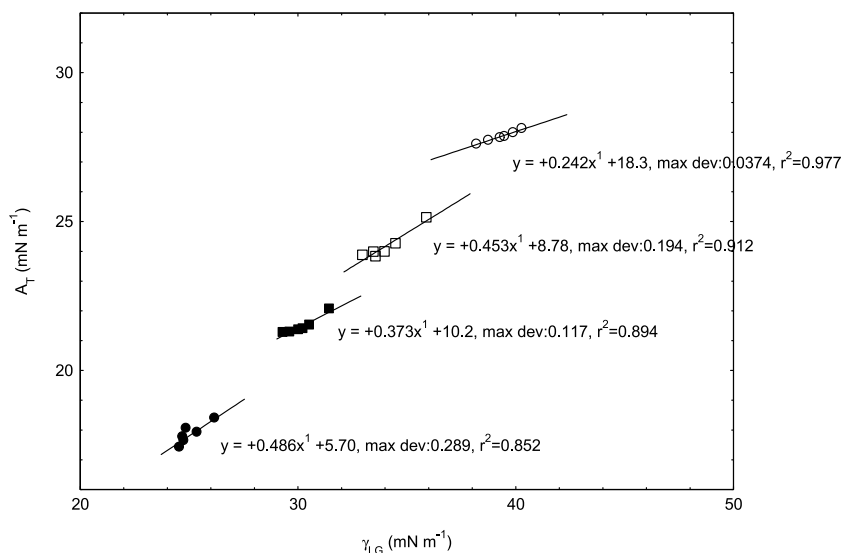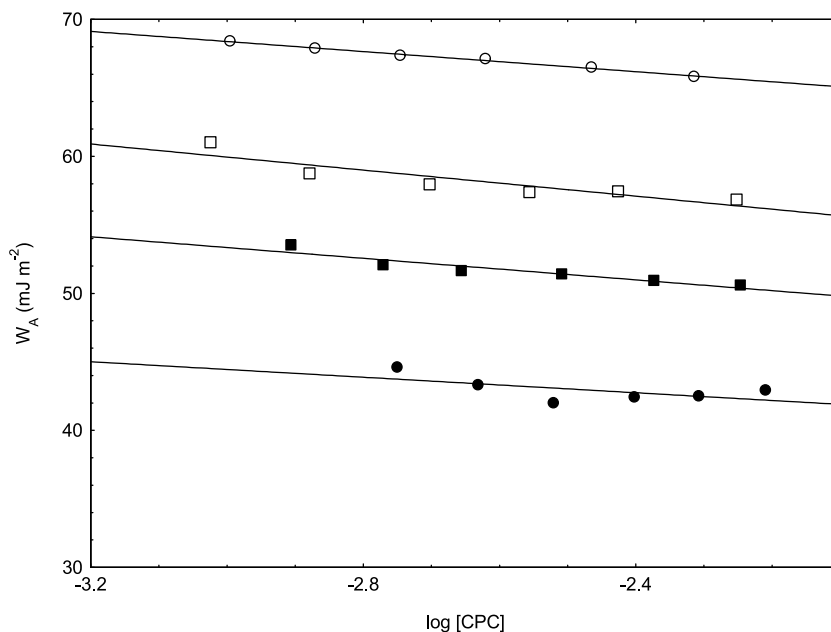

Fig. 4. CA vs concentration of CPC in water (o) and various parts by volume of 2-PrOH (0.10 (□), 0.20 (■), and 0.30 (●)) at 298.15 K.

Fig. 5. A_T vs interfacial tension between gas/liquid (Γ_{LG}) of CPC in water (o) and various parts by volume of 2-PrOH (0.10 (□), 0.20 (■) and 0.30 (●)) at 298.15 K.

Fig. 6. W_A vs log [CPC] in water (o) and various parts by volume of 2-PrOH (0.10 (□), 0.20 (■), and 0.30 (●)) at 298.15 K.

interactions and improved wetting behavior. Anionic surfactants, such as AOT and SDS, exhibit a more pronounced reduction in CA compared to cationic surfactants like CTAB. This is likely due to the stronger electrostatic interactions between negatively charged head groups and the glass surface, enhanced by the presence of 2-PrOH. These trends demonstrate that 2-PrOH improves not only the spreading of surfactant solutions but also their adhesion to hydrophilic surfaces, making them more effective in applications requiring strong wetting and adhesion.

A_T quantifies the strength of liquid/solid interactions, with higher values indicating better wetting. As shown in Table 2, A_T increases with 2-PrOH content, corresponding to a reduction in γ_{LG}, further enhancing the solution's ability to adhere to the glass surface. The plots are fitted linearly as per equation (5) and the ratio $\frac{\Gamma_{SL}}{\Gamma_{LG}}$ was evaluated from the slope. Fig. 5 illustrates the linear relationship between A_T and γ_{LG} for CPC in water and varying 2-PrOH concentrations. The evaluated slopes (+0.24 in water; +0.45, +0.37, and +0.48 in 0.10, 0.20, and 0.30 parts by volume of 2-PrOH, respectively) indicate unequal adsorption at solid/liquid and liquid/air interfaces ($\Gamma_{SL} < \Gamma_{LG}$) [21,36]. A similar investigation was performed on cationic surfactant (Dodecyldimethylammonium Bromide,

DDAB) and anionic surfactant (AOT) on the glass surface [36]. They found the slope +0.831 (for DDAB) and +0.854 (for AOT). In comparison with this result, our values are less positive indicating the amphiphiles are less populated in the air/solution interface in the presence of 2-PrOH.

Fig. 6 shows W_A as a function of CPC concentration in water and different 2-PrOH contents. Higher W_A values, which indicate stronger adhesion, are observed with increasing 2-PrOH volume fractions. This suggests that 2-PrOH enhances adhesive forces between the surfactant solution and the glass surface, resulting in better wetting and stronger adhesion. Interestingly, the work of adhesion values of DDAB and AOT solutions on PTFE and glass surfaces reported in prior studies provides a valuable context for interpreting our results. Biswal [36] noted that the work of adhesion of DDAB solutions on PTFE and glass surfaces above CMC was 28.55 mJm^{-2} and 30.94 mJm^{-2}, respectively, whereas AOT solutions exhibited slightly higher values of 32 mJm^{-2} and 35.24 mJm^{-2}, respectively. These observations highlight the work of adhesion varies notably across surfactants and surface types, with glass showing higher adhesion than PTFE, consistent with our findings.

A recent study [40] demonstrated that 2-PrOH significantly reduces surface tension and improves wettability on porous coated paper substrates when combined with surfactants such as SDS and Brij-35, particularly at an optimal concentration of 5–7.5 wt%. This enhancement occurs due to the migration of 2-PrOH and surfactant molecules to the liquid/air interface, effectively altering the interfacial tension properties. These findings are consistent with the role of 2-PrOH in our study, where its addition reduced surface tension and enhanced the wetting behavior of surfactant solutions on glass surfaces, demonstrating the synergistic effect of alcohol and surfactants in optimizing surface wettability.

4. Conclusions

This study investigated the surface properties of anionic (AOT, SDS) and cationic (CPC and CTAB) in water and different parts by volume (0.10, 0.20, 0.30) of 2-PrOH at 298.15 K. The finding revealed that the addition of 2-PrOH significantly influences the adsorption, aggregation, and wetting properties of the surfactant studied. Subsequent mixing if 2-PrOH increases the CMC by reducing the solvent polarity and weakening hydrophobic interaction, thereby delaying the micellization. Surface excess concentration (A_{min}) decreases while the minimum surface area (Γ_{max}) increases, reflecting a more dispersed arrangement of surfactant molecules at the air/liquid interface. Enhanced wettability is observed on hydrophilic glass surfaces, as indicated by lower CA, higher adhesion tension (A_T), and work of adhesion (W_A). These effects are more pronounced for anionic surfactants due to stronger electrostatic interactions with the glass surface. Overall, 2-PrOH acts as an effective co-surfactant, optimizing surfactant performance by enhancing spreading and adhesion, making it valuable for applications in detergents, coatings, and surface treatment.

CRediT authorship contribution statement

Sujit Kumar Shah: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology. **Pankaj Kumar Das:** Project administration, Resources, Software, Writing – original draft. **Ajaya Bhattarai:** Supervision, Validation, Visualization, Writing – review & editing.

Data availability statement

Upon request, the raw data necessary to reproduce the above findings will be made available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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