Review Article

Investigation of the interaction of sunset yellow dye with sodium dodecyl sulfate-sodium dodecyl benzene sulfonate mixed micelles

Yusuf Ali[1], Anirudh Srivastava [2]

1. MSc Scholar, Dept of Chemistry, Keral Verma Subharti College of Science,
2. Associate Professor, Research and Development Cell,
Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Abstract

The interaction of Sunset Yellow FCF (SSY), a commonly used anionic azo dye, with mixed micelles of sodium dodecyl sulfate (SDS) and sodium dodecylbenzene sulfonate (SDBS) was investigated using UV–visible spectrophotometry. By maintaining a constant dye concentration and varying the SDS mole fraction (α_{SDS}), significant changes in SSY's absorption spectra were observed. Pure SDS micelles showed limited interaction due to electrostatic repulsion, whereas SDBS-rich systems exhibited enhanced absorbance, attributed to π–π stacking between the aromatic rings of SDBS and SSY.Binding constants (K_b) were calculated using linear plots of $1/(A - A_w)$ versus $1/(c - c_0)$, confirming stronger dye binding in mixed micellar systems. The highest binding ($LogK_b = 3.703$) occurred at $\alpha_{SDS} = 0.1$, indicating an optimal SDS–SDBS ratio for SSY solubilization. Beyond this point, a slight decrease in binding efficiency was noted in pure SDBS micelles. These findings highlight the synergistic effects of SDS–SDBS combinations, where both hydrophobic and aromatic interactions contribute to enhanced dye incorporation. The study demonstrates the potential of mixed micelles to serve as effective carriers for dye solubilization and delivery, offering advantages over single-surfactant systems in formulation design and environmental applications.

Keywords: Sunset Yellow FCF, mixed micelles, sodium dodecyl sulfate, sodium dodecylbenzene sulfonate, dye–surfactant interaction.

Address for Correspondence: Dr Anirudh Srivastava, Research and Development Cell, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Email: ani_srivastava83@yahoo.co.in **Contact:** +91- 89240 76936

1. Introduction

Synthetic dyes are widely used in industries such as textiles, food, pharmaceuticals, and cosmetics due to their vivid colors, chemical stability, and low production cost. Among them, azo dyes dominate the market, constituting 60–70% of global dye usage [1-5]. These dyes, containing azo (–N=N–) linkages between aromatic rings, often include substituents that enhance solubility and binding affinity. One such example is Sunset Yellow FCF (SSY), a water-soluble monoazo dye known for its intense orange-yellow color and high stability, commonly used in beverages, confectioneries, and pharmaceuticals [6-8].

However, the environmental persistence of synthetic dyes like SSY poses significant ecological and health concerns. These dyes resist biodegradation and accumulate in water bodies, thereby affecting aquatic life and potentially entering the food chain [8]. Therefore, understanding the interaction of such dyes with self-assembling molecular systems like surfactant micelles is crucial. Surfactants—amphiphilic molecules with hydrophilic heads and hydrophobic tails—self-assemble into micelles above a critical micelle concentration (CMC), offering a versatile microenvironment that can encapsulate dyes and other poorly water-soluble substances [9-20].

These micelles can influence the solubility, photostability, and mobility of dyes in aqueous systems. For instance, Srivastava (2024) demonstrated that mixed micelles formed by anionic STS and cationic CTAB significantly improved the solubilization of SSY, where electrostatic and hydrophobic interactions contributed to enhanced dye encapsulation [12]. Similar systems using nonionic Pluronic-TPGS mixtures have improved the delivery of hydrophobic drugs like curcumin and paclitaxel [21]. In environmental applications, micellar-enhanced ultrafiltration (MEUF) has shown success in removing dyes and heavy metals from wastewater, using mixed micelles like SDS–Brij-35 or SDS–Triton X-100 to encapsulate pollutants efficiently [22, 23].

In the context of SSY, the negatively charged sulfonate groups typically repel anionic surfactants like SDS and SDBS [13]. Yet, hydrophobic interactions and π–π stacking between the dye's aromatic rings and the surfactant tails often overcome this electrostatic repulsion. Studies have shown that SSY can incorporate into SDS micelles, as evidenced by spectral shifts such as bathochromic (red) shifts in absorbance maxima and increases in molar absorptivity, indicating strong micelle–dye interaction [12, 14-17]. These interactions are pivotal in applications like textile dyeing, drug delivery, and wastewater remediation [24-26].

Notably, mixed micelles—combinations of two or more surfactants—provide enhanced physicochemical properties over single surfactant systems. They allow for tuning of surface charge, CMC, aggregation number, and solubilization capacity [27-29]. For example, combining SDS and SDBS—both anionic surfactants but with distinct structures (aliphatic vs. aromatic tails)—yields micelles with superior dye-binding properties due to enhanced hydrophobic and π–π interactions [12, 14-17, 31, 32]. These synergistic effects lower the CMC and increase encapsulation efficiency, as confirmed by negative interaction parameters (β) and favorable thermodynamic data such as binding constants (K_b) and Gibbs free energy changes (ΔG°) [33, 34].

In drug delivery, surfactant mixtures involving zwitterionic components like cocoamidopropyl betaine (CAPB) with anionic surfactants have improved the oral bioavailability of poorly soluble drugs by enhancing micellar stability and payload release profiles [18, 19]. Such tunable systems are also being explored in food stabilization, nanoparticle dispersion, and agrochemical formulations [34].

Given this background, the present study focuses on investigating the interaction of Sunset Yellow dye with mixed micelles formed by SDS and SDBS. The goal is to understand how micellar composition influences dye solubilization, binding strength, and spectral properties. This work provides insight into micelle-assisted dye removal and delivery systems, offering a foundation for green and efficient technologies in environmental and industrial applications.

2. Experimental techniques

2.1. Preparation of Stock Solutions

For the study of mixed micellization behavior, stock solutions of all the required components were prepared using double-distilled water to ensure purity and minimize the interference of impurities. Sodium dodecyl sulfate (SDS), sodium dodecylbenzene sulfonate (SDBS), and the azo dye Sunset Yellow FCF (SSY) were used as received from commercial suppliers without further purification.

Each of the stock solutions of SDS, SDBS, and SSY was prepared at a concentration of 20 mmol L^{-1}. The solutions were freshly prepared and stored in clean, labeled glass containers. These stock solutions were used for the preparation of mixed micellar systems and dye–micelle interaction studies.

2.2. Preparation of Mixed Micellar Solutions

Mixed micelle solutions were prepared using combinations of SDS and SDBS at various molar (mole fraction) ratios. The total surfactant concentration in each mixture was kept constant, denoted by **$C \times (\alpha_{SDS} + \alpha_{SDBS})$**, where:

- α_{SDS} represents the mole fraction of SDS in the mixture.
- α_{SDBS} represents the mole fraction of SDBS in the mixture.

The mole fractions were varied systematically across the entire composition range, from $\alpha_{SDS} = 1.0$ (pure SDS) to $\alpha_{SDS} = 0.0$ (pure SDBS), typically in steps such as 1.0, 0.8, 0.6, 0.4, 0.2, and 0.0. Each mixture was prepared by accurately pipetting calculated volumes of the SDS and SDBS stock solutions into volumetric flasks, followed by dilution with distilled water up to the mark to maintain a constant total surfactant concentration.

These mixed micellar systems were allowed to equilibrate at room temperature (approximately 25 ± 1°C) for at least 30 minutes before further measurements to ensure complete micellization and homogeneity of the solution.

2.3. UV–Visible Spectrophotometric Measurements

The interaction between SSY and the SDS–SDBS mixed micelles was investigated using UV–visible absorption spectroscopy. All spectral measurements were carried out using a Shimadzu UV-1800 double-beam spectrophotometer, calibrated prior to each use to ensure accuracy and reproducibility.

Quartz cuvettes with a path length of 1.0 cm were used for all spectrophotometric measurements. The baseline correction was performed using distilled water in both reference and sample cuvettes before sample analysis.

For the analysis, a constant dye concentration of 0.01 mmol L^{-1} SSY was maintained in all test solutions. To this dye solution, varying compositions of SDS–SDBS mixed micelles (prepared as described above) were added, maintaining the mole fractions of SDS and SDBS from $\alpha_{SDS} = 1.0$ to $\alpha_{SDS} = 0.0$, while keeping the total surfactant concentration fixed.

Each prepared solution was thoroughly mixed and equilibrated at room temperature before recording the absorbance. The absorption spectra were recorded over an appropriate wavelength range (typically 300–600 nm) to monitor the characteristic peaks of SSY and to observe any shifts or intensity changes due to micelle formation and dye binding.

The binding constant (K_b) of SSY with the mixed micelles was calculated based on changes in absorbance with increasing surfactant mole fraction, using appropriate binding models and graphical methods.

3. Results and discussion

3.1. Interaction Mechanism and Spectral Behavior of Sunset Yellow (SSY) with SDS–SDBS Mixed Micelles

The interaction between Sunset Yellow FCF (SSY), a commonly used anionic azo dye, and the mixed micellar systems of sodium dodecyl sulfate (SDS) and sodium dodecylbenzene sulfonate (SDBS) was systematically examined using UV–visible spectrophotometry. A constant dye concentration of 0.01 mmol L^{-1} was maintained while varying the mole fraction of SDS (α_{SDS}) from 1.0 (pure SDS) to 0.0 (pure SDBS), keeping the total surfactant concentration constant [13].

The absorption spectra (Fig. 1) showed significant variation in the intensity and profile of SSY with changes in the SDS–SDBS composition. At α_{SDS} = 1.0, a moderate increase in absorbance was observed, indicating limited interaction between SSY and pure SDS micelles. This can be attributed to electrostatic repulsion between the negatively charged SSY and the anionic sulfate head groups of SDS. The solubilization here appears to be mainly due to hydrophobic interactions within the micellar core.

As the mole fraction of SDBS increased, especially in the range α_{SDS} = 0.9 to 0.1, a pronounced increase in absorbance was recorded, as shown in Figure 1. The enhancement in spectral intensity can be interpreted as a result of cooperative interactions involving hydrophobic effects and significant π–π stacking between the aromatic moiety of SDBS and the aromatic chromophore of SSY. Such specific interactions are consistent with earlier findings on aromatic dye–surfactant systems, where similar enhancements in dye solubilization were attributed to π–π stacking [34, 12, 14-17].

At α_{SDS}= 0.0 (pure SDBS), the absorbance reached its maximum, confirming strong binding and solubilization of SSY, as shown in Fig. 1. The presence of the benzene ring in SDBS contributes a unique interaction mechanism that is not present in SDS alone [13]. These observations are in agreement with previously reported studies such as those by Srivastava et al. (2014), who demonstrated that phenol red showed strong binding with cationic surfactants like CPC due to favorable electrostatic interactions [15, 16]. However, in the present study, the enhancement in SSY binding

with anionic SDBS-containing systems, despite the electrostatic repulsion, can be clearly attributed to π–π interactions, a feature not observed in systems lacking aromatic surfactant components [15].

Furthermore, the increase in absorbance in mixed micelles as compared to pure SDS micelles aligns with literature on mixed micellar systems where synergistic effects, such as improved packing, result in better solubilization of hydrophobic or amphiphilic dyes [35]. The tunability of the micellar environment by adjusting the SDS-SDBS ratio enables modulation of the solubilization efficiency and binding affinity for SSY, making this system more versatile than single-surfactant micelles. ***Binding constant of SSY with mixed micelle***

In order to use the following equation (Eq. 1) to calculate the binding efficiency of SSY in the presence of SDS-SDBS, binding constants (K_b) were established [15]:

$$\frac{1}{A - A_w} = \frac{1}{A_m - A_w} + \left(\frac{1}{K_b(A_m - A_w)}\right)\left(\frac{1}{(c - c_0)}\right)^{N_m} \quad (1)$$

Where A represents the absorbance of prepared samples, A_w represents the absorbance of SSY in water alone, A_m represents the absorbance of SSY when bound to SDS, SDBS, and SDS-SDBS, c represents the concentration of the aforementioned components, c_0 represents the CMC of the aforementioned components, N_m represents the molar concentration of bound SSY per mole of the micelle and mixed micelle, and K_b represents the binding constant. From the reported values, the CMC of the SDS-SDBS mixed micellar system was taken into account [Srivastava et al. 2024 (a)]. In Table 1 and Fig. 2 from α_{SDS} 1.0 to 0.0, graphs and values of $1/(A-A_w)$ vs. $1/(c-c_0)$ were displayed, and Eq. 4.1 verified that these plots were linear when N_m = 1.0. [12-19]. From Fig. 2, the slope and intercept ratios were used to calculate the K_b. According to Table 1, the K_b of SSY was higher in SDS-SDBS mixed micellar systems and lower in single micellar systems.

The binding plots of $1/(A - A_w)$ versus $1/(C - C_0)$ for various α_{SDS} ratios exhibited excellent linearity with high correlation coefficients ($R^2 \approx 0.98–0.99$), indicating the validity of the 1:1 complex formation model between SSY and the mixed micelles.

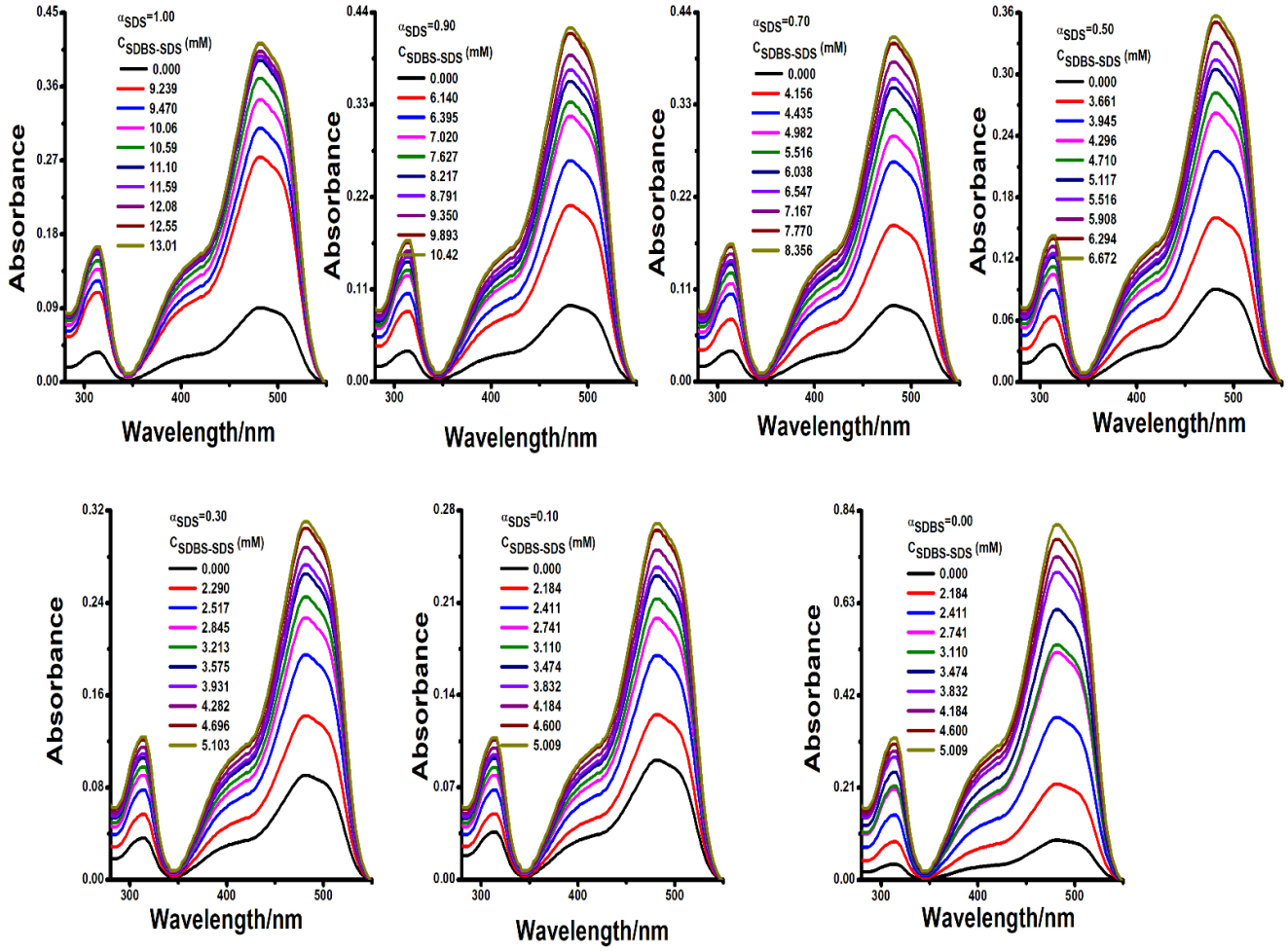

Fig. 1: Representative UV spectra of SSY (0.05 mmol L^{-1}) in SDS-SDBS mixed micelle at varying concentrations of α_{SDS} 1.0 to 0.0. Relative standard uncertainties were u_r= ±5%.

Table 1: The K_b values in the presence of vary mole fraction of SDS-SDBS mixed micelles in aqueous medium

Mole Fraction (α_{SDS})	Log K_b	CMC[a]
1.0 (pure SDS)	2.353	0.00810
0.9	3.484	0.00590
0.7	3.528	0.00402
0.5	3.645	0.00357
0.3	3.694	0.00222
0.1	3.703	0.00213
0.0 (pure SDBS)	2.846	0.00200

CMC[a] [13]

The K_b values show a clear dependence on the micelle composition. The binding constant increases with increasing SDBS content in the SDS–SDBS mixture, reaching a maximum at α_{SDS} = 0.1 (i.e., 0.9 α_{SDBS}). Beyond this point, further replacement of SDS by SDBS leads to a slight decrease in K_b at α_{SDS} = 0.0 (pure SDBS). This trend suggests an optimal synergistic interaction between SDS and SDBS that enhances SSY binding up to a certain SDBS concentration.

This enhanced interaction could be attributed to the structural differences in the surfactants: SDS is a simple aliphatic anionic surfactant, while SDBS contains a bulky benzene ring that can engage in π–π interactions with the aromatic SSY molecule. The combination of SDS and SDBS likely facilitates a mixed micellar environment with improved hydrophobic and electrostatic interactions, favoring SSY incorporation into the micelle core.

The observed behavior is in agreement with earlier studies on mixed surfactant systems showing non-ideal synergistic effects on binding constants and micellar solubilization capacities [36]. A similar enhancement in binding constant due to aromatic surfactant components was also reported by Srivastava et al. 2024 (a), who found that dyes like methyl orange or SSY bind more effectively in micelles formed with SDBS than SDS alone [12, 13].

Therefore, the present results not only highlight the role of surfactant composition in modulating dye–micelle interaction but also confirm that mixed micelles provide a more favorable microenvironment for SSY binding compared to pure SDS or SDBS systems. This finding is particularly relevant in formulation design for dye solubilization, delivery, or controlled release systems.

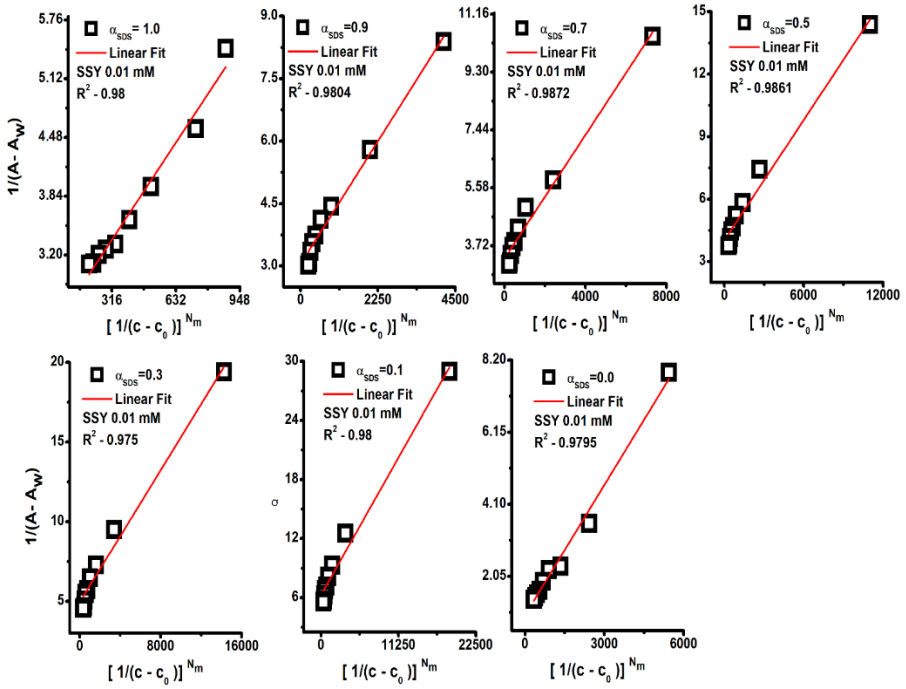

Fig. 2: Plots of SSY in the presence of SDS-SDBS mixed micelle at varying concentrations of α_{SDS} 0.0 to 1.0, according to Eq. (4.1) showing the variation of $1/(A - A_w)$ with $1/(c - c_0)^{Nm}$. The solid red line showed the linear fitting used to determine the K_b from the intercept and slope ratio. Relative standard uncertainties were u_r= ±5%.

4. Conclusion

This study investigates the interaction of the anionic azo dye SSY with SDS, SDBS, and their mixed micellar systems using UV–visible spectroscopy. The micellar composition significantly influenced dye solubilization and binding behavior. Pure SDS micelles showed limited interaction with SSY due to electrostatic repulsion, whereas the inclusion of aromatic SDBS enhanced absorbance intensity, especially in mixed systems.

The strongest interaction occurred at α_{SDS} = 0.1, indicating a synergistic effect. This enhancement was attributed to hydrophobic interactions and π–π stacking between SDBS's aromatic ring and the dye's chromophore—absent in SDS-only systems. Binding constants (K_b), determined using a 1:1 complexation model, increased with higher SDBS content, peaking at α_{SDS} = 0.1 before slightly declining in pure SDBS.

These results suggest that mixed micelles of SDS and SDBS offer an optimized environment for SSY encapsulation, surpassing the performance of single-component micelles. The findings highlight the role of surfactant synergy and π–π interactions in improving dye solubilization, with potential applications in dye removal, formulation, and delivery systems.

Declarations

Ethical Approval is not applicable for this work.

Competing Interest declaration

Authors are not any competing interest.

Data availability statements

Data source and support are not used for this work.

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5. Reference

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