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Critical Analysis of Surfactant-Dye Interaction: A Review

Chandradip Kumar Yadav[1], Ajaya Bhattarai[2*], Tulasi Prasad Niraula[2], Amar Prasad Yadav[1], Manoj Kumar Adhikari[1],Yog Prakash Yadav[3], Duryodhana Yadav[4], Sanjay Singh[3]

[1]Central Department of Chemistry, Tribhuvan University, Kantipur, Nepal
[2]Mahendra Morang Adarsh Multiple Campus, Tribhuvan University, Biratnagar Nepal
[3]Amrit Science Campus, Tribhuvan University, Nepal
[4]Nepal Academic of Medical Sciences, Nepal
*Corresponding author; *bkajaya@yahoo.com*

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Abstract

The interaction between surfactants and dyes is fundamental in achieving the desired coloration and properties in various applications, shaping the functionality and effectiveness of dye-related processes across multiple industries. Further research and advancements in this field will continue contributing to innovative solutions and improved sustainability. While mixed surfactants offer these advantages, the choice between using a single surfactant or a mixture depends on the specific application, the desired properties, cost considerations, and compatibility with other formulation components. It's important to carefully evaluate the application requirements and conduct appropriate testing to determine the most effective approach. In this work, the physical-chemical characteristics and solubilization of reactive dyes in single and mixed micellar media are elaborated. Compared to the single-micellar medium, the mixed-micellar medium showed improved reactive dye trapping, which was attributed to the presence of both cationic and nonionic surfactants, namely cetyltrimethylammonium bromide (CTAB) and triton X-100. In this interactional study, two reactive dyes were used: Reactive Black 5 (RB) and Reactive Yellow 145 (RY). It is noteworthy to examine the modeling and micellization of mixed surfactant systems in an aqueous medium including dodecyl trimethylammonium bromide (DTAB) and sodium dodecyl sulfate (SDS). The anionic-rich and cationic-rich interactions between methylene blue (MB) and methyl orange (MO) in aqueous solutions were clearly shown in the diagram.

1. Introduction

Surface-active agents, sometimes known as surfactants, are substances that reduce the surface tension between two phases, usually a liquid and a solid or another liquid. They consist of molecules with a hydrophobic "tail" that repels water and a hydrophilic "head" that loves water. They can interact with water as well as oils or fats according to their molecular structure (Schramm et al., 2003).

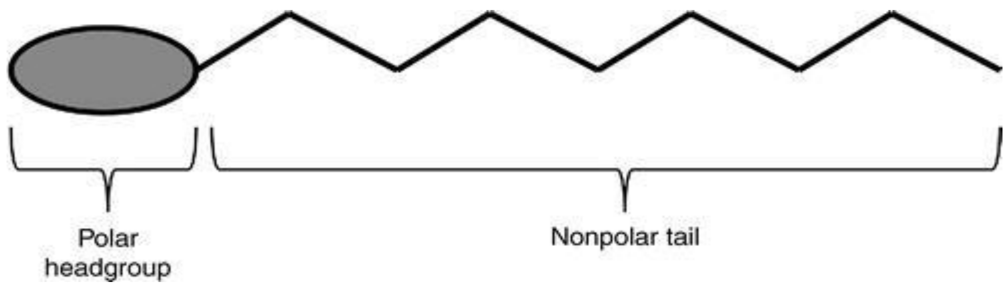

Fig. 1: Surfactant (Rosen et.al., 2003)

In simple terms, surfactants help to mix substances that would typically repel each other, like oil and water. They can make it easier for substances to spread or dissolve in a liquid, allowing for better cleaning, foaming, emulsifying, and dispersion.

Some common uses of surfactants

Detergents: Surfactants help remove dirt and oils from surfaces by breaking them down and allowing them to be washed away.

Emulsification: Surfactants enable the mixing of substances that would not normally combine, such as oil and water, to form stable emulsions like mayonnaise or salad dressings.

Foaming agents: Surfactants create and stabilize foams, which is useful in products like soaps, shampoos, and detergents.

Wetting agents: Surfactants reduce the surface tension of a liquid, allowing it to spread more easily on a surface (Shah et al., 2011).

Dispersants: Surfactants help disperse solid particles in a liquid, preventing them from clumping together. Understanding the surfactants is crucial in various industries, including cleaning products, cosmetics, pharmaceuticals, agriculture, food processing, and more. Their properties and functions make them vital components in a wide range of everyday products(Barni et al., 1991).

Mixed surfactant

Mixed surfactant is defined to a combination of two or more different surfactant compounds that are used together to enhance specific properties or functions. Combining surfactants can lead to a synergistic effect, resulting in improved performance and versatility compared to using a single surfactant. This approach is commonly utilized in various industrial applications and consumer products to achieve desired characteristics and performance.

The combination of mixed surfactants is typically done to achieve a specific balance between hydrophilic (water-loving) and hydrophobic (water-repelling) properties, tailor the surface activity, enhance stability, control foaming, or improve emulsification properties. Each surfactant component contributes its unique characteristics to the overall performance of the mixture (Sachin et al., 2019).

Some benefits of mixed surfactants

Enhanced performance: Combining surfactants can lead to improved cleaning, emulsification, dispersion, or foaming properties beyond what each surfactant can achieve individually.

Cost-effectiveness: Utilizing a mixture of surfactants can often be more cost-effective than using a single surfactant to achieve the desired performance levels.

Versatility: Different surfactants have distinct properties, and combining them can allow for customization and versatility in meeting specific product requirements.

Stability and compatibility: Mixing surfactants can enhance the stability and compatibility of the formulation, ensuring that the product remains effective and consistent over time.

Tailored formulations: By selecting specific surfactants and adjusting their ratios, manufacturers can tailor formulations to suit the intended application and optimize performance. The combination of surfactants is a complex process that involves considering various factors, including the chemical nature, concentration, ratios, and interactions between the surfactants. This practice is widespread across industries such as personal care products, cleaning agents, pharmaceuticals, agriculture, and more, where achieving the desired properties and functions is crucial for product effectiveness and consumer satisfaction (Fatma et al., 2013).

Importance of mixed surfactants

Mixed surfactants offer several important advantages and applications across various industries due to their enhanced capabilities compared to single surfactants. Here are some key points of the importance of mixed surfactants:

Enhanced performance and efficiency: Combining different surfactants allows for fine-tuning properties like foaming, wetting, emulsifying, and detergency, resulting in superior performance compared to individual surfactants. The synergistic effect of mixed surfactants often leads to improved efficiency in processes such as cleaning, where they can better remove dirt, grease, and stains (Rashid et al., 2020).

Versatility and flexibility: Mixed surfactants can be tailored to meet specific application requirements by adjusting the composition and ratios of the surfactants, providing flexibility in formulation design. They enable the development of products with a wide range of characteristics suitable for different applications, including personal care, household cleaning, agriculture, pharmaceuticals, and more.

Cost-effectiveness: Utilizing a mixture of surfactants can be a cost-effective approach compared to using high concentrations of a single surfactant to achieve the desired properties. Manufacturers can achieve the desired performance at a lower cost by combining less expensive surfactants with specialized or more expensive ones (Rosen *et al.*, 2012).

Stability and formulation improvement: Mixing surfactants can improve the stability and shelf life of formulations by providing a more robust and balanced system, minimizing phase separation and degradation over time. They can enhance the compatibility of the formulation with other ingredients, leading to a stable and effective product.

Tailored applications: Mixed surfactants allow for customization of formulations based on the specific requirements of different applications, such as tailoring the emulsification properties in cosmetics or adjusting the foaming behavior in detergents.

Environmental and regulatory considerations: Combining surfactants can help in designing products with reduced environmental impact by using a mix of surfactants that are biodegradable and environmentally friendly. The use of mixed surfactants can also assist in complying with regulatory guidelines related to environmental and safety standards (Vankar, 2017).

Innovative product development: Researchers and developers continuously explore new combinations of surfactants to create innovative products with improved performance and novel properties, driving advancements in various industries. In Overall, the importance of mixed surfactants lies in their ability to optimize product performance, enhance formulation stability, achieve cost-effectiveness, and support the development of versatile and effective solutions for a diverse range of applications.

1.1 Dye and its importance

A dye is a colored substance that can be applied to various materials to impart color to them. It is designed to chemically or physically bind to the surface of the material, resulting in a vibrant and lasting coloration. Dyes are used in a wide range of applications, including textiles, paper, plastics, food, cosmetics, printing, and more. In a general sense, a dye is a complex compound or mixture of compounds that can absorb certain wavelengths of light and reflect or transmit others, creating the perception of color to the human eye. Dyes are usually dissolved or dispersed in a solvent or carrier medium before application. The color imparted by a dye can be influenced by its chemical structure, molecular size, bonding mechanisms, and the material it is applied (Gokturk & Tuncay, 2003).

Importance of dyes

The importance of dyes is multifaceted and can be summarized as follows:

Coloration and aesthetics: Dyes are essential for adding color to a wide range of materials, enhancing their appearance, and making them more visually appealing and attractive to consumers.

Fashion and textile industry: The textile industry relies heavily on dyes to color fabrics and garments, allowing for a diverse range of clothing and fashion choices.

Identification and branding: Dyes are used for branding and differentiating products. Unique colors help identify products, labels, packaging, and trademarks.

Art and creative expression: Dyes play a critical role in arts and crafts, enabling artists to create intricate and colorful designs on various surfaces like paper, fabric, and more.

Visual communication: In graphic design, printing, and signage, dyes are used to convey messages and information effectively through the use of color.

Safety and visibility: Dyes are used in safety equipment, signs, and markers to enhance visibility and safety by using specific colors that are easily recognizable.

Food and beverage industry: In the food industry, dyes are used to color food products, enhancing their visual appeal and making them more attractive to consumers.

Medical and biological applications: Dyes are used in medical diagnostics, microscopy, and biological research for staining tissues and cells to enhance visibility and aid in research and diagnostics.

Environmental applications: Dyes are used in environmental monitoring and research to study water and soil flow, pollution, and other environmental factors.

Scientific research and testing: Dyes are used in laboratories for various scientific experiments, including microscopy, DNA analysis, and biochemical assays. dyes are fundamental to our daily lives, impacting industries, aesthetics, creativity, safety, and scientific advancements. Their ability to add color and enhance visual appeal makes them a crucial element in a variety of applications (Muntaha & Khan, 2020).

1.2 Surfactant-dye interaction

The interaction between surfactants and dyes refers to the way surfactant molecules interact with dye molecules, affecting the dispersion, solubility, stability, and overall behavior of the dye in a particular system. This interaction is crucial in various applications, including dyeing processes, emulsion stabilization, formulation of dye-based products, and more (Khan & Al-Bogami, 2013).

Dye solubility and dispersion: Surfactants can enhance the solubility of dyes by reducing intermolecular forces and allowing better dispersion of dye molecules in a solvent or medium. This is particularly important in dyeing processes where uniform dye distribution is desired.

Wetting and spreading: Surfactants can improve the wetting and spreading of dyes on the substrate surface, ensuring even dye coverage and penetration during dyeing or coating processes.

Emulsification and micellization: Surfactants can form micelles, which can encapsulate dye molecules, improving their stability and preventing aggregation. This is vital in emulsifying dye-containing formulations.

Stabilization of dispersions: Surfactants can stabilize dye dispersions, preventing dye particles from agglomerating and settling. This is particularly important in inkjet printing and pigment-based applications.

Dye fixation and adhesion: Surfactants can enhance the adhesion and fixation of dyes to substrates by improving the affinity between the dye molecules and the substrate surface. This is essential in dyeing processes, ensuring a strong and lasting color attachment.

Control of dye aggregation: Surfactants can influence the aggregation or self-assembly behavior of dye molecules, which is crucial in achieving desired optical properties, such as color intensity or hue.

Compatibility and stability: Surfactants must be chosen carefully to ensure compatibility with the dye molecules and to maintain the stability of the dye formulation or system. Incompatibility may lead to phase separation or degradation.

Foaming and processing: The interaction between surfactants and dyes can affect foaming behavior during processing, such as in textile dyeing or printing applications. the surfactant-dye interaction is essential for optimizing dyeing processes, developing stable dye formulations, improving color intensity and uniformity, and achieving the desired properties in various dye-related applications. Researchers and industries continuously study and manipulate these interactions to enhance the efficiency and effectiveness of dyeing processes and dye-based product (Behera et al., 2007).

1.3 Mixed surfactant dye interaction

The term "mixed surfactant-dye interaction" refers to the complex interplay between a combination of surfactants and dye molecules in a particular system or medium. In this context, multiple surfactant compounds are used together, and their interaction with dye molecules is studied or manipulated to achieve specific effects or properties related to dye dispersion, stability, color intensity, adhesion, and other relevant characteristics (Sachin et al., 2018).

Importance of mixed surfactant-dye interaction

Synergistic effects: The combined use of multiple surfactants may result in a synergistic effect, enhancing the overall performance and properties of the dye. The interaction can lead to improved dispersion, solubility, stability, and color development compared to using a single surfactant.

Optimized formulation: The surfactant mixture is carefully selected and formulated to achieve desired outcomes, such as better dye dispersion, even coloration, enhanced adhesion, or increased color intensity. The ratio and type of surfactants can be adjusted to optimize the formulation for specific applications.

Dye solubility and dispersion: Mixed surfactants can influence the solubility and dispersion of the dye molecules in the medium, affecting the dyeing process and resulting in a more uniform and vibrant coloration of the substrate.

Stabilization and aggregation control: The surfactant mixture can help stabilize dye dispersions, preventing aggregation and ensuring consistent color distribution. This is crucial in applications like inkjet printing, where stable and finely dispersed dye particles are essential.

Surface wetting and adhesion: The surfactant-dye interaction affects the wetting and spreading of dye on the substrate surface, influencing the dye's adhesion and affinity for the material. This is important for achieving good color penetration and adhesion. Compatibility and Formulation Stability: Understanding how the surfactants and dye interact is essential for formulating a stable and compatible mixture. The compatibility of the surfactants with the dye is crucial for maintaining stability and preventing phase separation or degradation.

Application-specific optimization: The interaction is tailored based on the intended application, such as textile dyeing, ink formulation, or coatings. Different applications may require different surfactant combinations to achieve the desired color quality and performance. The study and utilization of mixed surfactant-dye interaction are significant in industries like textile, printing, paints, cosmetics, and other fields where color quality and stability are critical. By understanding and optimizing this interaction, manufacturers can enhance the efficiency, aesthetics, and overall performance of dye-based products and processes (Gohain et al., 2008).

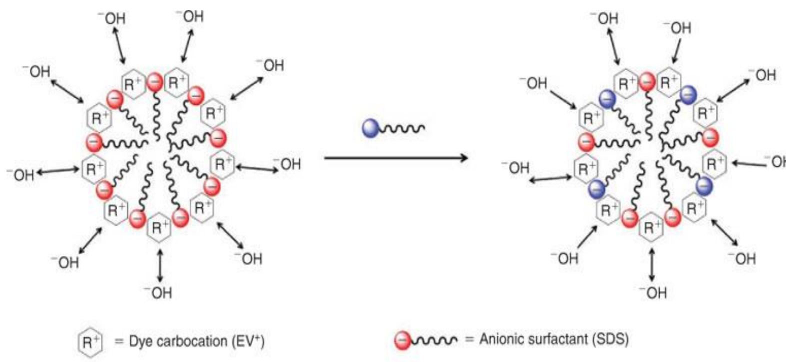

Fig. 2: Reparented the schematic diagram of mixed surfactant dye interaction. when surfactants dissolve in water and mixed solvent media (Lunkim *et al*., 2012).

1.4 Application of mixed surfactant -dye interaction

The application of mixed surfactant-dye interaction is diverse and spans across various industries. By combining surfactants with dye molecules, tailored formulations can be created to enhance color dispersion, stability, adhesion, and other properties in specific applications. Here are several key applications of mixed surfactant-dye interaction (Barni et al., 1991):

Textile dyeing: In textile dyeing, the interaction between mixed surfactants and dyes plays a vital role in achieving even color distribution, improving dye penetration, enhancing color fastness, and providing better adhesion to textile fibers. The surfactant-dye complex ensures efficient dyeing and enhances the quality of the final dyed fabric.

Inkjet printing: Formulating inks for inkjet printing involves optimizing the interaction between surfactants and dyes. The surfactant-dye combination ensures uniform dispersion and stability of dye particles, preventing nozzle clogging, and facilitating precise and high-quality printing.

Paints and coatings: The interaction between mixed surfactants and dyes is crucial in formulating colored paints and coatings. Surfactants help disperse and stabilize the dye particles within the paint or coating, ensuring uniform color distribution and long-lasting coloration on the target surface.

Cosmetics: In the cosmetics industry, mixed surfactants are used to improve the dispersion and stability of dyes in various cosmetic products like lipsticks, eyeshadows, and nail polishes. This enhances color intensity, application properties, and adherence to the skin or nails(Benkhaya et al., 2022).

Food coloring: Surfactant-dye interaction is employed in formulating food colorings. This interaction helps disperse and stabilize the dye molecules in the food product, ensuring consistent and appealing coloration while complying with safety and regulatory standards.

Printing and packaging: In the printing and packaging industry, the interaction between mixed surfactants and dyes is utilized to produce vibrant, high-quality printing inks. The formulation enhances adhesion, color consistency, and print quality, vital for marketing and branding purposes.

Biomedical and diagnostic applications: In biomedical applications, surfactant-dye interaction is used to formulate dyes for staining tissues, cells, or biomolecules for visualization and analysis under microscopy. This enhances the accuracy and clarity of the diagnostic process.

Photovoltaic devices: The efficiency of dye-sensitized solar cells (DSSCs) is influenced by the interaction between dyes and surfactants. Mixed surfactants can improve dye adsorption, stability, and electron transfer, leading to enhanced energy conversion efficiency in DSSCs. By leveraging the interaction between mixed surfactants and dyes in these applications, manufacturers can optimize color quality, stability, adhesion, and other properties, resulting in better product performance and consumer satisfaction.

2. Results and Discussion

Surfactant and dye interaction are discussed in different aspects in the below diagrams. These involve different types of interaction surfactant -surfactant, surfactant -dye, surfactant-solvent interaction.

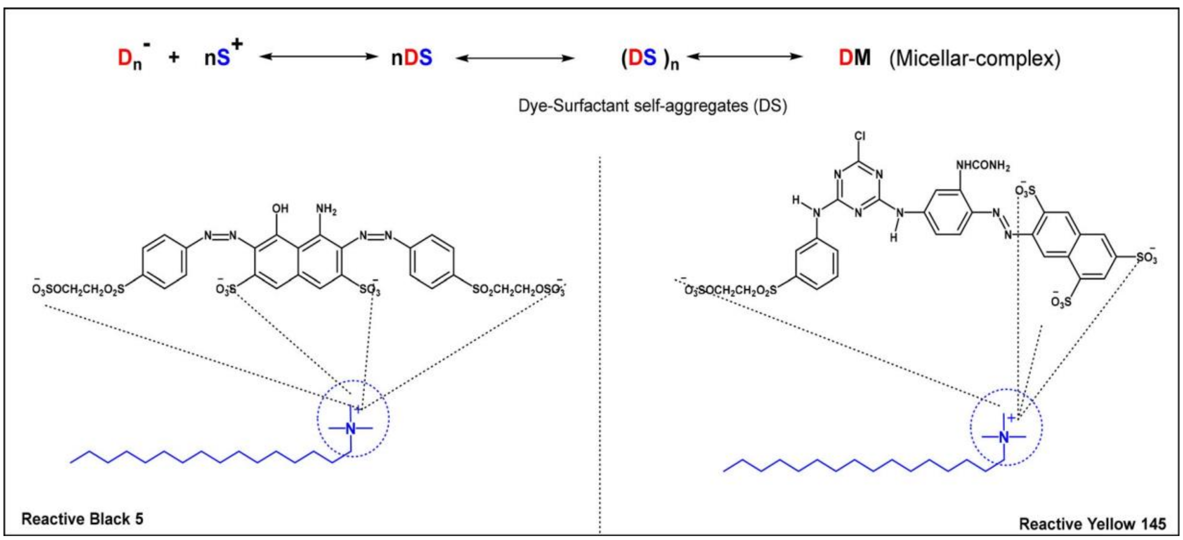

Fig. 3: Dye–surfactant aggregation and ion-pair formation of dyes (Noor *et al*., 2022)

Dye–surfactant pairs (DS) were produced in the pre-micellar area through the interaction of anionic dyes (Dn—) and cationic surfactant (Sξ). The dye-surfactant complex (DM) was produced when the DS couplings self-aggregated to form dye-surfactant aggregates (nDS), which were then entrapped in micelles (M). These aggregations formed in the post-micellar concentration area as a result of the dye molecules' adsorption onto the micelles and subsequent penetration within the micelles. The formation of ion pairs, dye association inside the surfactant micelle, and dye localization within the micelles are depicted in Figure 3. indicates where RB and RY molecules are expected to be present in single (CTAB) and mixed (CTAB TX) micelle media. The hydrophilic head group portion of the micelle and its hydrophobic core are separated by a polarity gradient. Based on their polarity and partition coefficients, different loci of dye molecules were present in the micelles of single and mixed surfactants. Because dye molecules have a high ionic character, they adapted in the micelle's palisade and core regions as opposed to adsolubilizing close to the outside region.

In the diagram explain different type of interaction. surfactant dye, surfactant-surfactant, surfactant solvent, dye-dye, hydrophobic interaction, hydrophilic interaction which is reported from (Schin .et al 2021) Cationic surfactant rich in the solution.

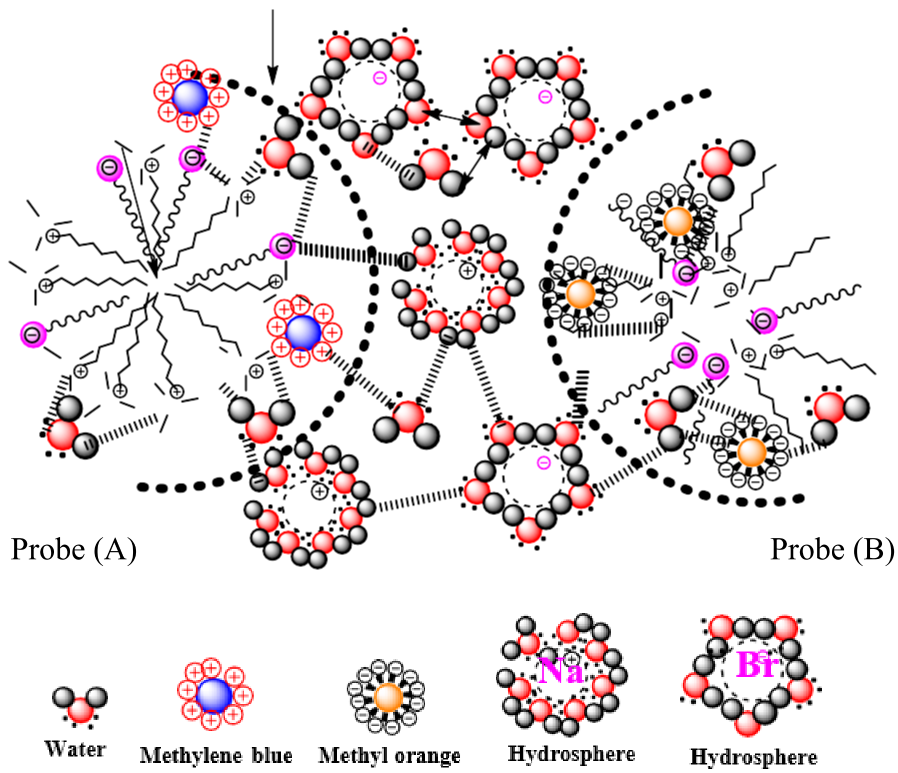

Fig. 4: Representation of micelle structure in the anionic surfactant (SDS) rich system with MB and MO (Sachin *et al.*, 2021).

MB with DTAB-rich with lower refractive index value due to weakening of intermolecular interactions (between same charges in the DTAB and MB) with CMC formation and MB used as a probe (A). MO with DTAB-rich with higher refractive index value due to strong intermolecular interactions (between opposite charges of DTAB and MO) with reverse CMC formation and MO used as a probe (B). The mixed micellar solution of CTAB rich in the surfactant dye solution was demonstrated in Figure 4 to be the most effective medium for encapsulating and entrapping the reported anionic dyes. In the single-micellar system, the data show that the dyes penetrated deeply toward the micelle core, in contrast to thin mixed-micellar media. This suggests greater solubilization and strong dye–surfactant interactions. Negative values of DGb and DGp provide credence to the process's spontaneous character. The higher negative magnitudes during the single surfactant treatment implied greater dye partitioning. Lower binding and partitioning Gibb's free energies indicated greater dye penetration into the micelles.

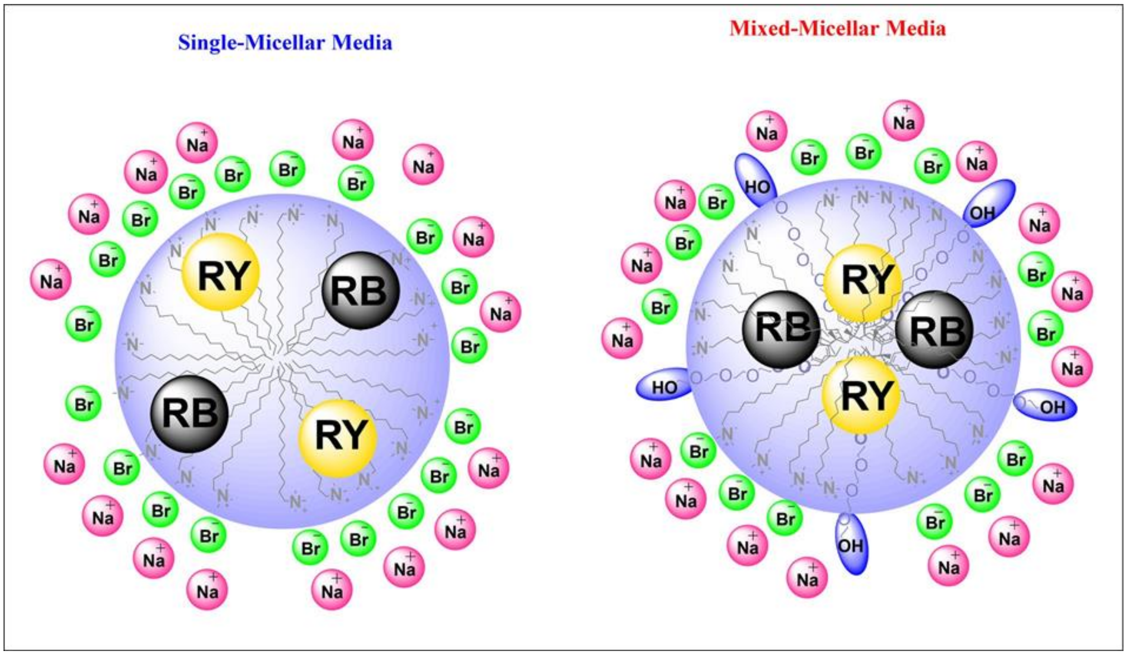

Fig. 5: Partitioning and loci of RB and RY dye molecules in single and mixed-micellar media (Noor *et al*., 2022)

The hydrophobic organic component was situated toward the tail ends of the micelle core, as were the hydrophilic head groups of surfactants. Comparable results were observed with RY dye, indicating that mixed-micelles had deeper penetration than surfactant (CTAB) micelles. According to structural investigations of RB and RY, the presence of highly dissociable anionic groups attracted the cationic groups of the surfactant. In consequence, the molecules of both dyes readjusted as they moved from the aqueous phase toward the palisade micellar region, which is situated immediately beneath the outer micellar surfaces. Higher values of the partition coefficients (Kx) of both dyes in the single-micellar media indicated their approximate position and locus in the palisade region of micelles since there was more room available than in bigger mixed-micelles of mixed micellar media. The many forms of interaction are explained in the graphic that follows. According to Schin et al. (2021), an anionic surfactant abundant in the solution, surfactant dye, surfactant-surfactant, surfactant solvent, dye-dye, hydrophobic interaction, and hydrophilic interaction.

MO with SDS-rich with lower refractive index value due to weaking of intermolecular interactions (between same charge of SDS and MO) with CMC formation and MO used as a probe (A). MB with SDS-rich with higher refractive index value due to strong intermolecular interactions (between opposite charge of SDS and MB) with reverse CMC formation and MB used as a probe (B).

3. Conclusion

In the above discussions, we can conclude that in the surfactant -dye in the solvent. There are different types of interaction. Surfactant-surfactant, surfactant solvent, surfactants -dye interaction. Among them, the interaction between surfactants and dyes is a complex and multifaceted phenomenon with significant implications for a wide range of applications. This interaction is essential for achieving desired properties and optimizing the performance of dye-related processes and products regarding surfactants-dye interaction.

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