An overview of surfactants, including their history and present-day applications

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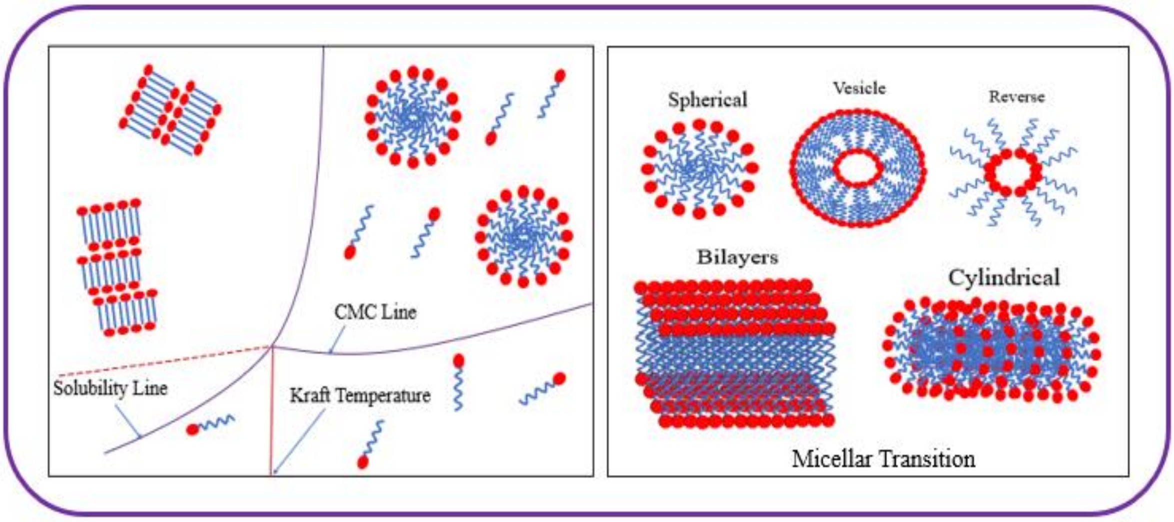
Abstract:



Surfactants are a distinct category of compounds with diverse structural properties. This article analyzes the physical properties and composition of surfactants, including their trade names, classifications, characteristics, and applications. Kraft Point, Cloud Point, and CMC are all included. The size and structure of surfactants, together with the micellar transition, are essential attributes that offer significant insights into industrial formulation. Surfactants are very interesting bio-medicinal options due to their unique amphoteric characteristics and capacity to solubilize both organic and inorganic pharmaceuticals. Surfactant self-assembly is a significant characteristic of drug delivery systems that improves the bioavailability of poorly water-soluble medicinal compounds by influencing their solubility.

Introduction:

Surfactant:

The term "surfactant" derives from surface-active agents, which are chemical compounds that reduce interfacial tension between two distinct phases by adsorbing at a surface or fluid-fluid interface. Surfactants are extensively employed compounds in many enhanced oil recovery applications due to their significance in diminishing interfacial tensions and their ability to modify wetting properties. Surfactants are categorized as amphiphilic or amphipathic molecules due to their dual structure, comprising a nonpolar (hydrophobic or hydrocarbon-attracting) segment and a polar (hydrophilic) component. The term "amphiphilic" denotes the characteristic of surfactant molecules possessing at least two components: a hydrophilic segment that is soluble in a specific fluid, such as water, and a hydrophobic segment that is insoluble in water. The origin of the word is the Greek "amphi," meaning "both." [1].

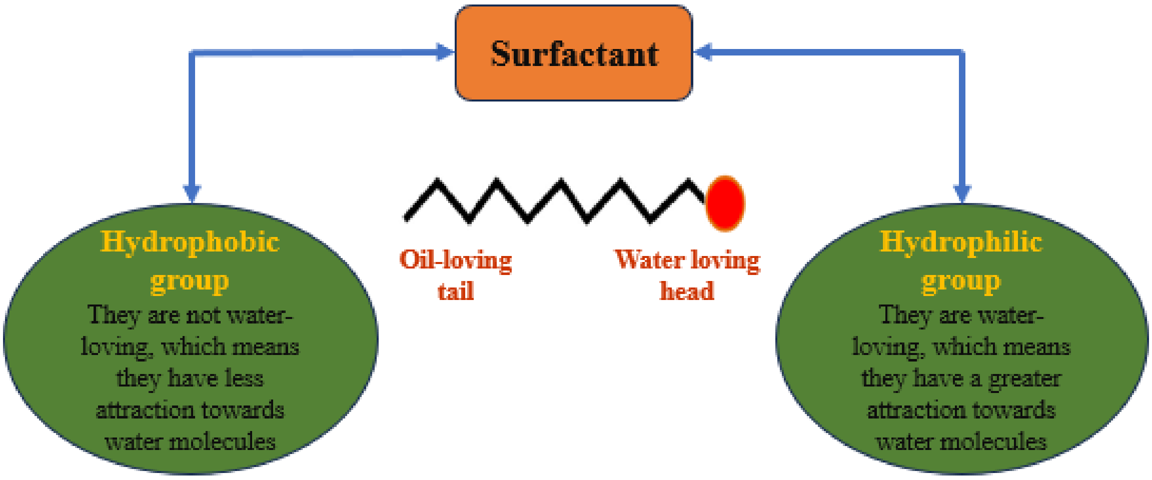


Figure 1. Surfactant-Hydrophilic and Hydrophobic

Surfactants are necessary for many technical processes, such as laundry, home, and personal care products. Depending on the particular application, the foamability of the surfactant solutions can be either a beneficial or undesirable feature in many of these systems. From a scientific and practical perspective, it is crucial to comprehend the process and identify the primary physicochemical and hydrodynamic elements that govern the foaming process [2]. Surfactants are organic compounds consisting of two chemically distinct portions with contrasting polarities: a head group that exhibits an affinity for polar phases and a tail group that is attracted to nonpolar phases. Surfactants, because of their distinctive structure, have a broad range of applications in reducing the tension between surfaces and interfaces of many phases. Their propensity to produce self-assembled structures in the solution can also result in the creation of micelles with sizes ranging from nanometers to microns. Surfactants, due to their amphiphilic properties, are well-suited for a wide range of industrial applications. These include the production of medicines, corrosion inhibitors for safeguarding metals such as steel, detergents, de-emulsifiers, wetting agents, oil recovery enhancers, pour-point depressants, pharmaceutical formulations, and drug delivery systems [3].

Self-assembly refers to the natural process in which molecules come together and form stable aggregates due to non-covalent interactions. Self-assembly is a well-acknowledged phenomenon in biological systems, such as lipid bilayers, the DNA duplex, and the tertiary and quaternary structure of proteins. The phenomenon of spontaneous aggregation of individual molecules in a solution, resulting in the formation of larger and more organized structures, is significant both in everyday life and in scientific research. An example of aggregation commonly observed in everyday life is the process by which detergent molecules form micelles in a water-based environment. The assembly of the phospholipid-based lipid bilayer membrane is the primary form of aggregation and is crucial for sustaining life. Chemists and physicists are highly interested in studying and replicating the procedures used in the production of phospholipid-based lipid bilayer membranes in different scenarios [4].

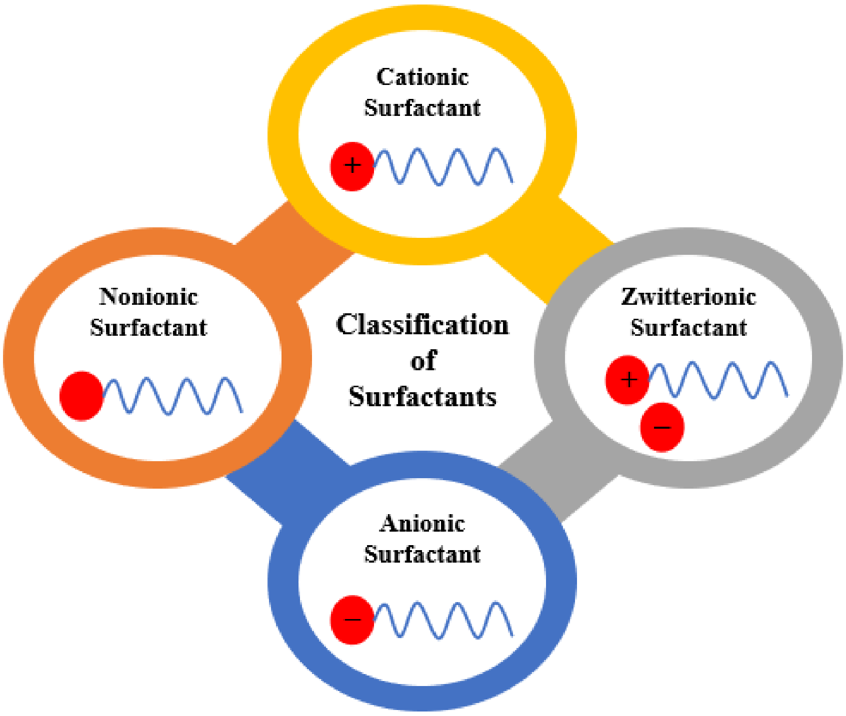


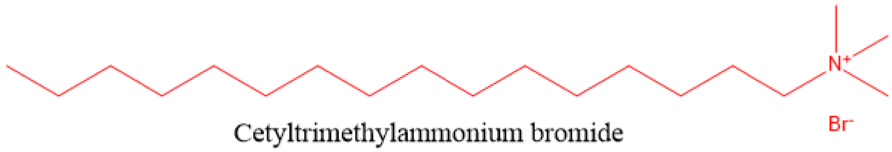
Figure 2. Classification of surfactants

Surfactants are classified into four groups. Surfactants are molecules, either ionic or nonionic, that decrease the surface tension of water when they are absorbed at the interface between air and water. Surfactants are substances that can interact with surfaces. Surfactants typically consist of amphiphilic molecules that possess a lengthy hydrocarbon tail and a polar head group. The head group of surfactants can be categorized as anionic, cationic, or nonionic, depending on whether it is negatively charged, positively charged, or uncharged, respectively [5]. There exist amphiphilic compounds with surface-active properties that possess both anionic and cationic centers in their head group. The term used to describe these substances is Zwitterionic surfactants. Double-chain surfactants refer to surfactants that possess two hydrocarbon chains connected to a polar head. Furthermore, some surfactants consist of two hydrophobic and two hydrophilic groups, which are commonly referred to as "Gemini" surfactants. Gemini surfactants can be conceptualized as surfactants composed of two conventional surfactant molecules that are chemically bonded at or near the head group. Amphiphilic molecules can possess two head groups, which can either be anionic, both cationic or one anionic and the other cationic. These head groups are connected by a hydrophobic spacer

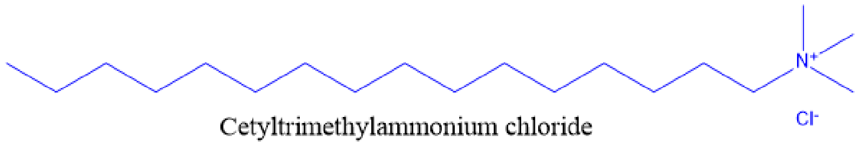
[6]. The molecules in question are referred to as "bola-amphiphiles," which are more popularly known as "bolaforms." The surface behavior of these molecules is influenced by both the length of the hydrocarbon chain and the characteristics of the head group(s). Amphiphiles possessing longer hydrocarbon chains exhibit greater surface activity in comparison to those with shorter hydrocarbon tails [7]. Amphiphiles containing a fluorocarbon chain exhibit more surface activity compared to those containing a hydrocarbon chain. The reason for this is that the fluorocarbon chain exhibits a higher degree of hydrophobicity compared to the hydrocarbon chain.

One of the main issues facing public health today is water contamination. The release of industrial effluents into aquatic habitats is a major contributing factor to the pollution of water resources. Most physical, chemical, and biological aspects of the ecosystem are impacted by industrial effluent and undergo gradual changes as a result. Paper, cardboard, textiles, coloring, and cosmetics are among the industries that produce colorful effluents. When dyes enter the environment, their complicated and dangerous molecular structures—poisonous, carcinogenic, and non-biodegradable—cause environmental difficulties. Additionally, the majority of dyes are heat- and light-resistant [8].

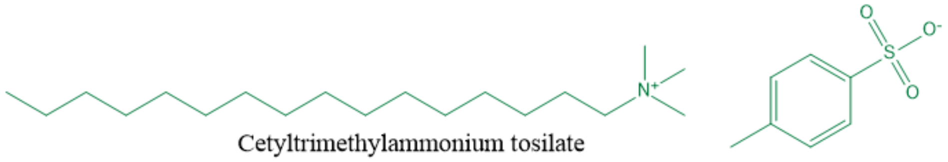
Cationic Surfactants:



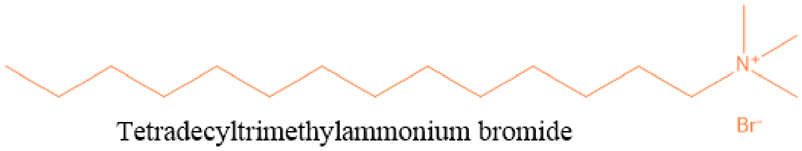
Cetyltrimethylammonium bromide
Chemical Formula: $C_{19}H_{42}BrN$



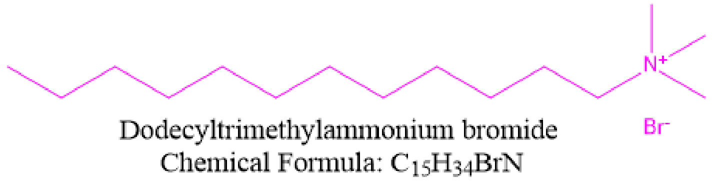
Cetyltrimethylammonium chloride
Chemical Formula: $C_{19}H_{42}ClN$



Cetyltrimethylammonium tosilate
Chemical Formula: $C_{26}H_{49}NO_3S$



Tetradecyltrimethylammonium bromide
Chemical Formula: $C_{17}H_{38}BrN$



Dodecyltrimethylammonium bromide
Chemical Formula: $C_{15}H_{34}BrN$

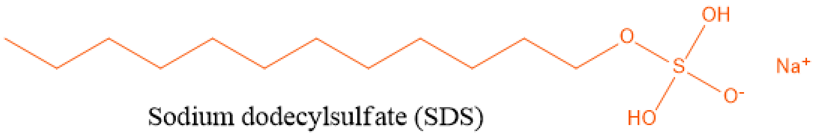
Figure 3. Cationic surfactants

Cationic surfactants are referred to as such because they have a positive charge on their polar head group. These possess an anionic counterion. Their bacteriostatic characteristics were acknowledged by Domagk in 1935, leading to their rise in popularity due to their commercial potential. This established the basis for the manufacturing of numerous commercial products. Two prevalent categories of cationic surfactants exist. The first group consists of amines, while the second group consists of quaternary amine salts. The quaternary ammonium compounds in the second group have alkyl chains with 8-18 carbon atoms [9].

The long-chain amine forms are derived from natural fats and oils or synthesized amines. They function as surfactants in their protonated state and are unsuitable for application at high pH levels. Quaternary amine cationic surfactants, which are pH-insensitive, are important for their role as fabric softeners. Cationic surfactants possess bactericidal properties. They are utilized in a wide range of businesses, including cleaning surgical equipment and creating powerful disinfectants for both household and hospital use. These industries are primarily found in the dairy and beverage sectors. It is noteworthy that many surfaces, such as metals, minerals, polymers, fibres, and cell membranes, typically carry a negative charge. As a result, cationic surfactants, which have an opposite charge, are drawn towards these surfaces. These features make them highly utilized as anticorrosion agents, fabric softeners and conditioners, antistatic agents, antiseptic agents, flotation collectors, anticaking agents, and bactericides. Two examples of common cationic surfactants are Cetyltrimethylammonium bromide (CTAB) and Cetyltrimethylammonium tosylate (CTAT).

Anionic Surfactants:

Sodium linoleate
Chemical Formula: $C_{18}H_{31}NaO_2$



Sodium dodecylsulfate (SDS)
Chemical Formula: $C_{12}H_{27}NaO_4S$

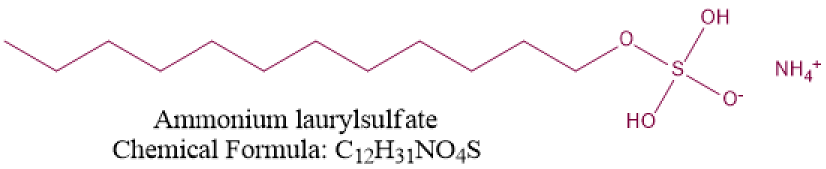


Figure 4. Anionic surfactants

These molecules consist of a negatively charged head group, making them anionic, and they also include a positively charged counterion. The non-polar tail consists of a linear alkyl group with a chain length of 12-16 carbon atoms. Anionic surfactants include carboxylates, sulfates, sulfonates, sulfosuccinates, alcohol sulfates, alkyl benzene sulfonates, phosphates, isethionates, and taurates. Sodium dodecyl sulfate (SDS) is the predominant anionic surfactant that is commonly studied. Anionic surfactants, which are the earliest type of surfactants, continue to be widely utilized in various sectors. These surfactants account for approximately 50% of global output due to their simplicity of synthesis and low cost. They possess excellent solubilizing properties and exhibit relatively low toxicity. Additionally, they are used in the processes of petroleum oil recovery and the remediation of polluted hydrogeology [10].

Nonionic surfactants:

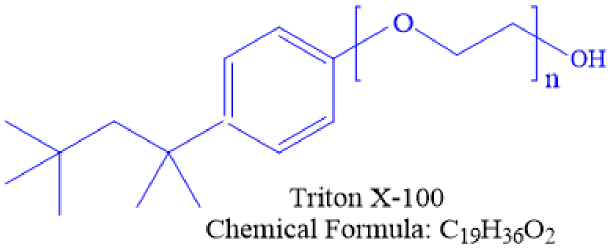


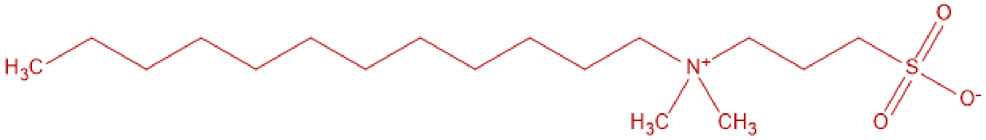
Figure 5. Nonionic surfactant

Due to the absence of charge on their head group, these molecules are nonionic and do not undergo significant ionization in water. Nonionic surfactants include polyoxyethylene alkyl phenols, alcohol ethoxylates, and alkyl phenol ethoxylates. The polar component typically consists of polyethylene glycol, with alkyl (Brijs) and alkyl aryl (Tritons) ethers widely recognized within this category. They possess excellent solubilizing properties and are often non-toxic. They have numerous uses in the petroleum and environmental sectors since they can be utilized as cosurfactants.

The surfactant solutions' physicochemical properties mostly vary with temperature. The impact of temperature on the solubility of nonionic surfactants in water exhibits a contrasting pattern compared to ionic surfactants. As the temperature rises, the solubility of nonionic surfactants generally decreases. However, there are certain nonionic surfactants derived from sugars that display an increase in solubility as the temperature rises. Triton X-100 is a highly prevalent nonionic surfactant.

Along with these, ethylene oxide-propylene oxide block (EO-PO) copolymers play a significant role as nonionic surfactants. Pluronics® (BASF) are commercially accessible water-soluble linear triblock copolymers (PEO-PPOPEO) that belong to the class of nonionic surfactants. These copolymers are widely used in diverse fields due to their numerous applications. The Pluronics® have gained significant attention over the past two decades due to their wide range of industrial and therapeutic uses. The commercially available Pluronics® include L121, P103, P105, P85, F127, and F108.

Zwitterionic or amphoteric:

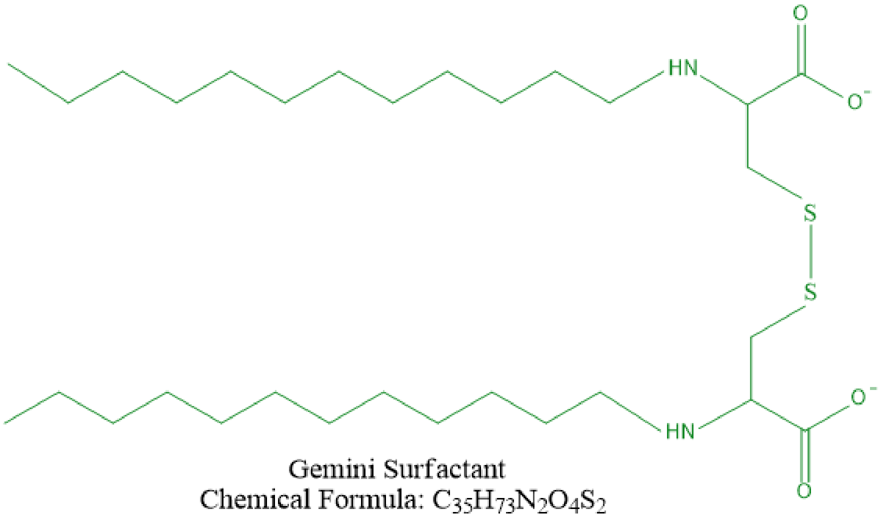


3-(Dodecyldimethylammonio)propane-1-sulfonate
Chemical Formula: $C_{17}H_{37}NO_3S$

Figure 6. Zwitterionic surfactant

The pH of the solution determines whether this type of surfactant has a positive or negative charge. At the isoelectric point, they have both negative and positive charges. These surfactants operate similarly to nonionic surfactants at the isoelectric point. On pH change, there is a gradual shift towards an anionic and cationic nature [11].

Gemini Surfactants:



Gemini Surfactant
Chemical Formula: $C_{35}H_{73}N_2O_4S_2$

Figure 7. Gemini Surfactant

Gemini surfactants consist of two hydrophobic chains and two hydrophilic groups connected by a spacer unit. The discovery of Gemini surfactants is a significant advancement in the field of surfactant chemistry. The term "Gemini surfactant," coined by Menger and Littau, is used in surfactant literature to refer to dimeric surfactants that have two hydrophilic groups and two hydrophobic tails per molecule. Gemini surfactants consist of two hydrophobic tails linked by an alkyl chain known as a spacer. The spacer varies in length, typically consisting of either a methylene spacer or an oxyethylene spacer [12]. Multiple types of Gemini surfactants are available based on the charge of the hydrophilic head group, including anionic, cationic, nonionic, zwitterionic, and hetero Gemini [13]. Gemini surfactants provide enhanced characteristics in comparison to traditional surfactants, including lower critical micelle concentration (CMC) values, lower Krafft points, decreased surface tension at the CMC, and enhanced surface activity. They are utilized in oil recovery and soil remediation, among other uses. They are utilized in gene therapy as a carrier for gene delivery into cells.

Krafft Point (KP) and Cloud Point (CP):

Ionic surfactants readily dissolve in water, and their solubility is significantly influenced by temperature. The temperature at which the solubility of surfactants sharply increases is referred to as the Krafft point (KP). Below the Krafft point (KP), the solubility of the surfactant is attributed to monomers, while beyond the KP, the solubility is attributable to the production of micelles. The Krafft point is the minimum concentration at which micelles begin to form and the lowest concentration of surfactant that offers optimal advantages. It is used to characterize a given surfactant in a particular solvent. The solubility of a surfactant at the Krafft point is referred to as the Critical Micelle Concentration (CMC) at that specific temperature [14].

At the Krafft point, the solubility of the surfactant is equivalent to its critical micelle concentration (CMC). The Krafft point is the temperature at which the alkyl chains melt, causing the surfactant crystals to dissolve into micelles and monomers, as seen in Figure 8. Understanding the Krafft temperature is essential before using a surfactant. Nonionic surfactants typically do not exhibit Krafft points. The solubility of nonionic surfactants reduces with increasing temperature, leading to phase separation at a specific temperature known as the Cloud point. This occurs when the surfactant-rich phase of inflated micelles splits, sometimes accompanied by a significant rise in dispersion turbidity [15].

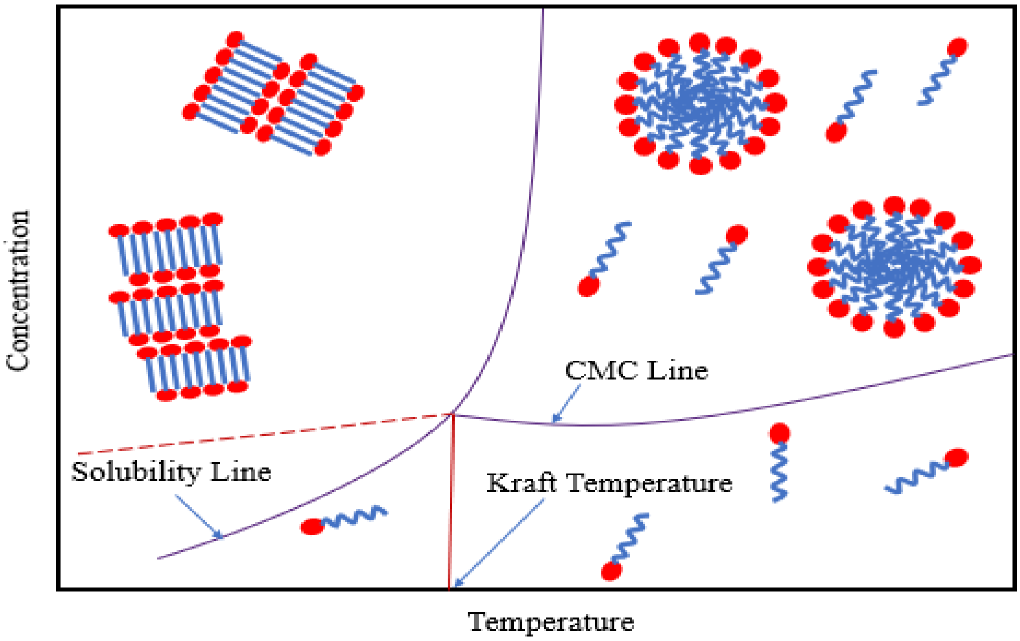


Figure 8. Kraft point

Micelle formation and CMC:

Surfactants, when dissolved in a certain solvent at low concentrations, can adsorb at interfaces and significantly change the physical properties of those interfaces. The term "interface" refers to the limit between different phases of matter, such as liquid/liquid, solid/liquid, and gas/liquid systems. In the case of gas/liquid systems, the term "surface" can also be used. The adsorption behavior is influenced by the solvent type and the chemical structure of surfactants with amphiphilic properties [16].

Surfactants are particularly suitable at the surface or interface between two immiscible phases due to their amphiphilic character. Surfactants adsorb at the air-water interface in aqueous solutions, influenced by both attractive and repulsive forces. Surfactant molecules adsorb by shifting their hydrophobic tails away from water at the air-water interface, while their hydrophilic heads remain in contact with water. At a specific concentration of surfactant, the interface becomes saturated, causing surfactant molecules to be drawn into water and form aggregates called micelles. This concentration level is referred to as the critical micelle concentration (CMC) [17]. In a micelle structure, the non-polar tails are oriented toward the interior of the aggregate, while the polar head groups face toward the solvent. Surfactant micelles are colloids that are not stable due to being in dynamic equilibrium with their unassociated components. Micelles in solution are in a constant state of equilibrium, continuously forming and breaking apart. The kinetics of micellization are primarily influenced by the surfactant's structure.

The driving factor behind surfactant adsorption at an interface is the reduction of the free energy of the interface, also known as surface tension (γ), which is directly proportional to the work required to expand the surface/interface. The drop in the system's free energy is due to the weak interaction between the hydrocarbon tail and water molecules in the micelle. Micellization is a spontaneous process. The reduction in γ and CMC is influenced by the surfactant's structure and the characteristics of the two non-mixing phases that collide at the interface.

Surfactants, when dissolved in an aqueous solution, reduce the hydrogen bonding between water molecules. The decrease in entropy is believed to result from the disruption of the typical hydrogen-bonded arrangement of water, leading to the formation of a clathrate-like structure of water around the hydrocarbon chain of the surfactant, often referred to as icebergs. The highly organized clathrate cages lead to the disruption of the typical hydrogen-bonded structure, causing a decrease in water entropy and consequently reducing the overall entropy of the system. To offset this entropy change, the non-polar tail of the surfactant associates and reduces the number of water molecules involved in constructing the clathrate cage. Therefore, this entire process is energetically advantageous but unfavorable in terms of entropy.

Hydrophobic tails interact at a specific concentration of surfactant due to unfavorable entropy changes known as the hydrophobic interaction. Micelle production has a dual effect on the system's entropy. The micelle has a highly uniform structure, which reduces the system's entropy. The increase in entropy occurs due to the breaking of the clathrate cages, allowing water molecules to return to the bulk solution, thus raising the total entropy of the system. Micellization is a spontaneous phenomenon driven by entropy.

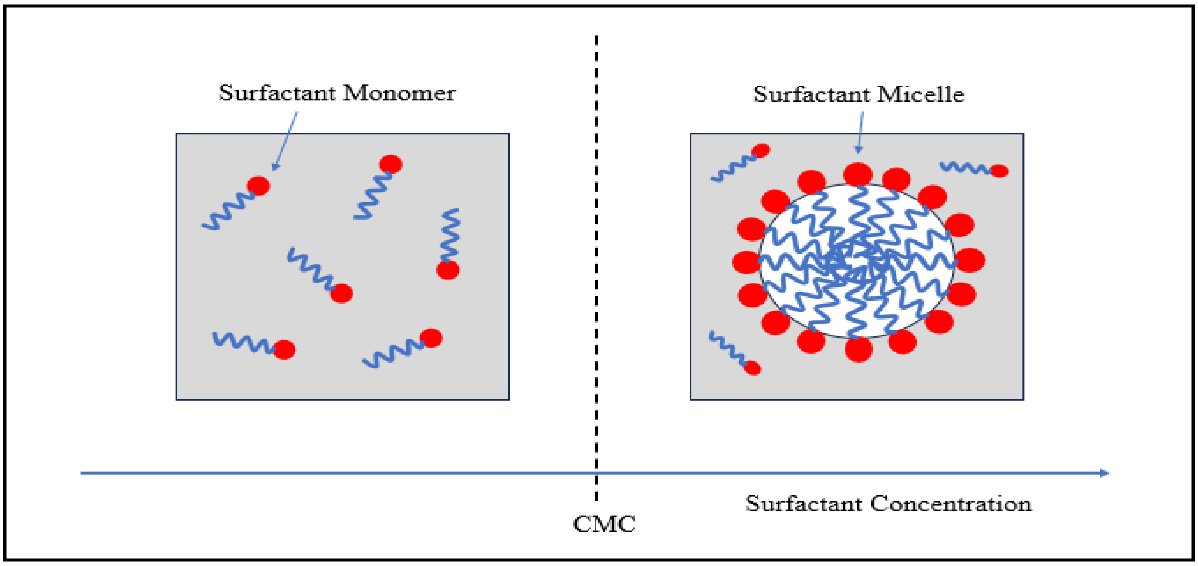


Figure 9. Micelle Formation and CMC

Mixed Micelles:

Surfactant efficiency can be enhanced by blending them with other surfactants to customize their characteristics for specific uses. Surfactant combinations are commonly utilized in industrial applications due to their enhanced qualities in comparison to their constituents. Thus, mixed surfactant systems are utilized in nearly all practical applications of surfactants instead of using a single surfactant. Mixed micelles can originate from many sources. The variability in the size of commercial surfactants or the presence of contaminants during manufacturing may often be the cause. Additionally, the cost of producing combinations is lower than that of their isomerically single counterparts and often exhibits superior physicochemical properties compared to single pure surfactants. Surfactant systems with diverse structures are of greater theoretical and industrial significance [18]. Some mixed micellar systems exhibit synergistic behavior. Typically, a mixed micelle refers to a micelle composed of surfactants. However, when solubilizates are added to surfactant micelles, mixed micelles are also formed. Aggregation tendency is influenced by the attractive synergism and repulsive antagonism interactions, reflecting the critical micelle concentration (CMC) values in comparison to individual elements. Mixed surfactant systems exhibit enhanced adsorption at surfaces at low concentrations by forming mixed monolayers, which reduces surface tension. Surfactant monomers over the critical micelle concentration (CMC) co-operatively self-aggregate in the solution to create mixed micelles. Various methods are employed to ascertain the critical micelle concentration (CMC) and to get insight into the structure of mixed micelles [19]. Mixed micellization can result in both ideal and nonideal mixing. The hydrophobic effect is not specific to the surfactant head group, leading to the formation of randomly mixed surfactant aggregates. This suggests ideal mixing components. However, in mixtures with different surfactants, non-ideal mixing occurs due to electrostatic repulsion between the polar head groups. Reduced critical micelle concentrations and surface tensions in mixed systems compared to individual surfactant systems often result in synergistic effects due to the non-ideal interactions of the components. Mixed micelles exhibit behavior that is of significant importance for understanding the performance of mixed surfactant systems. This knowledge can be applied in different fields such as detergency and increased oil recovery. Multiple studies have been conducted on mixed micellar systems that consist of a diverse array of surfactant types, such as combinations of nonionic, anionic, and cationic systems, as well as their binary blends with zwitterionic surfactants [20-22]. Mixed surfactant systems, including surfactants with different structures, are of significant interest in theoretical and industrial fields [23].

Various theoretical models have been proposed to comprehend the assembly of mixed micelles. Lange was the first to suggest a model that Clint used [24], which assumes the optimal mixing of surfactants in the micellar phase according to the phase separation model. Rubingh provided a model for nonideal mixed systems based on regular solution theory (RST) [25], which is widely utilized by several research groups [26]. Rosen and colleagues [27, 28] Conducted an in-depth analysis of Rubingh's nonideal solution approach for establishing mixed micelles in binary mixed surfactant systems [25]. They used surface tension data to assess the molecular interactions and positioning of surfactants in the adsorbed mixed monolayer at the air/water interface. Maeda's method is utilized to characterize the stability of mixed ionic-nonionic surfactant systems [29].

Over the past few years, research on the combined micellization of Gemini surfactants with traditional surfactants, mostly ionic and non-ionic ones, has grown increasingly common. These mixes are more appealing because of the synergistic properties between the surfactants. The investigation of synergism in mixtures containing Gemini and conventional surfactants is focused on the development of micelles and monolayers at the air-water interface [29, 30]. The study investigated the significant influence of non-polar chain length and spacer group length on the interactions of conventional and dimeric surfactants in mixed micelles, as well as the non-ideality of binary monomeric-dimeric surfactant mixes.

Micellar Aggregation Number (Nagg)

The "aggregation number" (Nagg) is defined as the total quantity of surfactant monomers or ions present in a micelle. Techniques such as light scattering, osmometry, and fluorescence are employed to determine Nagg. It mostly relies on the molecular characteristics of surfactants and several environmental conditions, including temperature, pressure, pH, and nonpolar solubilizates [31].

The CMC and Nagg show divergent patterns. In aqueous conditions, an increase in the carbon atom count of the non-polar tail leads to a decrease in the critical micelle concentration (CMC), resulting in an increase in the aggregation number (Nagg). Lower Nagg is ascribed to the repulsion between the polar head groups of ionic surfactants and those of nonionic surfactants. Surfactant micelles exhibiting a significant degree of counterion binding have elevated Nagg values. An increase in the size or charge of the polar part (head group) of an ionic surfactant, for a given chain length, results in intramicellar repulsions and raises the system's free energy. Such systems mostly exhibit low Nagg.

For nonionic polyoxyethylenated surfactants, Nagg diminishes as the polyoxyethylene block increases. This can be attributed to the increased steric barrier resulting from the hydration of the additional oxyethylene groups. The presence of electrolytes in ionic surfactant systems facilitates charge neutralization and enables denser packing of surfactants within the micelle, hence elevating the critical micelle concentration (CMC). In the case of nonionic surfactants, the influence of electrolytes on the Nagg remains confusing, as both increases and decreases in Nagg have been seen.

For nonionic surfactants, an increase in temperature leads to a reduction in the hydration of the nonpolar tail, hence promoting micellization. Furthermore, an increase in temperature leads to the rupture of the structured water surrounding the non-polar tail, hence inhibiting micellization. Ionic surfactants typically exhibit a reduction in Nagg with increasing temperature, whereas nonionic surfactants show an opposing trend.

Micellar size and shape

Micelles exhibit a spherical morphology around the critical micelle concentration (CMC), but they may adopt various geometries at higher solution concentrations. Surfactants create aggregates of various forms, as enumerated in Figure 10. [32]. Ionic surfactants frequently produce smaller micelles (Nagg ~10-100), in contrast to nonionic surfactants (Nagg > 100). This is attributable to the electrostatic repulsion among charged head groups in ionic surfactants being greater than the steric repulsion among head groups in non-ionic surfactants. So, we can say that the structure of the surfactant, specifically the relative sizes of the hydrophilic head group and the hydrophobic tail, affects how the micelle forms. The equilibrium assembly is controlled by the conflict between the head group's desire to bind to the solvent and the hydrocarbon tails' desire to avoid interacting with the solvent as much as possible. The micelle structure may vary in shape, ranging from spherical to rod-like, disc-like, or lamellar forms.

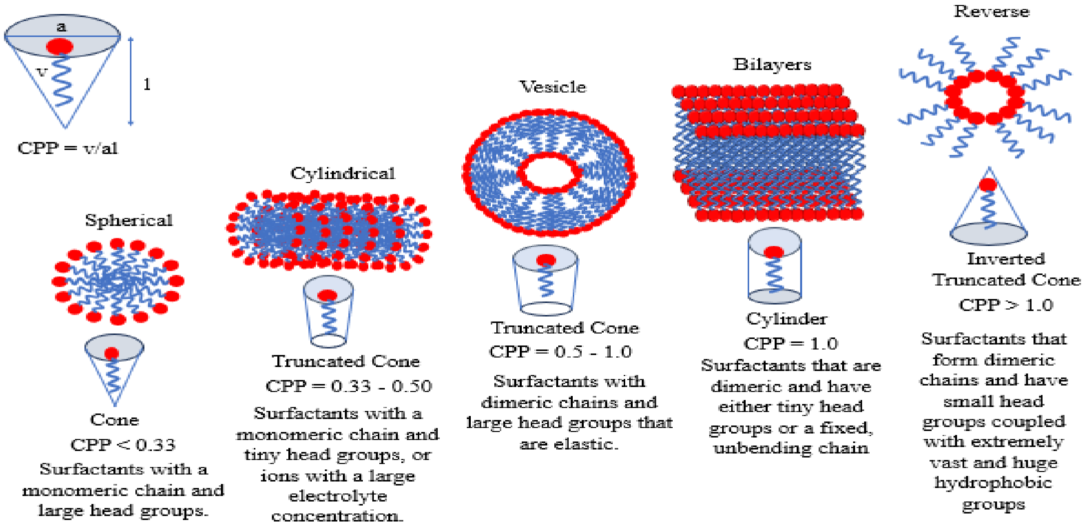


Figure 10. Various configurations of surfactant molecules and the parallel shape of micelles.

Israelachvili and colleagues [19] claimed that the packing parameter theory is the most effective framework for comprehending the self-aggregation of surfactants. The primary factor in this expansion is the dimensionless ratio known as the packing parameter P, which is the ratio of the volume v of the non-polar tail to the product of the area a occupied by the polar head and the chain length l of the non-polar tail of the surfactant.

$$P = \frac{v}{a \,\mathrm{x}\, l}$$

Surfactant molecules exhibit a conical shape when P~0.33, resulting in the formation of spherical micelles. If the shape resembles a truncated cone, it results in cylindrical micelles with a P value ranging from 0.33 to 0.5. Suppose P > 0.5, cylindrical-shaped micelles and bilayer micelles are anticipated to form from surfactant molecules. For disk-shaped structures and vesicles, the value of P should be between 0.5 and 1.0, predominantly nearer to one. Surfactants with a truncated inverted cone shape possess a P value greater than 1 and create reversal structures. Diverse configurations of surfactant molecules and their resultant micellar architecture. They are enumerated in Table 1. Micellar transformations in aggregates from one form to another are contingent upon solution variables such as electrolyte concentration and pH.

General Uses and Applications

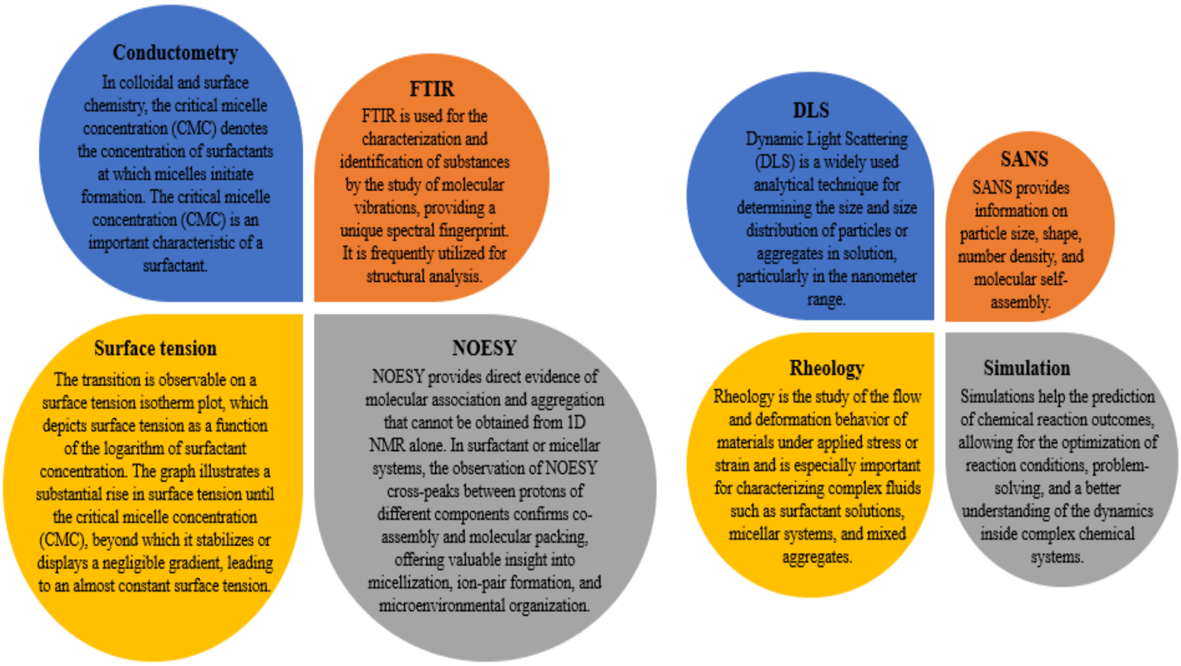
- **Household and Industrial Cleaning:** A primary application is in detergents, soaps, and cleansers that emulsify and remove dirt, grease, and oils by combining them with water [33, 34]. Surfactant breaks down the contact between oil and water, allowing dirt and oil to remain suspended. This enables their removal. Surfactants can do this because they contain both hydrophilic and hydrophobic groups. Since antiquity, soap has been made by saponifying glycerides, oils, and lipids with NaOH or KOH and producing glycerol as a by-product. Although soap is the finest detergent, it is susceptible to acidic pH and hard water. To be an effective detergent, a surfactant must have a good wetting agent, a good solubilizing agent, and the ability to remove oil from washing fluid.

- **Cosmetics:** Emulsifies water and oil to give lotions and creams a stable, smooth texture. By making it easier for items to distribute across surfaces like the skin or lips, they guarantee more even dispersion. Certain surfactants may provide moisturizing and softening properties to the skin and hair. Surfactants may serve as thickening agents in cosmetic formulations. In lipsticks, they facilitate the dispersion of insoluble pigments, resulting in a smooth and consistent shade [35, 36].
- **Food Industry:** Assist in enhancing product texture, stabilizing emulsions, and assuring uniform distribution of ingredients in beverages [37, 38]. Surfactants are used in the production of food products for oil solubilization, liquor emulsification, and cholesterol extraction. Nonionic surfactants are the most prevalent type of surfactant used as a food emulsifier in the food industry. Low-mass surfactants have great mobility at the interface and can help reduce interfacial tension. As a result, they frequently cover the newly formed oil-water interface in the emulsification process. Examples include lecithin, monoglycerides, and glycolipids. A high-mass surfactant coats the protein and carbohydrate groups. The opposite charge on the protein attaches to the surfactant's head group. Surfactants with small molecules and polysaccharides are two significant groups of surfactants that are used in the stabilization of emulsions and have a wide range of potential applications in food [39]. The most frequent example is air cell formation in ice cream [40].
- **Paints and Coatings:** Promote the emulsification of oils and enhance adhesion, hence augmenting the overall quality of paints. They are utilized to uniformly distribute pigments and fillers inside the paint mixture, which is essential for color constancy and opacity. Surfactants inhibit the aggregation of pigments (flocculation). In the emulsion polymerization process for producing latex binders, surfactants stabilize the polymer particles, enhancing the shelf-life, mechanical stability, and freeze-thaw stability of the resultant paint [41, 42].

- **The textile industry:** Surfactants facilitate the uniform penetration of dyes and other chemicals into fibers throughout dyeing and manufacturing processes. Surfactants work as fabric softeners to impart a smooth, soft texture to fabrics and as antistatic agents to inhibit the accumulation of static electricity. Certain surfactants function as fiber lubricants, diminishing friction and facilitating the smoother processing of yarns and fabrics [43, 44].
- **Personal Care Products:** Used in shampoos, body washes, conditioners, and toothpaste to generate lather, cleanse, and facilitate the emulsification of oil and water-based components [33, 45].
- **Pharmaceuticals:** Active in drug formulation to enhance the solubility of poorly soluble pharmaceuticals, hence enhancing their efficacy and absorption in the body. Specific polymeric surfactants are utilized to alter medication release, resulting in prolonged or delayed-release formulations. In complex systems such as liposomes and nanoparticles, surfactants are crucial for constructing the vesicular structures that encapsulate and transport medications to designated destinations. Cationic surfactants frequently possess antibacterial characteristics and are utilized as preservatives in formulations and as disinfectants for wounds [34, 46-48].
- **Agriculture:** Utilized in pesticide and herbicide formulations to enhance the dispersion and adhesion of sprays on plant surfaces [49-53]. Surfactants reduce the surface tension of herbicide, pesticide, and fungicide spray solutions, allowing for closer contact between plant surfaces and spray droplets. It brings pesticides into direct contact with the surface of the leaf, and pesticides are thus used as crop protectors. Surfactants commonly used in herbicides include ethoxylated alcohol, alkylphenols, alkylamines, and sorbitan [54].
- **Oil and Mining Industries:** Utilized in oil extraction to facilitate the mobilization of oil inside subterranean reservoirs and in ore flotation to isolate important minerals. They are used to avoid wellbore instability, regulate shale expansion, and inhibit drill cuttings from adhering to the apparatus. In coal mining, surfactants can aggregate fine coal dust, enabling it to be transported similarly to heating oil. They function as collectors in flotation, facilitating the separation of valuable minerals from waste rock [55-57].
- Water pollution is one of the biggest environmental issues that humans face worldwide, particularly in underdeveloped nations, where the most contaminated water is caused

by harmful synthetic organic chemicals. Water pollution caused by organic contaminants primarily occurs due to the discharge of these contaminants during industrial manufacturing processes or the application of pesticides to crops. The harmful and detrimental effects of these organic pollutants have a direct influence on both human health and ecology. Consequently, there has been a recent surge in the desire to discover efficient treatments and methodologies for remedying polluted water or chemical effluent. Several published studies have focused on the removal of organic contaminants from wastewater using various remediation strategies. Among the employed approaches, sorption is the most promising and commonly applied technique for removing pollutants in general from the environment because of various advantages offered in simplicity, energy saving, cost-effectiveness, and efficiency. A wide range of adsorbents, such as fly ash, carbon nanotubes, bentonite, clay, charcoal, activated carbon, agricultural wastes, composites, and grafted polymer, have been documented in the literature for their ability to adsorb organic contaminants from polluted wastewater [58].

Different Techniques have been used for analysis:



Conductometry

In colloidal and surface chemistry, the critical micelle concentration (CMC) denotes the concentration of surfactants at which micelles initiate formation. The critical micelle concentration (CMC) is an important characteristic of a surfactant.

FTIR

FTIR is used for the characterization and identification of substances by the study of molecular vibrations, providing a unique spectral fingerprint. It is frequently utilized for structural analysis.

Surface tension

The transition is observable on a surface tension isotherm plot, which depicts surface tension as a function of the logarithm of surfactant concentration. The graph illustrates a substantial rise in surface tension until the critical micelle concentration (CMC), beyond which it stabilizes or displays a negligible gradient, leading to an almost constant surface tension.

NOESY

NOESY provides direct evidence of molecular association and aggregation that cannot be obtained from 1D NMR alone. In surfactant or micellar systems, the observation of NOESY cross-peaks between protons of different components confirms co-assembly and molecular packing, offering valuable insight into micellization, ion-pair formation, and microenvironmental organization.

DLS

Dynamic Light Scattering (DLS) is a widely used analytical technique for determining the size and size distribution of particles or aggregates in solution, particularly in the nanometer range.

SANS

SANS provides information on particle size, shape, number density, and molecular self-assembly.

Rheology

Rheology is the study of the flow and deformation behavior of materials under applied stress or strain and is especially important for characterizing complex fluids such as surfactant solutions, micellar systems, and mixed aggregates.

Simulation

Simulations help the prediction of chemical reaction outcomes, allowing for the optimization of reaction conditions, problem-solving, and a better understanding of the dynamics inside complex chemical systems.

Diverse methodologies have been applied to studying the generation and properties of micelles in aqueous surfactant solutions. Methods such as conductometry [17, 59-61], surface tension [62-65], viscometry [66-69], and rheology [70, 71] have been used. Among the mentioned methodologies, microscopy, spectroscopic, and scattering techniques are extensively employed to ascertain the structure and microenvironment of the constituent system. These include Fourier Transform Infrared Spectroscopy (FTIR) [72-74], Nuclear Magnetic Resonance (NMR/NOESY) [75-78], Dynamic Light Scattering (DLS) [79, 80], and Small-Angle Neutron Scattering (SANS) [81-84].

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