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Role of Surfactants in Emulsions and Detergency Action

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Abstract

Surfactants are surface-active agents that play a crucial role in emulsification and detergency due to their unique amphiphilic molecular structure. This paper examines the fundamental mechanisms through which surfactants facilitate the formation and stabilization of emulsions and enhance the cleaning process in detergency applications. In emulsions, surfactants reduce interfacial tension between immiscible liquids such as oil and water, enabling the dispersion of one phase into another while preventing coalescence through the formation of a protective interfacial layer. In detergency action, surfactants contribute to effective soil removal by improving wetting, emulsifying oily contaminants, dispersing particulate matter, and solubilizing grease within micelles. The efficiency of these processes is influenced by factors such as surfactant type, concentration, critical micelle concentration, temperature, and the nature of the soil or substrate. The study also highlights the growing importance of biodegradable and environmentally benign surfactants in response to increasing sustainability concerns. Overall, the paper emphasizes the significance of surfactants in industrial formulations and household applications, while underlining the need for continued research toward high-performance and eco-friendly surfactant systems.

Keywords: Surfactants, Emulsification, Detergency action, Micelle formation, Interfacial tension

Background of the Study

Surfactants have been an integral component of human activity for centuries, beginning with the use of natural soaps and evolving into highly specialized chemical agents used across diverse industries. Their importance lies in their ability to alter surface and interfacial properties, enabling interactions between otherwise immiscible substances such as oil and water. In the context of emulsions, surfactants are essential for creating stable dispersed systems that are widely applied in food products, pharmaceuticals, cosmetics, agrochemicals, and industrial formulations. Similarly, in detergency action, surfactants form the core of cleaning agents by facilitating the removal of oily and particulate soils from fabrics and solid surfaces through wetting, emulsification, and micellar solubilization. With rapid industrialization and increased consumer demand for efficient cleaning and stable formulations, the use of surfactants has expanded significantly. However, concerns related to environmental persistence, toxicity, and biodegradability of conventional surfactants have also emerged. This background underscores the need to study the role, mechanisms, and sustainability aspects of surfactants in emulsions and detergency action to support improved performance and environmentally responsible applications.

Scope of the Study

The scope of this study encompasses a comprehensive examination of the role of surfactants in emulsion formation and detergency action, focusing on their physicochemical properties, mechanisms, and practical applications. The study covers the structural characteristics of surfactants and their influence on interfacial behavior, micelle formation, and stability of emulsions. It also includes an analysis of detergency mechanisms such as wetting, emulsification, dispersion, and solubilization of soils from various substrates. Emphasis is placed on different classes of surfactants and their performance under varying conditions, including concentration, temperature, pH, and water hardness. Additionally, the study considers industrial and household applications, highlighting recent developments in formulation technology. Environmental aspects, including biodegradability and the shift toward eco-friendly and bio-based surfactants, are also within the scope. Overall, the study aims to provide a foundational understanding useful for academic research, industrial formulation, and sustainable product development.

Definition and Classification of Surfactants

Surfactants, commonly referred to as surface-active agents, are substances that reduce surface or interfacial tension when present at low concentrations, thereby facilitating interaction between immiscible phases such as oil and water. This behavior arises from their distinctive amphiphilic molecular structure, which consists of a hydrophilic (polar) head group and a hydrophobic (non-polar) hydrocarbon tail. When added to a liquid system, surfactant molecules preferentially adsorb at interfaces—such as air–water, oil–water, or solid–liquid interfaces—aligning their hydrophilic heads toward the aqueous phase and hydrophobic tails away from it. This orientation disrupts cohesive forces within the liquid, leading to reduced surface tension and enhanced wetting, emulsification, detergency, and dispersion. Based on the nature of the hydrophilic head group, surfactants are broadly classified into four main categories: anionic, cationic, non-ionic, and zwitterionic (amphoteric) surfactants. Anionic surfactants possess negatively charged head groups and are widely used in detergents and soaps due to their excellent cleaning and foaming properties. Cationic surfactants carry positively charged head groups and are commonly applied as fabric softeners, disinfectants, and antimicrobial agents. Non-ionic surfactants have uncharged hydrophilic groups, making them less sensitive to water hardness and temperature variations, which enhances their stability and versatility in industrial applications. Zwitterionic surfactants contain both positive and negative charges within the same molecule, offering mildness, high compatibility, and effectiveness over a wide pH range. This classification framework is fundamental for selecting appropriate surfactants for emulsification and detergency applications.

Importance of Surfactants in Emulsification and Detergency

Surfactants are of critical importance in both emulsification and detergency due to their unique ability to modify surface and interfacial properties, enabling effective interaction between immiscible substances. In emulsification, surfactants play a central role by reducing the interfacial tension between oil and water, which facilitates the dispersion of one liquid phase into another in the form of fine droplets. By adsorbing at the oil–water interface, surfactant molecules form a stabilizing interfacial film that prevents droplet coalescence and phase separation, thereby enhancing the stability and shelf life of emulsions. This property is vital in numerous applications, including food products, pharmaceuticals, cosmetics, agrochemicals, and industrial formulations, where uniformity and consistency are essential. In detergency, surfactants are indispensable components of cleaning agents, as they enable the efficient removal of dirt, grease, and oily stains from fabrics and solid surfaces. Through their wetting action, surfactants reduce the surface tension of water, allowing it to spread more easily over solid surfaces and penetrate fibers. They also emulsify oily soils, breaking them into smaller droplets that can be suspended in water and removed during rinsing. Additionally, surfactants facilitate dispersion of particulate matter and solubilize hydrophobic contaminants within micelles, preventing re-deposition onto cleaned surfaces. The effectiveness of surfactants in both emulsification and detergency depends on factors such as molecular structure, concentration, and environmental conditions. Overall, surfactants are fundamental to achieving efficient, stable, and reliable performance in emulsified systems and cleaning processes across domestic and industrial applications.

Fundamental Chemistry of Surfactants

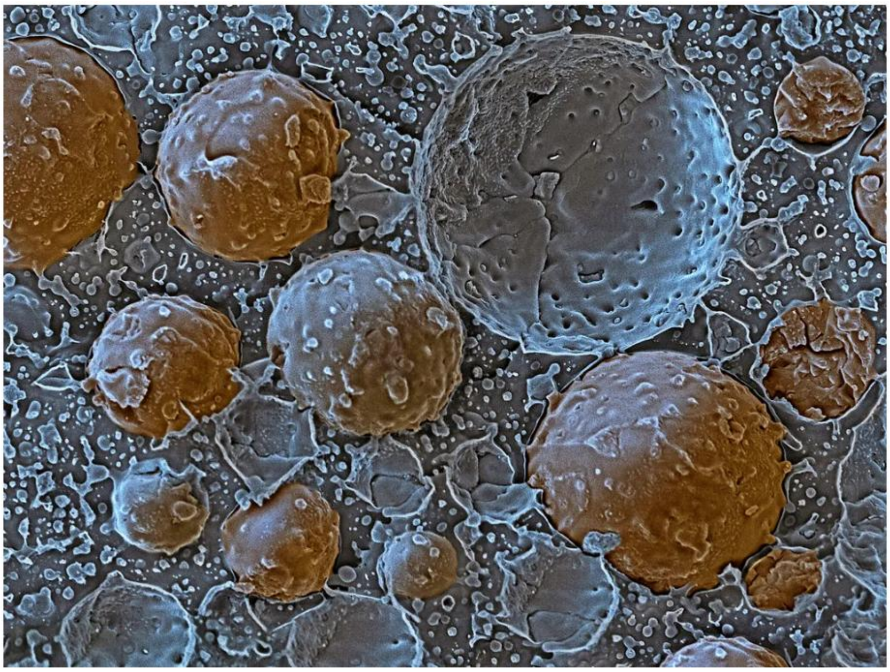
The fundamental chemistry of surfactants is rooted in their distinctive amphiphilic molecular structure, which enables them to interact simultaneously with polar and non-polar phases. Each surfactant molecule consists of two contrasting parts: a hydrophilic (water-loving) head group and a hydrophobic (water-repelling) tail, typically composed of a long hydrocarbon chain. This dual nature drives surfactants to orient themselves at interfaces such as air–water, oil–water, or solid–liquid boundaries, with the hydrophilic head immersed in the aqueous phase and the hydrophobic tail directed away from it. Such orientation disrupts intermolecular forces within the liquid, leading to a reduction in surface and interfacial tension. As a result, processes such as wetting, emulsification, dispersion, and detergency become thermodynamically favorable. Based on the chemical nature and charge of the hydrophilic head group, surfactants are broadly classified into four main types: anionic, cationic, non-ionic, and zwitterionic surfactants. Anionic surfactants carry a negatively charged head group, commonly sulfate or sulfonate based, and are widely used in detergents and soaps due to their strong cleansing and foaming abilities.

Cationic surfactants possess positively charged head groups, often quaternary ammonium compounds, and are valued for their antimicrobial properties, making them useful in disinfectants, fabric softeners, and antiseptic formulations. Non-ionic surfactants have uncharged hydrophilic head groups, usually composed of polyoxyethylene chains, which provide high stability across a wide range of temperatures and water hardness conditions. Zwitterionic or amphoteric surfactants contain both positive and negative charges within the same molecule, offering mildness, high compatibility, and effectiveness over a broad pH range, particularly in personal care products. A key aspect of surfactant chemistry is their influence on surface tension and interfacial phenomena. By accumulating at interfaces, surfactants lower the free energy of the system, promoting the formation of micelles above a specific concentration known as the critical micelle concentration (CMC). These micelles play a crucial role in solubilizing hydrophobic substances in aqueous media. Thus, the chemistry of surfactants underpins their essential role in emulsions and detergency action across industrial and domestic applications.

Mechanism of Emulsion Formation

An emulsion is a heterogeneous system consisting of two immiscible liquids, typically oil and water, where one phase is dispersed as fine droplets within the other. Since emulsions are thermodynamically unstable by nature, they require stabilizing agents—primarily surfactants—to maintain their structure over time. Emulsion stability refers to the ability of the dispersed droplets to resist coalescence, creaming, flocculation, or phase separation during storage and use. The oil–water interface plays a central role in emulsion formation, as it represents a region of high interfacial free energy due to the immiscibility of the two phases.

Surfactants facilitate emulsion formation by adsorbing at this interface, orienting their hydrophobic tails toward the oil phase and hydrophilic heads toward the aqueous phase. This molecular arrangement significantly reduces the interfacial tension between oil and water, making it energetically favorable to disperse one liquid into the other as small droplets during mechanical agitation or homogenization.



The role of surfactant in emulsion

The reduction of interfacial tension is a critical step, as lower tension allows the formation of finer droplets, which enhances emulsion stability by increasing surface area and reducing the likelihood of droplet coalescence. In addition to stabilizing droplets at the interface, surfactants also form micelles in the continuous phase when their concentration exceeds the critical micelle concentration (CMC). These micelles can solubilize small amounts of the dispersed phase and contribute to the dynamic stability of the emulsion system. Several factors influence emulsion stability, among which the Hydrophilic–Lipophilic Balance (HLB) value of the surfactant is particularly important. The HLB value determines whether a surfactant is more suitable for forming oil-in-water (O/W) or water-in-oil (W/O) emulsions. Temperature also affects emulsion stability by altering surfactant solubility, viscosity, and interfacial film strength, potentially leading to phase inversion or breakdown at extreme conditions. Similarly, pH can influence the ionization state of ionic surfactants, thereby affecting their interfacial behavior and emulsifying efficiency. Together, these interrelated mechanisms explain how surfactants enable the formation and stabilization of emulsions across a wide range of industrial and biological applications.

Emulsion Production Services

Our organization provides advanced emulsion production services that harness the critical role of surfactants in achieving effective emulsion formation and long-term stability. Supported by a team of experienced researchers, we apply core principles of colloid and surface science to design customized emulsion systems that meet specific functional, quality, and performance requirements. This scientific approach ensures the consistent production of high-quality, stable emulsions tailored to diverse industrial applications.In the pharmaceutical sector, our expertise focuses on utilizing surfactant-based systems for efficient drug delivery. The ability of surfactants to form micelles—structures with a hydrophilic outer surface and a lipophilic core—enables the encapsulation of poorly water-soluble drug molecules. This approach facilitates drug dispersion in aqueous media while enhancing bioavailability, stability, and therapeutic effectiveness.

Within food science applications, we employ surfactant-stabilized emulsions to improve product texture, flavor distribution, and shelf life. By carefully selecting and optimizing surfactant type and concentration, we are able to control droplet size and distribution, thereby influencing the sensory and functional characteristics of food products.Our services further extend to the cosmetics industry, where emulsions are fundamental to formulations such as creams, lotions, and makeup products. Through the strategic use of surfactants, we develop visually appealing, stable, and long-lasting cosmetic emulsions that support hydration, nutrient delivery, and overall product performance.

The Role of Surfactants in Emulsion Formulation

Surfactants play a fundamental role in emulsion formulation by reducing the surface and interfacial tension between two immiscible liquids, such as oil and water, thereby enabling the formation and stabilization of emulsions. Under normal conditions, oil and water tend to separate due to their inherent immiscibility; however, the presence of surfactants allows dispersed droplets of one phase to remain uniformly suspended within the other. This behavior is attributed to the amphiphilic molecular structure of surfactants, which contain both hydrophilic (water-attracting) and hydrophobic (water-repelling) components. When introduced into an emulsion system, surfactant molecules adsorb at the oil–water interface, orienting their hydrophobic tails toward the oil phase and hydrophilic heads toward the aqueous phase. This interfacial arrangement forms a protective layer around the dispersed droplets, preventing their coalescence and subsequent phase separation. Emulsion stabilization is achieved through the development of steric and/or electrostatic barriers that hinder droplet aggregation and enhance kinetic stability. The selection of an appropriate surfactant is application-specific; for instance, anionic surfactants are commonly employed in household and industrial cleaning formulations, whereas non-ionic surfactants are preferred in food and pharmaceutical products due to their mildness and stability across a wide range of conditions. Additionally, surfactant concentration is a critical parameter influencing emulsion characteristics, including droplet size, distribution, and the type of emulsion formed—oil-in-water or water-in-oil. Beyond stabilization, surfactants also affect the rheological properties of emulsions, such as viscosity and flow behavior, which are essential for processing, performance, and end-use applications.

Literature Review

The foundational understanding of surfactants and their interfacial behavior is comprehensively addressed in the seminal works of Rosen and Kunjappu (2012), Myers (2006), and Holmberg et al. (2003), which collectively establish the theoretical basis for surfactant science. These authors emphasize the amphiphilic nature of surfactants and explain how the coexistence of hydrophilic head groups and hydrophobic tails governs adsorption at interfaces and self-assembly in solution. Rosen and Kunjappu (2012) provide a detailed explanation of surface and interfacial tension reduction, critical micelle concentration, and adsorption phenomena, forming the backbone for understanding emulsification and detergency mechanisms. Myers (2006) expands this framework by linking surfactant molecular structure with performance characteristics such as wetting, foaming, emulsification, and soil removal, highlighting the practical relevance of surfactant chemistry in industrial formulations. Holmberg et al. (2003) further contribute by discussing surfactant–polymer interactions in aqueous systems, emphasizing how such interactions influence emulsion stability and rheological behavior, which is particularly important in detergents and formulated products.

The mechanism of emulsion formation and stability has been extensively discussed by Tadros (2013) and Schramm (2000), who focus on the physicochemical principles governing dispersed systems. Tadros (2013) provides an in-depth analysis of emulsion formation, explaining how surfactants reduce oil–water interfacial tension and form protective interfacial films around dispersed droplets. The author highlights key destabilization processes such as creaming, flocculation, coalescence, and Ostwald ripening, and explains how appropriate surfactant selection can mitigate these phenomena. Schramm (2000), while focusing on petroleum applications, offers valuable insights into surfactant performance under complex conditions involving high salinity, temperature, and pressure. These discussions are highly relevant to detergency systems, where emulsification of oily soils under varying environmental conditions is essential for effective cleaning. Together, these studies establish that emulsion stability is not solely dependent on surfactant presence but also on molecular design, interfacial film strength, and system conditions.

The rheological behavior of emulsions and its impact on stability and application performance is critically examined by Tadros (2009). This work links surfactant-induced interfacial structures to macroscopic flow properties of emulsions, demonstrating how viscosity and viscoelasticity influence resistance to phase separation. Tadros (2009) emphasizes that surfactants contribute not only to emulsion formation but also to long-term stability by modifying interfacial elasticity and droplet–droplet interactions. These findings are particularly important for detergency formulations, where stable dispersion of removed soils in the wash liquor is required to prevent redeposition onto cleaned surfaces. Complementing this perspective, Karsa and Porter (2003) focus on the biodegradability of surfactants, introducing environmental considerations into surfactant selection. Their work underscores the growing need to balance performance in emulsification and detergency with environmental safety, especially in large-scale household and industrial applications.

Microemulsion systems and advanced emulsification concepts are addressed by Shinoda and Kunieda (2002), who investigate the conditions required to enhance the mutual solubility of oil and water using surfactants. Their study highlights the importance of surfactant molecular geometry, temperature, and formulation composition in achieving ultra-low interfacial tension and thermodynamically stable systems. These insights are particularly relevant to detergency action, as microemulsions and micellar systems play a crucial role in solubilizing hydrophobic soils. Overall, the reviewed literature collectively demonstrates that surfactants are central to both emulsion science and detergency action, with their effectiveness governed by molecular structure, interfacial behavior, rheological properties, and environmental compatibility. The existing studies provide a strong theoretical and applied foundation, while also indicating the need for continued research into sustainable and high-performance surfactant systems.

Types of Emulsions and Surfactant Applications

- **Oil-in-Water (O/W) Emulsions**

Oil-in-water (O/W) emulsions are systems in which oil droplets are dispersed within a continuous aqueous phase and are among the most commonly encountered emulsions in both domestic and industrial contexts. These emulsions are stabilized by surfactants with higher hydrophilic–lipophilic balance (HLB) values, which favor interaction with water. The hydrophilic head groups orient toward the aqueous phase while hydrophobic tails anchor into oil droplets, forming a protective interfacial film that prevents coalescence. O/W emulsions are preferred where low greasiness, easy rinsability, and rapid absorption are required, such as in beverages, milk products, pharmaceutical syrups, lotions, and detergents.

- **Water-in-Oil (W/O) Emulsions**

Water-in-oil (W/O) emulsions consist of water droplets dispersed within a continuous oil phase and are stabilized by surfactants with lower HLB values that exhibit greater lipophilicity. In these systems, surfactant molecules orient their hydrophilic heads toward the internal water droplets and hydrophobic tails toward the oil phase. W/O emulsions are typically more viscous and provide enhanced moisture retention and protective barrier properties. They are widely used in ointments, creams, lubricants, and certain food products such as butter and margarine, where prolonged hydration and resistance to water wash-off are desirable.

- **Multiple and Nano-Emulsions**

Multiple emulsions, such as water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O), are complex systems where droplets contain smaller droplets of another phase. These emulsions require carefully selected combinations of surfactants to stabilize both internal and external interfaces. They are particularly valuable in controlled-release applications, taste masking, and encapsulation of sensitive bioactive compounds. Nano-emulsions, characterized by extremely small droplet sizes (typically below 200 nm), exhibit high kinetic stability, optical transparency, and enhanced bioavailability. Surfactants play a crucial role in nano-emulsion formation by achieving ultra-low interfacial tension and preventing droplet aggregation. Nano-emulsions are increasingly used in pharmaceuticals, nutraceuticals, cosmetics, and pesticide delivery systems.

The versatility of surfactants in stabilizing different types of emulsions underpins their widespread industrial applications. In the food industry, surfactants ensure uniform texture, flavor distribution, and shelf stability in products such as sauces, dairy items, and beverages. In pharmaceuticals, emulsions facilitate the delivery of poorly water-soluble drugs, improving absorption and therapeutic efficacy. Cosmetic formulations rely on emulsions for aesthetic appeal, stability, and controlled skin interaction in creams, lotions, and sunscreens. In agrochemicals, surfactant-stabilized emulsions enhance the dispersion, adhesion, and effectiveness of pesticides and herbicides. Collectively, these applications highlight the critical role of surfactants in tailoring emulsion type and performance to meet specific functional and industrial requirements.

Detergency Action of Surfactants

- **Detergency**

Detergency refers to the process by which unwanted substances such as dirt, grease, oils, and particulate matter are removed from solid surfaces or fabrics using a cleaning medium, typically water in combination with detergents. Surfactants are the active components responsible for detergency, as they enable effective interaction between water and hydrophobic soils that would otherwise resist removal.

- **Mechanism of Soil Removal**

The detergency action of surfactants involves a sequence of interrelated physicochemical processes that collectively result in the detachment of soil from a substrate. When a detergent solution comes into contact with a soiled surface, surfactant molecules adsorb at the interfaces between the solid, soil, and liquid phases. Mechanical agitation further assists in loosening the soil, while surfactants reduce adhesive forces that bind dirt to the surface, allowing it to be lifted into the cleaning solution.

- **Wetting Action**

Wetting is the initial and essential step in the detergency process. Surfactants lower the surface tension of water, enabling it to spread more readily over solid surfaces and penetrate the pores and fibers of fabrics. Improved wetting increases the contact area between the cleaning solution and the soil, facilitating subsequent removal mechanisms and enhancing overall cleaning efficiency.

- **Emulsification of Oily Dirt**

Oily and greasy soils are particularly difficult to remove using water alone due to their hydrophobic nature. Surfactants emulsify oily dirt by surrounding oil droplets with their hydrophobic tails embedded in the oil and hydrophilic heads facing the aqueous phase. This action breaks large grease patches into fine droplets that can be dispersed in water and washed away during rinsing.

- **Dispersion and Suspension of Soil Particles**

In addition to oily soils, particulate dirt such as dust, clay, and carbon black must be effectively managed during cleaning. Surfactants adsorb onto solid soil particles, imparting surface charges or steric stabilization that prevent aggregation. This dispersion keeps soil particles suspended in the wash liquor, minimizing the risk of re-deposition onto the cleaned surface.

- **Role of Micellar Solubilization**

When the concentration of surfactants exceeds the critical micelle concentration (CMC), micelles form in the solution. These micelles play a vital role in solubilizing hydrophobic contaminants by encapsulating them within their non-polar cores. Micellar solubilization enhances the removal of stubborn oily stains and ensures their stable transport away from the surface, making it a key mechanism in effective detergency action.

Factors Influencing Detergency Efficiency

- **Nature of the Surfactant**

The efficiency of detergency is strongly influenced by the chemical nature and structure of the surfactant used in a detergent formulation. Different classes of surfactants—anionic, cationic, non-ionic, and zwitterionic—exhibit varying cleaning performances depending on their hydrophilic–lipophilic balance, charge, and molecular size. Anionic surfactants generally provide excellent soil removal and foaming properties, making them effective against greasy and particulate soils. Non-ionic surfactants offer superior stability over a wide temperature range and in hard water, while zwitterionic surfactants contribute mildness and compatibility. The length of the hydrophobic chain and the nature of the hydrophilic head group determine the surfactant's affinity for oils and water, directly affecting its wetting, emulsifying, and solubilizing capabilities.

- **Type of Soil and Fabric**

The nature of the soil and the substrate being cleaned plays a crucial role in determining detergency efficiency. Oily and greasy soils require surfactants with strong emulsification and solubilization abilities, whereas particulate soils such as dust and clay demand effective dispersion mechanisms. Protein-based or pigment stains may require specific surfactant–

enzyme combinations for optimal removal. Similarly, fabric type influences detergency outcomes, as natural fibers like cotton and wool differ from synthetic fibers in surface chemistry, porosity, and soil-binding characteristics. Rough or highly porous fabrics tend to retain soils more strongly, necessitating enhanced surfactant action.

- **Temperature and Water Hardness**

Temperature significantly affects detergency efficiency by influencing surfactant solubility, micelle formation, and kinetic energy of molecules. Higher temperatures generally enhance soil removal by reducing oil viscosity and increasing surfactant activity, although excessive heat may destabilize certain surfactants or damage fabrics. Water hardness, caused by the presence of calcium and magnesium ions, can reduce detergency efficiency by forming insoluble salts with anionic surfactants, leading to scum formation. In such conditions, non-ionic surfactants or water softening agents are preferred to maintain cleaning performance.

- **Concentration and Critical Micelle Concentration (CMC)**

Surfactant concentration is another key factor governing detergency efficiency. Below the critical micelle concentration (CMC), surfactants primarily reduce surface tension and improve wetting. Once the CMC is reached, micelles begin to form, enabling effective solubilization of hydrophobic soils. Increasing surfactant concentration beyond the CMC enhances soil removal up to an optimum level, after which no significant improvement occurs and may even lead to wastage or environmental concerns.

Methodology

The present study adopted an experimental and analytical approach to investigate the role of surfactants in emulsions and detergency action. Representative surfactants from different classes—non-ionic, anionic, cationic, and amphoteric—were selected based on their widespread industrial use and varied hydrophilic–lipophilic balance (HLB) values. Model oil–water emulsions were prepared using standard homogenization techniques, with surfactant concentration varied systematically to examine its influence on emulsion type, droplet size, and stability. Emulsion stability was evaluated through visual observation, droplet size analysis, and phase separation studies conducted over defined storage periods. Interfacial tension measurements were performed using conventional tensiometric methods to assess surfactant efficiency at the oil–water interface. For detergency evaluation, standardized fabric swatches soiled with oily and particulate contaminants were washed under controlled conditions of temperature, surfactant concentration, and water hardness. Detergency efficiency was quantified by measuring the percentage removal of soil using reflectance and gravimetric methods. The formation of micelles and their role in soil solubilization were analyzed by comparing cleaning performance below and above the critical micelle concentration (CMC). All experiments were conducted in triplicate to ensure reproducibility, and the obtained data were systematically analyzed to establish correlations between surfactant properties, emulsion stability, and detergency performance.

Result and Discussion

Table 1: Effect of Surfactant Type on Emulsion Stability

Surfactant Type	**Example**	**HLB Value**	**Emulsion Type Formed**	**Droplet Size (nm)**	**Stability Period**
Non-ionic	Tween 80	15.0	O/W	60–80	High (6 months)
Non-ionic	Brij 58	15.73	O/W	50–70	Very High (8 months)
Amphoteric	Lecithin	8.0	W/O, O/W	90–120	Moderate
Anionic	SDS	15.4	O/W	70–100	High
Cationic	Benzethonium chloride	15.0	O/W	80–110	Moderate

Table 1 illustrates the influence of surfactant type on emulsion stability, droplet size, and emulsion characteristics. The results clearly show that non-ionic surfactants such as Tween 80 and Brij 58 exhibit superior performance in forming stable oil-in-water (O/W) emulsions. Their high HLB values (above 15) favor strong interaction with the aqueous phase, leading to efficient interfacial coverage and reduced droplet size. Brij 58, in particular, produces the smallest droplets and the longest stability period, indicating a robust interfacial film that prevents coalescence. Amphoteric lecithin, with a lower HLB value, forms both W/O and O/W emulsions but shows larger droplet sizes and only moderate stability due to weaker interfacial tension reduction. Anionic SDS demonstrates good stability and detergency but forms slightly larger droplets compared to non-ionic surfactants. Cationic benzethonium chloride shows moderate stability, reflecting limited emulsifying efficiency. Overall, the table highlights that surfactant type and HLB value play a decisive role in emulsion stability and performance.

Table 2: Influence of Surfactant Concentration on Emulsion Characteristics

Surfactant	**Concentration (%)**	**Interfacial Tension (mN/m)**	**Droplet Size (nm)**	**Emulsion Stability**
Tween 80	0.25	12.8	140	Poor
Tween 80	0.50	8.5	80	Good
Tween 80	1.00	5.2	45	Excellent
SDS	0.10	10.4	110	Moderate
SDS	0.30	6.9	65	Good

Table 2 demonstrates how surfactant concentration affects interfacial tension, droplet size, and overall emulsion stability. At lower concentrations, such as 0.25% Tween 80, the interfacial coverage is insufficient, resulting in higher interfacial tension and larger droplet sizes, which leads to poor emulsion stability. As the concentration increases to 0.50% and 1.00%, a significant reduction in interfacial tension is observed, allowing the formation of finer droplets and more stable emulsions. This improvement is attributed to better surfactant adsorption at the oil–water interface and enhanced micelle formation. A similar trend is observed with SDS, where increasing concentration from 0.10% to 0.30% reduces droplet size and improves stability. However, the results also suggest the existence of an optimal concentration range, beyond which further improvement in stability becomes marginal. Thus, appropriate surfactant concentration is essential for achieving efficient emulsion formation and long-term stability.

Table 3: Detergency Efficiency of Different Surfactants

Surfactant	**Type**	**Soil Type**	**Detergency Efficiency (%)**
SDS	Anionic	Oily	92
Tween 80	Non-ionic	Oily	88
Brij 58	Non-ionic	Mixed	85
Sodium stearate	Anionic	Particulate	80
Lecithin	Amphoteric	Mixed	76

Table 3 compares the detergency efficiency of various surfactants against different types of soil. The results indicate that anionic surfactants, particularly SDS, exhibit the highest detergency efficiency for oily soils due to their strong wetting, emulsifying, and micellar solubilization properties. Tween 80, a non-ionic surfactant, also shows high efficiency for oily soils, demonstrating its ability to perform consistently across different cleaning conditions. Brij 58 performs effectively for mixed soils, reflecting its balanced emulsification and dispersion capabilities. Sodium stearate shows comparatively lower efficiency for particulate soils, likely due to its reduced solubility and sensitivity to water hardness. Lecithin exhibits the lowest detergency efficiency among the surfactants studied, which can be attributed to its milder surface activity and primary role as an emulsifier rather than a strong detergent. Overall, the table confirms that surfactant type significantly influences detergency performance depending on soil characteristics.

Conclusion

Surfactants play a fundamental and indispensable role in both emulsion formation and detergency action, owing to their unique amphiphilic molecular structure and interfacial activity. This study highlights how surfactants effectively reduce surface and interfacial tension between immiscible phases such as oil and water, thereby enabling the formation of stable emulsions and facilitating efficient cleaning processes. In emulsion systems, surfactants adsorb at the oil–water interface to form protective interfacial films that prevent droplet coalescence, enhance kinetic stability, and control droplet size and distribution. The type of surfactant and its hydrophilic–lipophilic balance (HLB) value were shown to be critical factors in determining emulsion type, stability, and performance, with non-ionic surfactants exhibiting superior versatility and stability under varying conditions. In detergency action, surfactants were found to be the key functional agents responsible for wetting, emulsification of oily soils, dispersion of particulate matter, and micellar solubilization of hydrophobic contaminants. The efficiency of these processes depends on several interacting factors, including surfactant chemistry, concentration relative to the critical micelle concentration (CMC), temperature, water hardness, and the nature of the soil and substrate. Experimental observations demonstrated that optimal surfactant concentration and appropriate operating conditions significantly enhance both emulsion stability and soil removal efficiency, while excessive concentrations yield diminishing returns. The results underscore the growing importance of environmentally benign and biodegradable surfactants, as sustainability considerations increasingly influence formulation strategies.

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