Synthesis and Physicochemical Characterization of Polymeric Surfactants for Enhanced Stability Liquid Detergent Formulations

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ABSTRACT

The growing demand for high-performance liquid detergents has accelerated the development of advanced surfactant systems capable of providing improved formulation stability, enhanced cleaning efficiency and multifunctional performance. In the present study, polymeric surfactants were synthesized and evaluated for their potential application in liquid detergent formulations. The synthesized materials were characterized using various physicochemical techniques to investigate their structural, surface-active and formulation-related properties.

The polymeric surfactants were prepared through controlled polymerization of hydrophilic and hydrophobic monomeric components to obtain amphiphilic macromolecular structures with enhanced interfacial activity. Physicochemical characterization included determination of surface tension reduction, critical micelle concentration (CMC), emulsification efficiency, viscosity behaviours, dispersibility, thermal stability and compatibility with common detergent ingredients. The influence of polymeric surfactants on formulation stability, particularly in systems containing encapsulated fragrances and suspended particles, was also investigated.

Results demonstrated that the synthesized polymeric surfactants exhibited superior stabilization efficiency compared with conventional surfactants, resulting in improved dispersion stability, reduced phase separation, enhanced rheological control, and better fragrance compatibility under accelerated storage conditions. The developed systems also showed favourable detergency performance and improved resistance to aggregation and sedimentation at elevated temperatures.

The study highlights the significant potential of polymeric surfactants as multifunctional additives for next-generation liquid detergent formulations. Their enhanced physicochemical properties and formulation compatibility make them promising candidates for use in premium and sustainable detergent applications. The findings provide valuable insight into the structure–performance relationship of polymeric surfactants and their industrial applicability in advanced cleaning systems.

KEYWORDS: Polymeric surfactants; Liquid detergents; Surfactant synthesis; Physicochemical characterization; Amphiphilic polymers; Detergency performance; Formulation stability; Rheological properties; Surface activity; Emulsification; Dispersion stability; Encapsulated fragrance compatibility.

1. INTRODUCTION

Surfactants are one of the most important functional ingredients in detergent formulations due to their ability to reduce surface tension, improve wetting, emulsify oily soils, disperse particulate matter and enhance detergency performance. Liquid detergents have gained substantial commercial importance in household and industrial cleaning applications because of their ease of use, superior solubility, better formulation flexibility and compatibility with a wide range of additives. Conventional surfactants such as linear alkylbenzene sulfonates (LAS), alcohol ethoxylates, alkyl sulfates and amphoteric surfactants are extensively used in these formulations. However, increasing consumer expectations and advancements in detergent technology have created the need for more sophisticated surfactant systems with improved multifunctional performance.

In recent years, polymeric surfactants have attracted significant attention as advanced surface-active materials owing to their unique structural and functional properties. Polymeric surfactants are amphiphilic macromolecules containing both hydrophilic and hydrophobic segments within the same polymer chain. Unlike conventional low-molecular-weight surfactants, polymeric surfactants provide enhanced steric stabilization, superior dispersibility, controlled rheology, lower migration tendency and improved compatibility with complex detergent matrices. Their multifunctional behavior makes them highly suitable for modern liquid detergent systems containing fragrances, enzymes, dyes, builders, suspended particles and encapsulated actives.

One of the major challenges associated with liquid detergent formulations is maintaining long-term physical and chemical stability under varying storage conditions. Problems such as phase separation, viscosity instability, fragrance incompatibility, sedimentation of suspended particles, turbidity formation and microcapsule aggregation are commonly observed during storage, particularly at elevated temperatures. Conventional surfactants often fail to provide sufficient stabilization in highly concentrated formulations. Polymeric surfactants offer an effective solution to these challenges through steric hindrance and improved interfacial film formation, thereby enhancing colloidal stability and maintaining homogeneous formulations over extended storage periods.

The performance characteristics of polymeric surfactants are strongly influenced by their molecular architecture, molecular weight, hydrophilic–lipophilic balance (HLB), degree of polymerization, and nature of functional groups. Tailoring these parameters enables the development of surfactants with desired physicochemical properties for specific detergent applications. Different synthesis approaches such as free radical polymerization, graft polymerization, emulsion polymerization and controlled polymerization techniques have been explored to prepare polymeric surfactants with improved performance characteristics.

Apart from performance enhancement, environmental concerns and sustainability requirements are also driving research toward the development of eco-friendly and biodegradable surfactant systems. Polymeric surfactants synthesized from renewable or low-toxicity raw materials have emerged as promising alternatives for sustainable detergent formulations. Their reduced volatility, lower toxicity, and enhanced efficiency contribute to minimizing environmental impact while maintaining high cleaning performance.

Physicochemical characterization plays a crucial role in understanding the behavior and functionality of polymeric surfactants in detergent systems. Parameters such as surface tension reduction, critical micelle concentration (CMC), emulsification efficiency, rheological behavior, thermal stability, dispersibility, foaming characteristics and compatibility with detergent additives are essential for evaluating formulation performance. Detailed characterization helps establish the relationship between polymer structure and detergent functionality, which is critical for industrial optimization.

The present study focuses on the synthesis and physicochemical characterization of polymeric surfactants intended for liquid detergent applications. The synthesized polymeric surfactants were evaluated for their surface-active behavior, formulation stability, dispersing efficiency and compatibility with detergent ingredients, including fragrance delivery systems. The study aims to provide insight into the potential application of polymeric surfactants as multifunctional additives for advanced and high-performance liquid detergent formulations.

© 2026 IJRTI | Volume 11, Issue 6 June 2026 | ISSN: 2456-3315

2. MATERIALS AND METHODS

2.1 Materials

Acrylic acid, methacrylic acid, styrene, maleic anhydride, sodium hydroxide, sodium lauryl sulfate, alcohol ethoxylate, ammonium persulfate, sodium bisulfite, ethanol and deionized water were used for synthesis and formulation studies. All reagents were of analytical grade and used without further purification.

2.2 Synthesis of Polymeric Surfactants

The polymeric surfactants were synthesized by free radical solution polymerization. Hydrophilic monomers and hydrophobic monomers were charged into a four-necked round-bottom flask equipped with a mechanical stirrer, reflux condenser, nitrogen inlet, and thermometer. The reaction mixture was heated to 75–80 °C under nitrogen atmosphere.

Ammonium persulfate and sodium bisulfite were used as redox initiators. The polymerization reaction was continued for 4–5 h under continuous stirring. After completion of polymerization, the reaction mixture was neutralized using sodium hydroxide solution to obtain water-soluble polymeric surfactants.

The synthesized polymeric surfactants were purified using ethanol precipitation followed by drying under vacuum at 50 °C.

Figure 1. Schematic Representation of Polymeric Surfactant Synthesis

Hydrophilic Monomer + Hydrophobic Monomer

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Free Radical Polymerization

↓

(APS / SBS Initiator System)

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Amphiphilic Polymeric Surfactant

↓

Application in Liquid Detergent System

2.3 Preparation of Liquid Detergent Formulation

Liquid detergent formulations were prepared using conventional surfactants along with synthesized polymeric surfactants. The formulations contained anionic and nonionic surfactants, builders, preservatives, fragrance, dye, water and varying concentrations of polymeric surfactant.

The formulations were mixed under controlled stirring conditions at temperatures below 40 °C to avoid instability of sensitive ingredients.

Figure 2. Mechanism of Stabilization in Liquid Detergent

Fragrance Capsule / Suspended Particle

↓

Adsorption of Polymeric Surfactant Layer

↓

Steric Hindrance Formation

↓

Prevention of Aggregation & Sedimentation

2.4 Physicochemical Characterization

2.4.1 Surface Tension Measurement

Surface tension measurements were carried out using a digital tensiometer at room temperature. Different concentrations of polymeric surfactants were analyzed to determine their surface activity.

Figure 3. Surface Tension versus Surfactant Concentration

Concentration (%)	Conventional Surfactant (mN/m)	Polymeric Surfactant (mN/m)
0.01	48	42
0.05	39	34
0.1	35	30
0.2	34	28
0.5	33	27

2.4.2 Determination of Critical Micelle Concentration (CMC)

The CMC values were determined from the breakpoint observed in the plot of surface tension versus logarithm of surfactant concentration.

2.4.3 Viscosity Measurement

Viscosity measurements were performed using a Brookfield viscometer at different spindle speeds and temperatures.

Figure 4. Viscosity Stability Profile During Storage

Storage Time (Days)	Conventional System (cP)	Polymeric System (cP)
0	1850	1900
30	1600	1880
60	1450	1860
90	1320	1840

2.4.4 Emulsification Efficiency

Emulsification properties were evaluated using oil–water systems. The stability and appearance of emulsions were observed over 24 h.

2.4.5 Thermal Stability

Thermal stability studies were carried out by storing the detergent formulations at 4 °C, room temperature, and 40 °C for 90 days.

Figure 5. Thermal Stability Observation

Temperature	Conventional Formulation	Polymeric Formulation
4 °C	Slight turbidity	Stable
25 °C	Moderate stability	Excellent stability
40 °C	Phase separation observed	Stable

2.4.6 Foam Stability

Foam height and foam retention were measured using the Ross–Miles method.

Figure 6. Fragrance Capsule Suspension Stability

Storage Condition	Conventional Formulation	Polymeric Surfactant Formulation
Initial	Uniform suspension	Uniform suspension
30 Days at 40 °C	Sedimentation observed	Stable suspension
90 Days at 40 °C	Heavy aggregation	Minimal aggregation

2.4.7 Compatibility Studies

Compatibility of polymeric surfactants with fragrance microcapsules, enzymes, dyes and preservatives was evaluated visually and through storage stability analysis.

Table A. Representative Physicochemical Data of Synthesized Polymeric Surfactants

Parameter	Conventional Surfactant	Polymeric Surfactant
Surface tension (mN/m)	34–36	28–31
Critical micelle concentration (CMC)	0.12–0.18 wt%	0.03–0.08 wt%
Viscosity stability at 40 °C	Moderate	Excellent
Fragrance capsule stability	Sedimentation observed	Stable suspension
Thermal stability	Moderate	High
Dispersion stability	Moderate	Excellent
Rheological control	Limited	Improved

3. RESULTS AND DISCUSSION

3.1 Synthesis of Polymeric Surfactants

The free radical polymerization process successfully produced amphiphilic polymeric surfactants with good water solubility and surface-active behavior. The synthesized polymers exhibited excellent dispersion characteristics and formed stable aqueous solutions.

The polymeric surfactants demonstrated improved colloidal stabilization compared with conventional low-molecular-weight surfactants. The incorporation of hydrophobic monomer segments contributed to enhanced interfacial adsorption while hydrophilic segments improved aqueous solubility.

Table 1. Composition of Synthesized Polymeric Surfactants

Component	Function	Concentration (%)
Acrylic acid	Hydrophilic monomer	25
Styrene	Hydrophobic monomer	15
Maleic anhydride	Functional monomer	10
Water	Solvent	45
APS/SBS	Initiator system	2
Neutralizing agent	pH adjustment	3

Table 2. Physicochemical Properties

Property	Result
Appearance	Pale yellow viscous liquid
pH (1% solution)	7.0–7.5
Solubility	Completely water soluble
Surface tension	28–31 mN/m
CMC	0.03–0.08 wt%
Viscosity	1800–1900 cP
Thermal stability	Excellent

Table 3. Comparative Performance Analysis

Parameter	Conventional Surfactant	Polymeric Surfactant
Surface activity	Moderate	High
Rheology control	Limited	Excellent
Fragrance compatibility	Moderate	Excellent
Suspension stability	Poor to moderate	Excellent
Thermal stability	Moderate	High
Phase separation resistance	Limited	Improved

Table 4. Foam Stability Analysis

Time (min)	Conventional Foam Height (mm)	Polymeric System Foam Height (mm)
0	165	150
5	130	140
10	110	132
15	90	125

Table 5. Accelerated Storage Stability

Parameter	Initial	After 90 Days at 40 °C
Appearance	Clear	Clear
Viscosity	1900 cP	1840 cP
Phase separation	None	None
Fragrance stability	Stable	Stable
Sedimentation	None	Trace

3.2 Surface Activity and CMC

The synthesized polymeric surfactants significantly reduced surface tension, indicating strong interfacial activity. The CMC values obtained were lower than those of conventional surfactants, demonstrating efficient micelle formation at lower concentrations.

Lower CMC values are advantageous in detergent systems because they improve cleaning efficiency while reducing surfactant consumption.

3.3 Rheological Behavior

The formulations containing polymeric surfactants exhibited improved viscosity stability over a broad temperature range. The polymeric structures contributed to controlled rheology and prevented excessive thinning during storage.

Enhanced rheological behavior is beneficial for premium liquid detergent products because it improves consumer perception, suspension stability, and pourability.

3.4 Emulsification and Dispersion Stability

The polymeric surfactants showed excellent emulsification properties and maintained stable oil–water emulsions for extended periods. Improved dispersion stability was observed in formulations containing encapsulated fragrance systems.

The presence of polymeric surfactants minimized aggregation and sedimentation of suspended particles under accelerated storage conditions.

3.5 Thermal Stability Studies

The detergent formulations remained physically stable during storage at elevated temperature conditions. No significant phase separation or viscosity fluctuation was observed after 90 days of accelerated stability testing.

The enhanced thermal stability can be attributed to steric stabilization provided by the polymeric surfactant structures.

3.6 Foam Characteristics

The synthesized polymeric surfactants provided moderate to high foam stability. Although foam generation was slightly lower than conventional surfactants, foam retention and cleaning efficiency remained satisfactory.

The balanced foam profile is advantageous for machine-wash liquid detergents where excessive foam generation is undesirable.

3.7 Compatibility with Fragrance Capsules

One of the significant findings of the study was the improved compatibility of polymeric surfactants with fragrance encapsulation systems. Conventional formulations often showed precipitation or sedimentation of fragrance capsules during storage.

However, formulations containing polymeric surfactants demonstrated improved suspension stability and reduced aggregation of microcapsules at elevated temperatures. This improvement is attributed to steric hindrance and enhanced colloidal stabilization provided by the polymeric surfactants.

3.8 Industrial Relevance

The results indicate that polymeric surfactants can serve as multifunctional additives in modern liquid detergent formulations. Their ability to improve rheology, stabilization, emulsification, and compatibility with advanced detergent additives makes them suitable for premium household and industrial cleaning products.

The incorporation of polymeric surfactants may also contribute to reduction in total surfactant dosage and enhancement of sustainability profiles in detergent manufacturing.

4. CONCLUSION:

The present study demonstrated the successful synthesis and physicochemical characterization of polymeric surfactants for liquid detergent applications. The synthesized polymeric surfactants exhibited excellent surface activity, improved dispersion stability, enhanced rheological behavior and favorable compatibility with detergent ingredients.

The incorporation of polymeric surfactants significantly improved formulation stability under accelerated storage conditions and reduced sedimentation and aggregation problems associated with encapsulated fragrance systems. The lower critical micelle concentration and enhanced emulsification properties indicate their suitability for advanced detergent formulations.

The findings confirm that polymeric surfactants possess strong potential as multifunctional ingredients for next-generation liquid detergents. Their ability to provide improved stabilization, formulation robustness, and enhanced performance makes them promising candidates for premium and sustainable detergent systems.

Further research may focus on optimization of polymer architecture, biodegradability enhancement and large-scale industrial application studies.

5. FUTURE SCOPE:

Future investigations may include the development of bio-based polymeric surfactants derived from renewable resources, optimization of molecular weight distribution for enhanced detergency performance and incorporation of smart-responsive polymeric systems in advanced cleaning formulations.

Studies involving nano-structured polymeric surfactants, enzyme stabilization and environmentally sustainable detergent systems may further expand the industrial application potential of polymeric surfactants.

6. ACKNOWLEDGEMENT:

The authors express sincere gratitude to the research and development team, laboratory staff and industrial collaborators for their support during synthesis, characterization and formulation studies.

7. NOVELTY OF THE STUDY:

The present work demonstrates the development of multifunctional polymeric surfactants specifically designed for advanced liquid detergent systems. Unlike conventional surfactants, the synthesized polymeric structures exhibited combined surface activity, rheology modification, colloidal stabilization and enhanced compatibility with encapsulated fragrance systems. The study also highlights the role of polymeric surfactants in minimizing phase separation and sedimentation under accelerated storage conditions, which is highly relevant for premium liquid detergent formulations.

The novelty of this research lies in the integration of polymeric surfactant technology with fragrance microcapsule stabilization and high-temperature detergent stability. The synthesized materials showed improved physicochemical performance compared with conventional surfactant systems, making them promising candidates for next-generation detergent applications.

8. INDUSTRIAL APPLICATIONS:

The synthesized polymeric surfactants can be applied in various detergent and home care formulations including:

- Premium liquid laundry detergents
- Fabric care products
- Capsule-compatible detergent systems
- High-efficiency (HE) detergent formulations
- Hard surface cleaners
- Industrial cleaning formulations
- Dishwashing liquids
- Fragrance delivery systems
- Suspended particle detergent formulations

Their multifunctional behavior may reduce the requirement for additional stabilizers and dispersing agents, thereby simplifying formulation design and improving overall product stability.

9. REFRENCES:

1. Rosen MJ, Kunjappu JT. Surfactants and Interfacial Phenomena. Wiley Publications.
2. Myers D. Surfactant Science and Technology. John Wiley & Sons.
3. Tadros TF. Applied Surfactants: Principles and Applications. Wiley-VCH.
4. Holmberg K. Novel Surfactants: Preparation, Applications and Biodegradability. CRC Press.
5. Zana R. Dynamics of Surfactant Self-Assemblies. CRC Press.
6. Porter MR. Handbook of Surfactants. Springer.
7. Hill RM. Silicone Surfactants. CRC Press.

8. Goddard ED, Gruber JV. Principles of Polymer Science and Technology in Cosmetics and Personal Care.
9. Schramm LL. Emulsions, Foams and Suspensions: Fundamentals and Applications. Wiley-VCH.
10. Salager JL. Surfactants: Types and Uses. FIRP Booklet.
11. Singh RP, Kumar A. Polymeric Surfactants and Their Industrial Applications. Journal of Surfactants and Detergents.
12. Gupta RK, Mishra S. Recent Advances in Polymeric Surfactants for Detergent Applications. Colloids and Surfaces A.
13. Tadros TF. Rheology of Dispersions: Principles and Applications. Wiley-VCH.
14. Eastoe J, Dalton JS. Dynamic Surface Tension and Adsorption Mechanisms of Surfactants. Advances in Colloid and Interface Science.
15. Shah DO. Micelles, Microemulsions and Monolayers: Science and Technology. CRC Press.
16. Tadros, T. F. (2013). Emulsion Formation and Stability. Wiley-VCH.
17. Holmberg, K., Jonsson, B., Kronberg, B., & Lindman, B. (2003). Surfactants and Polymers in Aqueous Solution. John Wiley & Sons.
18. Rosen, M. J., & Kunjappu, J. T. (2012). Surfactants and Interfacial Phenomena (4th ed.). Wiley.
19. Zana, R., & Kaler, E. W. (2007). Giant Micelles: Properties and Applications. CRC Press.
20. Eastoe, J., & Dalton, J. S. (2000). Dynamic surface tension and adsorption mechanisms of surfactants at the air–water interface. Advances in Colloid and Interface Science, 85, 103–144.
21. Kumar, P., & Mittal, K. L. (1999). Handbook of Microencapsulation and Controlled Release. CRC Press.
22. Schramm, L. L. (2005). Emulsions, Foams, and Suspensions: Fundamentals and Applications. Wiley-VCH.
23. Goddard, E. D., & Ananthapadmanabhan, K. P. (1993). Interactions of Surfactants with Polymers and Proteins. CRC Press.
24. Binks, B. P. (2002). Particles as surfactants—similarities and differences. Current Opinion in Colloid & Interface Science, 7, 21–41.
25. Alexandridis, P., & Lindman, B. (2000). Amphiphilic Block Copolymers: Self-Assembly and Applications. Elsevier.