Ionic Liquid Surfactants: A Comprehensive Review of Their Synthesis, Properties, and Emerging Application

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Abstract: This review thoroughly discusses ionic liquid-based surfactants as a groundbreaking family of materials that connect conventional surfactants and ionic liquids. These unique compounds integrate the amphiphilic character of conventional surfactants with the distinctive features of ionic liquids, such as zero volatility, high thermal stability, and adjustable physicochemical properties. The review critically discusses their structural categories, synthesis methods, and outstanding properties like lower critical micelle concentrations and improved thermal stability. Applications in various industries such as enhanced oil recovery, pharmaceuticals, leather and textile processing, lubrication, nanoparticle synthesis, and environmental remediation are critically assessed. Though there are favourable performance benefits, production cost, scalability, and environmental issues are still challenges. This article summarizes recent trends in research and future prospects for revealing the revolutionary possibilities of ionic liquid-based surfactants in consolidating sustainable industrial processes and resolving multifaceted technological challenges.

Keywords: *Ionic Liquid Surfactants, Surface Activity; Sustainable Processing, Industrial Application.*

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I. INTORDUCTION

Surfactants, being amphiphilic molecules, have been a necessity in numerous industrial, scientific, and domestic applications for a long time because of their capacity to lower surface tension, stabilize emulsions, and create self-assembled structures like micelles and vesicles. Nevertheless, conventional surfactants tend to be limited by poor thermal stability, environmental toxicity, and limited solubility in certain solvents. These challenges have compelled the quest for novel alternatives that merge the advantageous properties of traditional surfactants with improved functionality and sustainability.[1], [2] Here, ionic liquid-based surfactants are a revolutionary family of materials that bridge the gap between ionic liquids and conventional surfactants, providing an unparalleled combination of tunable physicochemical properties, high thermal stability, and versatile applications. Their special properties, for example, virtually no volatility, high thermal and chemical stability, and adjustable polarity, have turned them into compelling candidates for many applications, from catalysis over energy storage to green chemistry[3]. When ionic liquid moieties were incorporated into surfactant building blocks, the ionic liquid-based surfactants were generated, which have inherited the useful properties of the ionic liquids but display amphiphilic behaviours like regular surfactants. This integration has created new avenues for designing surfactants with desired properties to suit the requirements of high-tech applications. The construction of ionic liquid-based surfactants entails the strategic assembly of ionic liquid cations (e.g., imidazolium, pyridinium, or ammonium) and anions (e.g., halides, organic, or inorganic species) into surfactant templates.[4], [5] This modular construction provides accurate control of their molecular architecture, allowing for the design of ionic liquid-based surfactants with specific surface activity, solubility, and self-assembly behaviour. In addition, ionic liquid-based surfactants have special characteristics like lower critical micelle concentrations (CMC), improved thermal stability, and the capacity to create various nanostructures, which make them extremely promising for applications from catalysis and drug delivery to environmental remediation and improved oil recovery. Though they have enormous potential, the synthesis and use of ionic liquid-based surfactants are not without problems. Problematics like exalted synthesis cost, possible toxicity and environmental issues, and requirements to better know their structure-property relation need to be overcome if the full promise they hold is to be seen. However, an increasing literature devoted to surfactants from ionic liquids proves their worth

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as a ubiquitous, innovative material category with potential solutions to some of the greatest dilemmas confronting today's science and industry.[6], [7], [8]

Ionic liquid-based surfactants exhibited promising use in different applications as evidenced from the given research papers. Salabat et al. created a surfactant-free ionic liquid (IL)-based microemulsion to prepare sensitized poly (methyl methacrylate)/TiO2 nanocomposites with the advantage of using ionic liquids for the synthesis of nanocomposites [9]. Shao et al. prepared a bifunctional imidazolium-based ionic liquid surfactant with improved surface-active property, emulsification capability, and CO2 capture activity, demonstrating the multifunctionalities of ionic liquid surfactants for decreasing interfacial tension and CO2 capture. [10] Ma et al. used a biocompatible sulfobetaine-type zwitterionic surfactant to prepare hydrophobic ionic liquid-based bicontinuous microemulsions, illustrating the potential of these surfactants in improving enzymatic reactions and obtaining high product yields with superior stereoselectivity.[11] These works together highlight the multifunctional character of ionic liquid-based surfactants in various applications from nanocomposite synthesis to enzymatic conversions.

Ionic liquid-based surfactants are different from conventional surfactants in some major ways. Ionic liquid-based surfactants, as pointed out in a number of research studies[6], [12], [13], have several key benefits including good interfacial activity, recyclability, high-temperature and salinity stability, and eco-friendliness. They have been found to decrease interfacial tension efficiently, stabilize microemulsions, and possess competitive properties for numerous applications, such as oil recovery and CO2 capture.[6],[13] Furthermore, the physicochemical behaviour of ionic liquids, like density, viscosity, and sound velocity, can be controlled by altering their chemical structure, making them versatile in their applications [13] Conventional surfactants, however, do not possess these unique features and environmental advantages, rendering ionic liquid-based surfactants a viable option for different industrial processes.

This review, which encompasses a detailed examination of the synthesis, behaviours, and industrial applications of ionic liquid-based surfactants, is intended to present an overview of the molecular design, physicochemical properties, and wide range of applications of ionic liquid-based surfactants. This review brings out the revolutionary role that ionic liquid-based surfactants can play in the development of green chemistry, nanotechnology, and biomedicine. In addition, it addresses the existing challenges and future research directions, providing insight into how ionic liquid-based surfactants can be further developed for sustainable and practical use in the future. The marriage of ionic liquids and surfactants presents a flexible platform for designing molecular structures to realize targeted functionalities. This review discusses the structure-property relationships of ionic liquid-based surfactants and how changes in their chemical composition affect their behaviour in various environments. The review also discusses the synergistic effects occurring when ionic liquid-based surfactants are added to complex systems, e.g., emulsions, microemulsions, and nanostructured materials.

II. FUNDAMENTALS OF IONIC LIQUIDS AND SURFACTANTS

Ionic liquids are an intriguing group of materials that are described as salts with melting points less than 100°C, many of which are liquid at room temperature. In contrast to typical salts like sodium chloride that have strong ionic interactions and high melting points, Ionic liquids are usually composed of asymmetric, bulky organic cations (such as imidazolium, pyridinium, or quaternary ammonium) combined with weakly coordinating anions (such as BF_4^-, PF_6^-). This asymmetry in structure reduces lattice energy by a great deal, hindering crystallization and the ability to stay in a liquid state at room conditions.[14], [15] Ionic liquids have unique features such as very low vapor pressure, thermal stability, high solvation properties, and very tunable physicochemical properties through careful selection of ions. These features have led Ionic liquids to be dubbed "designer solvents" where particular sets of ions can be used to create bespoke materials for specific applications. Surfactants, meanwhile, constitute another vital class of compounds defined by their ability to reduce surface tension between different phases.[16], [17] Their defining feature is an amphiphilic molecular structure containing both hydrophilic and hydrophobic portions within the same molecule. This dual nature enables surfactants to self-assemble into organized structures such as micelles, vesicles, and bilayers when present in solution above their critical micelle concentration (CMC). Traditional surfactants are generally characterized by their hydrophilic head as Anionic, Cationic, Non-ionic, and Zwitterionic, covering a range of applications from detergents to emulsifiers, dispersants, and wetting agents. The intersection of these two realms appears in the form of surface-active ionic liquids, filling the gap of versatility of the ionic liquids with the surface activity of traditional surfactants. surface-active ionic liquids often comprise ionic liquids with alkyl chains long in length incorporated within their cation structure to exhibit amphiphilic character similar to the standard surfactant. Surface-active ionic liquids, in such a structure, can display surfactant-like behaviour yet have the intrinsic qualities of ionic liquids. On dissolution in aqueous environments, these surface-active ionic liquids can even show the aggregation forms like micelles and others as well, effective at dissimilar phase interfaces [2], [7], [8]. What is so valuable about surface-active ionic liquids is the fact that they are both reaction media and surface-active agents at the same time. In comparison to traditional surfactants, surface-active ionic liquids tend to exhibit superior properties such as lower CMC values, much improved thermal stability, increased chemical versatility, and a solvation environment that can be optimized for particular purposes.[18] This blend of characteristics offers unprecedented opportunities in various areas such as catalysis, where the organized assemblies can deliver nanoreactors for accelerated reaction rates; separations, where their interfacial activity can be used to facilitate phase transfer operations; and materials

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science, where they can template the development of nanostructured materials with designed morphologies.[19]The combination of ionic liquid characteristics with surfactant functionality in surface-active ionic liquids through synergistic integration is a key frontier in chemical technology that promises novel solutions to problems in green chemistry, nanomaterials synthesis, and advanced separations processes.[1], [3], [9].

III. CLASSIFICATION IONIC LIQUID BASED SURFACTANTS

IONIC LIQUID BASED SURFACTANTS have come in many types, such as cationic, anionic, and zwitterionic shapes, with varied properties and future uses.

A. Anionic Ionic Liquid-Based Surfactants:

ILBS are a group of surface-active agents which incorporate the behavior of ionic liquids (ILs) into the amphiphilic behavior of conventional anionic surfactants. Such surfactants are usually formed by organic surfactant anions and cations like 1-butyl-3-methylimidazolium ([BMIM]). They have proved to be of great promise in numerous applications, ranging from battery design and control of reactions to other uses, because of their special properties [20] Anionic ILBS are environmentally friendlier and more chemically tunable than other typical ionic liquids, hence being preferable for future-oriented and sustainable applications.

B. Zwitterionic Ionic Liquid-Based Surfactants:

Zwitterionic ionic liquid-based surfactants are an exclusive type of amphiphilic molecules possessing the ionic liquid characteristics as well as zwitterion city of surfactants. Such surfactants have both the cationic and anionic groups present within the same molecule, thereby bearing a net zero charge. Such a structure conveys superior interfacial properties, stability, and adjustability, making Zwitterionic ionic liquid-based surfactants exceptionally powerful in diverse applications.[21].

C. Cationic Ionic Liquid-Based Surfactants:

Cationic ionic liquid-based surfactants are a group of surface-active agents that incorporate the amphiphilic character of conventional cationic surfactants with the properties of ionic liquids. These surfactants have a positively charged ionic liquid moiety (e.g., imidazolium, pyridinium, or ammonium) as the hydrophilic head group and a hydrophobic tail (e.g., alkyl or aromatic chain). Cationic Ionic Liquid-Based Surfactants are extensively researched because of their high surface activity, thermal stability, and tunable nature, which makes them applicable for a range of applications.[22]

Table Surface-Active Ionic Liquids (SAILs) Types [14]

Sr. No	SAIL Type	Key Features	Examples	Applications
1	Cationic SAILs	• Cationic headgroups • Hydrophobic alkyl chains • Strong adsorption on negative surfaces	• [C_{12}mim] [Br] • [C_{16}Py] [Cl] • N,N,N-trimethyl-N dodecyl ammonium bromide	• Antimicrobial agents • DNA/RNA interactions • Corrosion inhibitors
2	Anionic SAILs	• Anionic headgroups • Better biodegradability • Lower toxicity than cationic	• [Bmim][DS] • Sodium 1,4-bis(2-ethylhexyl) sulfosuccinate • Fatty acid IL salts	• Detergents • Enhanced oil recovery • Emulsifiers
3	Zwitterionic SAILs	• Both positive and negative charges • pH-responsive behaviour • Excellent biocompatibility	• 1-(carboxymethyl)-3-alkylimidazolium • Sulfobetaine-based SAILs • Phosphorylcholine-containing SAILs	• Biomedicine • Non-fouling coatings • Colloidal stabilization

Table 1 Advance in Surface-Active Ionic Liquids (SAILs) [1], [1], [1], [2], [4], [17], [23], [23], [24], [24], [25], [25], [26], [26], [27], [28], [28], [29], [30], [31]

Sr. No	SAIL Type	Key Features	Examples	Applications
1	Gemini SAILs	• Two amphiphilic units • Molecular spacer • Lower CMC values	• Bis-imidazolium with hexamethylene spacers • Bis(1-alkyl-3-methylimidazolium bromide) • Pyridinium-based geminis	• Solubilization • Surface modification • Gene transfection
2	Task-Specific SAILs	• Additional functional groups • Enhanced selectivity • Multi-functionality	• Thiol-functionalized imidazolium • Amino-functionalized SAILs • Epoxy-functionalized SAILs	• Metal extraction • CO_2 capture • Catalysis
3	Stimuli-Responsive SAILs	• Switchable properties • Environmental triggers • Reversible behavior	• Thermosensitive oligo(ethylene glycol) SAILs • pH-responsive SAILs • Azobenzene-containing photosensitive SAILs	• Smart materials • Controlled release • Switchable emulsions
4	Magnetic SAILs	• Paramagnetic components • External manipulation • Recoverable	• Iron-containing imidazolium SAILs • Magnetic nanoparticle-SAIL composites • Gadolinium-incorporated SAILs	• Separations • Targeted delivery • MRI contrast agents
5	Bio-Based SAILs	• Renewable resources • Improved biodegradability • Reduced toxicity	• $[C_{12}mim][Gly]$ • Choline-fatty acid SAILs • Sugar-based SAILs	• Green chemistry • Biocompatible interfaces • Pharmaceutical applications
6	Polymeric SAILs	• Polymerizable groups • Network formation • Enhanced stability	• Poly(1-vinyl-3-dodecylimidazolium bromide) • Polymerized phosphonium SAILs • SAIL block copolymers	• Coatings • Membrane materials • Stabilizers

IV. APPLICATION OF IONIC LIQUID BASED SURFACTANTS

Ionic liquid surfactants are new-generation surfactants that show great potential as alternatives to traditional surfactants in cleaning agents and detergents. Ionic liquid surfactants possess some novel features including high thermal stability, low volatility, and tunable physicochemical properties, thereby making them apt for different cleaning processes. Ionic liquid surfactants, when added to a detergent formulation, can promote better solubilization of hydrophobic impurities and improve the cleaning performance. Their capacity to create stable micelles at lower concentrations than conventional surfactants make it possible to use less dosage in cleaning products, which could result in more environmentally friendly and economical solutions. The ionic character of these surfactants also makes them interact well with both polar and non-polar materials, making it easier to remove a broad variety of stains and soils from various surfaces. The flexibility of ionic liquid-based surfactants also enables them to be tailored to particular cleaning applications, including hard surface cleaning, laundry detergents, or industrial degreasing chemicals, which further broadens their potential uses in the cleaning market.

A. Enhanced Oil Recovery (Eor)

Ionic liquid-based surfactants have emerged as promising alternatives to conventional surfactants in enhanced oil recovery (EOR) operations. Their unique molecular structure allows them to significantly reduce oil-water interfacial tension to ultra-low values (as low as 10^{-2} mN/m) while effectively altering reservoir rock wettability from oil-wet to water-wet. These properties enable the extraction of residual oil that remains trapped after primary and secondary recovery methods. What distinguishes Ionic liquid-based surfactants from traditional surfactants is their exceptional stability under harsh reservoir conditions, including high temperatures, pressures, and salinity levels. Studies have shown that imidazolium-based ionic liquids can recover up to 15% of residual oil post-water flooding. The versatility of Ionic liquid-based surfactants is further demonstrated in their applications across different EOR techniques surfactant flooding, micellar flooding, and

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wettability alteration—with specialized formulations (catanionic and zwitterionic Ionic liquid-based surfactants) consistently outperforming conventional options. Their ability to form stable nano emulsions with droplet sizes of 138-148 nm and high zeta potentials (>40 mV) ensures long-term effectiveness even in challenging reservoir environments. Despite these advantages, widespread adoption hinges on addressing concerns regarding environmental impact, optimization for specific reservoir conditions, and economic viability of large-scale production.[32], [33], [34], [35]

B. Pharmaceuticals And Drug Delivery Systems

Ionic liquid-based surfactants have emerged as innovative excipients in pharmaceutical formulations and drug delivery systems, addressing key challenges in modern therapeutics. These materials offer exceptional solubilization capabilities for poorly water-soluble drugs a property particularly valuable considering that approximately 70% of new drug candidates exhibit limited aqueous solubility. The amphiphilic structure of Ionic liquid-based surfactants enables them to form various self-assembled nanostructures including micelles, vesicles, and liquid crystalline phases at lower critical micelle concentrations than conventional surfactants, providing stable drug encapsulation with reduced excipient loads. Their structural tunability allows pharmaceutical scientists to precisely engineer drug-carrier interactions, leading to controlled release profiles and improved pharmacokinetics. In transdermal and transmucosal delivery applications, Ionic liquid-based surfactants demonstrate superior penetration enhancement by temporarily disrupting lipid organization in biological membranes without causing permanent damage. Recent studies have focused on developing stimuli-responsive Ionic liquid-based surfactants systems that respond to specific physiological triggers like pH variations in tumour microenvironments or enzymatic activity in the gastrointestinal tract, enabling site-specific drug release. Despite these advantages, the biocompatibility of Ionic liquid-based surfactants remains a critical consideration, with ongoing research focusing on designing structures that maintain functional benefits while minimizing cytotoxicity and potential immunogenic responses through careful selection of cation-anion combinations and incorporation of biodegradable components.[36], [37], [38]

C. Textile And Leather Processing

Ionic liquid-based surfactants are revolutionizing textile and leather industries by combining the beneficial properties of ionic liquids (thermal stability, low volatility, tunability) with surfactant functionality, creating multifunctional processing agents. In textile applications, these compounds enhance dyeing processes through improved dye solubilization, fibre penetration, and color uniformity while reducing energy consumption; they also serve as effective carriers for functional finishes (antimicrobial, flame-retardant) and facilitate fibre surface modifications. In leather processing, these surfactants support more environmentally friendly operations by reducing harmful chemicals in dehairing and liming, enhancing tanning agent distribution, lowering chrome usage, and improving finishing application quality and leather properties. Despite their significant advantages, challenges including high production costs, scalability issues, and concerns about toxicity and biodegradability must be addressed through ongoing research into bio-based alternatives, optimized synthesis methods, and comprehensive environmental impact assessments before widespread industrial adoption can occur.[39], [40], [41]

D. Lubricants And Additives

Ionic liquid surfactants have vast promise as lubricants and additives for industry with greater performance benefits compared to traditional alternatives. Ionic liquid surfactants create durable boundary films on surface materials, minimizing contact between fibres during processing and mechanical operations while, at the same time, ensuring equipment protection against wear. Ionic liquid surfactants' great thermal stability ensures they retain lubrication properties in high-temperature manufacturing environments without degrading and increasing machinery lifespan. During textile processing, they enable easier passage of yarns through machinery with less fibre breakage during spinning and weaving as well as softening and improvement in drape of finished fabric. In the manufacture of leather, these surfactants help improve slip behavior during mechanical operations such as buffing and staking, with more even finishes and better tactile properties. They inhibit undesirable charge buildup on synthetic fabrics and on leather surfaces during processing and final use. Secondly, these materials can be engineered as multistrand additives with the functions of lubrication, water repellency, softening, or antimicrobial activity, optimizing processing steps. As more sustainable alternatives to conventional petroleum-based lubricants, ionic liquid surfactants generally exhibit reduced volatility, lowered toxicity, and increased biodegradability, advancing sustainability efforts in these industries.[42], [43], [44], [45]

E. Ionic Liquid Surfactant Nanoparticle Synthesis

Ionic liquid surfactants have proven to be potent directing agents in the synthesis of nanoparticles, providing unparalleled control over nanoparticle size, morphology, and surface characteristics. These advanced surfactants play the dual roles of stabilizing agents and structure-directing templates during particle formation, producing highly ordered self-assembled structures that direct nanoparticle growth. Their ionic nature ensures robust electrostatic stabilization, avoiding agglomeration while ensuring long-term colloidal stability. Unlike traditional surfactants, ionic liquid analogues have functionality across extreme reaction conditions, such as high temperature and different solvent environments, broadening the available synthesis parameter space. They have low vapor pressure, which allows reactions at elevated temperatures without loss by evaporation, supporting green chemistry design principles through lowered solvent demand. Their very high tunability via headgroup, counterion, and alkyl chain length variations enables accurate nanoparticle property engineering for application in catalysis, sensing, biomedicine, and electronics. Of special interest is their capacity to stabilize metal nanoparticles both sterically and electrostatically,

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producing smaller particle sizes with narrower size distributions than conventional techniques. For quantum dots made of semiconductors, ionic liquid surfactants improve luminescence characteristics by offering improved surface passivation, minimizing defect states while maximizing quantum yield. For magnetic nanoparticle synthesis, the compounds allow for precise control of magnetic anisotropy and interparticle interactions, essential for data storage and biomedical imaging applications. Recent studies show their efficiency in forming hierarchical nanostructures and hollow materials through templating processes. As manufacturing technologies evolve, ionic liquid surfactants hold the potential to transform nanomaterial synthesis by integrating efficient synthesis control with enhanced environmental profiles, leading to more sustainable nanomaterial production in various industrial applications.[46], [47], [48]

F. Ionic Liquid Surfactants In Environmental Remediation

Ionic liquid surfactants are a novel strategy for environmental remediation that provides improved capacity for treating sophisticated contamination situations in soil, groundwater, and industrial wastewaters. The ionic liquid surfactants demonstrate improved performance for mobilizing and solubilizing hydrophobic organic contaminants like petroleum hydrocarbons, polycyclic aromatic compounds, and chlorinated solvents from contaminated media. Their amphiphilic nature enables them to interact with both the hydrophobic pollutants and the aqueous phase, promoting micelle formation that sequesters pollutants and aids in their removal. The exceptional versatility of ionic liquid surfactants, realized through structural adjustment of their cationic, anionic, and alkyl moieties, makes it possible to design for particular contaminant compositions and environmental conditions. This ability to customize is especially useful for dealing with mixed contaminant situations or high-pH environments where traditional surfactants fail. Strong thermal stability in these materials enables their use in thermal remediation processes, with no degradation of surfactant activity under steam injection or electrical resistance heating. In heavy metal remediation, functionalized ionic liquid surfactants show remarkable selective extraction ability via chelating groups integrated within their composition, facilitating the removal of organic contaminants and metal pollutants in tandem. Their low volatility has the advantage of greatly limiting atmospheric emissions in field operations, providing enhanced safety to workers and the possibility of prolonged treatment periods without replenishment. More sophisticated formulations incorporating biodegradable additives counter past worries about surfactant persistence in treated ecosystems. Recent research is aimed at creating ionic liquid surfactants with increased specificity for priority pollutants, better biodegradability profiles, and lower production costs to enable wider application in environmental management practices. Although more expensive than traditional remediation surfactants, their increased efficiency, lower dosage rates, and recoverability and reusability potential often lead to favourable overall economics for difficult remediation projects .[49], [50]

V. CONCLUSION

Ionic liquid-based surfactants represent a significant advancement in surfactant technology, offering unprecedented opportunities for innovation across multiple industrial sectors. Their unique integration of ionic liquid properties with conventional surfactant functionality creates compounds with exceptional versatility and performance capabilities. Through this review, we have demonstrated how the strategic modification of their molecular architecture through variations in cation structure, anion selection, and alkyl chain length enables precise tuning of their physicochemical properties for targeted applications. The remarkable thermal stability, negligible volatility, and enhanced interfacial activity of these compounds provide substantial advantages over traditional surfactants, particularly in challenging operating environments. Their demonstrated efficacy in enhanced oil recovery, pharmaceutical formulations, textile and leather processing, lubrication, nanoparticle synthesis, and environmental remediation underscores their broad industrial relevance and transformative potential.

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