



Review-ionic liquids: Advances in design, properties, and applications for green chemistry and energy systems

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Abstract

Ionic liquids (ILs), composed entirely of cations and anions, have emerged as versatile “designer solvents” due to their low volatility, high thermal stability, wide electrochemical windows, and tunable physicochemical properties. Their unique structures enable applications across catalysis, electrochemistry, biomedicine, nanotechnology, and environmental remediation. This review provides a concise overview of recent advances in ILs, focusing on their classification, synthesis, properties, and major applications in green chemistry and energy systems. Current challenges including toxicity, scalability, and recovery are highlighted, along with perspectives for next-generation ILs.

Keywords: Ionic liquids, green chemistry, catalysis, energy storage, nanotechnology, sustainable chemistry

Introduction

Ionic liquids (ILs) are a unique class of molten salts that remain liquid at or near room temperature, generally composed of bulky organic cations such as imidazolium, pyridinium, ammonium, or phosphonium, and a wide range of inorganic or organic anions^[1, 4]. Unlike traditional salts such as sodium chloride, which crystallize at high temperatures, ILs exhibit low melting points due to the asymmetry and delocalized charge distribution of their ions. This unusual structural feature gives rise to their most defining properties: negligible vapor pressure, non-volatility, high thermal and electrochemical stability, wide liquidus range, and remarkable structural tunability^[5, 7].

These attributes have made ILs attractive as “designer solvents” since their physicochemical characteristics can be systematically tuned by appropriate selection of cation–anion combinations. For instance, variations in alkyl chain length or the incorporation of functional groups enable precise control over hydrophobicity, hydrogen-bonding capability, viscosity, polarity, and solvation power^[8, 10]. This level of customization allows ILs to outperform conventional molecular solvents in many contexts, particularly where selective solubilization, environmental sustainability, or stability under extreme conditions is required.

From a green chemistry perspective, ILs offer distinct advantages over volatile organic solvents (VOCs). Their negligible vapor pressures prevent harmful emissions, reducing atmospheric pollution and occupational hazards^[11, 12]. Moreover, ILs can dissolve a wide spectrum of substrates, ranging from biopolymers like cellulose to metal salts, gases, and nanoparticles^[13, 14]. Such versatility positions ILs as enabling media in biomass valorization, catalysis, separations, and nanotechnology. However, their environmental friendliness remains debated, as issues of toxicity, biodegradability, and cost of synthesis continue to limit their large-scale adoption^[15, 17].

In recent decades, ILs have transitioned from niche laboratory solvents to multifunctional materials in diverse fields. In catalysis, they serve not only as reaction media but

also as co-catalysts, stabilizers of active species, and supports for heterogeneous catalytic systems^[18, 19]. In electrochemistry, their high ionic conductivity and wide electrochemical windows make them promising electrolytes for next-generation energy storage devices such as lithium-ion batteries, supercapacitors, and fuel cells^[20, 22]. In biomedical sciences, third-generation ILs are being engineered for enhanced solubility and delivery of poorly soluble drugs, antimicrobial agents, and bio-responsive materials^[23, 25]. In nanoscience and materials engineering, ILs act as stabilizing agents, templating media, or functionalizing ligands for nanoparticles, graphene, carbon nanotubes, and polymer composites^[26, 28]. Furthermore, environmental applications such as CO₂ capture, pollutant removal, and lubrication highlight their role in sustainable technologies^[29, 31].

The trajectory of IL research reflects both their scientific promise and technological challenges. While the diversity of possible ion combinations theoretically yields millions of IL structures, only a fraction has been explored experimentally. Challenges such as synthetic cost, recovery and recycling, toxicity, and limited industrial scalability continue to hinder broader adoption^[32, 34]. Recent advances in bio-based ILs, task-specific ionic liquids (TSILs), and hybrid IL–nanomaterial systems provide promising strategies to overcome these barriers^[35, 37].

This review article aims to present a concise yet comprehensive overview of the advances in ionic liquids, emphasizing their design strategies, physicochemical properties, and broad spectrum of applications in catalysis, electrochemistry, nanotechnology, biomedicine, and environmental sustainability. By highlighting recent developments, challenges, and future perspectives, this work seeks to demonstrate how ILs are evolving from laboratory curiosities to central players in the advancement of green chemistry and energy systems.

Historical Development

The study of ILs dates back to the mid-20th century, but their prominence increased with room-temperature ionic

liquids (RTILs) in the 1990s [11, 13]. Early research emphasized electrochemical stability, followed by catalytic and green chemistry applications [14, 16]. More recently, biomedical and nanotechnology-focused ILs have been developed [17, 19].

Classification of Ionic Liquids

ILs can be broadly categorized as [20, 22]:

- **Neutral anion-cation ILs:** stable, low-melting, often used as solvents.
- **Acidic ILs:** based on protic ammonium or $AlCl_3$ systems, useful for catalysis.
- **Basic ILs:** contain anions like acetate or lactate, enhancing solubility and catalysis.
- **Amphoteric ILs:** with dual proton donor/acceptor behavior (e.g., HSO_4^- , $H_2PO_4^-$).

Task-specific ionic liquids (TSILs) extend these classes by tailoring functionalities for targeted applications [23, 25].

Synthesis of Ionic Liquids

IL synthesis involves cation formation (quaternization) followed by anion exchange (metathesis) [26, 27]. Common cations include imidazolium, pyridinium, phosphonium, and ammonium [28]. Anion variation (e.g., PF_6^- , BF_4^- , acetate, lactate) tunes solubility, hydrophobicity, and stability [29]. Halogen-free and bio-based ILs are increasingly developed to reduce toxicity [30, 31].

Properties of Ionic Liquids

Key physicochemical properties include:

- **Low vapor pressure & non-volatility:** safer than VOCs [32].
- **Thermal & electrochemical stability:** wide operational window [33].
- **Ionic conductivity:** valuable in batteries and supercapacitors [34].
- **Solvation power:** dissolving cellulose, biomolecules, and nanoparticles [35].
- **Tunable polarity & viscosity:** via cation/anion design [36].

Toxicity remains a concern, with imidazolium-based ILs often more toxic than bio-derived ILs [37, 38].

Applications of Ionic Liquids

Catalysis

ILs act as solvents, co-catalysts, or active catalytic media in reactions such as alkylation, oxidation, and polymerization [39, 41]. Supported IL phase catalysts (SILPCs) combine the benefits of homogeneous and heterogeneous systems [42].

Electrochemistry and Energy Storage

ILs are promising electrolytes for lithium-ion batteries, fuel cells, and supercapacitors due to their non-flammability and high conductivity [43, 46]. They also aid hydrogen storage and low-heat energy harvesting [47].

Biomedicine

Third-generation ILs improve drug solubility, bioavailability, and antimicrobial activity [48, 49]. Their tunable miscibility supports targeted drug delivery systems.

Nanotechnology and Materials

ILs stabilize nanoparticles, graphene, carbon nanotubes, and cellulose nanomaterials, enabling applications in sensors, coatings, and hybrid gels [50].

Environmental Applications

ILs facilitate CO_2 capture, oil refining, gas absorption, and lubrication, offering sustainable alternatives to volatile organic solvents.

Challenges and Limitations

Despite their promise, ILs face hurdles such as:

- High cost and synthesis complexity.
- Toxicity and environmental persistence.
- Recovery and recycling challenges.

Efforts focus on bio-based ILs, deep eutectic solvents (DESs), and scalable green syntheses.

Future Perspectives

Next-generation ILs will likely be:

- Task-specific and bio-derived, minimizing toxicity.
- Hybrid IL-nanomaterials, enhancing conductivity and stability.
- Scalable electrolytes for advanced batteries and supercapacitors.
- Sustainable solvents for biomass valorization and carbon capture.

Conclusion

Ionic liquids represent a powerful class of functional solvents with vast potential in green chemistry, energy systems, nanotechnology, and medicine. While toxicity and scalability remain challenges, rapid progress in task-specific and bio-inspired ILs suggests a promising future for sustainable chemistry and advanced materials.

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