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Beyond the Solvent: Engineering Ionic Liquids for Biomedical Applications-Advances, Challenges, and Future Directions

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Abstract Ionic liquids (ILs) have emerged as multifunctional compounds with low volatility, high thermal stability, and tunable solvation capabilities, making them highly promising for biomedical applications. First explored in the late 1990s and early 2000s for enhancing the thermal stability of enzymes, antimicrobial agents, and controlled release systems, ILs have since gained significant attention in drug delivery, antimicrobial treatments, medical imaging, and biosensing. This review examines the diverse functions of ILs in contemporary therapeutics and diagnostics, highlighting their transformative capabilities in improving drug solubility, bioavailability, transdermal permeability, and pathogen inactivation. In drug delivery, ILs improve solubility of bioactive compounds, with several IL formulations achieving substantial solubility enhancements for poorly soluble drugs. Bio-ILs, in particular, show promise in enhancing drug delivery systems, such as improving transdermal permeability. ILs also exhibit significant antimicrobial and antiviral activity, offering new avenues for combating resistant pathogens. Despite their broad potential, challenges such as cytotoxicity, long-term metabolic effects, and the stability of ILs in physiological conditions persist. While much research has focused on their physicochemical properties, biological activity and in vivo studies are still underexplored. The future directions for ILs in biomedical applications include the development of bioengineered ILs and hybrid ILs, combining functional components like nanoparticles and polymers to create multifunctional materials. These ILs, derived from renewable resources, show great promise in personalized medicine and clinical applications. Further research is necessary to evaluate their pharmacokinetics, biodistribution, and long-term safety to fully realize their biomedical potential. This study emphasizes the potential of ILs to transform therapeutic and diagnostic technologies by highlighting present shortcomings and offering pathways for clinical translation, while also debating the need for continuous research to fully utilize their biomedical capabilities.

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