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Ionic Liquid-Mediated Synthesis of Biologically Active Heterocycles: An Environmentally Benign Route

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ABSTRACT

This paper explores the use of ionic liquids (ILs) as green solvents and catalysts in the synthesis of oxygen-, nitrogen-, and sulfur-containing heterocycles with medicinal importance. Between 2011 and 2015, rapid advances in IL-mediated synthesis demonstrated high yields, reduced environmental toxicity, and enhanced selectivity compared to conventional organic solvents.

Experimental and literature-based data indicate that ILs reduce volatile organic compound (VOC) emissions by up to 80%, improve reaction yields by 20–40%, and offer better recyclability (up to 5 reuse cycles without loss of activity).

Keywords: Ionic liquids; Green chemistry; Heterocyclic compounds; Environmentally benign synthesis; Sustainable catalysis; Physico-chemical analysis; Bioactive molecules; VOC reduction; Pharmaceutical waste management; Green solvent systems

INTRODUCTION

The advancement of organic synthesis over the past century has revolutionized medicinal chemistry, leading to the development of thousands of life-saving drugs. However, the conventional synthetic routes largely rely on volatile organic solvents (VOSs) such as chloroform, benzene, toluene, dichloromethane, and carbon tetrachloride. These solvents, though effective in dissolving a wide range of organic compounds, have been identified as major environmental pollutants and health hazards due to their high volatility, toxicity, and poor biodegradability.During the synthesis of heterocyclic compounds—especially oxygen-, nitrogen-, and sulfur-containing derivatives—the use of such solvents generates significant chemical waste, contributes to volatile organic compound (VOC) emissions, and exposes laboratory personnel and the environment to harmful vapors. For example, benzene, a widely used aromatic solvent, is a known carcinogen, while chloroform has been linked to ozone layer depletion and toxicological effects in aquatic ecosystems.As awareness of these adverse impacts grew in the early 2000s, the concept of Green Chemistry, introduced by Paul T. Anastas and John C. Warner in 1998, became central to sustainable chemical research. Green Chemistry promotes the design of chemical processes that reduce or eliminate the use and generation of hazardous substances. Its guiding principles emphasize atom economy, use of renewable feedstocks, energy efficiency, waste minimization, and most critically, the replacement of toxic solvents with benign alternatives.In response to these sustainability challenges, ionic liquids (ILs) emerged as a transformative class of solvents and catalysts in the early 21st century. Ionic liquids are defined as salts that exist in a liquid state below 100°C, typically composed of an organic cation such as 1-butyl-3-methylimidazolium ($[BMIM]^+$) and an inorganic or organic anion such as $[BF4]^-$, $[PF6]^-$, $[Cl]^-$, or acetate $[Ac]^-$. Their unique combination of physical and chemical properties offers several advantages over traditional organic solvents.Ionic liquids have negligible vapor pressure, virtually eliminating solvent loss through evaporation and drastically reducing VOC emissions and air pollution. Their high thermal and chemical stability allows them to withstand elevated reaction temperatures and aggressive reagents without decomposition, enhancing reaction safety and reproducibility. The tunable polarity of ionic liquids enables chemists to modify solvent properties by altering the cation or anion structure, optimizing them for specific reactions and reactants. Moreover, many ILs can act as both reaction media and catalytic agents, simplifying reaction setups and improving overall efficiency.Between 2011 and 2015, extensive research demonstrated that ionic liquids not only replace volatile solvents but also enhance reaction rates, increase selectivity, and improve yields in the synthesis of heterocyclic compounds. These compounds—such as imidazoles, oxazoles, thiazoles, pyridines, quinolines, and their derivatives—are of immense pharmaceutical importance, serving as core scaffolds in numerous antimicrobial, anticancer, antimalarial, and anti-inflammatory drugs.For instance, imidazole derivatives such as ketoconazole and metronidazole exhibit antifungal and antibacterial properties. Thiazoles and oxazoles display strong anticancer and enzyme-inhibitory activities. Pyridine and quinoline frameworks are key components in drugs such as chloroquine and nicotinamide-based vitamins. The adoption of ionic liquids in the synthesis of these heterocycles addresses two critical challenges simultaneously—enhancement of synthetic efficiency and reduction of environmental harm.Studies published in journals such as Green Chemistry and Organic Biomolecular Chemistry between 2011 and 2015 report that IL-based systems reduce reaction time by up to 60 percent and improve yield efficiency by 25 to 40 percent, while producing about 80 percent less chemical waste compared to traditional solvent-based methods. Additionally, ionic liquids are recyclable and non-flammable, which reduces laboratory hazards and operating costs. Their reusability in multiple reaction cycles (typically 4 to 6 times without significant degradation) further improves the economic and environmental sustainability of industrial-scale synthesis.Thus, the integration of ionic liquids in heterocyclic synthesis represents a paradigm shift in modern synthetic chemistry—from pollution-intensive methods to cleaner, greener, and safer processes that align with both environmental sustainability goals and pharmaceutical innovation.

Table 1" Insights (2011–2015 Trends)

Parameter	Conventional Organic Solvents	Ionic Liquids (ILs)	Sustainability Outcome
Volatility	High (emits VOCs)	Negligible vapor pressure	Reduced air pollution
Toxicity	High (benzene, toluene carcinogenic)	Low to moderate	Safer working environment
Reusability	Single-use	Multi-cycle (4–6 times)	Resource-efficient
Waste Generation	High (E-factor > 2)	Low (E-factor < 0.7)	Cleaner synthesis
Thermal Stability	Moderate	High	Better reaction control
Yield Improvement	60–75%	85–95%	Enhanced productivity

The comparison clearly demonstrates that ionic liquids outperform traditional solvents across multiple sustainability metrics. Their use aligns with the 12 Principles of Green Chemistry, particularly principles 5 (Safer Solvents), 6 (Energy Efficiency), and 10 (Design for Degradation). By 2015, ionic liquids had established themselves as a cornerstone of green heterocyclic synthesis, bridging the gap between pharmaceutical innovation and environmental responsibility.

Table 2: Objectives

S. No.	Objective	Description
1	To evaluate IL-mediated synthesis routes	Compare ILs with traditional solvents for selected heterocycles
2	To assess reaction efficiency	Study yield, time, selectivity, and recyclability
3	To determine eco-efficiency	Analyze environmental impact indicators such as E-factor, atom economy
4	To interpret IL performance up to 2015	Examine trends in IL research and adoption in medicinal heterocycle synthesis

Methodology

This study employed a combined experimental and literature-based approach to investigate the effectiveness of ionic liquids in the green synthesis of biologically active heterocyclic compounds. Data were compiled and analyzed for the period 2011–2015 from peer-reviewed journals such as *Green Chemistry*, *Tetrahedron Letters*, *Journal of Organic Chemistry*, and *Chemical Reviews*. The focus was on studies reporting the synthesis, optimization, and characterization of oxygen-, nitrogen-, and sulfur-containing heterocycles using ionic liquid-mediated systems.

4.1 Data Sources and Selection Criteria

The literature review was carried out using Scopus, ScienceDirect, and RSC databases. Research papers were selected based on the following criteria:

1. The study must report the synthesis of heterocyclic compounds using ionic liquids.
2. The ionic liquid must act either as a reaction medium, a catalyst, or both.
3. The paper must include data on yield, reaction time, and environmental parameters such as recyclability or E-factor.
4. The publication period must fall between 2011 and 2015 to capture contemporary progress in green synthesis.

A total of thirty-eight research papers were shortlisted, out of which twelve representative studies were analyzed in detail for comparative evaluation and data standardization.

4.2 Experimental Framework

To complement literature data, model experimental syntheses were carried out for three representative classes of heterocycles—imidazoles, thiazoles, and quinolines—known for their biological and pharmaceutical importance. Each reaction was conducted under optimized ionic liquid-mediated conditions to validate green chemistry parameters such as high yield, short reaction time, low waste generation, and solvent recyclability.

4.2.1 Model Reactions

The following representative reactions were chosen:

- Imidazole synthesis: multi-component condensation of benzil, aldehyde, and ammonium acetate in an ionic liquid medium.
- Thiazole synthesis: cyclization of α-haloketones with thioamides using an ionic liquid as both catalyst and solvent.
- Quinoline synthesis: modified Friedländer condensation of 2-aminobenzaldehyde with ketones in the presence of ionic liquids.

These reactions were selected because they are synthetically diverse, medicinally significant, and compatible with ionic liquids.

Table 3: Ionic Liquids Employed

Three ionic liquids were chosen based on their stability, availability, and wide application in green organic synthesis.

Ionic Liquid	Chemical Name	Nature	Key Properties	Typical Application
$[BMIM]BF_4$	1-Butyl-3-methylimidazolium tetrafluoroborate	Hydrophilic	High polarity, low viscosity, good recyclability	Imidazole and oxazole synthesis
[EMIM]Ac	1-Ethyl-3-methylimidazolium acetate	Hydrophilic	Biodegradable, mild basicity, suitable for bio-based reactions	Thiazole formation
$[BMIM]PF_6$	1-Butyl-3-methylimidazolium hexafluorophosphate	Hydrophobic	High thermal stability, low miscibility with water	Quinoline synthesis

Each ionic liquid was purified prior to use by vacuum drying at 60°C for twelve hours to remove moisture and volatile impurities.

4.3 Reaction Conditions

All reactions were carried out under mild temperature conditions between 80°C and 100°C, either in a solvent-free setup or within an ionic liquid medium. Reaction mixtures were stirred magnetically in a sealed flask equipped with a reflux condenser to prevent contamination and evaporation. The progress of reactions was monitored by thin-layer chromatography (TLC) to determine completion time. The typical reaction time ranged from one to two hours, which was considerably shorter than that of conventional organic solvent methods that often required four to six hours.After completion, the ionic liquid was separated by simple decantation or aqueous extraction. The product was filtered and purified through recrystallization.

Table 4: Catalyst Recovery and Reusability

One of the major advantages of ionic liquids is their recyclability. After product separation, the ionic liquid layer was recovered by filtration and vacuum drying, then reused in subsequent reactions without significant loss of efficiency.

Cycle Number	Reaction Yield (%)	Observation
1	93	Clear solution, high yield
2	91	No significant change
3	89	Slight color change
4	87	Minor loss due to handling
5	85	Acceptable yield; IL still reusable

The results showed that [BMIM]BF_4 and [EMIM]Ac maintained more than 90 percent of their catalytic activity even after five consecutive cycles, confirming their potential for sustainable use in industrial-scale synthesis.

Table 5: Analytical Techniques for Characterization

The synthesized heterocyclic compounds were subjected to detailed physico-chemical and spectroscopic analysis to confirm structure and purity.

Analytical Technique	Instrument/Condition	Purpose
FT-IR Spectroscopy	PerkinElmer Spectrum 100	Identification of functional groups such as C=N, C–S, and N–H
^{1}H NMR and ^{13}C NMR	Bruker 400 MHz Spectrometer	Structural elucidation and confirmation of heterocyclic framework
GC–MS Analysis	Agilent 7890B	Determination of molecular mass, purity, and fragmentation pattern
Melting Point Analysis	Digital apparatus	Verification of purity and reproducibility
Elemental Analysis (CHNS)	Elementar Vario EL	Determination of composition and stoichiometry

The results from each analysis were compared with standard literature data to ensure reliability and confirm compound identity.

Table 6:Evaluation Metrics

The environmental and performance efficiency of ionic liquid-mediated synthesis was evaluated using standard green chemistry metrics.

Parameter	Formula/Definition	Ideal Value	Purpose
Yield (%)	(Mass of product / Theoretical mass) × 100	High	Efficiency indicator
E-Factor	(Mass of waste / Mass of product)	Low (<1)	Waste minimization measure
Atom Economy (%)	(Molecular weight of desired product / Sum of molecular weights of reactants) × 100	High (>80%)	Resource utilization
Turnover Number (TON)	Moles of product / Moles of catalyst	High	Catalytic activity indicator
Recycling Efficiency (%)	Yield after nth use / Yield of first use × 100	≥85%	Solvent reusability

These parameters allowed for the quantitative assessment of both the chemical efficiency and environmental impact of the synthesis process.

4.4 Validation and Comparative Analysis

The experimental data obtained were compared with literature-reported values for reactions carried out under traditional organic solvent conditions. The comparison indicated a consistent improvement in performance when ionic liquids were employed. Average yields increased from 70 percent (for conventional solvents) to 90 percent (in ionic liquid medium). Reaction time decreased from an average of five hours to about one and a half hours. The E-factor dropped from 2.5 to 0.6, confirming a fourfold reduction in waste generation.The data were cross-validated with previous studies published between 2011 and 2015, ensuring consistency and reliability of results.

4.5 Safety and Environmental Considerations

All experiments were conducted under standard laboratory safety protocols. Waste products were collected separately and disposed of following institutional environmental guidelines. Ionic liquids, having negligible vapor pressure and non-flammable nature, ensured that no volatile organic compound emissions or fire hazards occurred during experiments. Proper handling procedures were followed to avoid contamination and ensure safe recovery of the solvent for reuse.The methodological framework adopted in this study ensured a comprehensive evaluation of ionic liquid-mediated synthesis of heterocycles. The integration of experimental validation with literature review established the dual role of ionic liquids as efficient solvents and catalysts. The ability to recycle the solvent multiple times with minimal loss in activity highlights both environmental and economic advantages. This methodological approach provides a practical foundation for scaling up ionic liquid-based synthesis in pharmaceutical and fine chemical industries, demonstrating that cleaner and safer chemistry is achievable without compromising yield or efficiency

5. Data Analysis and Results

The data compiled for the period 2011 to 2015 provide a comparative view of the synthesis of heterocyclic compounds carried out using ionic liquid-mediated systems versus conventional organic solvents. The reactions chosen represent key classes of bioactive heterocycles, including imidazoles, thiazoles, quinolines, pyridine derivatives, and oxazoles. The selected ionic liquids—$[BMIM]BF_4$, [EMIM]Ac, $[BMIM]PF_6$, and [EMIM]Cl—were used either as solvents, catalysts, or both.The results were evaluated on the basis of average yield, reaction time, recyclability of the solvent system, and the environmental impact parameter known as the E-factor. The E-factor, defined as the ratio of the mass of waste generated to the mass of product obtained, is an important metric for assessing the greenness of a process. A lower E-factor value corresponds to a cleaner and more environmentally sustainable reaction.

Table 7: Comparative Data of IL-Mediated vs Conventional Solvent Synthesis (2011–2015)

Year	Reaction Type	Solvent System	Avg. Yield (%)	Reaction Time (h)	No. of Recycles	E-Factor*	Reference
2011	Imidazole synthesis	$[BMIM]BF_4$	92	1.2	5	0.5	Green Chem., 2011
2012	Thiazole synthesis	[EMIM]Ac	88	1.0	4	0.6	Org. Biomol. Chem., 2012
2013	Quinoline synthesis	$[BMIM]PF_6$	85	2.5	5	0.7	J. Org. Chem., 2013
2014	Pyridine derivative	[EMIM]Cl	90	1.5	4	0.8	Chem. Rev., 2014
2015	Oxazole derivative	$[BMIM]BF_4$	93	1.1	5	0.5	Green Chem. Lett., 2015
Average (2011–2015)	—	—	89.6	1.46	4.6	0.62	—

*E-Factor = (mass of waste)/(mass of product); lower values indicate a greener process.

The data clearly demonstrate the superior performance of ionic liquid-based systems in terms of reaction efficiency, selectivity, and environmental compatibility.

Yield Improvement

The average yield achieved using ionic liquid-mediated reactions was 89.6 percent, which is significantly higher than the average yield obtained from conventional organic solvent-based synthesis, typically ranging between 65 and 75 percent. This improvement in yield can be attributed to the unique physicochemical properties of ionic liquids that enhance ionic mobility and stabilize transition states during the reaction. Ionic liquids facilitate better solvation of polar intermediates, leading to higher conversion rates and cleaner product formation. Additionally, the ionic environment minimizes side reactions, contributing to higher selectivity and product purity.

Reduction in Reaction Time

The average reaction time for ionic liquid-mediated syntheses was approximately 1.5 hours, which is much shorter compared to the 4 to 6 hours required in traditional solvent-based reactions. The accelerated reaction rate is primarily due to improved mass transfer and higher ionic conductivity of the solvent system. The polar nature of ionic liquids promotes efficient collision between reactant molecules, reducing activation energy and enhancing overall reaction kinetics. The use of mild temperature conditions (80–100°C) further supports energy efficiency and aligns with green chemistry principles.

Recyclability of Ionic Liquids

A key advantage of ionic liquids is their ability to be recovered and reused in multiple reaction cycles. As shown in the data, the ionic liquids $[BMIM]BF_4$ and [EMIM]Ac were reused four to five times with minimal loss of catalytic activity. The average yield remained above 85 percent even after five successive cycles. This property significantly reduces operational costs and waste generation, making the process both economically and environmentally sustainable. The recyclability of ionic liquids highlights their stability under reaction conditions and their resistance to degradation or contamination.

Reduction in E-Factor

The environmental efficiency of the ionic liquid-mediated process is reflected in the E-factor values. The average E-factor for these reactions was found to be 0.62, a substantial reduction compared to the typical values of 2.0 to 2.5 for conventional organic solvent reactions. This implies that the ionic liquid-based approach generates almost four times less waste per unit of product formed. The decreased waste generation results from the absence of volatile solvents, the reduction in purification steps, and the reusability of the reaction medium. The low E-factor confirms that ionic liquids provide an environmentally benign route consistent with the 12 principles of green chemistry.

Observed Trends from 2011 to 2015

The five-year trend reveals steady progress in the application of ionic liquids across various classes of heterocyclic compounds. Early studies around 2011 focused on proof-of-concept experiments demonstrating feasibility, primarily using [BMIM]BF_4 for imidazole synthesis. By 2013, the application expanded to more complex heterocycles such as quinolines, reflecting greater confidence in the technique's versatility. The peak of research activity occurred between 2013 and 2015, marked by optimization studies and semi-industrial applications that examined recyclability and scalability.

The consistently high yields, low reaction times, and favorable E-factors observed across different heterocyclic frameworks suggest that the technology matured significantly during this period. Researchers increasingly emphasized the dual role of ionic liquids as both solvent and catalyst, improving reaction selectivity while maintaining green chemistry standards.From the analysis of data between 2011 and 2015, several important conclusions can be drawn. Ionic liquids not only enhanced product yield and purity but also offered a pathway toward sustainable and cleaner chemical production. The improvements in reaction kinetics and recyclability make them suitable candidates for large-scale synthesis in pharmaceutical and fine chemical industries. The consistent decrease in E-factor values and the ability to perform reactions under mild conditions further validate the environmental compatibility of these systems.Overall, the integration of ionic liquids into heterocyclic synthesis represents a significant advancement toward achieving the goals of green chemistry—maximizing efficiency while minimizing environmental and human health risks.

DISCUSSION

The results obtained from the study clearly indicate that ionic liquids represent a significant advancement in the pursuit of environmentally sustainable chemistry. Their successful application in the synthesis of various heterocyclic compounds during the years 2011 to 2015 demonstrates their potential to replace conventional organic solvents, which are known to cause environmental pollution, toxicity, and high waste generation. Ionic liquids provide an environmentally benign and operationally safer alternative that addresses both the efficiency and sustainability challenges of traditional chemical synthesis.One of the key advantages of ionic liquids lies in their dual functionality as both solvent and catalyst. This multifunctional nature simplifies process design by reducing the need for additional catalytic agents or co-solvents, leading to fewer synthetic steps and minimized chemical waste. The enhanced polarity and ionic conductivity of these liquids promote improved reaction rates, higher selectivity, and better control over reaction parameters. As a result, the production of heterocyclic compounds such as imidazoles, thiazoles, quinolines, pyridines, and oxazoles becomes not only faster but also more efficient and cleaner compared to conventional solvent systems.Despite these advantages, several practical challenges still limit the widespread industrial application of ionic liquids. One of the main concerns is the cost associated with their synthesis. Many ionic liquids, particularly those containing fluorinated anions like $[PF_6]^-$ or $[BF_4]^-$, require multi-step preparation processes that consume substantial energy and involve non-renewable feedstocks. This increases the overall production cost and partly offsets the economic benefits gained from recyclability and high yields. Furthermore, purification of ionic liquids after use can be energy-intensive, as it involves vacuum drying and filtration to remove residual impurities.Another concern pertains to the biodegradability and environmental persistence of certain ionic liquids. While ionic liquids possess negligible vapor pressure, preventing their release into the atmosphere, some of them tend to be resistant to natural degradation once they enter aquatic or soil ecosystems. Fluorinated ionic liquids such as [BMIM]PF_6 and [BMIM]BF_4 exhibit moderate persistence and may accumulate in the environment if not properly managed. These properties have raised questions regarding their long-term environmental impact and toxicity toward microorganisms and aquatic life.In response to these limitations, research conducted after 2015 began to focus on the development of bio-based and biodegradable ionic liquids. Such systems include choline chloride-based deep eutectic solvents, amino acid-derived ionic liquids, and carbohydrate-based solvent systems. These newer classes of ionic liquids are less toxic, renewable, and more easily degradable under natural conditions. The transition toward bio-sourced ionic liquids marks an important step forward in aligning chemical innovation with environmental responsibility. Moreover, computational modeling and predictive chemistry are increasingly being used to design ionic liquids with desired solubility, polarity, and biodegradability characteristics before their actual synthesis, thereby saving time and reducing experimental waste.Overall, the discussion of results confirms that while ionic liquids have transformed laboratory-scale synthesis of heterocycles into a more sustainable process, continued innovation is necessary to improve their cost-effectiveness and ecological compatibility for industrial adoption.

7. Table 8: Environmental Impact Metrics Comparison (2011–2015 Average Values)

Parameter	Traditional Solvent	Ionic Liquid	% Improvement
VOC Emission (g/L)	150	20	86.7% ↓
Waste Generation (kg/kg product)	2.5	0.6	76% ↓
Reaction Yield (%)	70	90	28.6% ↑
Energy Consumption (kWh/kg product)	12.0	7.5	37.5% ↓
Catalyst Recyclability (cycles)	0	5	—

The comparative environmental data highlight the superior performance of ionic liquids over traditional solvent systems across all major sustainability parameters.

In terms of volatile organic compound emissions, ionic liquids demonstrated an 86.7 percent reduction compared to conventional solvents. This remarkable decrease is attributed to their non-volatile nature, which prevents solvent loss through evaporation. As a result, laboratory air quality improves, and the risk of atmospheric contamination is nearly eliminated.Waste minimization is another major advantage of ionic liquids, as the total waste generated per kilogram of product decreases from 2.5 kilograms in traditional systems to only 0.6 kilograms in ionic liquid-based systems. This represents a 76 percent reduction in waste generation, primarily due to reduced solvent disposal and the reusability of the ionic medium. The lower E-factor of these systems confirms that the majority of the input material is converted into the desired product, leading to improved atom economy and process sustainability.Energy efficiency also shows a notable improvement. The average energy consumption dropped from 12.0 kWh per kilogram of product in conventional synthesis to 7.5 kWh in ionic liquid-mediated reactions. The shorter reaction times and reduced need for prolonged heating contribute to this 37.5 percent reduction in energy use, aligning the process with energy-efficient principles of green chemistry.Although the initial cost of ionic liquids may be higher than that of conventional solvents, their long-term economic benefits are realized through multiple reuse cycles. On average, an ionic liquid can be reused five times without significant loss in efficiency. This recyclability reduces the frequency of solvent replacement and waste disposal costs, enhancing the overall economic viability of the process.The combination of high reaction yields, minimal waste generation, low energy consumption, and multiple reuse cycles makes ionic liquids an attractive and sustainable choice for heterocyclic synthesis, particularly in medicinal and fine chemical industries.

CONCLUSION

The findings of this study confirm that ionic liquid-mediated synthesis of heterocyclic compounds offers a viable, green, and scalable approach to chemical production up to the year 2015. The data strongly support that ionic liquids serve as effective replacements for conventional volatile organic solvents by providing safer, cleaner, and more efficient reaction environments. Their unique physicochemical properties enable reactions to proceed with higher yields, shorter reaction times, and significantly lower environmental impact.The application of ionic liquids aligns closely with the 12 Principles of Green Chemistry, particularly in reducing hazardous solvent use, improving atom economy and reaction efficiency, and enabling catalyst recyclability. The ability to recover and reuse ionic liquids across multiple reaction cycles without significant degradation adds to their practical and environmental advantages. These factors contribute directly to the advancement of sustainable medicinal chemistry, offering new pathways for producing bioactive heterocyclic compounds while minimizing the ecological footprint of chemical processes.However, to fully realize the potential of ionic liquids in industrial-scale applications, future research should continue to address the limitations related to cost, synthesis, and biodegradability. Post-2015 developments indicate a growing interest in bio-derived ionic liquids, deep eutectic solvents, and hybrid solvent systems that combine the performance of ionic liquids with improved environmental compatibility. Additionally, computational modeling and molecular simulation are expected to play an increasingly important role in predicting solvent–reactant compatibility, optimizing process parameters, and designing ionic liquids with tailored properties for specific applications.In conclusion, the adoption of ionic liquid-mediated synthesis represents a paradigm shift in modern chemistry—moving away from pollution-intensive practices toward a cleaner, safer, and more sustainable approach that supports both scientific innovation and environmental stewardship.

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