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## Advanced ionic liquid technologies for sustainable reaction intensification

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The global imperative of carbon neutrality and stringent environmental regulations necessitates the transition from conventional volatile organic solvents to sustainable alternatives in chemical processes. Ionic liquids, characterized by negligible vapor pressure, exceptional thermal stability, and highly tunable physicochemical properties, have emerged as powerful solvents for reaction intensification. This review summarizes recent advances in ionic liquids-based intensification strategies across three critical areas: catalytic reactions, organic synthesis, and alternative energy applications. In catalytic systems, ILs substantially enhance reaction kinetics and selectivity, while facilitating catalyst stability and recyclability. For organic synthesis, ILs enable greener reaction conditions, minimizing side reactions and improving yields through tailored solvation effects. Within alternative energy technologies, coupling ILs with microwave irradiation further accelerates reaction rates, reduces energy consumption, and enables highly efficient, selective conversions under remarkably mild conditions. Despite these promising benefits, industrial adoption remains limited due to production cost constraints, compatibility issues, and mass-transfer limitations arising from ionic liquids viscosity. Therefore, future research should prioritize computationally guided ionic liquids design, cost-effective synthetic routes, and optimized continuous-flow processing, promoting scalable, efficient, and economically viable industrial applications of ionic liquids-based reaction intensification technologies.

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### Sustainability spotlight

The pervasive use of volatile organic solvents in chemical manufacturing contributes substantially to environmental pollution and carbon emissions, underscoring an urgent need for sustainable alternatives. This review emphasizes the transformative role of ionic liquids as tunable, non-volatile solvents that facilitate reaction intensification across diverse processes. By enhancing energy efficiency, increasing reaction yields, and enabling catalyst reuse, ionic liquids significantly reduce waste and energy consumption. These advances directly support the achievement of multiple UN Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production), positioning IL-based technologies as pivotal enablers of greener industrial transformation.

## 1 Introduction

The global chemical industry faces a pivotal transformation, driven by the urgent imperatives of climate change and resource sustainability. The convergence of carbon neutrality goals with the principles of green chemistry has elevated the development of environmentally benign manufacturing processes from a discretionary technological pursuit to an industrial necessity.<sup>1,2</sup> This paradigm shift demands a fundamental departure from conventional volatile organic solvents, including benzene,

toluene, and chloroform, which are characterized by significant toxicity, flammability, and environmental persistence.<sup>3</sup> The continued reliance on these solvents represents a major barrier to achieving a circular economy, highlighting a critical need for innovative alternatives that combine operational performance with ecological responsibility. Within this context, ionic liquids (ILs), a distinguished class of molten salts with melting points at or near ambient temperature, have emerged as a transformative platform. These materials are defined by their negligible vapor pressure, exceptional thermal stability, and structurally tunable nature, which collectively enable the molecular-level design of task-specific solvents.<sup>4,5</sup> In reaction intensification, ILs function not merely as passive media but as active participants that engage in specific molecular interactions, effectively reducing activation barriers and enhancing reaction kinetics. These interactions facilitate improved product yields and selectivity while enabling more efficient

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transformations under milder operating conditions.<sup>6</sup> Furthermore, the ability of ILs to form multiphase systems and their strong affinity for catalytic species underpin streamlined catalyst recovery and *in situ* separations, which are fundamental to sustainable process design.

The extensive versatility of ILs has been documented in a substantial body of review literature, with previous works providing valuable insights into specific aspects of their chemistry and applications. Foundational reviews have systematically detailed their fundamental properties and general synthesis pathways,<sup>7,8</sup> establishing the basis for their designation as “designer solvents.” Subsequent specialized reviews have offered profound analyses of their roles as catalysts and stabilizing agents in advanced catalytic systems,<sup>9</sup> with particular emphasis on their unique ability to create optimized microenvironments for metal complexes and nanoparticles. Parallel developments have been thoroughly examined in their application as ILs designer solvation environments,<sup>10</sup> where researchers have meticulously documented how specific cation-anion combinations can dramatically influence reaction pathways and selectivity profiles. Another significant research stream has comprehensively explored their effectiveness as mediators in processes activated by external energy fields such as microwave and ultrasound irradiation,<sup>11</sup> with detailed mechanistic studies revealing the underlying principles of energy transfer and dissipation in these complex systems. While these contributions have significantly advanced their respective subfields, the existing literature typically presents these functional dimensions in a compartmentalized manner. This disciplinary segregation has resulted in a fragmented understanding of ILs' full potential, leaving the sophisticated synergistic interconnections between their roles as catalytic phases, advanced solvent media, and energy transfer agents largely unexplored. The absence of an integrated analytical framework that systematically unifies these functional capabilities under the overarching objective of holistic process intensification represents a critical knowledge gap in the current literature, which is a gap that must be addressed to effectively guide the next generation of IL-based process design and accelerate their transition from laboratory innovation to industrial implementation.

This review is designed to address this critical gap by presenting a consolidated and forward-looking perspective that transcends conventional application-centric approaches. We introduce a unified, function-oriented framework to systematically examine how the molecular architecture of ILs enables three primary intensification mechanisms: acting as multifunctional catalytic phases and stabilizers, serving as tunable solvation environments for precise reaction control, and exhibiting synergy with external energy fields to achieve transformative process efficiencies. By integrating these themes, this work establishes clear structure–property–performance relationships that cross traditional disciplinary boundaries. Our analysis not only synthesizes the current state of the art but also provides a critical examination of persistent challenges, including economic viability, mass transfer limitations, and scalability, from a process engineering perspective. Ultimately,

this review aims to offer a strategic roadmap for the rational design and implementation of IL-based technologies, positioning them as essential contributors to the development of sustainable and intensified chemical processes (Fig. 1).

## 2 Fundamental properties and classification of ionic liquids

ILs represent a groundbreaking class of neoteric materials defined as salts that exist in the liquid state below 100 °C, with many remaining liquid at room temperature. This phase behavior originates from their unique molecular architecture, comprising structurally disparate organic cations and organic or inorganic anions. The strategic combination of bulky, asymmetric ions effectively frustrates crystalline lattice formation, resulting in depressed melting points. A complex interplay of intermolecular forces, including dominant coulombic interactions, directional hydrogen bonding, and van der Waals dispersive forces, collectively dictates their macroscopic physicochemical profile. This sophisticated synergy endows ILs with an exceptional combination of properties rarely found in molecular solvents, positioning them as versatile media for advanced engineering applications.

### 2.1 Fundamental characteristics of ionic liquids

The most quintessential property of ILs is their remarkably depressed melting point. Unlike classical ionic compounds that exhibit high melting temperatures due to symmetrical, densely packed lattices, ILs leverage steric hindrance and charge delocalization to significantly lower energy barriers for lattice disruption. For instance, 1-ethyl-3-methylimidazolium tetrafluoroborate ([EMIM][BF<sub>4</sub>]) melts at 12 °C, enabling liquid-phase processing under technologically mild conditions.<sup>12</sup>

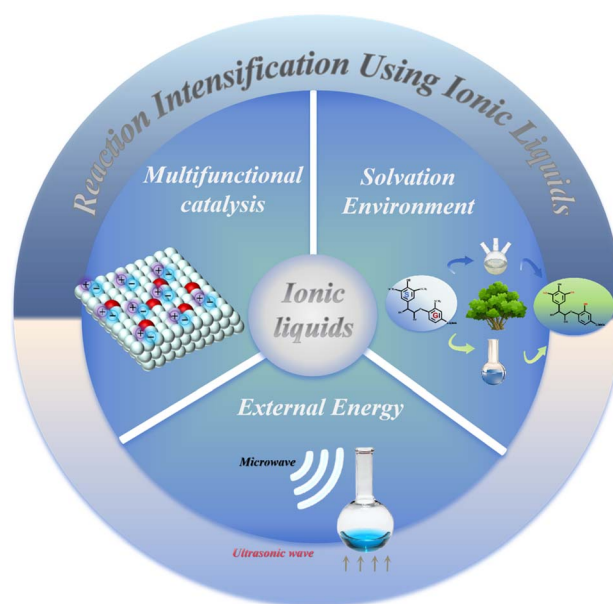


Fig. 1 Reaction intensification using ionic liquids.



Another defining characteristic is their immeasurably low vapor pressure under ambient conditions. The intense coulombic field generated between ions creates an energy barrier to volatilization that effectively eliminates solvent evaporation losses. This intrinsic non-volatility not only enhances operational safety by minimizing inhalation hazards but also substantially reduces environmental fugitive emissions, aligning with green chemistry principles.<sup>13</sup> ILs demonstrate exceptional thermal resilience, with decomposition temperatures typically spanning 200–300 °C, while advanced fluorinated anions or phosphonium cations can extend this range beyond 400 °C.<sup>14</sup> This robustness derives from the strength of ionic coordination and the covalent stability of constituent ions, enabling their deployment in high-temperature transformations where conventional solvents would undergo thermal degradation or hazardous decomposition. Electrochemically, ILs possess wide potential windows (3–6 V) that surpass aqueous and many organic electrolyte systems. This attribute, coupled with high ionic conductivity, establishes them as premier electrolyte candidates for next-generation energy storage devices, including lithium-metal batteries and supercapacitors.<sup>15</sup>

Perhaps the most powerful feature of ILs is their exquisite tunability. By manipulating cation–anion combinations and introducing functional groups, properties such as hydrophilicity, Lewis acidity, and miscibility can be precisely engineered. Hydrophilic ILs bearing hydroxyl or short alkyl chains exhibit complete water miscibility and exceptional solubility for polar substrates like carbohydrates and proteins. Conversely, hydrophobic ILs incorporating fluorinated anions or long alkyl chains create immiscible biphasic systems with water, ideal for extraction processes and as non-aqueous reaction media for organometallic catalysis.<sup>16,17</sup> This molecular-level design capability transforms ILs from mere solvents into functional components that actively participate in and enhance chemical processes.<sup>18</sup>

## 2.2 Classification of ionic liquids

The structural diversity of ILs necessitates a sophisticated, multi-parametric classification framework that captures their chemical complexity and functional specialization.<sup>19–21</sup> Moving beyond simplistic categorization, a holistic view that integrates structural, physicochemical, and application-based criteria provides invaluable guidance for rational solvent selection and design, as systematically organized in Fig. 2.

**2.2.1 Cationic core architecture.** The molecular scaffold of the cation fundamentally governs IL properties. Imidazolium derivatives dominate research due to favorable synthetic accessibility and balanced property profiles. Pyridinium analogs leverage aromatic  $\pi$ -systems for enhanced electrochemical and catalytic applications. Quaternary ammonium salts offer superior biocompatibility, while phosphonium variants provide unmatched thermal and chemical robustness for extreme condition processing. Beyond these well-established classes, triazolium-based ILs have recently garnered considerable attention as a prominent and emerging family.<sup>22–24</sup> Their core structure, a five-membered ring featuring three nitrogen

atoms, confers a unique set of physicochemical properties. The increased number of nitrogen atoms enhances their hydrogen-bonding capacity and allows for fine-tuning of their electronic character and Lewis basicity, which directly translates to superior performance in organocatalysis, such as in benzoin condensations and transesterification reactions.<sup>25–27</sup> A pivotal advantage of triazolium ILs is their exceptional adaptability to supported phase systems. Their structural robustness and strong surface interactions facilitate efficient immobilization onto various supports (*e.g.*, silica, magnetic nanoparticles, polymers), creating highly active and recyclable heterogeneous catalysts.<sup>28–30</sup> This synergy between molecular design and material engineering unlocks powerful applications in continuous-flow chemistry and sustainable catalytic processes, minimizing catalyst leaching and enabling streamlined product separation.<sup>31,32</sup>

**2.2.2 Proton transfer characteristics.** The synthesis pathway critically differentiates protic ionic liquids (PILs), generated through Brønsted acid-base neutralization, from aprotic ionic liquids (AILs) formed *via* quaternization reactions. PILs maintain active proton networks that enable superior proton conductivity and Brønsted acidity, whereas AILs exhibit enhanced electrochemical stability and broader liquidus ranges.<sup>21,33</sup>

**2.2.3 Functional acidity and basicity.** ILs can be molecularly engineered to function as neutral solvents, acidic catalysts *via* sulfonic acid functionalization or Lewis acidic anions, or basic mediators through amine functionalization or basic anions, effectively replacing conventional hazardous acids and bases in numerous catalytic cycles and separation processes.<sup>34</sup>

**2.2.4 Chirality and stereochemical control.** Chiral ILs incorporate stereogenic centers either within the cation, anion, or both, creating tailored chiral environments that induce enantioselectivity in asymmetric synthesis and provide novel mechanisms for chiral discrimination in separations.<sup>35,36</sup>

**2.2.5 Hydrophilicity-hydrophobicity continuum.** This practically vital spectrum, primarily determined by anion hydrophobicity and modulated by cation alkyl chain length, directly controls phase behavior with water, directly impacting extraction efficiency, biphasic catalysis, and biomolecule stability.<sup>37,38</sup>

**2.2.6 Heterogenized systems (supported ionic liquid phases).** The frontier of IL technology is witnessing a paradigm shift toward engineered materials that transcend conventional solvent roles. Chief among these are supported ionic liquid phases (SILPs), which represent one of the most successful implementations of the heterogenization concept.<sup>39</sup> SILPs masterfully integrate the distinctive advantages of homogeneous and heterogeneous catalysis by confining a tailored IL layer containing active species (*e.g.*, metal complexes, organocatalysts) within the pores of solid supports.<sup>40</sup> This unique architecture preserves the exceptional solvation environment and molecular-level tunability of ILs while enabling straightforward catalyst recovery, excellent recyclability, and implementation in continuous-flow reactors, effectively addressing key limitations of traditional homogeneous systems.



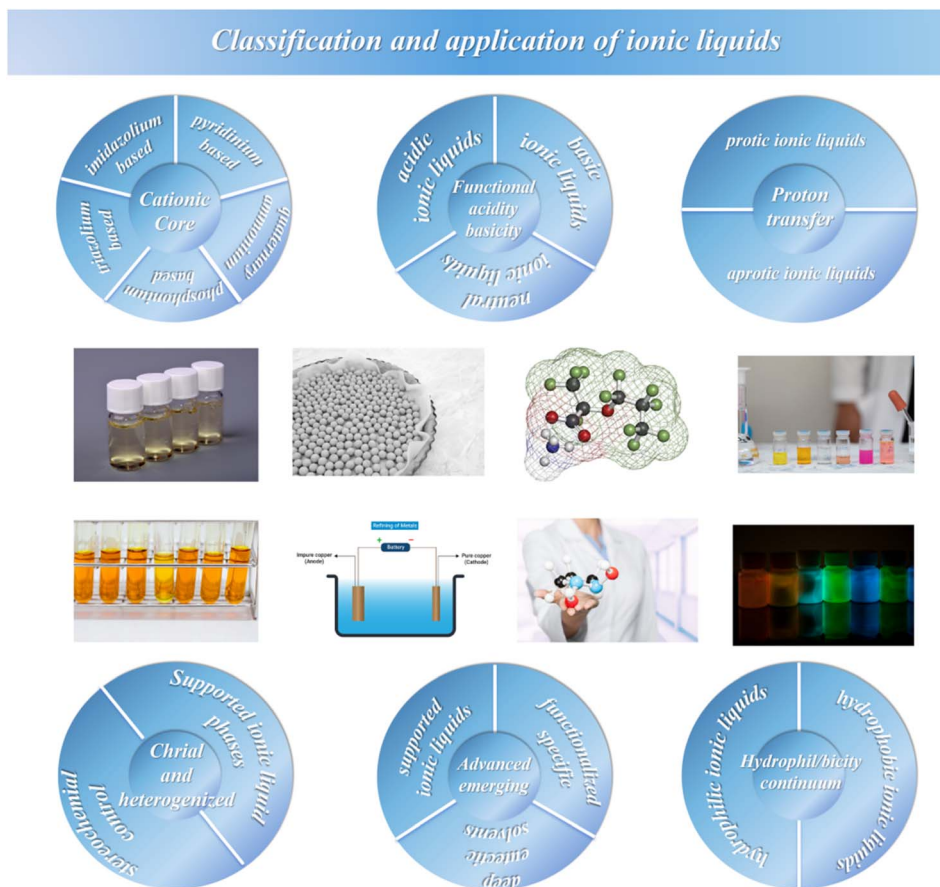


Fig. 2 Classification and application of ionic liquids.

**2.2.7 Advanced and emerging materials.** Beyond conventional catalytic applications, a particularly powerful manifestation of this synergy is found in supported ILs, where a thin IL membrane is immobilized on a high-surface-area solid support. This architecture enables the generation of active catalytic membranes where the IL acts as both reaction medium and separation layer, effectively creating membrane-like catalytic devices that operate under a continuous flow regime far from thermodynamic equilibrium. These functional membranes demonstrate remarkable potential for process intensification by performing simultaneous reaction and product separation in systems ranging from selective gas capture to enzymatic synthesis.<sup>41–43</sup> Building upon these advanced materials, the field continues to develop task-specific or functionalized ILs with precisely engineered functional groups for targeted molecular recognition, and deep eutectic solvents (DESS), readily tunable and often biodegradable alternatives that maintain many advantageous IL properties while offering enhanced sustainability profiles.<sup>44,45</sup> This integrated classification paradigm underscores the transformative “designer solvent” concept, providing a systematic foundation for exploiting ILs in sustainable process intensification across the chemical industries.

### 3 Reaction intensification using ionic liquids

In the field of chemical reaction intensification, ILs have emerged as powerful enablers owing to their unique physico-chemical properties. Through mechanisms such as solvent effects, intrinsic catalytic activity, and phase transfer catalysis, ILs have introduced new dimensions to traditional reaction systems, enabling substantial enhancements in process efficiency and selectivity.

#### 3.1 Ionic liquids as multifunctional catalytic phases: intrinsic activity and catalyst stabilization

ILs have revolutionized catalytic processes by transcending the conventional role of solvents to become integral, multifunctional components of the catalytic system itself.<sup>46</sup> Their structural versatility allows them to be engineered as intrinsic catalysts or as advanced functional matrices that dramatically enhance the performance and longevity of heterogeneous and enzymatic catalysts. This section delves into the molecular-level mechanisms underpinning these roles to a mechanistic understanding of intensification.

As intrinsic catalysts, task-specific ILs incorporate active sites directly into their ion structures, creating a homogeneous



catalytic environment with unique advantages. For instance, Brønsted-acidic ILs, such as those functionalized with sulfonic acid groups, do not merely act as proton donors akin to mineral acids. Their ionic nature generates a structured polar micro-environment that preferentially stabilizes charged transition states, as exemplified in esterification reactions.<sup>47</sup> This dual functionality, providing both high proton availability and tailored transition-state stabilization, results in superior catalytic activity and selectivity while circumventing the equipment corrosion and waste streams associated with traditional acids. Similarly, basic ILs with amine functionalities or basic anions can catalyze reactions like Knoevenagel condensations, offering a recyclable and safer alternative to conventional bases. As catalyst stabilizers and immobilization media, ILs provide a dynamically ordered, non-inert environment that profoundly influences the stability and reactivity of dispersed catalytic species.<sup>48</sup> In the immobilization of metal nanoparticles (NPs) for hydrogenation reactions, the IL matrix is not a passive spectator.<sup>49</sup> The coulombic interactions and nanoscale structuring of the IL create a protective, confined domain around the NPs. This nanocage effect, illustrated in Fig. 3, imposes a high energy barrier for NP migration and coalescence, effectively suppressing sintering and Oswald ripening. Furthermore, the IL can modulate the electronic density of the metal surface through electron-donor/acceptor interactions, potentially enhancing both activity and selectivity. This stabilization strategy extends to single-atom catalysts, where the IL's ions can coordinate with and stabilize isolated metal centers, preventing their aggregation.

In phase-transfer catalysis (PTC), ILs exhibit a sophisticated mode of action. They can function as efficient, often superior,

substitutes for traditional ammonium or phosphonium salts. Their dual nature, possessing both hydrophilic and hydrophobic character depending on their ion structures, enables them to facilitate the transport of anionic or cationic reactants across liquid–liquid interfaces. For example, in nucleophilic substitution reactions, the IL cation can form an ion pair with an inorganic nucleophile (e.g.,  $\text{MnO}_4^-$ ,  $\text{CN}^-$ ), solubilizing it in the organic phase and drastically accelerating the reaction rate.<sup>50</sup> The IL is not consumed in this process and can be easily separated and recycled due to its immiscibility with one of the product phases, embedding inherent process sustainability.<sup>51</sup> This principle of creating a beneficial ionic microenvironment extends to biocatalysis. The unique solvation properties of ILs can be tuned to form a protective hydration layer around enzymes, preserving their essential three-dimensional structure and thus their catalytic activity. Certain ILs can suppress the formation of hydrogen-bonding networks that lead to enzyme denaturation, thereby significantly expanding the operational window for biocatalysts to include higher temperatures and non-aqueous environments.<sup>52</sup> This has unlocked new avenues for performing enzymatic transformations under remarkably mild and green conditions.

### 3.2 Tunable solvation environments for reaction control

Beyond their roles as direct catalytic agents, ILs redefine reaction landscapes when employed as advanced, structured solvents. This section examines intensification achieved not through the IL's inherent catalytic sites, but *via* its capacity to create a finely-tuned solvation environment that manipulates reaction coordinates at a molecular level. The intensification arises from the IL's ability to pre-organize reactants, stabilize

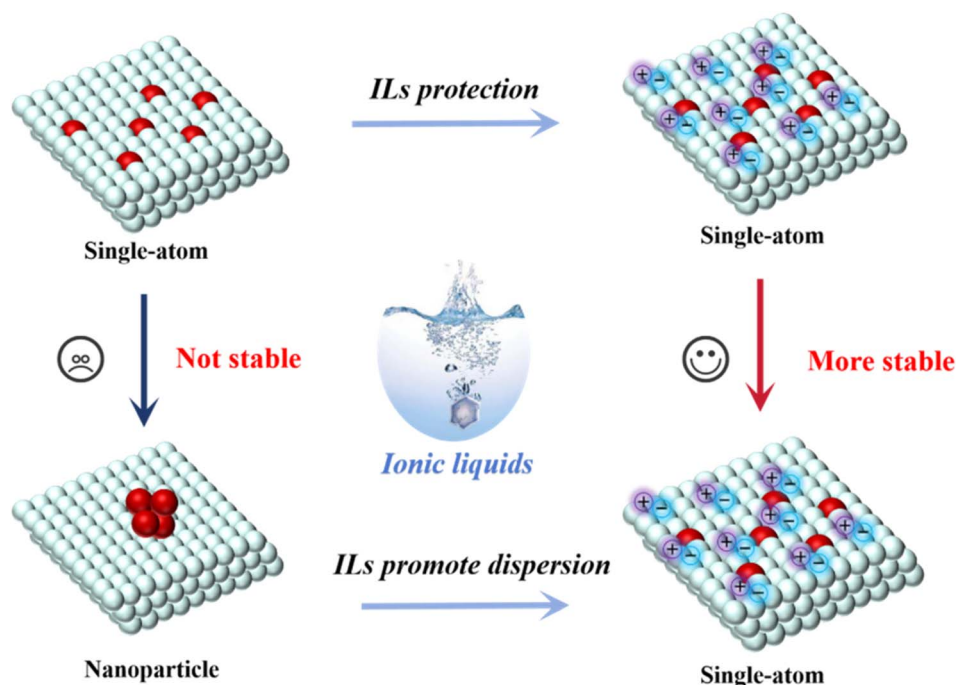


Fig. 3 Efficient single atom catalysts stabilized using ionic liquids. [Adapted from ref. 49 with permission from Elsevier, copyright 2019].



transient species, and alter local concentrations through a combination of its unique and designer physicochemical properties.

The pre-organized and highly polarized microenvironment within ILs is a cornerstone of their solvent-effect intensification. Unlike molecular solvents with transient polarity, the inherent ionic character of ILs generates a persistent, high-electric-field environment. This robust polarity can be precisely modulated by altering cation–anion combinations, allowing for the systematic solvation of polar reactants and the stabilization of charged or dipolar transition states. In nucleophilic substitution reactions (*e.g.*,  $\text{S}_{\text{N}}2$  reactions), this strong solvation can significantly lower the activation energy barrier by stabilizing the transition state more effectively than conventional solvents, leading to rate enhancements of several orders of magnitude.<sup>53</sup> This effect transcends mere solubilization, the IL acts as a dynamic participant that actively biases the reaction pathway toward the desired outcome.<sup>54</sup>

A powerful mechanism of intensification involves direct hydrogen-bonding interactions. ILs can function as versatile hydrogen-bond donors and/or acceptors, engaging in specific, directional interactions with solutes. As depicted in Fig. 4, this capability is pivotal in reactions like lignin demethylation,<sup>55</sup> where ILs form critical hydrogen bonds that facilitate bond cleavage. Similarly, in Diels–Alder cycloadditions, ILs do not merely provide an inert medium. They can selectively stabilize the electron-poor, polarized transition state through hydrogen-bond donation to the dienophile, thereby reducing the activation energy and enabling high yields and exceptional endo/exo selectivity under remarkably mild conditions.<sup>56</sup> The reported rate accelerations of an order of magnitude compared to molecular solvents underscore the profound kinetic influence of this specific solvation.

Furthermore, the structured nature of the ionic continuum itself contributes to intensification. ILs are not random soups of ions but possess a distinct, heterogeneous nanostructure with polar and non-polar domains. This inherent structure can lead to the compartmentalization of reactants, effectively increasing their local concentration and orienting them favorably for reaction. In complex transformations such as the Heck cross-coupling, the IL medium serves a dual purpose: it ensures the

effective solvation and stabilization of the palladium catalyst, preventing its decomposition, while simultaneously creating an optimal ionic environment that facilitates the key migratory insertion step, leading to improved yields and selectivity.<sup>57</sup> This principle extends to oxidation reactions, where the IL solvent can interact with the oxidant and/or the substrate to enhance oxidation efficiency and selectivity for the target carbonyl compound, often under milder conditions than required in volatile organic compounds.<sup>58</sup>

### 3.3 Synergistic intensification using external energy fields

The intensification potential of ILs is profoundly amplified when they are synergistically coupled with external energy fields, such as microwave (MW) irradiation and ultrasound (US). This paradigm transcends conventional heating and mixing, leveraging the unique physicochemical properties of ILs to achieve unprecedented control over energy deposition and mass transfer at the molecular scale. This section delineates the distinct mechanisms by which ILs mediate energy transduction from these fields, leading to dramatic enhancements in reaction rates and efficiencies.

In microwave-assisted systems, ILs function as exceptional molecular antennas and efficient energy transfer media. Their high ionic conductivity and substantial dielectric loss tangent enable superior microwave absorption compared to most molecular solvents. The intensification mechanism is twofold: first, MW irradiation induces rapid ion migration (ionic conduction) and dipole reorientation within the structured IL matrix, resulting in intense, instantaneous *in situ* heating through molecular friction.<sup>59</sup> This volumetric heating eliminates the thermal lag characteristic of conventional conductive heating, enabling almost instantaneous achievement of reaction temperatures and minimizing thermal degradation pathways. Second, the exceptionally high heating rates achievable in ILs can lead to the formation of localized hot spots with temperatures significantly exceeding the bulk measured temperature, providing the activation energy for otherwise sluggish transformations. This selective, rapid, and internal energy delivery directly translates to order-of-magnitude increases in reaction rates. Crucially, the non-volatile nature of ILs ensures that this dramatic process intensification is

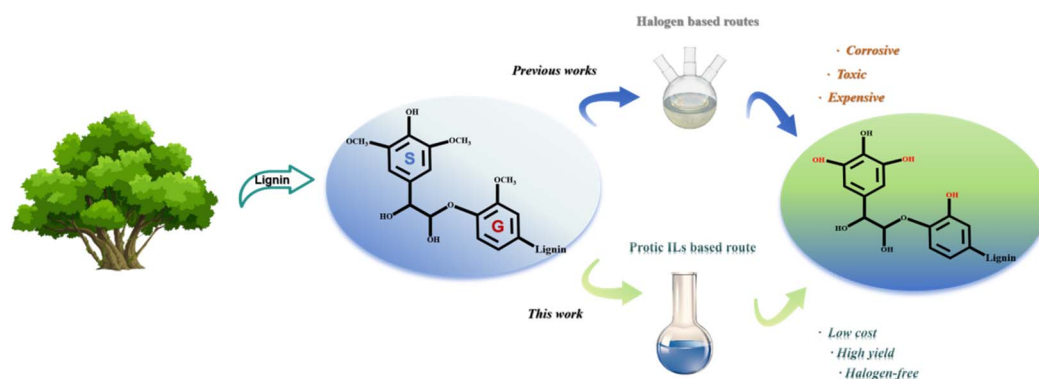


Fig. 4 Optimizing lignin demethylation using ionic liquids. [Adapted from ref. 55 with permission from Elsevier, copyright 2022].



coupled with straightforward post-reaction separation and recycling of both the IL and any dissolved catalyst.

In ultrasound-assisted systems, the synergy arises from the interaction between the IL and the physical effects of acoustic cavitation. The propagation of ultrasonic waves through an IL medium leads to the formation, growth, and violent implosive collapse of micro-bubbles. This cavitation process, schematized in Fig. 5, generates extreme localized conditions, transient temperatures of several thousand Kelvin and pressures of hundreds of atmospheres within microscopic zones.<sup>60,61</sup> The role of the IL in this process is critical. Its low vapor pressure and high cohesion energy density can influence cavitation bubble dynamics, potentially leading to more energetic collapses. The intense microjets and shockwaves generated by bubble implosion near an interface (*e.g.*, a catalyst surface) effectively obliterate mass transfer limitations by disrupting boundary layers and creating intense micro-mixing. This is particularly transformative for heterogeneous catalytic reactions or multiphase systems, where the diffusion of reactants to active sites is often the rate-limiting step. The ultrasonic field thus acts as an atomic-scale mixer, while the IL provides a stable, robust medium that withstands these extreme conditions and facilitates catalyst dispersion.

The confluence of ILs with these external energy fields represents a cornerstone of modern process intensification. It enables a shift from traditional, often inefficient, energy input methods to targeted, rapid, and highly efficient approaches. The synergistic effects, where the IL's properties are tailored to maximize energy coupling with the external field, not only boost kinetic performance but also open avenues for activating novel

reaction pathways under remarkably mild bulk conditions, paving the way for more sustainable and energy-efficient chemical manufacturing.

### 3.4 Synergistic enhancement of rate, selectivity, and catalyst reusability

The diverse applications and mechanisms of ILs discussed in the preceding sections collectively demonstrate that their most profound impact lies in enabling concurrent, synergistic enhancements across multiple critical reaction engineering parameters. Rather than offering isolated improvements, IL-based intensification technologies leverage their unique physicochemical properties and structural tunability to deliver integrated gains in reaction kinetics, selectivity, and catalyst reusability, thereby establishing a cornerstone platform for sustainable process innovation.

The dramatic rate accelerations observed in IL-mediated processes, as exemplified by esterification and Diels–Alder reactions, originate from the ILs' ability to directly engage with and stabilize key transition states. This is not merely a consequence of high polarity but arises from specific, designable interactions, such as hydrogen bonding,  $\pi$ – $\pi$  stacking, or electrophilic activation, which effectively lower the activation energy barrier. The pre-organized and highly polarized micro-environment of ILs acts as a tailored entatic state that pre-optimizes the reaction coordinate, leading to kinetic enhancements often unattainable in molecular solvents. Beyond kinetics, ILs provide an unparalleled level of selectivity control by creating nanostructured solvation environments around reactive sites. In transformations such as Friedel–Crafts

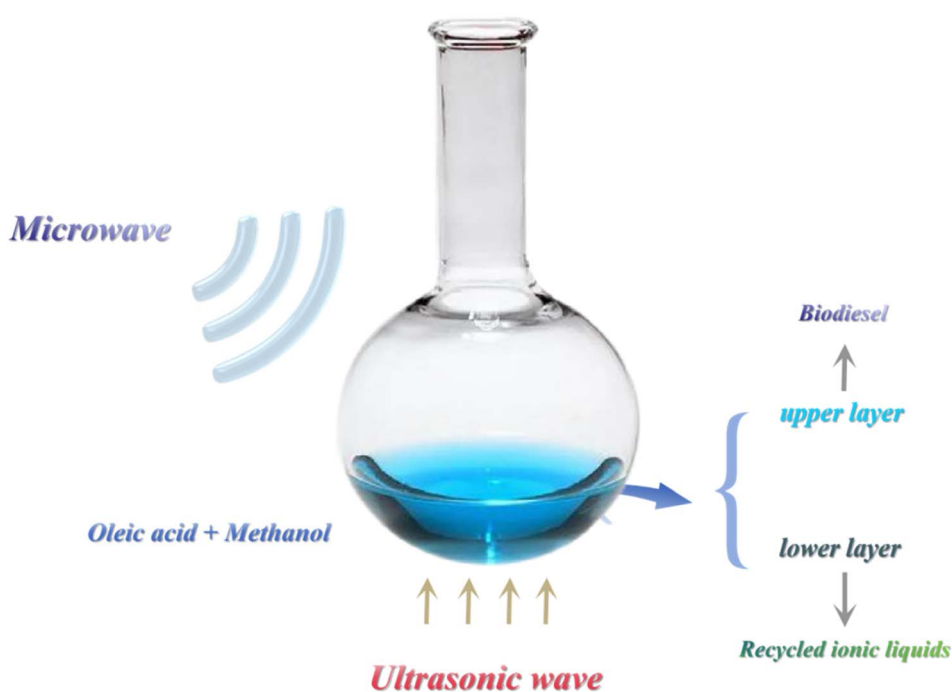


Fig. 5 Enhancement mass transfer process of ionic liquids by microwave. [Adapted from ref. 61 with permission from American Chemical Society, copyright 2024].



alkylation and asymmetric hydrogenation, the IL forms well-defined solvation cages that exert precise steric and electronic influence on reactant orientation. This sophisticated molecular discrimination, a direct result of the cation–anion interplay and nanoscale heterogeneity of ILs, preferentially stabilizes the transition state for the desired pathway. This capability to suppress competing reactions at a fundamental level directly translates to superior atom economy and significantly reduces the complexity and cost of downstream product purification.

From a process engineering standpoint, the most transformative advantage is the seamless facilitation of catalyst recovery and reuse. The intrinsic non-volatility and engineerable phase behavior of ILs enable straightforward product separation *via* decantation or extraction. More critically, the robust, multi-faceted interactions between the IL matrix and catalytic species (*e.g.*, metal nanoparticles, organocatalysts) effectively suppress the primary deactivation pathways of leaching and sintering. This principle of electrostatically stabilized nanoconfinement, as illustrated in continuous-flow hydrogenation and hydroformylation processes, allows IL-based systems to achieve exceptional catalytic longevity and recyclability, performance metrics that remain a significant challenge in conventional solvent systems. The curated examples in Table S1 systematically map these fundamental enhancement principles to specific chemical transformations, establishing clear structure–property–performance relationships. In conclusion, it is this integrated multi-parameter enhancement, where improvements in rate, selectivity, and stability are not traded off but are synergistically achieved, which underscores the transformative potential of ILs. This holistic intensification paradigm positions IL-based technologies as pivotal enablers for pioneering the next generation of efficient, selective, and economically viable sustainable chemical processes.

## 4 Conclusion, challenges and future outlook

Ionic liquids technology, characterized by its green, efficient, and tunable nature, represents an innovative and forward looking approach to process intensification in the chemical industry. Its application in reaction process domains has demonstrated the potential to transform traditional chemical processes. In reaction systems, ILs enhance reaction rates and selectivity through solvent effects and catalytic functionalities, often enabling reactions under milder conditions and facilitating catalyst recyclability. However, several challenges still hinder the widespread industrial adoption of IL technologies. High production costs, insufficient long-term stability data, potential corrosiveness, and limitations in mass transfer (especially due to high viscosity) remain major obstacles. Addressing these issues will require coordinated efforts between academia and industry to promote integrated innovation across fundamental research and applied development. On one hand, deeper understanding of structure–property relationships and AI-assisted molecular design could facilitate the

development of next-generation ILs with lower cost and higher performance. On the other hand, process intensification and the design of dedicated equipment must be optimized to enable reliable, scalable, and economically viable operations. Looking ahead, the evolution of ILs technology will center on two key directions: technological innovation and industry integration. In materials development, priority should be given to synthesizing low-cost, high-performance ILs. This includes exploring new synthetic pathways, utilizing renewable biomass or industrial by-products as precursors, and employing computational screening methods to balance performance and cost. In process engineering, continuous-flow processing and solvent recycling are critical to improving operational efficiency and reducing costs. Advanced mass transfer solutions, such as microreactor technology and enhanced mixing systems, which could address many-induced limitations.

## Author contributions

Pengzhi Bei: writing – original draft (lead). Data curation (lead); validation (lead); Jiayin Zhao: data curation (lead); writing – review and editing (lead); Xiaolu Gao: data curation (supporting); writing – review and editing (lead); Yuning Qi: conceptualization (supporting); validation (lead); Peng Jia: validation (lead); Zehua Cheng: formal analysis (supporting); methodology (supporting); Lili Deng: investigation (supporting); validation (lead); Xingtang Xu: investigation (supporting). Zhenzhong Li: validation (lead); investigation (supporting).

## Conflicts of interest

The author declares no conflicts of interest.

## Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: <https://doi.org/10.1039/d5su00694e>.

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