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Review Article

Ionic Liquid System: Design, Principles, Properties and Advanced Applications

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ABSTRACT

Ionic liquids (ILs) form an entirely new type of salt that continues to exist as a liquid up to rather low temperatures—normally less than 100 °C. They differ from traditional molecular solvents in that ILs have virtually no vapour pressure, extremely high thermal and chemical stability, and highly tunable physicochemical properties. Since the IL's chemical properties can be modified through the selection of its constituent cations and anions, ILs can be designed specifically for particular purposes, enabling them to be versatile across many different fields of study. Due to their unique features, ionic liquids are becoming more popular in many areas of application, including bioengineering, chemical separation processes, catalysis, electrochemistry, and energy storage technology. The diversity of both organic and inorganic substances can be dissolved in an ionic liquid and their relative availability and environmental benefits in comparison to traditional volatile organic solvents continue to drive greater interest in ionic liquids both scientifically and industrially. In this article, we will discuss some of the major classifications of ionic liquids based on their structural diversity and chemical composition. We will also provide an overview of the various synthesis and production methods used to create ionic liquids, while noting current advancements in the [scalable, sustainable] production of ionic liquids. We will also discuss some of the major physicochemical properties of ionic liquids including viscosity, conductivity, polarity, and solvation characteristics, and how they are applicable to a variety of practical applications. While there are numerous advantages associated with ionic liquids, there are also several challenges which must be considered: high production costs, potential toxicity, environmental persistence, and difficulties using the material on a large scale.

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This review discusses these major current limitations and provides an overview of emerging strategies for overcoming them. It also highlights future research directions with respect to developing consentable, cheaper, and more specific-use ionic liquids, which will allow ionic liquids to reach their full potential as scientific and industrial materials.

INTRODUCTION

Growing awareness of the need to find environmentally safe solutions to long-standing environmental issues has forced an increasing number of consumers to seek environmentally safer alternatives to conventional volatile organic solvent products. Due to their very low vapor pressure as well as the ionic nature of ionic liquid components, ionic liquids are considered to be an excellent environmentally friendly alternative to conventional solvent products because they significantly reduce pollution emissions. [1, 2]. The liquid state of numerous ionic liquids at or close to room temperature is a result of the low strength of the electrostatic attractions between their constituent ions. In contrast to the case of simple inorganic salts, which are made up of small, highly charged ions that can pack together efficiently into tightly fitted crystals, ionic liquids comprise large, asymmetrical and, in many cases, delocalized ions. These types of ions decrease the magnitude of ionic attractions and make it difficult to pack efficiently into solid form, thus significantly lowering the amount of lattice energy necessary for ionic liquids to form a stable crystalline structure and thus enabling the ionic liquids to exist in the form of liquid within relatively low temperature rangess [3].

While there are many claims made about the environmental friendliness (i.e., "greenness") of ionic liquids, it is ultimately up to each of us to perform an independent analysis in order to determine if ionic liquids meet our own sustainability criteria. This analysis must include not only the chemical properties of ionic liquids (such as their toxicity, biodegradable nature, and degree of persistence in the environment) but also the impact of the entire lifecycle (from raw material extraction, through manufacturing and use, to disposal or recycling) of ionic liquids on all other environmental aspects. Only when all of these factors are assessed holistically is it possible for us to ascertain whether or not ionic liquids meet our sustainability criteria: that is, whether they will cause long-term damage to the environment or ideally leave it unchanged—if not improved—when compared to their pre-production condition after their use has ended and finally, after having disposed of or recycled them. [4]. Ionic liquids can be adjusted to suit the desired functions by customizing the composition of the cations and anions. An example might include selecting cations and anions that have very low viscosity, low polarity, high thermal stability, and high solubility and conductivity. There is a wide range of applications that can benefit from the properties described above. As a result, they are being researched and applied successfully in industrial applications including but not limited to catalysis, separation, material synthesis, and energy related technologies.

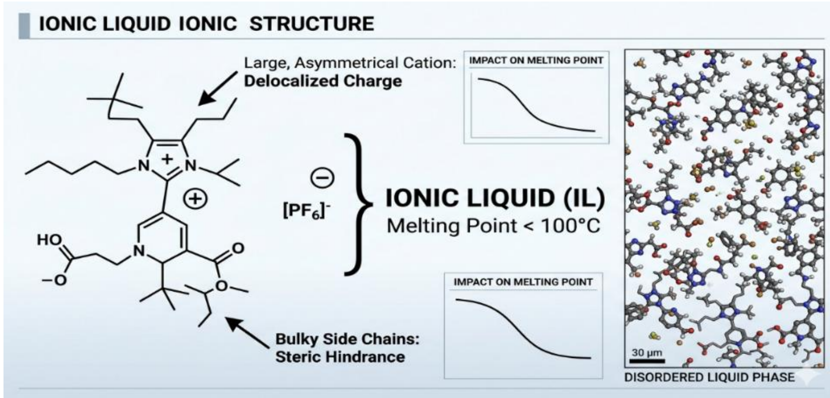

Fig.1. Ionic liquid Ionic Structure

Classification of Ionic Liquids

Cation-Based Systems

The ionic component of an ionic liquid heavily impacts its characteristics and performance. Organic cations form the basis of an ionic liquid, with the standard structures of a cation being imidazolium, pyridinium, ammonium, and phosphonium. Each of these cationic structures has its own structural and electronic characteristics; thus, these features are important to an ionic liquid's overall physicochemical characteristics. Researchers can manipulate the properties of ionic liquids to make them appropriate for different applications by modifying the cationic structure. For example, changing the length of the alkyl chain, substituting with functional groups, or changing the structure of the cationic ring will lead to significant changes in intermolecular interactions in the ionic liquid. As a result, viscosity, ionic conductivity, density, polarity, and thermal stability can be controlled precisely through these synthetic techniques The internal resistance to the flow of ionic liquids is denoted by their viscosity and is determined by the size, symmetry and flexibility of the cation component. The larger or more complicated cation will create higher viscosities due to increased van der Waals interactions and steric hindrance. Ionic conductivity (a critical electrochemical/energy-storage property) is also dependent on the structural characteristics of the cation. The ability of the cations to move in solution affects ionic conductivity. The thermal stability of ionic liquids, which are used in high-temperature processes, is also determined by the inherent structure of the cationic framework. Thus, by rationally designing and modifying the cations used to create ionic liquids, one can have significant control over the physicochemical properties of the ionic liquids formed. This ability to tailor the properties of ionic liquids makes them very versatile materials, enabling the application of ionic liquids in multiple areas such as green chemistry, pharmaceuticals, catalytic processes, electrochemical applications and separation technologies. [5].

Key Cationic Influences

The versatility of these liquids stems from the "tunable" nature of these cations:

- **Separation of Structural Asymmetry:**

The structural asymmetry of the ions within ionic liquids is a significant contributor to their physical state of matter. The ions in ionic liquids do not form crystalline lattices like traditional salts (which exhibit significant order) due to their large, non-spherical shapes, along with a non-uniformly distributed charge across the ion. Given the structurally complex nature of ions, the individual ions will not efficiently pack together, resulting in a significant reduction of the electrostatic forces that otherwise encourage crystallization. This leads to ionic liquids having a low melting point and often having liquid-like states at or near room temperature. Therefore, ionic liquids are often referred to as "room temperature molten salts" because of their inability to form a stable crystalline lattice.

Cations of Imidazolium and Pyridinium:

Imidazolium and pyridinium-based cationic compounds are widely studied as cations of ionic liquids because of their desirable physicochemical characteristics. The charge of these aromatic cations is delocalized over the entire ring system, allowing for enhanced ionic mobility and decreased ion-ion interaction. As such, ionic liquids which contain these types of cations have relatively low viscosities and high ionic conductivities. This makes them excellent candidates for use in electrochemical applications such as electrolytes for batteries, supercapacitors, fuel cells, and electrochemical sensors. Quaternary ammonium and phosphonium cations form an additional major subset of cations found in ionic liquids and, unlike the cationic species derived from aromatic compounds, both of these types of cationic species are fully saturated and will typically have a much greater degree of thermal stability and chemical stability than either of the aforementioned cation types. As a result of their respective degrees of thermal and chemical stability, ammonium and phosphonium-based ionic liquids considerably outperform other types of ionic liquids in terms of thermal and chemical stability, allowing both types of ionic liquids to remain viable for a wide range of applications, including but not limited to industrial manufacturing processes, high-temperature catalytic reactions, and lubricant systems and other applications that would typically use conventional solvents but be unable to continue use because of concerns regarding the thermal and/or oxidative instability of the solvent system. [5]. The physicochemical properties of ionic liquids can be adjusted systematically through alterations/modifications to the molecular structure of the cation, either by changing the length of the alkyl chain or adding certain functional groups. Variations in the alkyl chain length will result in different physicochemical properties, such as viscosity, hydrophobicity, density, and intermolecular interactions, within the ionic liquid. In general terms, increasing the alkyl chain length results in increased hydrophobicity/van der Waals forces and therefore may cause an increase in viscosity and a change in solvation behaviour. Similarly, the addition of functional groups, such as hydroxyl, ether, nitrile, or carboxyl, allows for additional modification of polarity, hydrogen-bonding characteristics, and coordination properties of the ionic liquid. Therefore, through modifying the structure of the ionic liquid researchers can design ionic liquids that are tailored for specific tasks such as the selective extraction of heavy metals, separation processes, and catalytic reactions. Because of these modifications, ionic liquids can be designed with precise properties for use in a variety of applications across multiple fields. For example, specially-designed ionic liquids have been used successfully for the selective extraction of metals, separations, catalytic reactions, and in pharmaceutical formulations. These types of ionic liquids also exhibit tunable ionic conductivities and electrochemical stabilities, which illustrate their promise as high-performance electrolytes in advanced energy storage technologies (e.g. next-generation batteries and supercapacitors)

Anion-Based Systems

In addition to anions affecting the physicochemical and operational characteristics of ionic liquids, anion composition is a key determinant of many of the properties described above, and as such, the selection of appropriate anions is vital for designing ionic liquids with specific characteristics for their intended purpose. The solubility of ionic liquids in water and other solvents is also determined primarily by the anion used. Anions that lead to hydrophilic ionic liquids can effectively mix with water. In contrast, anions that produce hydrophobic ionic liquids will create two distinct phases in the presence of water, making them ideal for chemical and physical separation/extraction processes. The ability of anions to coordinate with metal atoms also determines how well ionic liquids interact with metal ions, which is critical when using ionic liquids to extract metals, catalyse a chemical reaction, or purify products. Through the selective pairing of various anions and appropriate cations, ionic liquids can be rationally designed to exhibit desired physicochemical characteristics, following the "designer solvent" philosophy, where the chemical structure of the liquid is altered through the rational selection of the ions comprising the liquid. The manipulation of ionic liquids through a systematic approach allows for the engineering of ionic liquids to meet specific thermodynamic and kinetic demands to be used in numerous scientific and industrial applications.[6] Additionally, many types of ionic liquids that are produced with suitable anions have very little solubility in water and separate into two liquid phases. This hydrophobicity is desired in situations that require clear phase separation, such as in biphasic catalytic systems, where the ionic liquid can selectively solvate catalysts but is immiscible with the product phase, allowing for ease of catalyst recovery and reuse. Likewise, in extraction processes, the immiscibility between ionic liquids and water provides a more efficient and selective way to partition target compounds between aqueous and non-aqueous phases, thereby enhancing the overall efficiency and selectivity of separation processes.

Protic and Aprotic Ionic Liquids

Protic ionic liquids are created by the transfer of protons through the interaction of Brønsted acids and Brønsted bases. The transfer of a proton creates extensive hydrogen-bonding interactions between the ionic species formed during the creation of protic ionic liquids. Strong hydrogen-bonding interactions produce a strong hydrogen-bonding network between the ionic species and, therefore, can have a major effect on the physicochemical properties of protic ionic liquids, such as viscosity, polarity and proton conductivity. These hydrogen-bonding structures can often enhance the transport of protons, making protic ionic liquids a very attractive candidate for use in proton-conducting systems and fuel cell technologies. In contrast, aprotic ionic liquids are typically produced through the alkylation of an organic base to form a stable cation that will be combined with a suitable anion. Unlike protic ionic liquids, aprotic ionic liquids are generally produced without using proton transfer and, therefore, exhibit less hydrogen-bonding interactions than protic ionic liquids. The difference in structure results in greater chemical, thermal and electrochemical stability for aprotic ionic liquids than for protic ionic liquids. Due to their larger electrochemical window and greater stability when exposed to degradation, aprotic ionic liquids are considered very good candidates for use in electrochemical systems, such as batteries, supercapacitors and other advanced energy storage systems, where long-term stability is critical. [7, 8].

Preparation Methods

The production of ionic liquids typically consists of two phases to produce the desired cation–anion combination. The first step establishes the formation of the cation which is usually accomplished through a quaternization reaction process in which an organic base, such as an amine, imidazole or pyridine, reacts with a pertinent alkylating agent, which is usually an alkyl halide or other polar-type electrophilic compound. The formation of a cation occurs when the nucleophilic nitrogen atom in the organic base attacks the alkylating agent via a nucleophilic substitution reaction resulting in the formation of a cation with a positively charged quaternary ammonium or imidazolium or pyridinium. This process will convert a non-ionic organic molecule into a stable ionic molecule. The resulting quaternary salt is used as the precursor to the ionic liquid and typically has a halideanion derived from the alkylating agent. This first step is extremely important because the resulting cationary molecule's structure, mainly the type of substituent groups and the alkyl chains added to the cation during the alkylation reaction process, has a major impact on the final ionic liquid's physicochemical properties such as viscosity, hydrophobicity and thermal stability. The subsequent steps of generation of the ionic liquid typically include anion exchange or metathesis reactions in which the original anion is replaced with a more appropriate anion to produce the desired ionic liquid. [9]. The next step, after this activity is accomplished, usually involves an anion exchange procedure to swap out the original anion in the quaternary salt for another that is more appropriate. This operation, which is commonly referred to as anion metathesis, provides the basis for further customizing the ionic liquid by replacing it with an alternative anion that will provide the physicochemical characteristics you wish to achieve. During the above process, where initial halide or some other form of anion is formed upon quaternization, another anion is substituted for the initial one through a reaction with suitable salts or acids. Because the new anion is critical in defining the overall characteristics of the ionic liquid such as that will determine the ionic liquid's hydrophilicity or hydrophobicity, viscosity, thermal stability, and electrochemical properties. Thus, when selecting an anion during the exchange step, researchers have an ability to tune ionic liquids to achieve desired physical and/or chemical properties. The tunability of ionic liquids makes them so advantageous; ionic liquids can be developed to meet particular needs associated with applications such as usage in catalytic systems, separation processes, pharmaceutical formulations and/or electrochemical systems. [10]. The preparations of ionic liquids must be conducted under conditions that ensure the ionic liquids whose purity has a high level of cleanliness, because if there are only small amounts of contamination from impurities, this will change the physical and chemical characteristics of the ionic liquids and their overall use in applications. Any remaining residue left over from the synthesis (as an example, any unreacted reactants, the solvents used in the synthesis, water or any by-products formed during the synthesis, etc) will have an effect on many important properties of the ionic liquids like viscosity, conductivity, thermal stability, and electrochemical performance. The presence of impurities will also interfere with intermolecular forces of the ionic liquids which will ultimately also alter the arrangement of the ionic liquids and their functional characteristics. Therefore, the presence of contamination may also create variability in the experimental data of the ionic liquids and thereby limit the validity and repeatability of scientific studies of the ionic liquids.

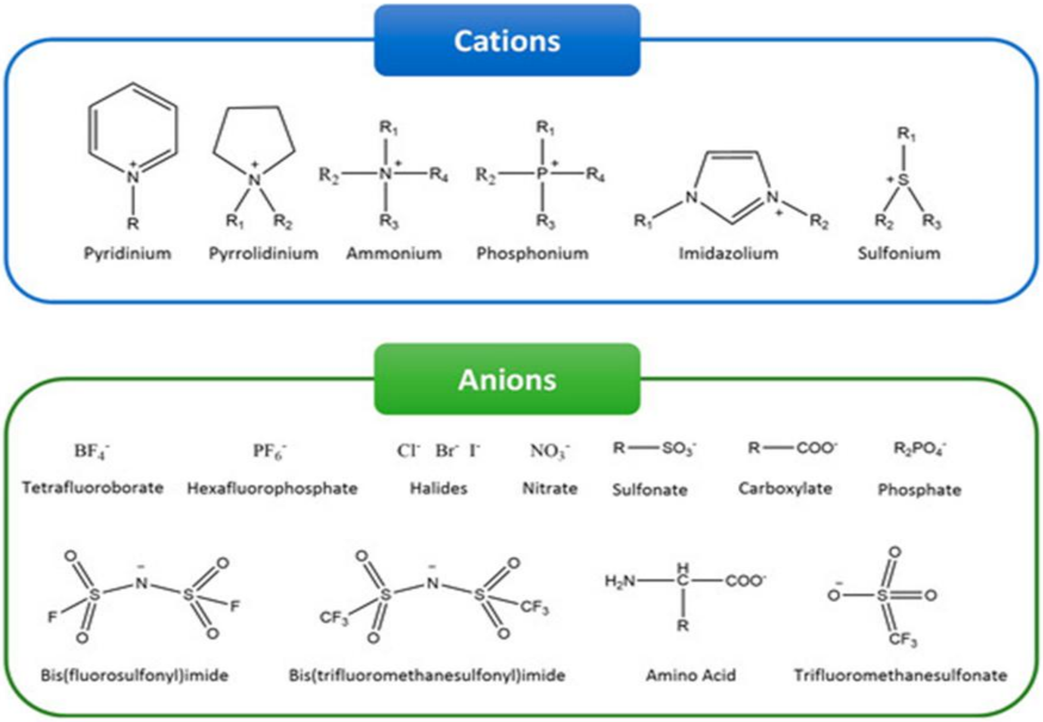

Fig. 2 Commonly used Cations and anions Species

Because of the above reasons, it is imperative that adequate procedures for purifying the ionic liquids and care are taken during and after the synthesis to ensure that the ionic liquids meet purity criteria. In order to evaluate the inherent properties of ionic liquids accurately and also ensure repeatable experimental conditions for research and industrial applications of ionic liquids, maintaining a high level of purity is of utmost importance. [11].

Physicochemical Characteristics

Thermal Stability

Ionic liquids are highly regarded for their excellent thermal stability and resistance to thermal degradation. The majority of ionic liquid systems can withstand elevated temperatures without undergoing significant decomposition, with many reported to be thermally stable at temperatures above 300 °C. Strong electrostatic interactions between cations and anions as well as the structural stability of their organic ionic structures are responsible for the high level of thermal stability of ionic liquids. The thermal stability of ionic liquids makes them uniquely suited to applications involving high-temperature conditions where conventional organic solvents would typically evaporate or degrade. The negligible vapor pressure of ionic liquids further enhances their applicability in high-temperature applications because ionic liquids do not evaporate at elevated temperatures. It should be noted, however, that the precise thermal stability of an ionic liquid depends on the specific combinations of cations and anions utilized. Variations in structural characteristics including the ionic framework, substituent groups on the cation or anion, and intermolecular forces will all determine when thermal decomposition begins; consequently, there will be variations in the thermal stability of different ionic liquids. Regardless of these potential variations, the high thermal stability of ionic liquids is one of the most attractive features, allowing them to be used in applications such as catalysis, heat transfer systems, and high-temperature chemical reactions. [12].

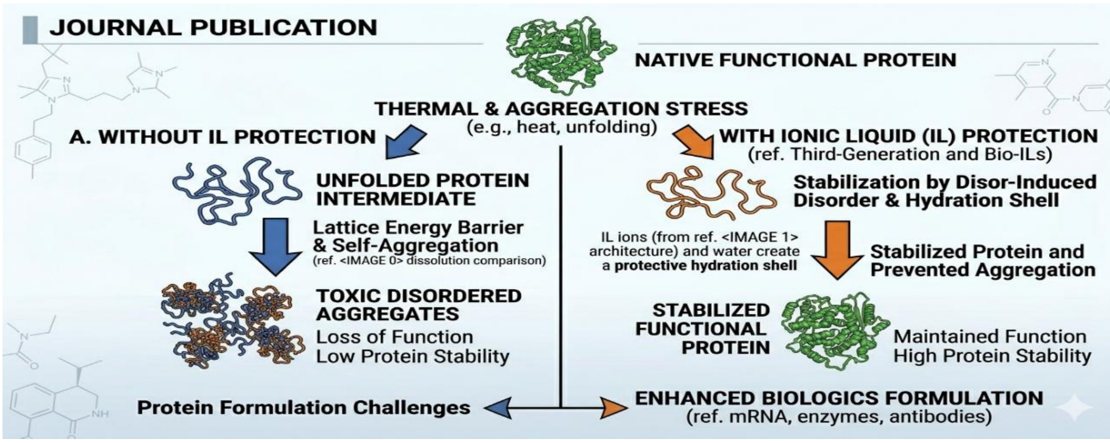

Fig.3. Thermal Stability of Without IL Protection and with IL Protection

Viscosity

One of the main drawbacks of ionic liquids is their relatively large viscosity when compared to traditional organic solvents, mainly a result of the strong electrostatic attractions and large amounts of intermolecular forces between the ions that constitute the ionic liquid solution. This high viscosity restricts the ability for ions and molecules to move throughout the liquid, therefore resulting in reduced fluid flow and mobility of the molecules within the ionic liquid. In practical applications involving the use of ionic liquids, the high viscosities associated with these systems will have significant impacts on the efficiency of an ionic liquid-based process. For example, the slow diffusion of reactants and products in a catalysis or extraction process will result in longer reaction times and lower overall process efficiencies. As a result, mass transport of species through the use of ionic liquids may limit the performance of systems that require rapid molecular transfers. To overcome this issue, researchers have been working to modify the structure of ionic liquids through the use of suitable cation–anion combinations, reducing the length of alkyl chains in the ionic liquid structures, or adding functional groups to the ionic liquid structures that exhibit lower intermolecular attractions. Additionally, researchers have explored using slightly elevated temperatures and combining ionic liquids with compatible co-solvents to lower viscosity and enhance mass transport performance in practical applications. [13].

Solvation Properties

Ionic liquids can be characterized by their ionic structure and unique properties, which allow them to dissolve a vast variety of materials (e.g., organic compounds, inorganic salts, and even complex macromolecules). An ionic liquid consists of a cation (+) and an anion (−) that display highly varied and strong intermolecular forces through hydrogen bonding, van der Waals interactions, and electrostatic attraction. Because of these intermolecular interactions, ionic liquids have excellent solvation properties and can therefore solvate molecules with very different chemical properties. Because of this, ionic liquids will dissolve a broad range of substances, and some ionic liquids have been shown to dissolve polymeric substances (e.g., cellulose), which usually cannot be solubilized in common solvents because of their extensive network of hydrogen bonds. The ability of ionic liquids to solubilize many different materials makes them particularly useful in a number of areas, including biomass processing, polymer chemistry, catalysis, and the development of advanced materials. [14].

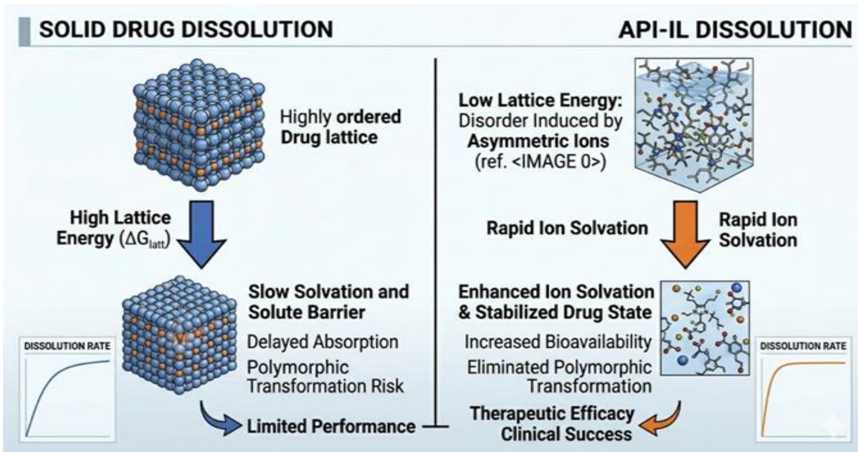

Fig.4. Dissolution Behaviour of Pure drug and API-IL System

Applications

Catalysis

At present, ionic liquids serve not just as a solvent but also as an effective medium for catalysis in many different reactions. Their ability to act as both a reaction facilitator and a physical medium through which reactants can interact effectively with one another means that ionic liquids can enhance the ways in which reactants and catalysts interact with one another, thus affecting the pathways through which reactions occur and also improving the overall performance of the reaction. In some cases, using ionic liquids during a reaction creates a greater separation between the desired product(s) and unwanted by-products than would otherwise be produced. Additionally, because ionic liquids have very little vapor pressure and can be "tuned" to possess specific solvation properties, removing and recovering the products from the reaction becomes easier. Many times, ionic liquids separate from reactions, and in some cases, the catalyst will remain dissolved in an ionic liquid while the products will form their own separate phase. This property allows the product(s) to be isolated much more easily than traditional methods, enhances the reuse of both the ionic liquid and catalyst, and significantly increases the overall efficiency and sustainability of the reaction process. [17, 18].

Energy Storage and Conversion

Due to their unique properties as conductive materials and their resistance to thermal decomposition, ionic liquids are extremely attractive for use in a variety of advanced energy applications. The ionic nature of ionic liquids allows for the efficient transport of charge, and the wide electrochemical window of ionic liquids allows for stable operation at many different voltages. Because of the lack of volatility and the high thermal stability of ionic liquids, they will perform reliably in many situations where conventional electrolytes have either degraded or evaporated. These attributes make ionic liquids well-suited for application within lithium-ion battery systems, supercapacitor systems and fuel cell systems. In lithium-ion batteries, ionic liquids are a non-flammable alternative to a liquid organic electrolyte and improve the safety and thermal stability for the operation of lithium-ion batteries. In supercapacitors, the high ionic conductivity and thermal stability of ionic liquids contribute to improved charge-discharge performance and long cycle life. In fuel cells, ionic liquids enhance the transport of ions within the fuel cell while maintaining the physical integrity of the fuel cell at elevated operating temperatures. The high conductivity, durability, and chemical stability of ionic liquids suggest that these materials represent promising candidates for the next generation of electrochemical and energy storage technologies. [19–21].

Separation Technologies

Due to their adjustable physical and chemical properties and excellent solvating abilities, ionic liquids are gaining more and more interest as a solvent for different types of selective separation operations. The mixtures of the cations and anions in ionic liquids can be selected so that there is a specific interaction with either the target species (i.e., molecules or ions) or non-target species, which makes them excellent solvents for separation processes. One of the most prominent uses of ionic liquids is as solvents for absorbing and separating carbon dioxide from gas mixtures. Ionic liquids can be engineered to have a specific polarity, a high degree of thermal stability and can also form specific types of interactions with carbon dioxide, which results in their efficient absorption and separation from gas mixtures. This makes ionic liquids a promising candidate to be used in the development of carbon capture technologies to help reduce greenhouse gas emissions. Ionic liquids are also being investigated for their ability to recover and separate metal ions from large, complex mixtures. The ionic liquids' ability to coordinate with metal ions provides a means for the selective extraction of target metal ions from aqueous or multi-component systems. This makes ionic liquids particularly useful in processes for hydrometallurgy, the recycling of precious metals, and the purification of industrial waste products. Therefore, ionic liquids' ability to be adjusted and to interact selectively with other chemicals makes them ideal candidates for new, advanced separation and extraction processes. [22, 23].

Biomass Processing

By breaking through hydrogen-bonding in lignocellulosic biomass, ionic liquids allow for efficient processing to produce biofuels or value-added chemicals from such biomass [24].

Pharmaceutical and Biotechnological Applications

Recent studies demonstrated that ionic liquids offer good opportunities for highly specialized applications within both medicine and biology. Due to their unique physicochemical properties (e.g., tunable polarity, very good solvation characteristics, structural symmetry), ionic liquids are able to interact very well with biological molecules of differing chemical structures. Therefore, researchers are increasingly considering the use of ionic liquids in developing novel biomedical and pharmaceutical products. An area where ionic liquids will receive increasing amounts of investigation is in the development of drug formulations designed as drug delivery vehicles. Specifically, because ionic liquids can enhance the solubility and bioavailability of poorly soluble pharmaceutical products, developing drug formulations with ionic liquids increases the stability, permeability, and controlled-release characteristics of pharmaceutical products. Ionic liquids have also been shown to have utility as enzyme stabilizers. Specifically, the solvent environment of ionic liquids can stabilize and maintain the three-dimensional structure and activity of enzymes in situations where traditional organic solvents may result in denaturation of the enzymes. In addition, some ionic liquids have been shown to possess antimicrobial activity, which suggests that they could also be used as components in the development of antimicrobial formulations. Ionic liquids are effective against many different microorganisms; their effectiveness can be attributed to the mechanism by which the ionic liquid disrupts the membrane of cells or influences the metabolic processes of certain microorganisms. Therefore, as more research is completed, there will be greater utilization of ionic liquids to enhance and develop innovative biomedical technologies such as drug formulations, biocatalysis, and antimicrobial therapy. [25].

ADVANTAGES

The unique physicochemical properties and structural variety of ionic liquids are two of their primary benefits. Their extremely low vapour pressure is among their most significant attributes, which means they are not as volatile as traditional solvents, thus limiting the escape of vapours from the environment. Furthermore, this has two key advantages: 1) it creates additional safety in handling and use, and 2) creates potential for the use of ionic liquids as eco-friendly replacements for conventional organic solvents. Additionally, ionic liquids are resistant to chemical degradation and can remain stable in terms of their physical and chemical properties (even at elevated temperatures). Their outstanding thermal and chemical stability allows ionic liquids to be used successfully in many types of engineering and industrial applications. The characteristics of ionic liquids make them appropriate for any process in which a conventional solvent would evaporate, decompose, or become unstable. Another major benefit of ionic liquids is their customizability. By changing the molecular structure of the ionic liquid (for example changing the cation, anion or functional groups), researchers can create ionic liquids with specific properties to meet specific needs. With this flexibility of structure, ionic liquid-based materials and polymers with tunable properties have been created.) [1, 2, 6]. Ionic liquids can typically be recovered and reused many times with little or no reduction in performance. Their ability to be recycled results in less waste production and greater efficiency in the process. As such, their properties make ionic liquids a desirable material for sustainable system design and for environmentally friendly engineering practices. [17].

Limitations

Despite their many advantages, ionic liquids' widespread use is severely constrained by significant challenges. The first limitation is the high cost of producing and synthesizing ionic liquids. In many cases, ionic liquids can be very complex and involve multiple reaction steps, numerous reagents, and time-consuming purification procedures. As a result, manufacturing costs can be greatly increased and the commercial viability of ionic liquids is severely limited. Another serious limitation concerns the uncertain toxicity of, and the long-term environmental impact of, ionic liquids. Many ionic liquids are designated as environmentally friendly, as they exhibit negligible vapour pressure; however, some research indicates that some ionic liquids may have toxic effects on biological systems, or that some ionic liquids may persist in the environment. As a result, more research is required to evaluate the ecological safety of ionic liquids and to develop more eco-friendly ionic liquids [26–28]. The third limitation associated with ionic liquids is the technical difficulty associated with purifying them. It is essential to remove unreacted reagents, by-products, solvents, and water from ionic liquids to achieve a high level of purity. If even small amounts of unreacted reagents or impurities are present, they can have a dramatic adverse effect on the ionic liquid's physiochemical properties and performance in real-world applications. In addition, many ionic liquids tend to be very highly viscous, which can create practical limitations. High degrees of viscosity will impede the movement and diffusion of molecules, thereby reducing the rate at which chemical reactions occur. This limitation could have a negative impact on the efficiency of these processes and would limit the ability of ionic liquids to be used in large-scale industrial operations requiring quick mass transfer and reaction kinetics [13].

Future Perspectives

Presently, researchers are exploring ways to create unique ionic liquids to serve a purpose in certain areas of industry [29]. Furthermore, there is a growing demand for producing genuine bio-ionic liquids derived solely from renewable sources, to produce more sustainable products for use in more sustainable applications [30]. Researchers have also begun producing hybrid combinations of ionic liquids and their corresponding nanomaterials, for improved energy storage and catalyzing [31]. However, before the industrialization of these materials can occur successfully, issues related to cost-effectiveness and producing these materials on a larger scale must be resolved [32].

CONCLUSION

Ionic liquids (ILs) can be used as an innovative and multifaceted type of material for many different industrial applications. Due to their very tunable (or easily changed) structures and unique physical and chemical characteristics, ionic liquids are particularly suitable for a variety of applications in areas such as catalysis, energy storage, separations, and advanced material synthesis. By modifying the cationic (positively charged) and anionic (negatively charged) components of the ionic liquid, researchers can create a specific ionic liquid with precise properties. This ability to create tailored ionic liquids makes them increasingly significant and impactful in contemporary chemical and engineering research. Additionally, certain characteristics of ionic liquids (e.g., low volatility, thermal stability, and excellent solvation properties) can be utilized in the development of sustainable and environmentally friendly chemical processes. These properties contribute to the potential for ionic liquids to be used as alternatives to organic solvents for developing greener chemical technologies.

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