

Sustainable Green Solvents: Ionic Liquid-Based Hydrogels

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Abstract

Green solvents have been widely used in a wide range of applications, such as catalysis, separation sciences, energy storage and pharmaceutical applications. The main ingredient in the collection of the environmentally benign reagents is ionic liquids (ILs). Ionic liquid-based hydrogels are being used in the biological sciences and medicinal chemistry fields because of their excellent biocompatibility and biosafety features. The versatility of ionic liquids is great, as they can be formulated as membranes, surfactants, polymers or monomers. Due to the increased demand for sanitary, practical, and sustainable energy technology, energy emission monitoring is currently considered an object of study for the study of gels synthesized through ionic liquids. This fixation is particularly pronounced in the development of systems for energy storage which are subject to fluctuating operational conditions. The present review deals extensively with these areas, analyzing many of the procedures using ionic liquid ingredients. Illustrates the various application of Ionic liquid-based hydrogel for Storage and conversion of energy at Solar Cell Applications, Electrochromic Devices, Environmental and Catalysis Applications. Biomedical Applications of Ionic Liquid-Based Hydrogels such as Antimicrobial Properties, Drug Delivery Hemostasis, and Adhesion Wound Healing and also discussed briefly in the research paper. It also throws light on sustainable green solvents-Ionic liquids-based Hydrogels and its application in various fields.

Keywords: Hydrogels; ionic liquids; green solvents; biomedical applications; energy storage; catalysis

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Received Date: April 03, 2026

Accepted Date: April 20, 2026

Published Date: May 10, 2026

Citation: Nidhi Jain, Sonali Bhosle, Smita Suhane, Seema Tiwari, Nidhi Yadav. Sustainable Green Solvents: Ionic Liquid-Based Hydrogels. Journal of Polymer & Composites. 2026; 14(Special Issue 2): S1263–S1274p.

INTRODUCTION

Hydrogels have a great effect, because of their porous nature, which follows from interpenetrating networks and large surface areas that can efficiently exclude the penetration of external chemical or molecular species [1]. Three-dimensional polymeric networks are Hydrogels with the extraordinary property of absorbing large quantities of liquids, which is attributed to the fact that they have an increased elastic modulus. The materials capable of holding their bodily fluids and water in their flexible and elastic structure can be a good simulator of the mechanical functions of living cell tissues of the natural environment.

The combination of physical properties of hydrogels with their functional versatility, biocompatibility and reversibility makes them reliable materials for myriads of applications. These include organ and tissue replacement, mediums of biological systems interaction and

even living tissues functional parts of their tissues. New and advanced applications that utilise different detection schemes, the versatility and the strength of the sensor designs include hydrogel sensors and biosensors. These types of materials have high potential in many different industries, due to their outstanding ability to serve as biocompatible compounds and due to their ability to transport ions [2, 3].

Ionic liquids are molten salts that contain organic or inorganic anions and organic cations that are combined and are therefore defined by melting points that are below 100C [4, 5]. These types of liquids have been called designer solvents and their physicochemical properties are readily designed by a selection of specific cations and anions. Theoretically, a total of 1018 possible ionic liquids can be produced and useful ionic liquids can be designed by incorporating definite functionality in the cations or anions. Such ILs have significant potential in their deliberate design which is due to the flexibility inherent in the anionic and cationic moieties.

Ion gels (or ionic liquid gels) are based on polymers networks in ionic liquid, and are regarded as attractive solid-state electrolyte environments, as are also hydrogels which are based on polymer gels. Such materials have wide electrochemical windows, high conductivity, non-flammability, and good chemical as well as thermal properties [6–9].

As a result of polymerization of certain material, hydrogel gels are aqueous ionic gels which are produced in the presence of electrolyte solutions which have relevant initiators and cross linking reagents [10]. The brightest example is the hydrogel polyacrylamide-based; the acrylamide monomers in this sort of system polymerizes with an electrolyte of KCl/NaCl nature, and this system has drawn a lot of academic interest [11, 12]. On the other hand, the other type are non-aqueous ionic gels which are polymer networks which have taken on the organic electrolyte solutions [13]. In recent years, lithium salts with poly (ethylene oxide) have been combined and have produced a very new non-aqueous ionic gel formulation [14]. However, the relatively low ionic conductivity of the lithium ions ($\sim 10^{-5}$ S cm $^{-1}$) at room temperature due to the low mobility of the lithium ions limits the practical utility of these materials. A possible way to overcome this weakness is through the use of ionic liquids in the polymer frame to enhance the levels of conductivity of the overall ion gels illustrated in Figures 1 and 2(a) [15].

Biomedical Applications of Ionic Liquid- Hydrogels

Ionic liquid- gels have become the topic of much interest lately in a number of sectors with a particular use. Ionic liquid-based gels have shown fantastic worth for the biomedical field as they can use the biological properties of ILs to treat infection and hemostasis. Conversely, ILs participate in the formation of various gels, where they can help dissolving the auxiliary material or they help medications get to the desired area Figures 2(b) and 2(c).

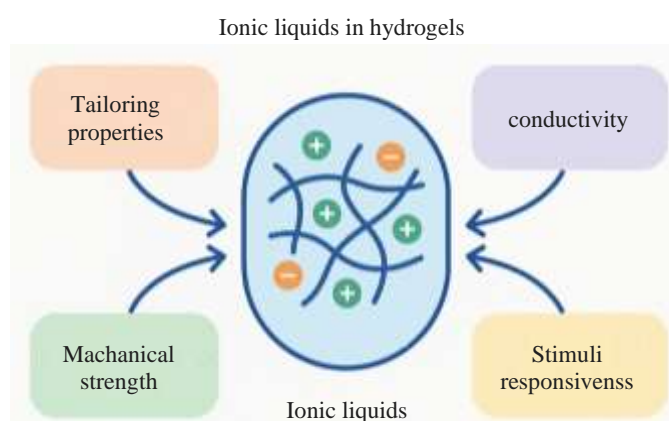


Figure 1. Ionic liquids role in hydrogels.

The main applications that the gels using ionic liquid are in blood sugar management and tumor treatment. Hydrogels are one of the important material class with the great utility in bio-sensing applications with immobilization and protective properties, which enhance biocompatibility of the materials Figure 3 [16–18].

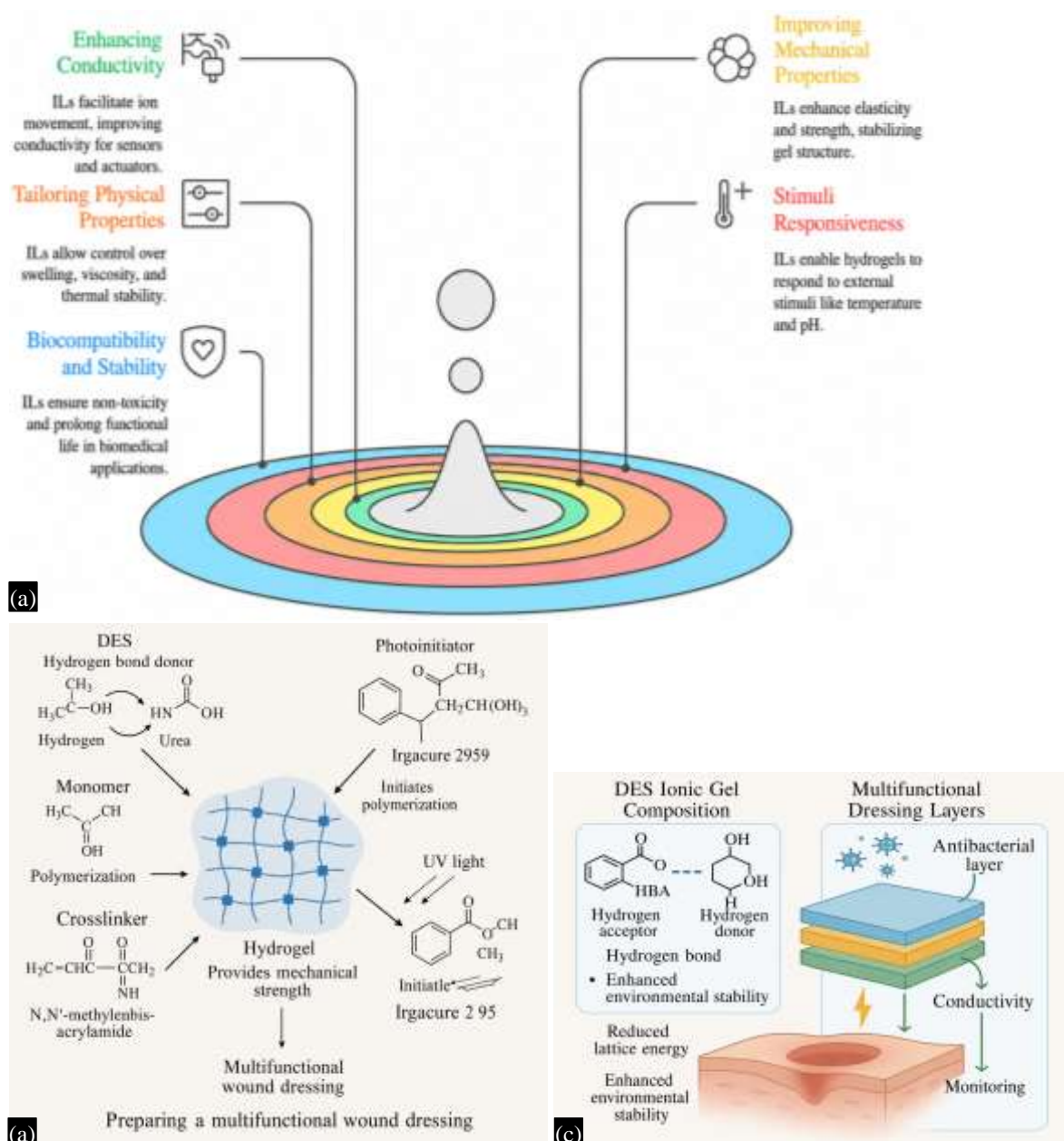


Figure 2. (a) The functional roles of ionic liquids in hydrogels; (b) The diagram illustrate the components used in preparing a multifunction wound dressing, including DES, monomer, crosslinker and photoinitiator. It also illustrates how these elements interact during polymerization to form hydrogel or polymer network; (c) The diagram illustrating the multifunctional wound dressing made from DES ionic gel 1. DES Ionic gel composition shows molecules representing hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD). - Indicate hydrogen bonds forming between HBA and HBD. 2. Multifunctional dressing layers- Antibacterial layer, conductive layer with electrical conductivity symbols or pathways, - Wound monitoring layer with sensors or indicators.

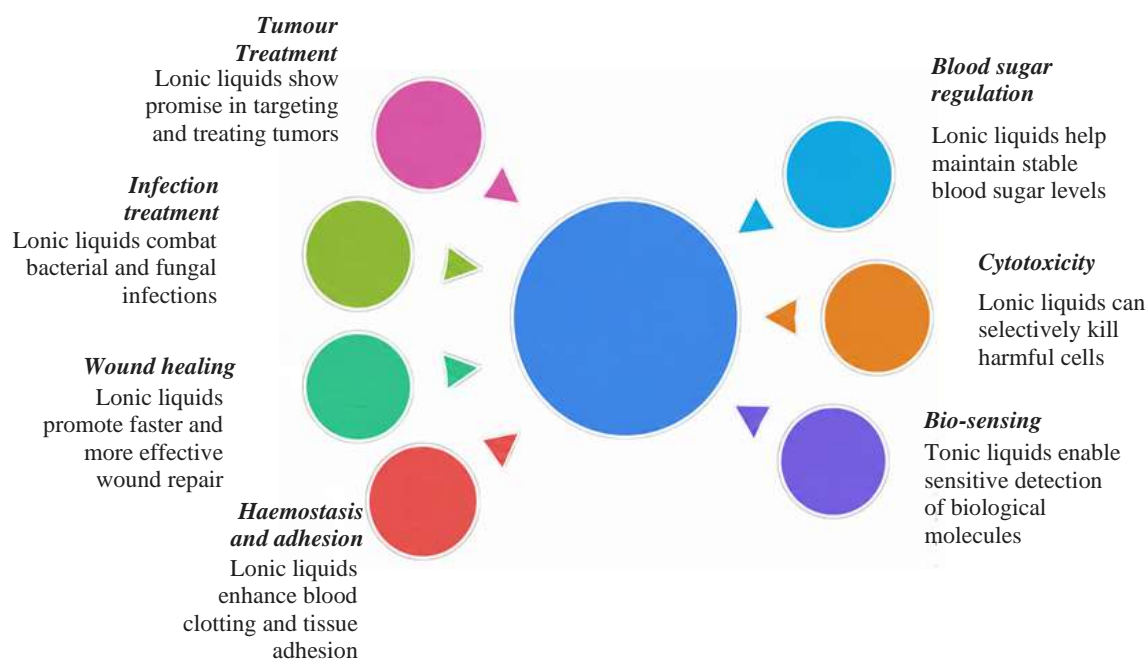


Figure 4. Various biomedical presentations of Ionic liquids in hydrogels.

Table 1. Sustainable green solvents-ionic liquids based hydrogels and its application in various field:

S.N.	Name of application	Application of hydrogel in various field	References
1	Infection treatment	A biological macromolecule with antioxidant properties, lignin can effectively boost the antioxidant activity of poly (ionic liquid) hydrogels. Li et al.	[30]
2	Cytotoxicity	The biocompatibility of the third-generation ILs was significantly increased by the presence of biodegradable natural ions, such as amino acids and. In place of halides choline and pseudohalides, such as BF 4 and PF 6, natural organic acids, such as malic acid, succinic acid, and tartaric acid, give ILs good biodegradability.	[40, 41].
3	Li-Ion Batteries	IL-based gels are found in most inventions, including Li-ion, Li-metal, Li-oxygen, and Li-polymer batterie Li-ion batteries, Li-metal batteries, Li-oxygen batteries, and Li-polymer batteries all contain IL-based gels, as do the majority of inventions.	[43, 44, 45].
4	Al-ion batteries	Because of their lavishness, superior resistance to oxygen and moisture, and four times more volumetric capacity than Li, Al-ion batteries offer an inexpensive, rechargeable, high-energy density battery choice. Schoetz et al	[50]
5	Ca-Ion Batteries	Because of their exceptional conductivity and high specific area, carbon-based materials such graphene, reduced graphene oxide (rGO), carbon black, and activated carbon (AC) carbon nanotubes (CNTs) have also been employed extensively as electrodes in SCs recently .	[55].
6	Supercapacitors	According to electrochemical experiments, the supercapacitor using IL-based gel electrolytes demonstrated encouraging performance with a specific capacitance of 1.5–3 mF cm ²	[56].
7	Electrochromic Device	Electrochromic devices (ECDs) are used in smart windows, locomotive mirrors, concealment glass, displays, electronic paper, military hide, and other architectural applications	[61, 62]
8	Heavy Metal Ions can be removed from Water with the help hydrogel incorporated IL	When it comes to removing heavy metal ions from wastewater, hydrogels are widely used because of their structural design, affordability, high water permeability, and biodegradability. Furthermore, because of their excellent thermal stability, broad electrochemical window, and capacity for structural design, ionic liquids exhibit significant promise in the fields of electrochemistry, separation, and catalysis	[63, 64]

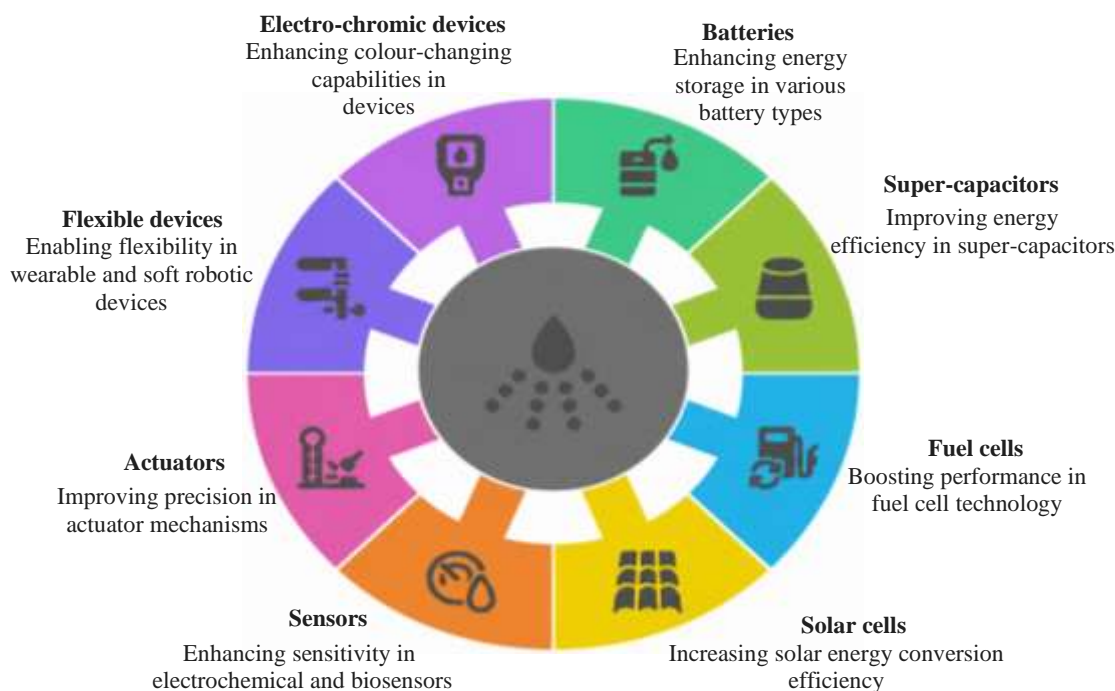


Figure 5. Illustrate the various application of Ionic liquid-based hydrogel for storage and conversion of energy

ENERGY STORAGE APPLICATIONS

Batteries

Ionic liquid-based hydrogel has witnessed great potential in the arena of batteries, specifically lithium-ion, sodium-ion, and other metal-ion batteries. Due to the extraordinary ionic conductivity and broad electrochemical windows, ILs are excellent electrolyte materials [32–35].

Lithium-Ion Batteries

IL-based gel polymer electrolytes have been widely researched for application in lithium-ion batteries. These materials provide better safety than the traditional liquid electrolytes with non-flammable materials and with lower possibility for leakage [36–38]. Recent strides have been made on how to develop ionogels with improved ionic conductivity and mechanical stability.

Sodium-Ion and Alternative Metal-Ion Batteries

With the increasing interest in alternatives to lithium-ion batteries, IL-based hydrogel has been tested for sodium-ion, potassium-ion, calcium-ion and aluminum-ion batteries [39–42]. The IL systems have the great advantage of allowing the IL properties to be tuned to optimise the ion transport for different metal ions.

Supercapacitors

Ionic liquid-based gel electrolytes has revolutionized the supercapacitor technology by facilitating high energy density, wide operating temperatures and good cycling stability for supercapacitors [43–46]. High ion conductivity and broad electrochemical windows are combined in ion-exchange membranes ensuring higher operating voltage than is possible with aqueous electrolytes.

Fuel Cells

Protic ionic liquid-based ionogels have emerged as encouraging electrolyte materials for fuel cells, particularly for operation at elevated temperatures and in non-humidified conditions [47–49]. These materials address many challenges associated with conventional polymer electrolyte membranes, including water management and temperature limitations. Figure 5 Illustrate the various application of Ionic liquid-based hydrogel for Storage and conversion of energy

CATALYSIS APPLICATIONS

Ionic liquid based hydrogels are good catalytic platforms because they can also immobilize the catalysts but do not prevent the reactants from getting access to the catalyst [50–52]. The IL phase offers a unique microenvironment which can be useful in increasing catalytic activity and selectivity. Current developments have been in the following areas:

Heterogeneous Catalysis

IL-hydrogels can be employed to immobilize homogeneous catalysts to give recyclable heterogeneous catalytic systems. This approach is realized by combining the merits of homogeneous catalysis (high activity and selectivity) with the practical benefits of heterogeneous catalysis (stress-free separation and recycling) [53–55].

Biocatalysis

Due to the biocompatibility of a large number of ionic liquids, IL-hydrogels are suitable for the immobilization of enzymes and biocatalytic uses. Enzymes entrapped in IL-hydrogels often exhibit improved stability and activity as compared to the aqueous systems [56–58].

ENVIRONMENTAL APPLICATIONS

Heavy Metal Removal

Ionic liquid-crosslinked hydrogels have been demonstrated to have excellent performance in removal of heavy metal ions from water. The mechanism depends on the range of concentrations and includes both physical adsorption and chemical complexation [59–61]. These materials present advantages like high adsorption capacity, selectivity and reusability.

Water Purification

IL-based hydrogels have the ability to be designed with certain functional groups to combat various kinds of water contaminants including organic contaminants, dyes and pharmaceutical residues [62–64]. The tunability nature of ILs permits development of task-specific materials fulfilling different purification needs.

ELECTROCHROMIC DEVICES

Ionic liquid-based gel electrolytes have allowed development of flexible, solid-state electrochromic devices that are fast switching and highly colored [65–67]. These devices have applications in smart windows, displays and wearable electronics. The use of IL-gels avoids the problems due to the use of liquid electrolytes, such as leakage and evaporation.

SOLAR CELL APPLICATIONS

IL-based gel electrolytes have been used successfully for dye-sensitized solar cells (DSSCs) and other photovoltaics [68–70]. These gel electrolytes solve the problem of liquid electrolyte stability as well as high ionic conductivity required for efficient device operation. Recent developments in this area are concerned with improving the long-term stability and efficiency.

CHALLENGES AND FUTURE PERSPECTIVES

Despite the great advances on hydrogel research in ILs, there are still several problems:

Cost and Scalability

The synthesis cost of many ionic liquids is costly, which limits the study of their potential large-scale applications. Future studies should be directed towards the development of cost-effective synthesis approaches, and the investigation of more economical IL alternatives [71].

Toxicity and Environmental Impact

While many ILs are regarded as "green solvents", comprehensive studies on toxicity are required.

The recyclability of ILs, both biodegradable ILs and thorough life-cycle estimations are necessary components for sustainable applications [72].

Extensive-Term Stability

Understanding and furthering the extended-term stability of IL-based hydrogels under a variety of operating conditions is still an important area of research. This includes thermal stability, electrochemical stability and mechanical durability

Standardization

The development of protocols for standardized testing and measures of performance would make it easier to compare different IL-hydrogels systems and enable more information to be transferred from laboratory to industry more quickly.

Green Solvents, and Important in Sustainable Chemistry

Green solvents are really important for chemistry. The old petrochemical solvents used in chemical and analytical processes can be replaced with solvents. Green solvents are special because they come from sources and can be used in chemical reactions that do not need a lot of pressure or heat. This means they use energy and are better for the environment.

For example there is a solvent called ethyl lactate that comes from corn. It is an example because it is biodegradable can be recycled does not corrode things and is not carcinogenic. Green solvents like ethyl lactate are the way to go for chemistry. They are good, for the earth. That is what matters [73].

Components of Ionic Liquid-Based Hydrogels?

When it comes to applications people usually prefer hydrogels that are tough and can handle different temperatures. Ionic liquid-based hydrogels generally consist of Ionic liquids (ILs), Polymeric network, Crosslinkers, Solvent phase Over the ten years there has been a lot of progress in making tough hydrogels using different methods. One type of hydrogel that is very strong and elastic is the network hydrogel. Double network hydrogels have two networks. One is weak and the other is strong and tightly connected. For example double network hydrogels made with alginate and polyacrylamide have two types of networks. One that is connected by ions and the other that is connected tightly. These double network hydrogels are very good at handling stress. Are very elastic. However making these strong connections between the networks usually requires heating or exposing them to light in a special environment.

Hydrogels Stimuli-Responsive

There are also hydrogels called stimuli-responsive hydrogels. These hydrogels are smart because they can change their properties, such as how strong they're how much they absorb, when they are exposed to certain things like temperature, light or chemicals. Stimuli-responsive hydrogels can change from a liquid to a state when they are exposed to something that triggers this change. The things that can trigger this change include temperature, light, electric or magnetic fields and certain chemicals. For instance physical things like temperature or light can cause a change while chemical things, like the level of acidity can also cause a change [77].

Challenges Exist in Large-Scale Production and Environmental Remediation?"

RTILs and nanotechnology can really help clean up water that is contaminated. This is a way to deal with water scarcity and pollution because it is sustainable and environmentally friendly. Usually chemicals are used to clean water. These chemicals can hurt people and the environment. When we use RTILs and nanotechnology we do not need to use many chemicals so the environment is not harmed as much. We do not need to use a lot of chemicals to purify water when we can use nanomaterials that can absorb and break down the things that pollute the water. RTILs are good because they are not flammable and they can withstand temperatures so they can replace other solvents that are not as safe.

RTILs and other ILs are very useful for many things and we can change their properties to fit our needs. We can make RTILs and other ILs to remove things from water like chromium and dye. Using ILs and nanotechnology gives us ways to solve the problem of contaminated water. So using nanotechnology and RTILs together is a way to make water purification better by using fewer chemicals and making the process more efficient. This is because we can design the materials and processes to fit our needs. RTILs and nanotechnology can really help us clean up contaminated water and make the water safer, for everyone [78].

CONCLUSION

Ionic liquid based hydrogels are a versatile class of materials that have applications in the biomedical, energy, catalysis, and environmental fields. And their Combined distinctive properties including advanced ionic conductivity, biocompatibility, tunable physicochemical characteristics, and environmental stability are fascinating for many applications. Recent developments have shown remarkable advances in overcoming some of the main challenges in the materials including mechanical stability, resistivity to ions, and integration of functions. Future research should focus on cost reduction, comprehensive sustainability assessments and upscaling the production means towards large scale adoption of these promising materials.

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