Carib.J.Sci.Tech

A Review on General Properties and Applications of Ionic Liquids

Authors & Affiliation:

Srinivasa Rao Aangothu[1],
Sowjanya Prathipati[1],
J N Pavan Kumar Chintala[2],
Soumini C[3],
Hari Babu Bollikolla[1*]

[1]Department of Chemistry, Acharya Nagarjuna University, Guntur-522510, AP-India
[2]Department of Physics, Sir C.R.R. College, Eluru, W.G. Dist, AP-India
[3]Department of Chemistry, M.E.S Ponnani College, Ponnani, Kerala, India

Corresponding Author

H B Bollikolla,
**Email: drharibabuanu@gmzil.com*

Received on 5th January 2019
Accepted on 28th December 2019

Abstract:
In this review the author summarized various applications of Ionic liquids such as solvents, electrolytes, catalysis, solar cells, fuel cells, polymer science, food & Bioproducts, Lubricants, etc. The review was attempt to make aware of usage of Ionic liquids in various fields and think of application of IL's in other fields also based on their properties.

Keywords: Ionic liquids, Fuel cells, Solar Cells, Electrolytes, Polymers, solvents, antistatic additives

Introduction

Ionic liquids (ILs) are also known as salts, they are appropriate to below melting points, frequently under room temperature; these are also being called as room temperature ionic liquids (RTILs). So ILs can be also considered as a novel and extraordinary set of solvents and are of unbelievable research attention to researchers in present years, because of their potential applications and unique properties in the industries and chemical process. ILs are usually molten salts they are made up of large organic asymmetric cation like as pyridinium, imidazolium, quaternary ammonium, pyrrolidinium, or tetra alkyl-phosphonium and inorganic/organic anion i.e., entirely composed by ions, ILs is suitable for the very well alteration of their properties during a nonstop combination of anions and cations, classified as "designer solvents", to make more efficient sustainable products and processes we are gaining to allow the design of solvents for the development. The achievement arises mainly due to their transport and thermo physical properties, and adaptability of their synthesis, controllable to be modified for a specified application[1-3]. Due to popularity is gained, in synthetic, separation and electrochemical processes. ILs may be also used as alternatives to volatile organic solvents (VOCs). As a result of a number of their unusual properties, they as exposure to stability on moisture and air, high thermal and chemical stabilities, ionic conductivity, adaptable miscibility, very low vapor pressure, non-flammability, broad range of viscosities and an capability to dissolve a wide range of organic and inorganic compounds and a lot of additional to suit the requirements of a particular procedure[4-7].

Since all of these attractive features ILs have been widely used as liquid phase reactions in alternatives to molecular solvents and are frequently considered as potential solvents for extractions, electrochemical purposes, chemical reactions, catalysis, , and a lot of other applications[6-9]. In the studies of vapour-liquid equilibrium ILs has also been reported as promising solvents in extractive distillation processes. Often, ILs is also known as "novel solvents" or "green solvents"[9-12].

IL's are non-volatile and they do not create atmospheric pollution under normal conditions, hence mainly arise from the reputation of "green solvents. The combination and option of the ions, physicochemical properties for example melting point, viscosity, polarity, solubility, thermal and electrochemical stability are able to be under attack. So, ILs are also known as "task-specific ionic liquids". Due to some potential advantages similar to low toxicity, high water, and air stability, structural organization, and appreciable conductivity, especially for electrochemical applications imidazolium-based RTILs are more often used[13-16]. To make different material sliding pairs good-looking, we are using unique combination characteristics of ILs. A slim lubricant film is present in the boundary of the lubrication regime; the physical adsorption is created by polar natures of ILs.

IL's became one of the most capable chemicals as solvents in the late 1990s. The first generation of ILs for example organo-aluminates can be regarded as limited, range of applications since they are not stable in water and air. In addition, these ILs were not inert towards a wide variety of organic compounds. As researchers have discovered in recent times that ILs are more than just green solvents and they showed interest in its practically exploding. They have established a number of applications and they synthesized water and air-stable ionic liquids based on an imidazolium cation like 1-alkyl-3-methylimidazolium and also tetrafluoroborate or hexafluorophosphate as the anion, the second generation of ionic liquids can be seen in the above systems[17-25]. Even though they can usually be prepared and stored outside of an inert atmosphere, these properties can significantly change at long time exposure, the formation of HF for both[BF4]− and [PF6]− decompose in the presence of water. Toward keep away from such unwanted reactions with water, in recent years chemically stable anions and more hydrophobic anions have got considerable concentration, for example, bis(trifluoromethylsulfonyl)imide,[NTf2]− trifluoromethanesulfonate, [CF3SO3]−, etc. the third generation and majority of recent Ionic liquids make up of these anions. The observed toxicities and chemical structure of the ions have been highlighted by major relationship between them, even though the detail that, mostly because of their commercial accessibility, the large majority of the presented studies have an alert on the imidazolium cation with different anions like [BF4]−, [CF3SO3]−, [NTf2]− [PF6]−, etc. A clear clarity should be made, from the outset, solvents should be avoided when the common generalizations of ILs are either green or toxic together extremes are entirely misleading.

General Properties of Ionic Liquids

ILs physicochemical properties can be varied by the variety of suitable cations and anions. The specific applications were possible to optimize the ionic liquids. However, the water content of the IL and the purity of the substances can be significantly affected by the physicochemical properties. Determination of accurate properties of some ILs is a challenging task, because of their most ILs are hygroscopic.

Density

The main frequently measured property of ionic liquids is density, (ρ). The related volumetric properties of ionic liquid mixtures are required for theoretical calculations and many applicative aspects[26,27]. The classical and thermodynamic approach is used to relate and compute the equilibrium properties of these mixtures in exacting, their information is indispensable. Since, at this point of analysis, these properties are of excessive importance for testing the available theories of solutions and for the growth of new models for mixing behaviors, the information of volume of liquid mixtures is more important than the equivalent density values. For realistic purposes water is less dense than Ionic liquids in general; the density of the ionic liquids has a major effect on the molar mass of the anions. We have listed the densities of pure ILs and solvents at room temperature and atmospheric pressure from the IL thermo- data sources on the base of different alkyl chain lengths of imidazolium cations with a number of anions considerations as given in **Table 1.**

Table 1: Density, ρ of some pure ILs and solvents at T = 298.15 K and atmospheric Pressure

S. No.	Ionic Liquids/solvents	ρ^a /g·cm^{-3}
1	1-ethyl-3-methylimidazolium trifluoromethanesulfonate, [EMIM][CF3SO3]	1.3853
2	1-butyl-3-methylimidazolium trifluoromethanesulfonate [BMIM][CF3SO3]	1.2976
3	1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)-imide, [EMIM][NTf2]	1.5184
4	1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)-imide, [BMIM][NTf2]	1.4357
5	1-ethyl-3-methylimidazolium tetrafluoroborate, [EMIM][BF4]	1.2868
6	1-butyl-3-methylimidazolium tetrafluoroborate, [BMIM][BF4]	1.2029
7	2-Methoxyethanol (ME)	0.9650
8	2-Ethoxyethanol (EE)	0.9300
9	2-Propoxyethanol (PE)	0.9130
10	N-Methyl-2-pyrrolidone (NMP)	1.0300

Speed of Sound

The expandable probing and thermal properties of materials of Ultrasound is complementary to other dimension modalities. Speed of sound provides given information about through travels concentrated systems of particles, they are size, structure, distribution, compressibility, chemical and phase state, in the absence of air bubbles. Different physical properties for example of hardness, microstructure, size, elastic constant and residual stress etc, investigated by using a highly non-destructive technique it is called Velocimetry. The nature of molecular interactions and other physicochemical behavior of binary and ternary ILs solvent and solvent-solvent systems had been sufficiently employed by understanding [28-32].

To investigate ionic liquids-solvent mixtures, an only small amount of samples are required for the speed of sound making it a realistic technique[33]. Its mainframe is to send them through the test object in a beam of short bursts of energy and to generate the speed of sound vibrations. To reflect the vibrations back to the instrument in addition to the far side of the test object and any intervals in the path of the ultrasonic beam. They are some recurrent changes in electrical voltage occurring at an ultrasonic rate as sound waves are generated since it is beyond the audible range. At the higher frequencies, the Speed of sound waves behaves similarly to light waves. Ultrasound waves can be propagated to some extent in any expandable material. The traveling or propagation of the waves occurs as a displacement of the consecutive elements of the medium. Each element of material to go back to its original position after movement an expandable substance which as restoring force that tends to restore. To study the physicochemical properties of the liquid mixtures, liquids, polymeric and electrolytic solutions is the main significant and generally accepted technique[34-39].

A little information about the magnitude and nature of various interactions provide a Speed of sound, u data but when joint with density measurements, the resulting thermodynamic parameters, that is excess speed of sound, excess isentropic compressibility, isentropic compressibility, molar isentropic compressibility, isentropic compressibility deviations, excess molar isentropic compressibility give essential information regarding strength and nature of different ILs-solvent and solvent-solvent interactions accountable for the anion-cation performance in binary/ternary mixtures[40-45]. Gaining information on the dynamics of systems is useful for the Speed of sound and its derived parameters data. ILs and solvents occur in a physical nature of the solutions and their structural changes as denoted ILs-solvent systems. In the case of pure ILs, ILs-solvent, and solvent-solvent systems various literature reviews tell that the speed of sound was found to be decreased with an increase in temperature whereas increased with an increase in pressure[46-51].

Applications of Ionic Liquids

IL's have been used in many applications as solvents they are electrolytes in materials, catalytic processes, in organic synthesis, as reagents, in separation technology and electrochemistry being designed as green solvents.

Ionic Liquids in Solvents

The chemical industries require environmentally friendly green processes. In the field as good solvents[52]. ILs has attracted worldwide awareness. While they are nonflammable, non-volatile and are hygienic and safe solvents. They may be designed as either hydrophilic or hydrophobic[53]. To get higher yields and lower manufacturing cost[54] ,ionic liquids can be valuable tools as reaction media in chemical processes, such as in catalytic reactions like hydroxylation, bio-catalytic, hydroformylation, and enzymatic reactions. They are also known as innocent solvents because ionic liquids act as inert solvents without any chemical interaction with catalysts or reactants. The inert ions are observed present in the ionic liquid solvents, particularly feebly coordinating anions such as $[PF_6]^-$, $[NTf_2]^-$, $[BF_4]^-$, and cations do not synchronize with the catalysts or reactants[55].A longer alkyl chains on the imidazolium cation for examples1-butyl-3-methylimidazolium hexafluorophosphate and related ionic liquids.

Ionic liquid finds a source of hope in reducing the organic solvent waste in coming years. These Ionic liquids may replace the organic solvents which are hazardous, toxic, and non-environmentally friendly used in the synthesis of chemical compounds.

Ionic Liquids in Electrolytes

Low volatility for RTILs have been investigated as a substitute electrolyte medium and have been exposed to be very good media in an electrochemical process, the intrinsic conductivity, extensive electrochemical windows and their capability to solvate a wide variety of compounds[56]. ILs is considered as an excellent solvent media in electrochemical sensing, on understanding the reaction mechanisms and comparing behavior in conventional electrolyte systems. Electrochemical sensors are classified into three main types based on the development of a potential (potentiometric), measurement of a redox current (amperometric), or a change in resistance (conduct metric). Amperometric sensors contain typically two or three electrodes associated with an electrolyte medium. To replace conventional electrolyte systems in amperometric or potentiometric sensors RTILs have the ability and this topic is useful in many laboratory investigations. Even though this investigation is still in the early stage and the sensors based on RTIL are so far to be commercialized. Lu et al[57], who used a task-specific ionic liquid contained a [NTf2]- anion and a tetra-alkyl ammonium cation with one carbon chain functionalized with a carboxylic acid group in voltammetric sensing in grouping with bismuth oxide (Bi2O3) for the electrochemical recognition of heavy metal oxides including copper oxide (CuO), lead oxide(PbO) and cadmium oxide (CdO). Sunet et al[58] employed an ionic liquid ([Bmim][PF6])-based carbon(graphite) ion gel electrode for the voltammetric detection of hydroquinone.

Ionic Liquids in Catalysis

(a) Ionic Liquids in Enzyme Catalysis

The advantage of enzyme-mediated kinetic resolution in ionic liquids has been shown. Due to the high enzyme thermostability in ionic liquids when conducted at elevated temperatures. The advantages of increased activity unlike conventional organic solvents, the main use of enzymes and substrates in ionic liquids have shown. An extensive solubility of substrates and Selectivity or stability of the enzyme. In addition, enzyme immobilization has been developed to enhance enzyme activity and avoid deactivation. Ionic liquids include biocatalytic reactions such as conversion, alcoholysis, trans-esterification, oxidation, synthesis, hydrolysis, de-racemization, ammonolysis, epoxidation, resolution, reduction, and so on. Erbeldinger‟s group[59] was first reported the enzyme-catalyzed reaction in a pure ionic liquid. Epoxidation reactions, amidation and lipase-catalyzed trans-esterification, in ionic liquids were reported by Lau et al[60]. In enantioselective transformations, enzymes can play important roles on catalysts which are mainly prominent. In the year 2001, Schöfer et al[61] and Itoh et al[62] had introduced Pioneering examples such as enantioselective reactions using enzymes in ionic liquids and were demonstrated independently.

(b) Ionic Liquids in Homogeneous and Heterogeneous Catalysis

In modern chemistry to understand the nature of chemical reactions, Homogenous and heterogeneous catalysis is the most important reaction media[63]. The two main characteristics of ILs offer the advantages of both homogenous and heterogeneous catalysts as shown as (i) catalysts may also dissolve the IL.(ii) reactants and products may be immiscible with the ILs. The advantages of solid ILs combine the immobilizing of catalyst and the advantages for liquid is to allow the catalyst to travel liberally[64]. The IL also gives an opportunity to control reaction chemistry in ionic nature indicated by Maginn and Brennecke[3] whichever by stabilizing the highly polar or ionic transition states or participating in the reaction.

In clean polymerization, ILs are utilized[65], halogenations[66], nitration[67], sulfonation[68] Friedel Crafts alkylation[69], reduction of aromatic rings[70], oxidation[71], carbonization[72], etc. Lagrost et al[73] used imidazolium [Bmim][NTf2], [Bmim][NTf2], [Bmim][PF6] and ammonium [(C8H17)3NCH3][NTf2] these are different types of electrochemical reactions and they investigate the oxidation of organic molecules in ILs based on ionic liquids as a response media. The conventional organic media although the structure of molecular solvents and ILs are expected to be quite different. As compared with their results propose the nature of investigated mechanisms is almost unchanged in ILs.

Ionic Liquids in Polymer Science

In recent years ILs have been used as one of the most precious and fabulous applications in polymer science. Numerous types of polymerization processes, mainly use as polymerization media, including ordinary free radical polymerization[74], reversible addition-fragmentation transfer (RAFT)[14], living/controlling radical polymerizations[75-80], in addition to coordination and ionic polymerizations[81,82]. In traditional polymerization media, ILs in polymer science are not limited. Up to decomposition temperature, ionic liquids have excellent ionic conductivity. This is an advantage to electrolyte matrices to play an important role. Though solid or quasi-solid ion-conductive electrolytes are generally selected over fluidic materials from the point of view of eliminating leakage. So, it is fashionable to change IL-based electrolyte solutions into a solid or quasi-solid form. Polymerization of methyl methacrylate (MMA) in 1-butyl-3-methylimidazolium hexafluorophosphate, ([BMIM][PF6]) explained by Li et al[83]. Up to 260^0 C the resulting polymer gels exhibited admirable thermal stability. To increase the ratio of room temperature ionic liquid to the polymer matrix, the glass transition temperature will be decreased. Polymerization of room temperature ionic liquid, 1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonyl)- imide, ([EMIM][NTf2]) with vinyl monomers (such as vinyl acetate, MMA, acrylonitrile, styrene, 2-hydroxyethyl methacrylate, methyl acrylate, and acrylamide) to prepare a series of polymer composites by Noda and Watanabe[84].

Ionic Liquids in Food and Bio-products Industries

As low cost, high sensitivity, and high-efficiency food analysis methods are still essential for quantification and determination of compounds of attention by food legislation. In this process, ILs using food analysis have gained significance, as generally for the determination of amount-limited compounds or non-desirable. Researchers have been focused on the case of some preservatives, such as antibiotics, dyes, heavy metals, and herbicides. In food analysis in extraction processes and also in solutions with ethanol or water are mostly used for 1-alkyl-imidazolium-based ILs. Especially for the determination of heavy metals and dyes have been mostly used in Fluorinated anions, for example, bis(trifluoromethyl sulfonyl)imide (NTf2-) tetrafluoroborate, (BF4-), hexafluorophosphate, (PF6-). 1-hexyl-3-methylimidazolium hexafluorophosphate ([Hmim][PF6]) is used for the determination of Safranin-T content in food matrices employed by Zhang et al[85]. The production of biodiesel from vegetable oils and bioethanol from sugar cane, ILs act an important role in the expansion of more “green” and efficient methods. To produce biodiesel from Jatropha oil reporting up to 93% of esterification rate by using 1-butyl-3-methylimidazolium tosylate ([Bmim][CH3SO3]) by Jiang et al[86]. Similarly, biodiesel production from soybean oil has been established as similar yields (93.2%) used by 3-(N,N,N-triethylamino)-1-propanesulfonic hydrogen sulfate by Zhang et al[87]. Further, a detailed review on the application of Ionic liquids in the food and bio-products industry was reported by Ariel *et al*[88].

Ionic Liquids in Solar Cells

With the rapid reduction of fossil fuels in addition to the unfortunate environmental problems of their combustion, there should be an immediate need, to develop alternative renewable energy sources. As well as demand for energy rising fast. To demand future generations, solar energy has to fulfill a crucial part of sustainable energy. As a low cost and substitute to conventional photovoltaic devices, nanocrystalline dye-sensitized solar cells (DSSCs) have been attracting more scientific and industrial attention. A distinctive DSSC has been prepared to a liquid electrolyte conventionally containing the iodide/triiodide redox couple to fill the pores of the films and contact nanoparticles and a dye coated mesoporous $TiO2$ nanoparticle film sandwiched between two conductive transparent electrodes. Ionic liquids have been easy solving the problems of liquid electrolytes. RTIL has been made of 1,3-dialkyl imidazolium cation has been included into poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) matrix and a perfluorinated anion such as ([BF4]-, [CF3SO3]-, [PF6]-) and to form free-standing RTIL polymer gel electrolytes for dual intercalating cells. In the presence of $TiO2$ and Pt nano-particles fluorinated polymers are photochemically stable. To prepare a polymer gel electrolyte for use in DSSCs by Wang et al[89] have been used to 1-methyl-3-propylimidazolium iodide and PVDF-HFP ionic liquids. Hydrophobic dye-coated nanocrystalline $TiO2$ electrodes were sandwiched with the counter electrodes and the space in between was filled with the ILs based electrolytes, for the manufacture of the photo-electrochemical cells. The maximum efficiency of polymer gel electrolyte-based DSSCs showed 74% at 540nm. The overall energy conversion yielded was 5.3% and do not depend more than on the light intensity.

Ionic Liquids in Fuel cells

A device that produces electricity through the redox reaction of molecules, researchers focused on developing eco-friendly energy sources and improving the environmental problems, a device is called a fuel cell. These releases zero amount of greenhouse gases from such a fuel cell. ILs are considered more and more while alternatives for conventional electrolyte materials in this method[90-92]. Even in a liquid state ILs propose the unique features of non-flammability and non-volatility at room temperature they show ionic conductivity of more than 10^{-2} $S{\cdot}cm^{-1}$ for close to the fuel cell applications levels[93,94]. Based on perfluorinated ionomer and IL, a proton-conducting membrane was demonstrated by Doyle et.al[95]. At more than 100°C Proton-conducting membranes for example Nafion suffers from the volatility of water. Proton conductivity decreases when the temperature is above 130°. Owing IL contains to non-volatility nature, in a transporting proton it works as a thermal stable solvent. At 180°C 1-butyl-3-methylimidazolium trifluoromethane sulfonate containing membranes study, that has been demonstrated to have an ionic conductivity of more than 0.1 $S{\cdot}cm^{-1}$. The ionic conductivity of proton-conducting membranes affects the size and the connectivity of the ionic clusters. Nafion membranes containing hydrophobic ILs exhibited a lesser ionic conductivity than those of the membranes containing hydrophilic ones.

Ionic Liquids in Lubricants

The distinctive properties of ionic liquids such as tremendously wide liquids range, high thermal stability, good flame resistance, and low vapor pressure make interesting candidates for their use as lubricants. In the green chemistry field, it is clear that a lubricant with improved lubrication properties leads to inferior energy consumption in the equivalent mechanical application by just dropping energy losses by friction. Furthermore, as all the material protected by a superior lubricant has a longer life span, raw materials that are necessary to replace corroded parts of the machinery and superior lubrication helps to save energy. Ionic liquids show very good wear and friction manners with various metal-metal combinations reported by Liu et al[96]. They choose [Hmim][BF4] as the ionic liquid in the technique to investigate the friction and wear manners is the ball-on-disc tribometer. The results demonstrate a steel-steel contact measurement by means of [Hmim][BF4] so as to obtain using an SRV (OPTIMOL) tester. The majority remarkable results of these studies, even phosphazene and perfluoropolyether lubricants which are known as high-performance lubricants, the group has found that [Hmim][BF4] and [C2C6im][BF4] shows with steel-steel contact inferior friction coefficients. An additional study, under vacuum conditions they reported[97] lower friction coefficients for three ionic liquids 1, 3-dialkyl imidazolium hexafluorophosphates ([Hmim][PF6], [C2C6im][PF6] and [C3C6im][PF6]) compared with a liquid paraffin lubricant activated with ZDDP (zinc dithiophosphates). These results indicate obviously that the extremely attractive tribological properties of ionic liquids are not only due to the formation of fluorinated surface species other than as well have to be credited to the nature of the couloumbic interactions in the lubricating film.

Ionic Liquids as Antistatic agents

Ionic liquids can be added to resins to act as antistatic agents. They can be employed in high-temperature operations since they are non-volatile and heat-resistant. They also have a high degree of transparency and are resistant to environmental (humidity) conditions. The structure of an ionic liquid is optimized and its compatibility with the target resin is adjusted to maintain resin transparency. The use of a modest amount of ionic liquid results in excellent antistatic performance. The main reason for IL's to have antistatic properties are Conductivity, Thermal stability, Ultra-low vapour pressure, Non-flammability, Good miscibility with a wide range of monomers and polymers, Transparency, Hydrophobicity.

In recent times, ILs have been evaluated as antistatic additives to a variety of plastics, with results showing a 100-fold reduction in surface resistance. For example, the usage of [Bmim] [BTA] in poly(methylmethacrylate) (PMMA) not only reduced electrostatic charge but also improved transparency, which is critical because PMMA is utilized in optical fibers.[98] Polyurethanes were also made using the same IL.[99,100] Ionic liquids can also be kneaded into polycarbonate resins and give good flame resistance. N1444 BTA, for example, performed well in polycarbonate (PC),[101].

Conclusion:

The authors successfully summarized various applications of Ionic liquids in the fields such as use as solvents in various industries, electrolytes, heterogeneous catalysis, solar cells, fuel cells, polymer industry, food & Bioproducts, lubricants. The review will provide all the basic information of general properties of IL's and provide basic knowledge for researchers who are begun to work with Ionic Liquids. However, some drawbacks with ionic liquids in respect to toxicity, preparation, and high cost in the process for use.

References:

1. Freemantle M. 1998. Designer solvents, Ionic Liquids may Boost Clean Technology Development. *Chem. Eng. New.s*, **76:** 32-37.
2. Wilkes J.S., Wasserscheid P., Welton T. 2008. Ionic Liquids in Synthesis, Wiley-VCH Verlag GmbH & Co., 2nd Ed.
3. Brennecke J.F., Maginn E.J. 2001. Ionic liquids: Innovative Fluids for Chemical Processing. *AIChE J.*, **47:** 2384-2389.
4. Hapiot P., Lagrost C. 2008. Electrochemical Reactivity in Room Temperature Ionic Liquids. *Chem. Rev.*, **108:** 2238-2264.
5. Welton T. 1999. Room-Temperature Ionic Liquids. Solvents for Synthesis and Catalysis, *Chem. Revs.*, **99:** 2071-2084.
6. Zhao D., Wu M., Kou Y., Min E. 2002. Ionic Liquids: Applications in Catalysis. *Catal. Today,* **74:** 157-189.
7. Zhou F., Liang Y., Liu W. 2009. Ionic Liquid Lubricants: Designed Chemistry for Engineering Applications. *Chem. Soc. Rev,* **38**: 2590-2599.
8. Davis J.J.H. 2004. Task-Specific Ionic Liquids. *Chem. Letters*., **33:** 1072-1077.
9. Hajipour A., Rafiee F. 2009. Basic Ionic Liquids. A short review. *J. Iranian Chem. Soc.,* **6:** 647-678.
10. Greaves T.L., Drummond C.J. 2008. Protic Ionic Liquids: Properties and Applications. *Chem. Rev.*, **108:** 206-237.
11. Newington I., Arlandis J.M.P., Welton,T. 2007. Ionic Liquids as Desiner Solvents for Nucleophilic Aromatic Substitutions. *Org. Lett.*, **9:** 5247-5250.

12. MacFarlane D.R., Pringle J.M., Howlett P.C., Forsyth, M. 2010. Ionic Liquids and reactions at the electrochemical interface. *Phys. Chem. Chem. Phys.,* **12:** 1659-1669.
13. Rogers R.D., Seddon K.R. 2003. Chemistry. Ionic Liquids-Solvents of the Future? Science, **302:** 792-793.
14. Ye C., Liu W., Chen Y., Yu L. 2001. Room Temperature. *Chem. Commun.,* **7:** 2244-2245.
15. Wilkes J.S. 2002. A Short History of Ionic Liquids-from Molten Salts to Neoteric Solvents. *Green Chem***.,** **4(2):** 73-80.
16. Walden, P., Bull. 1914. Molecular weights and electrical conductivity of several fused salts. *Acad. Imper. Sci***.,** **1:** 1800.
17. Nardi J. C., Hussey L., King L.A. 1978. AlCl3 /1-alkyl pyridinium chloride room temperature electrolytes, U.S. Patent 4 122 245.
18. Mamantov G., Murphy D.W., Broadhead J., Steele B.C.H. (Eds.), 1980. Materials for Advanced Batteries. Plenum Press, New York, 111.
19. Dupont J., Brazilian J. 2004. On the Solid, Liquid and Solution structural organization of imidazolium Ionic Liquids. *Chem. Soc.,* **15:** 341-350.
20. Gorman J. 2001. Green Chemistry Controls Environmental Pollution by using a Variety of Green Alternatives to Conventional methods. *Science News,* **160:** 156-158.
21. MacFarlane D.R., Meakin P., Sun J., Amini N., Forsyth M.J. 1999. *J. Phys. Chem.B,* **103:** 4164-4170.
22. Ito K., Nishina N., Ohno H. 2000. Enhanced Ion Conduction in imidazolium–Type Molten Salts. *Electrochim. Acta,* **45(8):** 1295-1298.
23. Garcia M.T., Gathergood N., Scammells P.J. 2005. Biodegradable ionic liquids. *Green Chem***.,** **7:** 9-14.
24. Tao G.H., He L., Sun N., Kou Y. 2005. New generation Ionic Liquids; cations Derived from Amino acids. *Chem. Commun***.,** **28:** 3562-4.
25. Yang Q., Dionysiou D.D. 2004. Photolytic Degradation of Chlorinated Phenols in room Temperature Ionic Liquids. *J. Photochem.. Photobiol. A: Chem.,* **165:** 229-240.
26. Stoppa A., Zech O., Kunz W., Buchner R. 2010. The conductivity of imidazolium based Ionic Liquids from (-35 to 195) c. A Variation of Cations Alkyl Chain. *J. Chem. Eng. Data,* **55:** 1768-1773.
27. Almeida H.F.D., Lopes J.N.C., Rebelo L.P.N., Coutinho J.A.P., Freire M.G., Marrucho I.M. 2016. Densities and Viscosities of Mixtures of two Ionic Liquids containing a common cation. *J. Chem. Eng. Data,* **61:** 2828-2843.
28. Kharakoz D.P., Sarvazyan A.P. 1993. Hydrational and intrinsic compressibilities of globular proteins. *Biopolymers,* **33(1):** 11-26.
29. Gekko K., Yamagami K. 1991. Flexibility of food proteins as revealed by compressibility. *J. Agric. Food Chem.,* **39(1):** 57-62.
30. Kharakoz D.P. 2000. Protein compressibility, dynamics, and pressure. *Biophys. J.,* **79(1):** 511-525.
31. Zafarani-Moattar M.T., Cegincara R.M. 2007. Viscosity, Density, Speed of Sound, and Refractive Index of Binary Mixtures of Organic Solvent + Ionic Liquid, 1-Butyl-3-methylimidazolium Hexafluorophosphate at 298.15 K. *J. Chem. Eng. Data,* **52:** 2359-2364.
32. Roy M.N., Sarkar B.K., Chanda R. 2007. Viscosity, Density, and Speed of Sound for the Binary Mixtures of Formamide with 2-Methoxyethanol, Acetophenone, Acetonitrile, 1,2-Dimethoxyethaane, and Dimethylsulfoxide at Different Temperatures. *J. Chem. Eng. Data,* **52:** 1630-1637.
33. Chalikian T.V. 2003. Volumetric properties of Proteins. *Annu. Rev. Biophys. Biomol. Struct.,* **32:** 207-235.
34. Riyazuddeen, T., Altamash, T. 2009. Ultrasonic Velocities and Densities of L-Histidine or L-Glutamic Acid or L-Tryptophan or Glycylglycine + 2 mol·L^{-1} Aqueous KCl or KNO_3 Solutions from (298.15 to 323.15) K. *J. Chem. Eng. Data.,* 54, 11, 3133–3139.
35. Riyazuddeen, S., Afrin, 2010. Ultrasonic Velocities and Densities of L-Phenylalanine, L-Leucine, L-Glutamic Acid, and L-Proline + 2 mol ·L-1 Aqueous NaCl and 2 mol ·L-1 Aqueous NaNO3 Solutions from (298.15 to 328.15) K. *J. Chem. Eng. Data***.,** **55:** 2643-2648.

36. Riyazuddeen. Basharat R. 2006. Intermolecular/interionic interactions in 1-isoleucine-,1-proline-,and 1-glutamine-aqueous electrolyte systems. *J. Chem. Thermodyn.*, **38(12):** 1684-1695.
37. Riyazuddeen. Bansal G.K. 2006. Intermolecular/interionic interactions in 1-leucine-,1-asparagine-,and glycylglycine-aqueous electrolyte systems. *Thermochim. Acta*., **445(1):** 40-48.
38. Riyazuddeen. Khan I. 2009. Effecct of KCl and kno3 on partial molal volumes and partial molal compressibilities of some amino acids at different temperatures. *Int. J. Thermophys*., ***30(2)*:** 475-489.
39. Santosh M.S. Bhat D.K., Bhat A.S. 2009. Molecular interactions in Glycylglycine –Mncl2 Aqueous solutions at (288.15, 293.15, 303.15, 308.15, 313.15, and 318.15)k. *J. Chem. Eng. Data*., **54(10):** 2813-2818.
40. Dubey G.P., Kaur P. 2013.Thermodynamic and spectral investigations of binary liquid mixtures of 2- butoxy ethanol with alcohols at temperature range of 293.15-313.15 k. *Fluid Phase Equilib*., ***354*:** 114-126.
41. Sanguri V., Dwivedi D.k., Singh N., Pandey N. Pandey J.D. 2008. Thermodynamic properties of multicomponent systems and hole theory. *J. Mol. Liq.*, **141:** 1-7.
42. Musiał M., Zorebski E., Rybczynska M.G. 2015. Is there any sense to investigate volumetric and acoustic properties of more binary mixtures containing ionic liquids?. *J. Chem. Thermodyn.*, **87:** 147-161.
43. Zorębski E., Dec E. 2012. Speeds of sound and isentropic compressibilities for binary mixtures of 1,2-ethanediol with 1-butanol, 1-hexanol, 1-octanol in the temperature range fom 293.15 to 313.15 k. *J. Mol. Liq.*, **168:** 61-68.
44. Dzida M., Zorębski E., Zorębski M., Żarska M., Geppert-ybczyńska M., Chorążewski M., Jacquemin J., Cibulka I. 2017. Speed of Sound and Ultrasound Absorption in Ionic Liquids. C*hem. Rev.* **117(5)**: 3883–3929.
45. Singh S., Aznar M., Deenadayalu N. 2013. Densities, speeds of sound, and refractive indices for binary mixtures of 1-butyl-3-methylimidazolium methyl sulphate ionic liquid with alcohols at T=(298.15, 303.15, 308.15, and 313.15) k. *J. Chem. Thermodyn.*, **57:** 238-247.
46. Dagade D.H., Shinde S.P., Madkar K.R., Barge S.S. 2014. Density and sound speed study of hydration of 1-butyl-3-methylimidazolium based amino acid ionic liquids in aqueous solutions. *J. Chem. Thermodyn.*, **79:** 192-204.
47. Reddy M.S., Khan I., T.K., Raju S.S. Suresh P., H. Babu, B. 2016. The study of molecular interactions in –ethyl-3-methylimidazolium trifluoro methanesulfonate + 1-pentanol from density, speed of sound and refractive index measurements. J. *Chem. Thermodyn.*, **98:** 298-308.
48. Abildskov J., Ellegaard M.D., O‟Connell J.P. 2010. Densities and isothermal compressibilities of ionic liquids- Modeling and application. *Fluid Phase Equilib.*, ***295*:** 215-229.
49. Krolikowska M., Hofman T. 2012. Densities, isobaric expansivities and isothermal compressibilities of the thiocyanate-based ionic liquids at temperatures (298.15–338.15 K) and pressures up to 10 Mpa. *Thermochim. Acta*, **530:** 1- 6.
50. Dzida M., Chorązewski M., Rybczynska M.G., Zorębski E., Zorębski M., Zarska M., Czech B. 2013. Speed of Sound and Adiabatic Compressibility of 1-Ethyl-3-methylimidazolium Bis(trifluoromethylsulfonyl)imide under Pressures up to 100 Mpa. *J. Chem. Eng. Data.*, **58:** 1571-1576.
51. Rybczynska M.G., Sitarek M. 2014. Acoustic and Volumetric properties of Binary Mixtures of ionic Liquid 1-Butyl-3-methylimidazolium Bis(trifluoromethylsulfonyl) imide with Acetonitrile and Tetrahydrofurann. *J. Chem. Eng. Data*, **59:** 1213-1224.
52. Earle M.J., Esperance S.S., Gilea M.A., Lopes J.N.C., Rebelo L.P.N., Magee J.W., Seddon K.R., Widegre J.A. 2006**.** The distillation and volatility of ionic liquids. *Natur.*, **439:** .831-834.
53. Murugesan S., Wiencek J.M., Ren R.X., Linhardt, R.J. 2006. Benzoate-based room temperature ionic Liquids –Thermal properties and glycosaminoglycan dissolution. *Carbohydrate Polymers*, **63:** 268-271.
54. Armstrong D.W., He L., Liu Y.S. 1999. Examination of Ionic Liquids and their interaction with molecules ,when used as stationary phases in gas chromatography. *Anal. Chem*., **71:** 3873-6.
55. Wasserscheid P. Schulz P. 2008. “Ionic Liquids in synthesis”, 2nd edn., *Wiley-VCH, Weinheim*, ***2*:** 369.

56. Buzzeo M.C., Evans R.G., Compton R.G. 2004. Non- Haloluminate Room –Temperature ionic Liquids in electrochemistry-A Review. *Phys. Chem. Chem. Phys.*, **5(8):** 1106-1120.
57. Lu D., Shomali N., Shen A. 2010. Task specific ionic liquid for direct electrochemistry of metal oxides. *Electrochem. Commun.*, **12:** 1214-1217.
58. Sun X., Hu S., Li L., Xiang J., Sun W. 2011. Sensitive electrochemical detection of hydroquinone with carbon ion gel electrode based on BMIMPF6 *J. Electroanalytical Chem*., **651:** 94-99.
59. Erbeldinger M., Mesiano A.J., Russell A.J. 2000. Enzymatic catalysis of formation of Z-aspartame in ionic liquid – An alternative to enzymatic catalysis in organic solvents. *Biotechnol. Prog*., **16:** 1129-1131.
60. Lau R.M., van Rantwijk F., Seddon K.R., Sheldon K.A. 2000. Lipase-catalyzed reactions in ionic liquids. *Org. Lett*., **2:** 4189-4191.
61. Schofer S.H., Kaftzik N., Wasserscheid P., Kragl U. 2001. Enzyme catalysis in ionic liquids: lipase catalyzed kinetic resolution of 1-phenyl ethanol with improved enantioselectivity. *Chem. Comm*., 425-426.
62. Itoh T., Akasaki E., Kudo K., Shirakami S. 2001. Lipase-catalyzed enantioselective acylation in the ionic liquid solvent system: reaction of enzyme anchored to the solvent. *Chem. Lett.*, **30:** 262-263.
63. Dupont J., Fonseca G.S., Umpierre .P., F.P., Fichtner P., Teixeira S.R. 2002. Transition-metal nanoparticles in imidazolium ionic liquids: recyclable catalysts for biphasic hydrogenation reactions. *J. Am. Chem. Soc.* **124:** 4228-9.
64. Morland, R.2001. Am. Chem. Soc. Div. *Industr. Eng. Chem.*, in: Proceedings of the 221st Am. Chem. Soc. National Meeting, San Diego.
65. Robin, Rogers D., Kenneth, Seddon R. 2003. Ionic Liquids as Green Solvents. *ACS Symposium Series.*, **856: DOI:** 10.1021/bk-2003-0856.fw001.
66. Earle, M.J., Katdare, S.P.World Patent WO 2002030852 **(2002)**.
67. Earle, M.J., Katdare, S.P.World Patent WO 2002030865 **(2002)**.
68. Earle, M.J., Katdare, S.P.World Patent WO 2002030878 **(2002)**.
69. Wasserscheid P. 2003. Potential to Apply Ionic Liquids in Industry. Kluwer Academic Publishers, Dordecht, 29-47.
70. Ota E. 1987. Some Aromatic Reactions Using $AlCl_3$-Rich Molten Salts. *The Electrochem. Soc*., 134: C512. (*Proc. Vol.* **1987-7** 1002).
71. Earle M.J., Katdare S.P. 2002. World Patent WO 2002030862.
72. Nemeth T., Bricker L., Holmgren C.J., Monson S.J., Lyle E. 2001. *US Patent* 628828.
73. Lagrost C., Carriei D., Vaultier M., Hapiot P. 2003. Reactivities of Some Electrogenerated Organic Cation Radicals in Room-Temperature Ionic Liquids: Toward an Alternative to Volatile Organic Solvents?. *J. Phys. Chem. A***.** **107:** 745-752.
74. Zhang H., Hong K., Mays J.W. 2002. Synthesis of Block copolymers of Styrene and Methyl Methacrylate by conventional Free Radical Polymerization in Room Temperature Ionic Liquids". *Macromol*. **35:** 5738-5741.
75. Sarbu T., Matyjaszewski K. 2001. ATRP of Methyl Methacrylate in the Presence of Ionic Liquids with Ferrous and Cuprous Anions. *Macromol. Chem. Phys.,* **202:** 3379-3391.
76. Ding, S., Radosz M., Shen Y. 2005. Ionic Liquid Catalyst for Biphasic Atom Transfer Radical Polymerization of Methyl Methacrylate. *Macromolecules*. **38:** 5921-5928.
77. Shen Y., Ding S. *2004.* Catalyst separation in atom transfer radical polymerization. *Prog. Polym. Sci.,* **29:** 1053-1078.
78. Biedron T., Kubisa P. 2003. Ionic liquids as reaction media for polymerization processes: atom transfer radical polymerization (ATRP) of acrylates in ionic liquids. *Polym. Int.*, **52:** 1584-1588.
79. Biedron T., Kubisa P. 2002. Atom transfer radical polymerization of acrylates in an ionic liquid: Synthesis of block copolymers. *J. Polym. Sci. Part A: Polym. Chem.,* **40:** 2799-2809.
80. Biedron T., Kubisa. P. 2001. Atom-Transfer Radical Polymerization of Acrylates in an Ionic Liquid. *Macromol. Repid. Commun*., 22: 1237-1242.

81. Perrir S., Davis T.P., Carmichael A.J., Haddleton D.M. 2002. First report of reversible addition-fragmentation chain transfer (RAFT) polymerization in room temperature ionic liquids. *Chem. Commun*., 2226-2227.
82. Chiefari J., Chong Y.K., Ercole F., Krstina J., Jeffery J., Lee TPT., Mayadunne, R.T.A., Meijs, G.F., Moad, C.L., Moad, G., Rizzardo, E., Thang, S.H. 1998. Living free-radical polymerization by reversible addition - Fragmentation chain transfer: The RAFT process. *Macromolecules*, 31(16): 5559-5562.
83. Li Z., Jiang J., Lei G., Gao D. 2006. Gel polymer electrolyte prepared by in situ polymerization of MMA monomers in room temperature ionic liquid. *Polym. Adv. Technol*., **17:** 604-607.
84. Susan M.A., T. Kaneko T., Noda A. Watanabe A.M.. 2005. Ion Gels Prepared by in Situ Radical Polymerization of Vinyl Monomers in an Ionic Liquid and Their Characterization as Polymer Electrolytes. *J. Am. Chem. Soc*., **127:** 4976-4983.
85. Zhang, L., Wu, H., Liu, Z., Gao, N., Du, L., Fu, Y. 2014. Ionic LiquidMagnetic Nanoparticle Microextraction of Safranin T in Food Samples. *Food Analytical Methods.,* **8:** 541-548.
86. Guo F., Fang F. Tian X.F., Long Y.D., Jiang L.Q. 2011. One-step Production of Biodiesel from High-acid Value Jatropha Oil in Ionic Liquids, Bioresource Technology. *Bioresour. Technol*.**,** **102:** 6469-6472.
87. Guo W., Li H., Ji G., Zhang G. 2012. Ultrasound-assisted production of biodiesel from soybean oil using Brønsted acidic ionic liquid as catalyst. *Bioresour. Technol*., **125:** 332-334.
88. Ariel A. C., Toledo Hijo, Guilherme J. Maximo, Mariana C. Costa, Eduardo A. C. Batista, Antonio J. A. Meirelles. 2016. Applications of Ionic Liquids in the Food and Bioproducts Industries. ACS Sustainable Chem. Eng., **4**: 5347−5369.
89. Wang P., Zakeeruddin S.M., Exnar I., Gratzel M. 2002. High efficiency dye-sensitized nanocrystalline solar cells based on ionic liquid polymer gel electrolyte. *Chem. Comm*., 2972-2973.
90. Ohno, H., Ed. Ionic Liquids: The Front, Future of Material Developments. *CMC*., Tokyo(2003).
91. Ohno, H., Ed. Ionic Liquid II: Marvelous Developments and Colorful Near Future. *CMC*, Publishing, Tokyo (2006).
92. Armand M., Endres F., MacFarlane D.R., Ohno H., Scrosati B. 2009. Ionic-liquid materials for the electrochemical challenges of the future. *Nat. Mater*., **8:** 621-629.
93. Hagiwara R., Ito Y. 2000. Room temperature ionic liquids of alkyl imidazolium cations and fluoroanions. *J. Fluorine Chem*., **105:** 221-227.
94. Xu W., Angell C.A. 2003. Solvent-free electrolytes with aqueous solution-like conductivities 2003. *Science*, **302:** 422-5.
95. Doyle M.,S. Choi K., and Proulx G. 2000. High-Temperature Proton Conducting Membranes Based on Perfluorinated Ionomer Membrane-Ionic Liquid Composites. *J. Electrochem. Soc*, 147: 34-37.
96. Chengfeng Ye., Weimin Liu, Yunxia Chen, Laigui Yu. Room-temperature. Chem. Commun., 2001, 2244-2245
97. Wang H., Lu Q., Ye C., Liu W. 2001. Tribological performance of phosphonium based ionic Liquids for an aluminum-on-steel system and opinions on lubrication mechanism. *Wear.* **261:** 1174-1179.
98. Tsurumaki A., Tajima .S., Iwata, T., Scrosati B., Ohno H. 2017. Evaluation of ionic liquids as novel antistatic agents for polymethacrylates. Electrochim,. Acta**. 248:** 556-561.
99. Tsurumaki A., Tajima S., Iwata T., Scrosati B., Ohno H. 2015. Antistatic effects of ionic Liquids for polyether based polyurethanes. Electrochim. Acta **175:** 13-17.
100. Iwata T., Tsurumaki, A., Tajima S., Ohno H. 2013. Bis(trifluoromethanesulfonyl)imide-Type Ionic Liquids as Excellent Antistatic Agents for Polyurethanes. *Macromol. Mater. Eng*.**, 299:** 794-798.
101. Xing C., Zheng X., Xu L., Jia J., Ren J., Li Y. 2014. Toward an optically Transparant, Antieletrostatic,and Robust polymer composite: Morphology and properties of polycarbonate /ionic Liquid composites. *Ind. Eng. Chem. Res.* **53:** 4304-4311.