A Review on Dicatonic Ionic Liquids: Classification and Application

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Abstract

Dicatonic ionic liquids are attractive new group of ionic liquids that acquire higher melting point, wider liquid range and better thermal stability. However, the exploration made on the utilization of these dicatonic ionic liquids in any application is still limited. To the best of the author’s knowledge, this is the first review article that discuss about this new type of ionic liquids. This review describes about ionic liquids in general and gives a survey on the latest developments and progress concerning dicatonic ionic liquids, from their classifications and properties to their employment in many applications.

Keywords: Dication; Ionic liquids; Geminal; Symmetrical; Asymmetrical; Heteroanionic; Synthesis

Introduction

Ionic liquids (ILs) are one of the most rapidly growing areas of chemistry research on new materials investigated in the last decade. Conventionally, ILs are entirely made by cation and anion that has melting point lower than 100°C. Therefore, they usually appear as liquid under ambient condition. They are alternatives to hazardous and volatile materials owing to their unique physicochemical properties such as higher thermal stability, simple recovery process and negligible vapour pressure that eliminate problem associated with volatility and flammability [1,2]. In addition, they are often labeled as “designer solvent”, as their properties, such as polarity, hydrophobicity, solvating activity, density, melting point, viscosity and others, can be tuned to some extent by changing the cation, anion or alkyl substituents on the cation [3-5]. Figure 1 illustrates common cations and anions used to form ILs.

ILs have been widely explored in the various inter-disciplinary research areas in the field of organic synthesis, catalysis, biocatalysis, material science, separation process, sensoristics, chemical engineering, medicine, green chemistry and electrochemistry [6-10]. The synthesis of ILs can be split into two steps [11,12]: a) Formation of desired cation: The desired cation can be synthesized either through quaternization reactions of amine with a haloalkane, by the protonation of the amine or geminal dicationic ILs can be synthesized joining two same cation candidates such as imidazolium or pyrrolidinium, which may contain cyclic or aliphatic chain, via either a rigid or a flexible spacer. Common spacer is an alkyl chain. Then, it is followed by second step of reaction of anion exchange. Some examples of symmetrical dicatonic ILs are shown in Figure 2. They represent several advantages over the traditional monocationic ILs in term of thermal stability and volatility, as well as tenability of physical and chemical properties [13]. Therefore, they have good potential to be used as lubricants, solvents for high-temperature uses, gas chromatography stationary phases, separation media and catalyst for esterification and transesterification reactions [14,15].

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In 2005, Armstrong and co-workers [16] studied structure and properties relationship by synthesizing 39 imidazolium-based and pyrrolidinium-based dicationic ILs. The head groups were linked with an alkyl chain (from 3 to 12 carbons long) and hence reacted with four different traditional anions (Br, NTf₂, BF₄, and PF₆). The thermal stability of these ILs in the range of -4 to +40°C, are found to be greater than those of most traditional monocationic ILs. Besides that, a decrease in melting point was observed when longer alkyl chains were used as spacer, which might be due to an increase in the number of closely related configurational states and possibly crystalline polymorphs for these ILs. In contrast, the density of the ILs decreased with increasing alkyl chain. However, the length of the alkyl chain did not give a significant effect on surface tension of the ILs. Instead, the increase of length of the substituted alkyl group on the imidazolium rings resulted to a decrease of the surface tension of the ILs. While the solubility of these dicationic ILs in water and heptane tend to be similar to those of the monocationic ILs, except for one case in which the dication was very hydrophobic.

In 2007, Zhang and co-workers [17] synthesized 17 ammonium-based symmetric imidazolium ILs by reacting tetramethylethylenediamine, tetramethylpropylendiamine or tetramethylhexylenediamine with 3 equivalent mole of 1-alkylbromide by using acetone as solvent in an ice bath for 24 h. It was then followed by anion exchange with LiNTf₂ at room temperature for 24 h to form dication ILs containing double NTf₂ anions. The compound was precipitated as solid or phase separated as liquid, depending on the compound species. All the prepared dication ILs were found to be miscible in dichloromethane, in 99.7% ethanol (w/w) and in acetone. But, they were immiscible in diethyl ether and water. These dicationic ILs exhibited five different types of phase transition behaviour on heating, but they showed one stage decomposition behaviour, at a decomposition temperature range of 340-420°C. Besides that, these dicationic ILs undergo exothermic decomposition, opposed from traditional ammonium-based monocationic ILs that undergo endothermic decomposition.

In 2011, Shirota and co-workers [18] compared the properties of imidazolium-based monocationic and dicationic ILs with four anions (NTf₂, NPF₆, BF₄, and NO₃). The properties are liquid density, shear viscosity, surface tension and thermal properties such as melting point, glass transition temperature and decomposition temperature. By using the same type of anion and cation with the corresponding alkylene linker/alkyl group, the noticeable features of physical properties of the dicationic ILs compared to those of monocationic ILs are: higher density, higher glass transition temperature and melting point, higher thermal stability, larger surface tension and higher shear viscosity. In the same study, the properties of the ILs were also compared with the reference alcohols. Throughout the study, they found that the alkyl-chain-length effect on the liquids density and surface tension in the dicationic ILs were qualitatively similar to that in the alkanediols, except for the shear viscosity.

Until now, all the discussed symmetrical or geminal ILs contained short or intermediate length of substituted alkyl group on the head group in the range of 0 to 8 carbons long. The dications were simply prepared by reacting the alkyl chain (spacer candidate) with double equivalent mole of the head groups. In 2007, Ding and co-workers [19] synthesized an imidazolium-based dicationic IL containing substituted alkyl group of 14 carbons long. The synthesis process was different from the previous discussed study, where it was synthesized by elimination reaction of substituted quaternary ammonium salts. The synthesis process involves four consecutive steps as shown in Figure 3. The properties of the dicationic ILs was then compared with that of monocationic ILs with similar length of substituted alkyl group. It was found that the dicationic IL possessed higher thermal stability, lower critical micelle concentration (CMC) values and larger d-spacing of crystal structure than that of monocationic ILs. The solubility of both monocationic and dicationic ILs in nine different solvents were also investigated. It was found that both compounds were immiscible with low polarity solvents, such as toluene, cyclohexane, ethyl acetate and petroleum ether, but miscible in methanol, acetonitrile and chloroform. However, dicationic IL has lower solubility in aceton and water compared to that of monocationic IL. This might be due to more hydrophobic nature of dicationic IL.

Asymmetrical dicationic ionic liquids: Besides symmetrical or geminal dicationic ILs, asymmetrical dicationic ILs are another type of dicationic ILs which consist of different head groups of cation which are also attached via a spacer such as alkyl chain. This asymmetrical ILs can be said to have dual functionality as they have two different head groups. In 2008, Zhang and co-workers [20] synthesized two asymmetrical dicationic ILs based on both imidazolium and aliphatic ammonium as potential electrolyte additives applied to lithium secondary batteries. The asymmetrical dicationic ILs were synthesized by reacting methyl imidazole with either bromoethyl trimethyl ammonium bromide or bromopentyltrimethylammonium bromide, followed by anion exchange reaction with Li NTf₂ to get 1-(3-methylimidazolium-1-yl)ethene-(trimethylammonium) b[ bis(trifluoromethanesulfonyl)imide], MIC2N111-(NTf₂), in a form of white solid and 1-(3-methylimidazolium-1-yl)pentane (trimethyl ammonium) b[ bis(trifluoromethanesulfonyl)imide], MICS5N111-(NTf₂), in a form of light yellow liquid. The structure of the ILs are shown in Figure 4, with n=2,5. The thermal properties were studied and MIC2N111-(NTf₂) shows solid-liquid transition characteristics, while MICS5N111-(NTf₂) has one of the lowest solid-liquid transformation temperature among analogues, and thus belongs to the greatest thermally stable ILs [20].

In 2010, Chang and co-workers [21] synthesized seven various...
symmetrical and asymmetrical dicationic ILs which contain (µ-oxo) bis[trichloroferrate(III)] anions, and characterized with regards to their solubility in solvents, crystal structures, and thermal properties. All synthesized ILs were in a form of yellow solid at ambient temperature. The ILs were found to be soluble in polar solvents such as water and methanol. The dication affected the melting point of these ILs by following the order of triphenylphosphonium > pyridinium > imidazolium dications and symmetrical > asymmetrical dicationic ILs. Dicationic ILs with a ring-type head group would have higher melting points attributed to the added π-n stacking, while symmetrical ILs have higher melting points due to easier packing. Besides that, the anion exists in either a linear or a bent form, depending on the dications [22]. In the following year, Chang and co-workers [23] again synthesized various symmetrical and asymmetrical dicationic ILs, but contained tetrachlorocobaltate (II) or tetrachloromanganate (II) anions. The ILs containing tetrachlorocobaltate (II) anions were in the form of blue solid, while the ILs containing tetrachloromanganate (II) anions were in the form of white solids. In the study, same trend was found for dicationic effect on melting point and also the solubility of the ILs in methanol and water [23].

**Heteroanionic dicationic ionic liquids**

Heteroanionic dicationic ILs are symmetrical or asymmetrical (head groups) dicationic ILs that have one dication with 2 different anions. In 2010, Chang and co-workers [22] synthesized a series of heteroanionic asymmetrical dicationic ILs by bridging pyridine group with aromatic or aliphatic compounds via alkyl chain of 3 carbons long. The diamions were either PF6-/Br- or NTf2-/Br-. The synthesis of these dicationic ILs involves three steps which are: addition of alkyl chain spacer by reacting pyridine with 1,3-dibromopropane, anion exchange with aromatic or aliphatic compounds via alkyl chain of 3 carbons long.

Then, these heteroanionic dicationic ILs were characterized in term of solubility and thermal stability. These dicationic ILs were found to be miscible with water, methanol and ethanol, but immiscible with aceton, ethyl acetate, tetrahydrofuran, diethyl ether, chloroform and hexane. Besides that, these dicationic ILs are miscible with methanol/diethyl ether and methanol/ethyl acetate co-solvents. For thermal properties, the thermal stability of these dicationic ILs affected by different second head groups follow the increasing order of the following: ammonium < piperidinium < imidazolium < pyrrolidinium. While for the anion effect, the dicationic ILs containing PF6-/Br- has higher thermal stability than NTf2-/Br-, which is in contrast with previous homoanionic dicationic ILs finding. This might be due to higher nucleophilicity of bromide anion to attack electrophilic S=O double bond in NTf2- anion in initial weight loss step at elevated temperature [22,24,25].

**Application**

Currently, dicationic ILs are extensively investigated as potential candidates in many application and used as separation material and catalyst candidates. The following sections discuss about their application.

**Separation material**

Carbon dioxide, CO2, is a part of natural gas and is produced as fossil fuel and coal gasification product. The concentrated amount of CO2 will lead to pipeline corrosion, decrease in calorific value of the natural gas streams and thus contribute to global warming and climate change. Several methods of CO2 separation was explored including chemical looping, chemical and physical absorption, solid adsorption, cryogenic separation and membrane separation. Among all method, membrane separation technology possesses attractive features such as high energy efficiency, low capital cost, ability to be applied offshore, ease in development of membrane modules and environmental friendly. However, the conventional supported liquid membrane method face several drawbacks such as liquid evaporation, unstable selectivity and flux through membrane. Thus, ionic liquids which has negligible volatility become the main focus as an alternative for supported liquid membrane technology. From [26,27] Studies the application of monocationic imidazolium based supported ionic liquid membrane, SILM, and got high CO2/CH4 selectivity of 25-45 and 100-120, respectively. Shahkampour [28] applied dicationic imidazolium based SILM for CO2/CH4 separation and compared with monocationic imidazolium based SILM as reference. The results shows that the dicaticonic based SILM show lower values for CO2/CH4 permeability and selectivity than monocationic based SILM due to their higher viscosity. For this separation application, viscosity of the ILs are dominant factor compare to number of cation. Hence, in order to investigate the effect of number of cation, lower viscous dicationic ILs could be used such as PEG-functionalyzed dicationic ILs.

**Catalyst**

Hydrolysis: Hydrogen has high potential as energy carrier, with an energy density of three times higher than that of petroleum. It releases energy with high efficiency through electro-oxidation reaction in fuel cells, which allows an environmental friendly energy source as an alternative to toxic materials such as cadmium and nickel [29]. It can be stored in a form of molecular hydrogen in tanks and vessels, in a form of atomic hydrogen or in a form of hydride ion in protide compounds such as borohydrides. Sodium borohydride has attracted huge attention as potential hydrogen storage material as it is stable in dry air and easily handled [30]. The hydrolysis of sodium borohydride to form hydrogen could be executed through a catalytic decomposition as shown in Equation 1.

\[
\text{NaBH}_4 + 2\text{H}_2\text{O} \rightarrow \text{NaBO}_2 + 4\text{H}_2
\]

Chinnapan studied the application of pyridinium-based dicationic ILs, namely, 1,1'-hexane-1,6-diylbis (3-methylpyrindinium) tetrachloronickelolate ([C6(Mpy)2][NiCl4]], as catalyst. They started by screening between two types of metal halide anions which are [NCl4]- and [CoCl4]-, towards the hydrolysis reaction of sodium borohydride and compared with conventional nickel boron (NiB) [31]. They found that the newly synthesized ([C6(Mpy)2][NiCl4]] generate higher amount of hydrogen even though the nickel content was 7 times lower than the conventional NiB catalyst. The catalyst could be reused at least five times and provides 5048 ml hydrogen generation over 23 h [32]. Using homogeneous catalyst for hydrolysis process is beneficial for continuous hydrogen production but face drawback in term of difficulty to stop the reaction for the hydrogen supply on demand [30]. Hence, Chinnapan further utilized the ([C6(Mpy)2]][NiCl4]] catalyst by fabricating various form heterogenous catalyst such as PVDF (poly(vinylidene fluoride))-IL nanofer composite [33], PVDF(poly(vinylidene fluoride))-IL-PEG (polyethylene glycol)-EGDMA (ethylene glycol dimethacrylate) nanofer composites [34], IL-MWCNT (multiwalled carbon nanotubes) [35] and rGO (reduced graphene oxide)-IL-CuO (copper oxide) nanocomposites [36]. All form of IL-incorporated heterogenous catalyst showed outstanding
performance in generating hydrogen compared to naked ([C₆(Mpy)₂][NiCl₄]) catalyst. Their activation energy in the range of 37.86–46.1 kJ/mol were significantly lower than that of ([C₆(Mpy)₂][NiCl₄]) catalyst with activation energy of 67.81 kJ/mol. The activation energy of these heterogeneous catalyst are less than Cobalt (75 kJ/mol) and nickel (71 kJ/mol) [37], nickel powder (62.7 kJ/mol) [38], Ni-Co-B (62 kJ/mol) [39], Ru (56 kJ/mol) [2], Co₃O₄ (77.96 kJ/mol) [40], Pt/LiCoO₂ (70 kJ/mol) [41], Ru/Graphite (61 kJ/mol) [42], PAN/CoCl₂/CNTs (52.85 kJ/mol) [43] and Ni-Fe-B (57 kJ/mol) [44]. However, they are still higher than Pd-Ni-B (31.1 kJ/mol) [45] and Co-B-TiO₂ (30.93 kJ/mol) [46]. Apart from that, they are easily recovered and can be used multiple times, especially PVDF-IL-PEG-EGDMA nanofiber composites which can be reused at least 9 times with good catalytic activity.

**Biodiesel production:** Biodiesel is a fuel safe, renewable, non-toxic, biodegradable and much less contaminant for the environment than conventional diesel. The common synthetic route of biodiesel production is the transesterification of triglycerides (TG) and esterification of free fatty acid (FFA) with alcohol which is normally methanol or ethanol. Generally, strong alkali and acid are the most widely used catalyst for the process due to their high catalytic activity. However, they faces several drawbacks where the acid and base processes are often related to decay, emulsification problem and also hazardous to environment. Therefore, the environmental friendly ionic liquids became a good substitute. More importantly, their miscibility and solvation properties can be adjusted by simply altering the cation and anion that results to different polarity [48]. Their conspicuous potential in biodiesel field is obvious as reviews regarding the role of ionic liquids as catalyst, co-catalyst, solvents and deep eutectic solvents (DES) for biodiesel production keep increasing by year [49-54].

Above all, SO₃H-functionalized acidic ILs shows excellent performance and high yield of biodiesel as the sulfonic group is the active site that supply H⁺ for protonation of carboxylic group in the triglycerides or free fatty acids [55-58]. In 2011, Fang [59] synthesized a series of ammonium-based dicationic ILs with dialkylsulfonic group and HSO₄⁻ anion, and compare their performance as catalyst with monocationic ILs. The best dicatonic IL was N,N,N',N'-tetramethyl-N,N'-dipropylsulfonic acid ethylenediammonium hydrogen sulfate. They found that using dicationic IL as catalyst results to 11% increase of conversion (dicatonic IL: 95%, monocationic IL: 85%) at the condition of 70°C, 6 h, n(ethanol):n(oil):n(IL)=1.8:1:0.2. After that, Chang [60] improved the performance by altering the structure of ILs synthesized by Fang. They added long alkyl chain (C₆H₄) on the dication, resulting to 87% of conversion with 10 times lower amount of IL at a better reaction condition (60°C, 4 h, n(methanol):n(oil):n(IL)=1:8:1:0.2). However, the esterification towards the performance of ILs as catalyst, such that the mass transfer for reaction may increase.

Compare to acidic ionic liquids, basic ionic liquids are famous for being able to catalyzed transesterification reaction in a shorter time, even though with the requirement that the free fatty acids present in the feedstock should be as low as 0.5% to prevent saponification. For basic catalyzed reaction, OH⁻ anion is the active site as it will start attacking the methanol molecule by taking away H⁺, resulting to formation of methoxide ion (CH₂O⁻). This nucleophilic methoxide ion will then attack the carbonyl group to complete transesterification reaction. Several researchers synthesized imidazolium-based monocationic and dicationic basic ionic liquids as shown in Table 1 [5,14,61-66].

Based on the results in Table 1, the monocationic IL, 1-butylyl-3-methylimidazolium hydroxide, BMIMOH, were able to catalyzed transesterification reaction in a very short time (50-70 min) compared to monocationic acidic ILs (~6 h), except for reaction done by Zhou
[65] and Han [61] that require 8 h and 4 h to get high conversion, respectively. It is worth to note that the two reactions were done at far higher temperature (120°C and 150°C) compared to others (40-60°C). The longer reaction time taken by BMImOH to catalyze the reaction at high temperature could be explained by the instability of hydroxide basic ILs at high temperature.

In 2010, Liang [14] synthesized a series of dicationic hydroxide basic ILs for the production of biodiesel from Cottonseed oil, where bis-(3-methyl-1-imidazolyl)-ethylenedihydroxide (Et[MIm][OH]) was found to be the best catalyst. At the first reaction executed for 2 h, the conversion achieved 91%, [14] which is almost similar to conversion of reaction catalyzed by monocationic basic IL, 1-ethyl-3-methylimidazolium hydroxide in 50 min (90%) [62]. Even though the dicationic ILs take double the time taken by monocationic ILs to catalyze the reaction for the same conversion, the monocationic ILs with the same head group. Therefore, performance they did not compare the performance of their dicationic ILs with several monocationic ILs (with almost the same structure with the monocationic ILs) as catalyst are compared. In general, dicationic ILs as catalyst are also costly, toxic, complex, hardly acquired, volatile and corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Therefore, the green ionic catalyst faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Besides that, the traditional catalytic reaction faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Therefore, the green ionic catalyst faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Besides that, the traditional catalytic reaction faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Therefore, the green ionic catalyst faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Besides that, the traditional catalytic reaction faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Therefore, the green ionic catalyst faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68].

In general, using dicationic ILs improved the conversion of feedstock to biodiesel as it provides more active site for the reaction to happen. In addition, the separation and recovery of dicationic ILs are easier than monocationic ILs as many of dicationic ILs are in solid form, while monocationic ILs are in liquid form.

### Esterification of carboxylic acid: Esterification of carboxylic acid with alcohol or alkyl halides is one of the most fundamental and commonly employed reactions in chemistry. The esterification processes are extensively applied in industry for a variety of desired end-products such as fatty acids, paints, flavors, fragrances, monomers, polymers, plasticizers and medicinal agents [67]. Conventionally, esterification reaction are usually catalyzed by mineral acids, Bronsted acids, Lewis acids, ion exchange resins and zeolites. However, the traditional catalyst faces several drawbacks such as the mineral acids are extremely corrosive and require large effort in removal and neutralizing them with a huge amount of base at the end [68]. Besides that, the traditional catalyst are also costly, toxic, complex, hardly-acquired, volatile and difficult to be separated from products [69]. Therefore, the green ionic liquids received a great deal of attention as alternative catalyst. There are several researchers published papers regarding dicationic ILs as catalyst for esterification of carboxylic acid with alkyl halide or alcohol [70-73]. Table 2 (entries 4-6) simplify the results obtained by them. The table list the best ILs catalyst with the reaction conditions. However, they did not compare the performance of their dicationic ILs with monocationic ILs with the same head group. Therefore, performance of several monocationic ILs (with almost the same structure with the dicationic ILs) as catalyst are compared. In general, dicationic ILs
could catalyzed the esterification reaction at lower temperature (25-72°C) in a shorter time (18 min to 2.5 h) with satisfactory yield (91-93%) as compared to monocationic ILs (temperature 80-90°, time 2 h, yield 87-96%).

Conclusion

Even though, the first dicationic ILs were synthesized over 10 years ago, the utilization of these dicationic ILs for any application are still very less. However, compared to conventional monocationic ILs, dicationic ILs possess higher melting point, wider liquid range, and better thermal stability. The structure of dicationic ILs also can be tuned to become either homooionic or heterooionic symmetrical or asymmetrical dicationic ILs. Therefore more type of ILs with more functional group can be synthesized for a wider application area or even improved current application. However, the performance of these dicationic ILs in all application should be compared with monocationic ILs with the same head or structure in order to evaluate and prove the enhancement made by the dicationic ILs. Besides that, since many of the chemical reaction and separation processes used in industry require the use of a large amount of ionic liquids, the study on toxicity of these dicationic ILs should be taken into account. The number of recyclability also should be done in maximum to reduce the cost of production as a whole.

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