

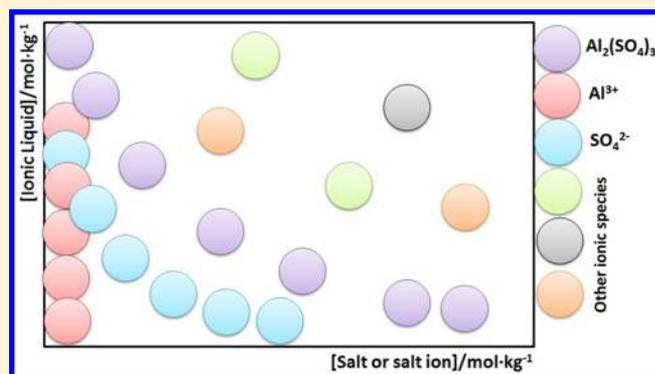
Effect of Polyvalent Ions in the Formation of Ionic-Liquid-Based Aqueous Biphasic Systems

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Supporting Information

ABSTRACT: Two main approaches were combined aiming at evaluating the impact of polyvalent salt cations on the formation of ionic-liquid-based aqueous biphasic systems (ABS): (i) experimental determination of a large array of ternary phase diagrams composed of sodium-, magnesium-, and aluminum-based salts with 1-butyl-3-methylimidazolium-based ionic liquids and (ii) determination of the ions speciation in each of these systems. The results here reported show, for the first time, that the phase behavior of ionic-liquid-based aqueous biphasic systems is not only dominated by the ability of the strong and “free” salting-out ions to interact with water creating thus hydration complexes but also a result of the interactions occurring between the different ions and, particularly, on their speciation in aqueous solutions. The gathered data indicate that the higher the salt ion valence, the more complex is its speciation with a number of different species in aqueous media present. Further results based on NMR spectroscopy and a proper analysis of the pH influence clearly demonstrated the impact of ion speciation through the phase separation and ABS formation.



1. INTRODUCTION

Aqueous biphasic systems (ABS) have received enormous attention because of their potential application for the extraction, separation, and/or purification of the most diverse biomolecules. In ABS the major component in each phase is water, and they are thus a mild physiological-like environment that prevents labile biomolecules from denaturation.¹ ABS are typically formed by two polymers, a polymer and a salt, or even two different salts in aqueous solutions; above a given concentration or temperature the mixture undergoes liquid–liquid demixing.² A number of different water-soluble polymers may be used as phase-forming components in ABS, with poly(ethylene glycol)s (PEGs), dextrans, and ficolls receiving the greatest attention.^{3–5} A wide range of applications for the polymer-based ABS in the separation of organic molecules, metal ions, and radiochemicals has been demonstrated.^{3–7} However, there are several drawbacks connected to polymer-based ABS, namely a high viscosity, and thus requiring a higher energetic input, and a limited range of polarities at their coexisting phases.^{8–11} For those reasons, there has been a large effort to find new alternatives to replace polymers as major constituents of ABS. In this context, ionic liquids (ILs) have been investigated as promising substitutes to hydrophilic polymers in ABS formulations.¹²

ILs are organic salts with melting temperatures below 100 °C.¹³ The bulky, and mostly asymmetric, cation prevents them to pack easily, unlike traditional salts, and hence leads to significantly low melting temperatures. The existence of IL-

based ABS was demonstrated by Rogers et al.¹⁴ by adding K_3PO_4 to an aqueous solution of 1-butyl-3-methylimidazolium chloride ($[C_4mim]Cl$), with formation of a biphasic system consisting of a $[C_4mim]Cl$ -rich upper phase and a K_3PO_4 -rich bottom phase. After this first impulse, numerous works describing different IL-based ABS have appeared in the literature in the past decade.¹² Those reports address not only a wide variety of ILs but also the use of various salting-out inducing salts,^{2,8,9,15–23} amino acids,^{24,25} carbohydrates,^{26–31} and polymers.^{32–35} The main advantage of using ILs in the creation of ABS lies in the fact that their polarities and affinities can be finely tuned by selecting a proper combination of cations and anions.¹¹ This feature is a major benefit of IL-based ABS given the difficulty of overcoming the limited polarity range of polymer-based ABS. In addition, compared to conventional polymer-based ABS, the coexisting phases of IL+ salt ABS are of lower viscosity³⁶ and are easily employed in chromatographic separation techniques.^{15,21} Subsequently, various application of IL-based ABS have been reported, especially concerning the extraction of target biomolecules, such as testosterone,⁸ penicillin G,^{16,37} amino acids,^{25,38–40} proteins,⁴¹ antioxidants,^{36,42} and alkaloids.^{15,31,43} IL-based ABS have also been applied in the extraction of small organic compounds from real and more complex samples/matrices, namely proteins from

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human body fluids,⁴⁴ penicillin G from its fermentation broth,⁴⁵ roxithromycin from aqueous effluents,⁴⁶ bisphenol A from biological fluids,⁴⁷ and separation and isolation of antibiotics and natural red colorants from their fermented broth.^{48,49}

Despite a growing number of publications dealing with IL-based ABS, in particular on their use as a promising medium for the extraction/purification of biomolecules,¹² there are only few reports that attempt to understand the molecular-level mechanisms behind the salting-in/-out phenomena.^{14,18,50–53} Rogers and co-workers¹⁴ were the first to propose that the formation of IL-based ABS is controlled by the competitive interaction between salt and IL ions toward the water molecules. This competition is won by the salt ions due to their high charge density, and thus higher hydration energy, when compared with the IL ions. Consequently, there is a migration of water away from the IL toward the salt ions. At certain concentrations, the more “hydrophobic” IL-rich layer separates from the salt and more water-rich phase.¹⁴ Later on, Rogers and co-workers¹⁸ concluded that the ability of the salt ions to salt-out ILs follows the well-known Hofmeister series and the ions’ Gibbs free energy of hydration, ΔG_{hyd} ⁵⁴ (data presented in Table 1). While most of the authors^{2,8,9,15–23}

salting-out agents.¹² However, it must be stressed that most of the reported works only considered monovalent salt cations;^{2,8,9,15–23} thus, the effect of polyvalent cations on the formation of IL-based ABS is poorly studied and yet to be understood.^{59–61}

Aiming at further delving into the mechanisms behind the IL-ABS formation, relevant at large for the understanding of the solubility of charged molecules in saline aqueous solutions, the ability of polyvalent cations through the formation of ABS is here investigated by carrying out a systematic and comprehensive study on the impact of mono-, di-, and trivalent salt cations. The strategy followed in this work consisted on a combined approach, namely the initial determination of the ternary phase diagrams of ABS constituted by ILs and NaCl, NaCH₃CO₂, Na₂SO₄, MgCl₂, Mg(CH₃CO₂)₂, MgSO₄, AlCl₃, Al(CH₃CO₂)₃, and Al₂(SO₄)₃, followed by a proper analysis of the speciation of the ions present in the respective aqueous solutions. The salt cations (Na⁺, Mg²⁺, and Al³⁺) and anions (SO₄²⁻, CH₃CO₂⁻, and Cl⁻) were selected to cover the Hofmeister series. In addition, the combinations with Na⁺, Mg²⁺, and Al³⁺ allow inferring on the effects of the monovalent, divalent, and trivalent ions regarding the ABS formation ability. A broad range of ILs was also investigated here with 1-butyl-3-methylimidazolium-based compounds. It is important to note that only hydrophilic ILs, i.e., ILs completely miscible with water at room temperature, were considered in this work to form IL-based ABS. NMR spectroscopy results were further used to evaluate the interactions occurring between the salt and IL ions. Finally, the influences of the pH of the aqueous solutions toward the phase diagrams behavior was ascertained and further confirm that the ions speciation extent cannot be discarded when evaluating the formation of IL-based ABS.

Table 1. Gibbs Free Energy of Hydration ($\Delta_{\text{hyd}}G$)⁵⁴ and Molar Entropy of Hydration ($\Delta_{\text{hyd}}S$)⁵³ of Several Ions

ion ^a	$\Delta_{\text{hyd}}G/(\text{kJ mol}^{-1})$	$\Delta_{\text{hyd}}S/(\text{J K}^{-1} \text{mol}^{-1})$
Na ⁺	-365	-111
K ⁺	-295	-74
Mg ²⁺	-1830	-331
Ca ²⁺	-1505	-252
Al ³⁺	-4525	NA
Cl ⁻	-340	-75
[CH ₃ CO ₂] ⁻	-365	-170
[HSO ₄] ⁻	-365	-129
OH ⁻	-430	-161
[SO ₄] ²⁻	-1080	-200
[CO ₃] ²⁻	-1315	-245
[PO ₄] ³⁻	-2765	-421
[C ₆ H ₅ O ₇] ³⁻	-2765	-421

^aThe ions in bold were studied in this work.

explained the rank of the salt ions to promote the formation of IL-based ABS based on their Gibbs free energy of hydration, a systematic investigation conducted by Shahriari et al.,⁵³ where a wide range of salts was employed, revealed that the ABS formation ability largely depends instead on the molar entropy of hydration of the salt ions.

Although the Hofmeister series effects related to the ions in aqueous solutions are ubiquitous, the molecular mechanisms by which the ions operate to induce a salting-in or a salting-out phenomenon are still not completely established.^{50–53} Several works have cast doubts on the notion that the stabilization/destabilization of the water structure by “kosmotropic” and “chaotropic” salt ions is the main phenomenon behind the Hofmeister series.^{55–58} A number of results suggest that salting-out inducing ions act mainly through entropic effects resulting from the formation of water–ion complexes, whereas salting-in inducing ions interact with the hydrophobic moieties of the IL, enhancing its solubility in water.^{50–52} Regardless of whether the IL-ABS formation process is driven by the Gibbs energy^{14,18} or entropy of hydration⁵³ of the salt ions, most authors agree that higher valence cations or anions should perform better as

2. EXPERIMENTAL SECTION

2.1. Materials. The studied ILs were 1-butyl-3-methylimidazolium chloride, [C₄mim]Cl, >99 wt % pure; 1-butyl-3-methylimidazolium bromide, [C₄mim]Br, >99 wt % pure; 1-butyl-3-methylimidazolium acetate, [C₄mim][CH₃CO₂], >98 wt % pure; 1-butyl-3-methylimidazolium trifluoroacetate, [C₄mim][CF₃CO₂], >97 wt % pure; 1-butyl-3-methylimidazolium methylsulfate, [C₄mim][CH₃SO₄], >99 wt % pure; 1-butyl-3-methylimidazolium ethylsulfate, [C₄mim][C₂H₅SO₄], >98 wt % pure; 1-butyl-3-methylimidazolium dimethylphosphate, [C₄mim][DMP], >98 wt % pure; 1-butyl-3-methylimidazolium thiocyanate, [C₄mim][SCN], >98 wt % pure; 1-butyl-3-methylimidazolium dicyanamide, [C₄mim][N(CN)₂], 98 wt % pure; 1-butyl-3-methylimidazolium tetrafluoroborate, [C₄mim][BF₄], 99 wt % pure; 1-butyl-3-methylimidazolium trifluoromethanesulfonate (triflate), [C₄mim][CF₃SO₃], 99 wt % pure; and 1-butyl-3-methylimidazolium toluene-*p*-sulfonate (tosylate), [C₄mim][TOS], 98 wt % pure. All ILs were acquired from IoLiTec (IL Technologies, Germany). The purities of these ILs were also confirmed by us using ¹H, ¹³C, and ¹⁹F NMR (when appropriate). The ILs were used without further purification. The chemical structures of the studied ILs are presented in Figure 1.

The salts used were NaCl > 99.9 wt % pure from Prolabo, MgCl₂·6H₂O > 99 wt % pure from Riedel-de-Haën, AlCl₃ > 98 wt % pure from Merck, Na₂SO₄ > 99.0 wt % pure from Labsolve, MgSO₄·7H₂O > 98 wt % pure from Panreac, Al₂(SO₄)₃ > 98 wt % pure from Himedia, NaCH₃CO₂ > 99.8 wt % pure from Pronolab, Mg(CH₃CO₂)₂·4H₂O > 99.5 wt % pure from Riedel-de-Haën, and Al(CH₃CO₂)₃ > 99.9 wt % pure

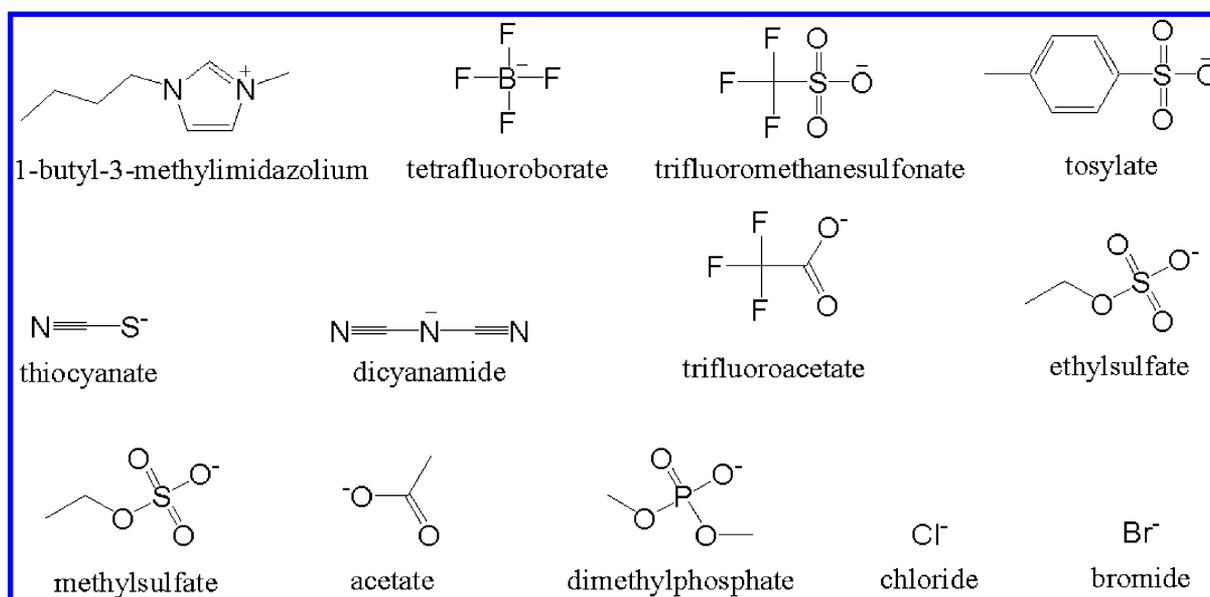


Figure 1. Chemical structures of the studied IL cations and anions.

from Sigma-Aldrich. The salts were used as received. The water employed was double distilled, passed across a reverse osmosis system, and further treated with a Milli-Q plus 185 water purification system. HCl at 37 wt % was acquired from Riedel-Haën, and NaOH > 99 wt % pure was from Panreac. The buffers used for the pH meter calibration were buffer pH 4.01, 7.00, and 9.21 from Mettler-Toledo GmbH.

2.2. Phase Diagrams. The experimental procedure adopted in this work follows the method previously validated by us for ABS constituted by ILs and salts.^{53,62,63} First, stock aqueous solutions of each salt with variable weight fractions (usually close to, yet below, its saturation solubility in water at room temperature), and aqueous solutions of each IL in the range from 60 to 95 wt % were prepared gravimetrically ($\pm 10^{-4}$ g) using an analytical balance (Mettler Toledo Excellence XS205 DualRange) and were used for the determination of the corresponding phase diagrams. The solubility curves data of the systems composed of IL, water, and salt were determined at 298 ± 1 K and atmospheric pressure using the cloud point titration method. In brief, repetitive dropwise addition of the aqueous salt solution to the aqueous IL solution was carried out until the detection of a cloudy solution, followed by the dropwise addition of ultrapure water until the detection of a clear and monophasic phase. All these additions were carried out under continued stirring. The ternary system compositions were determined by the weight quantification within $\pm 10^{-4}$ g.

For the pH effect studies, the pH of each aqueous solution and water was maintained at pH 2.0 or 12.0 ± 0.1 by the addition of HCl or NaOH, respectively, and controlled by pH measurements using a pH meter (Mettler Toledo S47 SevenMulti dual). It should be noted that all the solutions (water, salt, and IL aqueous solutions) were maintained at a fixed pH for the determination of the corresponding phase diagrams.

2.3. Spectroscopic Analysis. For the NMR analysis, the samples were placed in NMR spectroscopy tubes containing sealed reference capillaries with D₂O (Aldrich with >99.96% D atoms) as solvent and using 3-(trimethylsilyl)propionic-2,2,3,3-*d*₄ acid sodium salt (TSP) (Aldrich with >98% D atoms) as the internal reference and at 25 °C. Each ternary mixture of IL, salt,

and water was prepared gravimetrically ($\pm 10^{-4}$ g). In the ternary mixtures, the IL concentration was always kept at 0.01 mol kg⁻¹, while the concentration of salt ranged from 0.0 to 2.0 mol kg⁻¹. The ¹H or ¹⁹F NMR chemical shift deviations are defined according to eq 1⁵²

$$\Delta\delta_{\text{H}} = \delta H_{(\text{IL}+\text{salt})} - \delta_{\text{H}(\text{IL})} \quad (1)$$

where $\delta H_{(\text{IL}+\text{salt})}$ is the ¹H or ¹⁹F NMR chemical shift of the IL in the presence of the salt aqueous solutions and $\delta_{\text{H}(\text{IL})}$ is the ¹H or ¹⁹F NMR chemical shifts of the pure IL. The NMR spectra were recorded using a Bruker Avance 300 at 300.13 MHz.

2.4. Ion Speciation. The salt ions speciation and their concentration were calculated using VisualMINTEQ (version 3.0), a thermodynamic speciation model, based on the MinteqA2 software with the Minteq database.⁶⁴ The noteworthy capability of VisualMINTEQ to describe the metal ions speciation can be found elsewhere.^{65–69} In this thermodynamic calculation, the compositions of salt in the ternary mixtures were used as the input. For the pH study, the pH parameter was set to 2.0 or 12.0.

3. RESULTS AND DISCUSSION

The experimental weight fraction data are given in Tables 1S–42S of the Supporting Information. All phase diagrams are shown below in molality units, moles of solute (mole of IL or mole of salt) per kilogram of solvent (kg of (salt + water) or kg of (IL + water)), to avoid inconsistencies that may result from different molecular weights exhibited by the ILs and salts used.¹² It should be noted that the amount of water complexed to the commercial salts, for example MgSO₄·7H₂O, was removed in the calculations of the molality of salts and added to the water composition of each phase diagram. Since all systems studied in this work share the same IL cation, it allows us to evaluate the impact of the IL anion in addition to the salt cation and anion on the ABS formation.

3.1. Effect of the IL Anions. If the salt is kept constant, it is possible to evaluate the ability of the several anions combined with the [C₄mim]⁺ cation to induce the formation of ABS. Figure 2 presents the ternary phase diagrams for the ABS

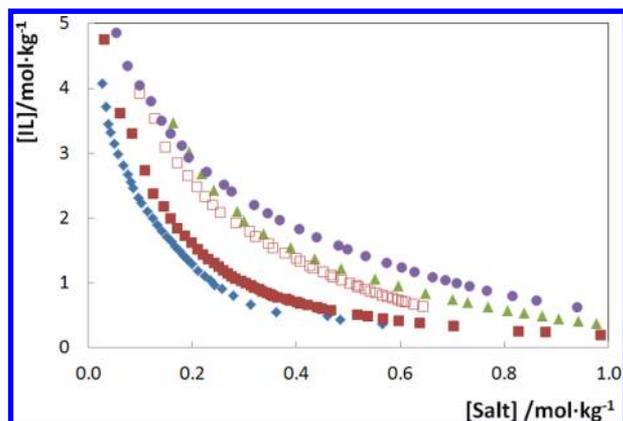


Figure 2. Ternary phase diagrams for systems composed of IL + $\text{Al}_2(\text{SO}_4)_3$ + H_2O at 298 K and atmospheric pressure. Symbols: ◆, $[\text{C}_4\text{mim}][\text{BF}_4]$; ■, $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$; □, $[\text{C}_4\text{mim}][\text{SCN}]$; ▲, $[\text{C}_4\text{mim}][\text{TOS}]$; and ●, $[\text{C}_4\text{mim}][\text{N}(\text{CN})_2]$.

formed by ILs + water + $\text{Al}_2(\text{SO}_4)_3$. The representation of the phase diagrams for systems composed of IL + water + other salts are given in Figures 1S–5S of the Supporting Information. The closer to the axis origin a binodal curve is the higher the ability of such a system for liquid–liquid demixing. Accordingly, the ABS formation ability of the ILs follows the order $[\text{C}_4\text{mim}][\text{BF}_4] > [\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3] > [\text{C}_4\text{mim}][\text{SCN}] > [\text{C}_4\text{mim}][\text{TOS}] > [\text{C}_4\text{mim}][\text{N}(\text{CN})_2]$. Similar trends on the ILs rank are observed irrespective of the salts used. The trend displayed also agrees well with previous results for ABS composed of ILs and Na_2SO_4 ,⁷⁰ phosphate-based,^{39,71} and citrate-based salts.⁷²

In these ternary mixtures, as previously mentioned, there is a competition between the salt ions and the ILs ions for the solvation by water molecules. Salt ions preferentially form hydration complexes, and as a result, the water molecules are removed from the ionic-liquid-solvation environment. The extent of this exchange process depends on the affinity of each IL toward water. Previous works have shown that ILs mainly interact with water through hydrogen bonding and in which the anion plays a major role as a hydrogen-bond acceptor.^{73–75} Consequently, the ability of water molecules to leave the IL–water solvation layer depends on the ILs hydrogen-bond acceptor strength. In general, a lower hydrogen-bond basicity of a given IL translates into a greater ability to form ABS.⁷⁰

Compared with our previous work with phosphate-based salts,^{39,71} it is noteworthy that although the anion's rank is more pronounced with phosphate-based salts, the sequence of ILs is not significantly changed. K_3PO_4 is able to salt-out a high number of ILs from aqueous solution, as it contains the high charge density PO_4^{3-} anion with an enhanced capacity for creating ion–water hydration complexes. However, and unexpectedly, $\text{Al}_2(\text{SO}_4)_3$ is only able to form ABS with a limited number of ILs. Indeed, we have tried to create ABS with $[\text{C}_4\text{mim}][\text{CH}_3\text{SO}_4]$, $[\text{C}_4\text{mim}][\text{C}_2\text{H}_5\text{SO}_4]$, $[\text{C}_4\text{mim}][\text{CH}_3\text{SO}_3]$, $[\text{C}_4\text{mim}]\text{Br}$, $[\text{C}_4\text{mim}]\text{Cl}$, $[\text{C}_4\text{mim}][\text{CH}_3\text{CO}_2]$, and $[\text{C}_4\text{mim}][\text{DMP}]$ with $\text{Al}_2(\text{SO}_4)_3$, and the two-phase formation was not observed. Keeping in mind that $\text{Al}_2(\text{SO}_4)_3$ contains a high charge density cation ($\Delta_{\text{hyd}}G(\text{Al}^{3+}) = -4525 \text{ kJ mol}^{-1}$), stronger than the $[\text{PO}_4]^{3-}$ anion ($\Delta_{\text{hyd}}G([\text{PO}_4]^{3-}) = -2765 \text{ kJ mol}^{-1}$) in K_3PO_4 , one might expect the former to be a stronger salting-out inducing salt and more proficient for the formation of ABS with a wide variety of ILs. This odd finding is

thus an indication that the formation of ABS composed of ILs and salts are not merely the result of the competition of the salt and IL ions for water molecules; a more complex scenario is present and will be discussed below.

3.2. Effect of the Polyvalent Salt Cations. Aiming to determine the influence of the salt in the IL-based ABS formation, a comparison of the different sets of results is carried out here. To get a broad picture of the salt effect, Figures 3 and

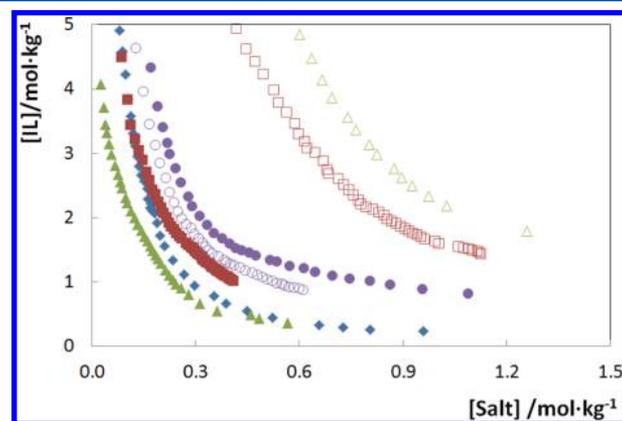


Figure 3. Phase diagrams for systems composed of $[\text{C}_4\text{mim}][\text{BF}_4]$ + salt + H_2O at 298 K and atmospheric pressure. Symbols: ◆, Na_2SO_4 ; ■, MgSO_4 ; ▲, $\text{Al}_2(\text{SO}_4)_3$; ●, NaCH_3CO_2 ; ○, $\text{Mg}(\text{CH}_3\text{CO}_2)$; △, NaCl ; and □, MgCl_2 .

4 present respectively the ternary phase diagrams of $[\text{C}_4\text{mim}][\text{BF}_4]$ or $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$ + water + different salts. It should be noted that $[\text{C}_4\text{mim}][\text{BF}_4]$ and $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$ can form ABS even with the weakest salting-out agent evaluated, NaCl . Prior to our work, Wang et al.⁷⁶ have reported that NaCl and NaCH_3CO_2 cannot form ABS with $[\text{C}_4\text{mim}][\text{BF}_4]$. In contrast with their results, and in agreement with other works,^{2,23} it was found that NaCl and NaCH_3CO_2 could both form ABS with this IL, as depicted in Figure 6S of the Supporting Information. Despite the discrepancy between our data and other literature data,^{2,23,60} the set of data here reported display the same IL trend, particularly for the sulfate-based salts. It should be stressed that $[\text{BF}_4]$ -based ILs are not water stable; they tend to suffer hydrolysis in contact with water while releasing hydrofluoric acid, even at room temperature.^{77,78} This instability might be the reason for these contradictory reported results since the amount of HF produced will largely depend on the time of equilibrium used in the experimental determination of each phase diagram.

Peculiar results were, however, observed in the ternary systems constituted by $[\text{C}_4\text{mim}][\text{BF}_4]$ or $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$ + water + salt. While the latter was able to undergo liquid–liquid demixing, the former did not undergo phase separation with AlCl_3 . It is well established that $[\text{C}_4\text{mim}][\text{BF}_4]$ has lower hydrogen-bond basicity than $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$.⁷⁹ Therefore, if $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$ can form ABS with AlCl_3 , one might anticipate $[\text{C}_4\text{mim}][\text{BF}_4]$ to form ABS as well. This phenomenon, once again, might be attributed to the instability of the $[\text{BF}_4]^-$ anion in the aqueous solution. We have previously shown that the degradation of $[\text{BF}_4]^-$ is highly influenced by the pH of the aqueous solution and that acidic media enhance the decomposition rate.⁷⁷ Therefore, the presence of AlCl_3 provides an acidic media and can be the major reason behind the inability of $[\text{C}_4\text{mim}][\text{BF}_4]$ to form

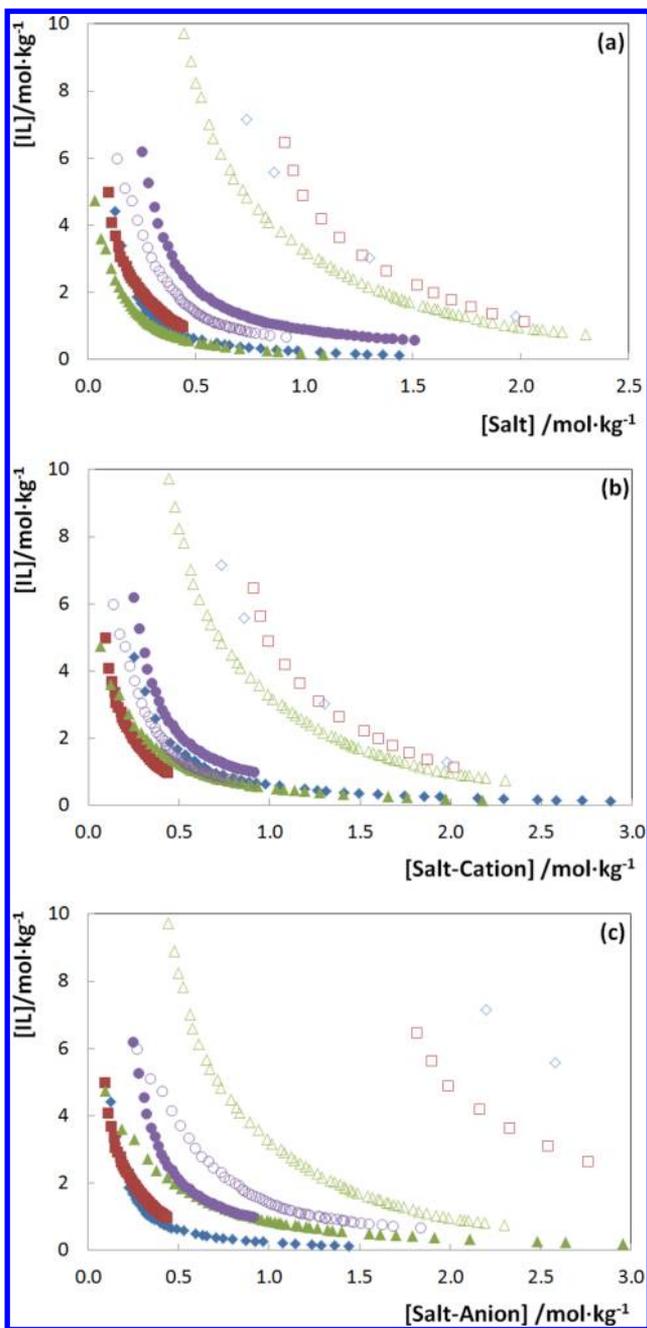


Figure 4. Phase diagrams for systems composed $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3] + \text{salt} + \text{H}_2\text{O}$ at 298 K and atmospheric pressure as a function of concentration of different species: (a) salt, (b) salt cation, and (c) salt anion. Symbols: \blacklozenge , Na_2SO_4 ; \blacksquare , MgSO_4 ; \blacktriangle , $\text{Al}_2(\text{SO}_4)_3$; \bullet , NaCH_3CO_2 ; \circ , $\text{Mg}(\text{CH}_3\text{CO}_2)_2$; \triangle , NaCl ; \square , MgCl_2 ; and \diamond , AlCl_3 .

ABS with this salt. Due to the instability of $[\text{C}_4\text{mim}][\text{BF}_4]$, the following discussion is focused on $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$, as the latter IL is water-stable and could form ABS with a large range of salts.⁵³

The increase in the salting-out strength of the salt is represented by the decrease in the amount of salt required for the formation of two phases at the same composition of IL. Since all systems presented in Figure 4 share the same IL, it allows the evaluation of the effect of salt anion and cation on the ABS formation. Based on the effect of the salt anion, from the ternary phase diagrams depicted in Figure 4a, and by fixing a common cation while varying the anion, a clear salting-out

trend can be established for the selected anions: $\text{SO}_4^{2-} > \text{CH}_3\text{CO}_2^- > \text{Cl}^-$. This rank is valid for both sodium- and magnesium-based salts. One might expect that $\text{Al}(\text{CH}_3\text{CO}_2)_3$ would also present a stronger salting-out effect than AlCl_3 . Nonetheless, since the former has very low solubility in water, almost negligible, we were unable to prepare ternary phase diagrams involving ILs and $\text{Al}(\text{CH}_3\text{CO}_2)_3$, and thus, for aluminum-based salts, the anion effect is ranked as $\text{SO}_4^{2-} > \text{Cl}^-$. From this trend it is visible that the divalent anions present a stronger salting-out ability than the monovalent Cl^- and as expected from the Hofmeister series.⁵⁴

Figure 4 (and Figures 7S–10S in the Supporting Information) also allows the study of the effect of salt cation—the major goal of this work. All published salt effect trends follow the well-known Hofmeister series, in which the cations with higher valence are better salting-out agents than those with lower valence.^{2,8,9,15–23} For that reason, one might expect that Al^{3+} will be the strongest salting-out agent followed by Mg^{2+} , whereas Na^+ is the weakest. For the chloride-based, Al^{3+} , unexpectedly, showed the weakest salting-out ability among the studied Cl-based salts, and accordingly the cation effect then can be ranked as $\text{Na}^+ > \text{Mg}^{2+} \approx \text{Al}^{3+}$. Furthermore, AlCl_3 was able to form ABS only with $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$. Meanwhile, for the sulfate-based, Al^{3+} showed the strongest salting-out ability, followed by Na^+ and then by Mg^{2+} . Furthermore, despite the instability of $[\text{C}_4\text{mim}][\text{BF}_4]$, NaSO_4 also entails a larger biphasic region than MgSO_4 (cf. Figure 6S in the Supporting Information), as observed by us and others.^{2,60} The same trend of the salt cation for the sulfate-based salts is also observed in the formation of ABS with $[\text{C}_4\text{mim}][\text{N}(\text{CN})_2]$, $[\text{C}_4\text{mim}][\text{TOS}]$, and $[\text{C}_4\text{mim}][\text{SCN}]$, as depicted in Figures 7S–10S in the Supporting Information. Therefore, it seems that for salts that do not follow the Hofmeister series, there are other factors at work governing the liquid–liquid demixing ability.

From the gathered results, the trend of IL-ABS formation was verified to be always consistent when different salt anions are compared; yet, the circumstances are quite different when evaluating the effect of the salt cations. The trend observed for the influence of the salt cation on the formation of IL-based ABS does not follow the ability of the ions to form hydration complexes. By definition, the Hofmeister series can be correlated with the hydration strength of individual ions (cf. Table 1). To interpret the Hofmeister series and salt effects on the formation of IL-based ABS, the Gibbs hydration energy^{14,18} or the entropy of hydration⁵³ of the ions are usually employed. Therefore, and aiming a better interpretation of the depicted phase diagrams, the phase diagrams were then represented considering the molality of the respective cation ($[\text{salt cation}]/\text{mol kg}^{-1}$) or anion ($[\text{salt anion}]/\text{mol kg}^{-1}$), and as depicted in Figures 4b and 4c, respectively. Again, no clear trend obeying the Hofmeister series was observed. This lack of conformity leads us to investigate whether the salts present in aqueous solution are totally dissociated or not and to consider the extent on the salt speciation in solution.

Rudolph et al.⁸⁰ have reported that at least four sulfate species can coexist in significant concentration in magnesium sulfate aqueous solutions: the unassociated $\text{SO}_4^{2-}(\text{aq})$ and three associated ion pairs of magnesium sulfate–water complexes. Their findings were further supported by Buchner et al.⁸¹ This is also true for other salts composed of cations and anions with similar water affinity: they have a higher tendency for ion pairing with each other and are, hence, uneasy to completely

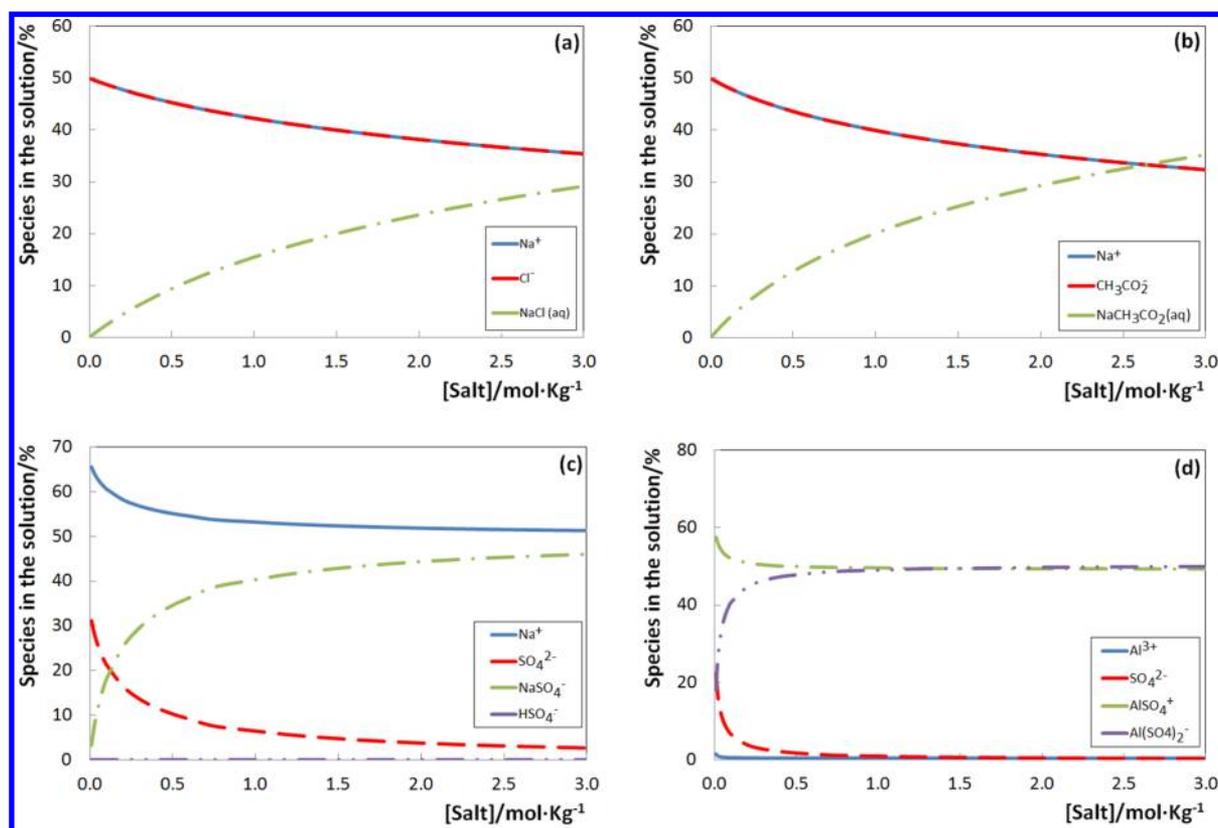


Figure 5. Ion speciation profile of the diverse salts in aqueous solutions at 298 K and at the respective pH observed in the experimental measurements estimated by VisualMINTEQ: (a) NaCl, (b) NaCH₃CO₂, (c) Na₂SO₄, and (d) Al₂(SO₄)₃.

dissociate into individual ions.^{82–84} This ion pairing obviously reduces the number of ions available to form hydration complexes and thus to “salt out” the IL from the aqueous solution to form a given ABS. Under such conditions, the Hofmeister series may not be applicable. Thus, the key in the formation of IL-based ABS is the concentration of “free” salting-out agents in aqueous media. Here, we define “free” salting-out agents as the completely dissociated ions and with their salting-out ability described by the hydration parameters reported in Table 1.

For the purpose of investigating the speciation of the salts used for IL-ABS formation the VisualMINTEQ was used to probe the ions speciation and their concentration in the aqueous solution. Figure 5 presents the speciation profile of the studied salts in aqueous medium. From the depicted data, it is clear that the simplest salt studied, NaCl, is not fully dissociated into their respective Na⁺ and Cl[−] ions. Indeed, some of them are present as NaCl ion pairs, and their concentration increases with increasing salt concentration in the aqueous medium. NaCH₃CO₂ presents a similar profile to NaCl, as these two salts contain two monovalent ions and thus give a similar ratio of cations and anions. The Na₂SO₄ salt contains two Na⁺ cations and one SO₄^{2−} anion, and the latter anion creates some complexity. Part of the SO₄^{2−} is present as NaSO₄[−] and HSO₄[−]. This leads to a reduction of the total number of the “free”, nonpaired, Na⁺ and SO₄^{2−} in aqueous solutions. While the sodium-based salt suffers from ion speciation, Al₂(SO₄)₃ displays a far more complex behavior. The dissolution of Al₂(SO₄)₃ into the aqueous solution does not only produce Al³⁺ and SO₄^{2−} ions. In fact, a wide variety of ions also appear in solution, such as hydroxo- and sulfate-aluminum

complexes. It seems that the higher the ion valence the more complex will be its ion speciation in aqueous media.

This effect may be explained in terms of the existence of more favorable interactions among salt ions. According to the “law of matching water affinity” proposed by Collins,⁸⁵ in aqueous salt solutions, the interactions in order of decreasing strength are as follows: kosmotrope–kosmotrope > kosmotrope–water > water–water > chaotrope–water > chaotrope–chaotrope. Oppositely charged ions tend to form contact ion pairs in solution if they have equal affinities for water but will separate if their water affinities are very different. For example, both Al³⁺ and SO₄^{2−} have high Gibbs hydration energies (cf. Table 1), making them strong salting-out inducing ions. In aqueous solution they tend to bind together by electrostatic interactions. As a consequence, there are numerous aluminum sulfate complexes formed in aqueous solution. It is striking to see how the effect of ion pairing between Al³⁺ and SO₄^{2−} significantly reduces the number of the “free” ions in aqueous environments.

The knowledge of the ion speciation, although an estimate, allows us to determine the “free” salt ions in aqueous solution, and the result in terms of phase diagrams representation is given in Figure 6 (and Figures 7d–10d and 7e–10e in the Supporting Information). When the phase diagram is plotted in function of the remaining “free” cation (cf. Figure 6a), instead of the total cation concentration, a clear salting-out trend can now be established. For the studied anions it can still be ranked as SO₄^{2−} > CH₃CO₂[−] > Cl[−], regardless of the cation. From the data presented, the binodal curves corresponding to the aluminum-based salts are now the closest to the origin, irrespective of the anion used. In addition, the magnesium-

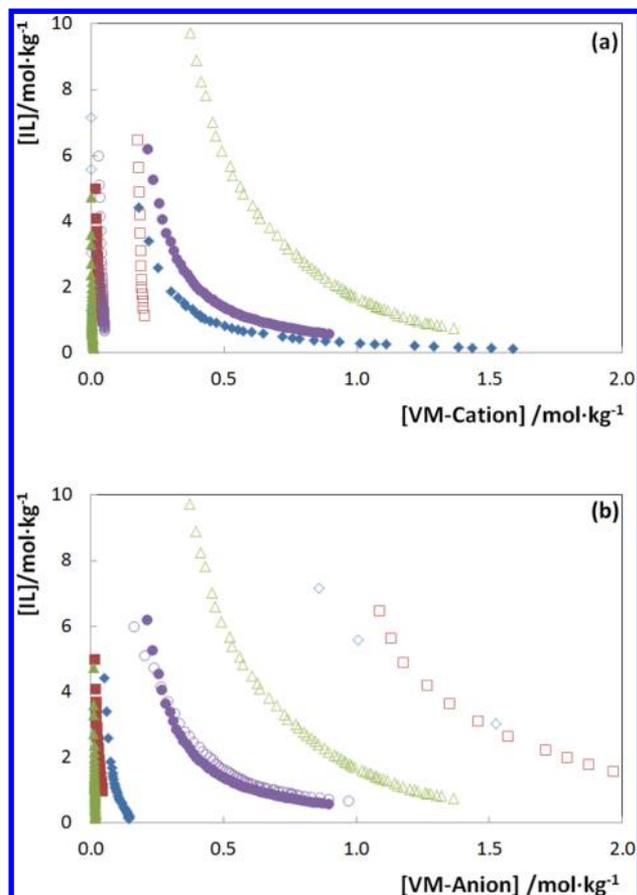


Figure 6. Phase diagrams for systems composed $[C_4mim][CF_3SO_3]$ + salt + H_2O at 298 K and atmospheric pressure as a function of free species in aqueous solution estimated using VisualMINTeq: (a) free salt cation and (b) free salt anion. Symbols: \blacklozenge , Na_2SO_4 ; \blacksquare , $MgSO_4$; \blacktriangle , $Al_2(SO_4)_3$; \bullet , $NaCH_3CO_2$; \circ , $Mg(CH_3CO_2)$; \triangle , $NaCl$; \square , $MgCl_2$; and \diamond , $AlCl_3$.

based ABS now present solubility curves in the middle rank, and the sodium-based systems are the furthest away from the origin. This “new” trend indicates the cations strength to induce phase separation as a function of the “free” ions in solution. The obtained sequence validates the salting-out potential predicted by the Hofmeister series, and it is also corroborated by what is expected from the hydration parameters presented in Table 1,⁵⁴ in which trivalent ions present the strongest salting-out effect, followed by divalent ions, whereas the monovalent cations are the weakest ones.

The question of whether the salt cation or anion is more responsible for the phase separation in IL-based ABS might also arise. It is believed, at present, that anions have a higher aptitude for hydration since they are more polarizable. Most works have focused on using monovalent cations, particularly sodium-based salts, which hydration energy is in the middle range for the monovalent anions. Thus, the effect of hydration of the anion seems to be more pronounced. However, from the analysis of the Gibbs free energy of hydration ($\Delta_{hyd}G$, Table 1), it seems clear that divalent and trivalent cations possess a large hydration shell which further provide a strong salting-out effect. For instance, the $\Delta_{hyd}G$ for Mg^{2+} is $-1830 \text{ kJ mol}^{-1}$, much higher than the highest $\Delta_{hyd}G$ for divalent anions such as $[CO_3]^{2-}$ ($-1315 \text{ kJ mol}^{-1}$). This effect becomes even more pronounced when moving to trivalent ions. While the trivalent

anions $[PO_4]^{3-}$ and $[C_6H_5O_7]^{3-}$ both present a $\Delta_{hyd}G$ of $-2765 \text{ kJ mol}^{-1}$, the Al^{3+} hydration energy is almost two times larger than that ($-4525 \text{ kJ mol}^{-1}$). Therefore, it is reasonable to assume that both the cation and anion of a given salt act cooperatively to affect the phase separation in IL-based ABS.

From the gathered results on the effect of polyvalent ions, it seems that the formation of IL-salt-based ABS is not just a direct consequence of the ability of each salt ion to form hydration complexes. Instead, the extent of interactions among the salt ions, which further control the ion speciation, also take place and play a crucial role on the formation of ABS.

In order to achieve a better understanding on the existence of ion specific interactions between salts and ILs, the ternary systems composed of $[C_4mim][CF_3SO_3]$, water, and $NaCl$, $MgCl_2$, or $AlCl_3$, were further investigated using 1H and ^{19}F NMR spectroscopy. With $[C_4mim][CF_3SO_3]$ it is possible to get a complete picture of the effect of the cation polyvalence by studying the salts constituted by Na^+ , Mg^{2+} , and Al^{3+} . The strong ability of $[C_4mim][CF_3SO_3]$ to promote ABS formation, i.e., to be salted-out from aqueous media, was previously demonstrated by the use of weak salting-out agents such as $NaCl$,⁵³ carbohydrates,³¹ and amino acids.²⁵ The chloride-based inorganic salts were thus chosen here for the spectroscopic analysis because chloride presents one of the weakest abilities to form ABS among other salt anions⁵³ and thus is more proficient to individualize the effect of the salt cation.

Figure 7 presents the 1H NMR chemical shift deviations for $[C_4mim][CF_3SO_3]$ in the presence of $NaCl$, $MgCl_2$, and $AlCl_3$ as a function of the salt concentration. In previous works, we have shown that negative chemical shift deviations result from unfavorable interactions between the IL and salt leading to a salting-out phenomenon.^{51,52} In this work, we have confirmed that unfavorable interactions between the salt and ILs are always present between the phase-forming components of ABS. In addition, the more evident unfavorable interactions are seen with the aromatic protons of the imidazolium ring—those that better interact with water by hydrogen bonding. The salt ions also display more favorable interactions with the IL cation than with the IL anion. This tendency derives from the fact that IL anions are typically more polarizable than the cations and thus more able to form hydration complexes, reflected by a reduction on their interactions with other species.

It is possible to observe that the unfavorable interactions of the IL anion, F(11), become more evident (negative) when moving from $NaCl$ to $AlCl_3$. This trend further corroborates the idea that in fact, the cation strength to induce the phase separation with a given IL follows their hydration energies and thus the Hofmeister series.

3.3. Effect of pH. Several salts used in this work have distinct acidic or alkaline character, and the pH is believed to play a role in the formation of IL-based ABS.^{63,86} For example, dissolution of Na_2SO_4 or $MgSO_4$ into water produce neutral (ca. pH 7) solutions, whereas $Al_2(SO_4)_3$ leads to acidic solutions (pH ca. 4). Furthermore, He et al.⁸ have shown that systems composed of $[C_4mim]Cl$ can undergo phase separation with the addition of appropriate amounts of alkaline aqueous solutions containing K_2HPO_4 , K_3PO_4 , K_2CO_3 , KOH , or Na_2HPO_4 salts. On the opposite side, when acidic to neutral salt aqueous solutions are used, such as those composed of KH_2PO_4 , K_2SO_4 , and $NaCl$, ABS were not formed.⁸ This previous work⁸ and others¹⁵ agree with the favorable formation of IL-based ABS at alkaline pH. Our group further showed the inability of Na_2SO_4 to form ABS with several ILs.⁷⁰ Although

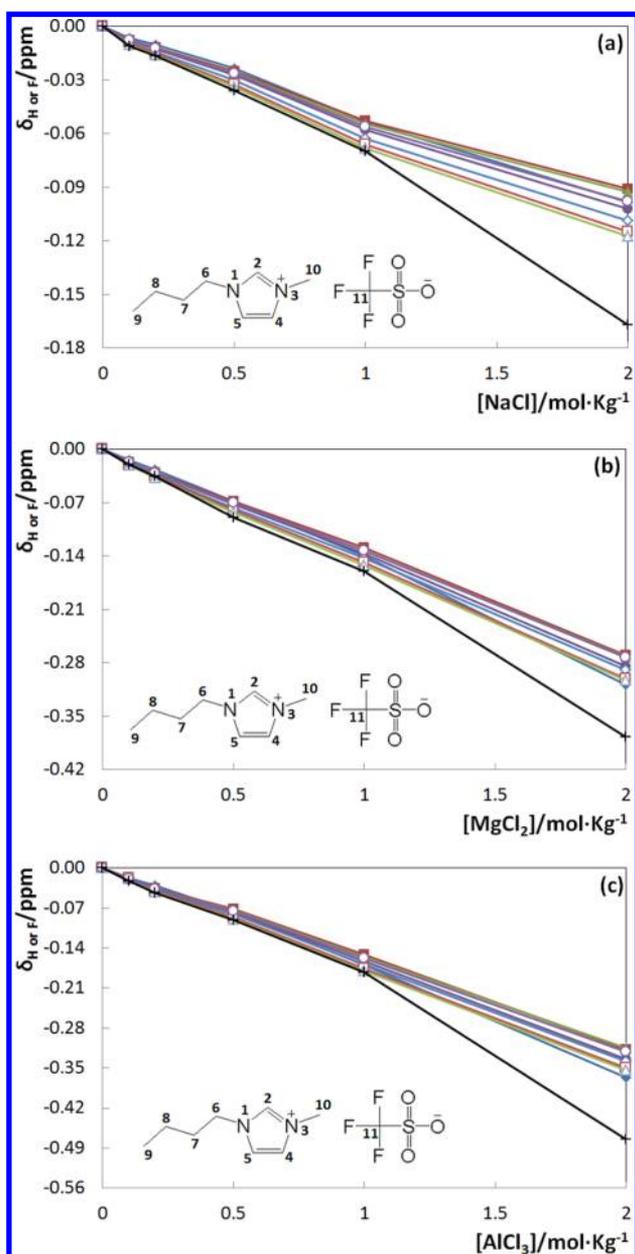


Figure 7. ^1H and ^{19}F NMR chemical shift deviations of $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$ (0.01 mol kg^{-1}) in the presence of various concentrations of chloride-based salts (relative to TSP in D_2O) (a) NaCl , (b) MgCl_2 , and (c) AlCl_3 . Symbols: \blacklozenge , H(2); \blacksquare , H(4); \blacktriangle , H(5); \bullet , H(6); \diamond , H(7); \square , H(8); \triangle , H(9); \circ , H(10); and $+$, F(11).

Na_2SO_4 will lead to neutral aqueous solutions, most of the coexisting phases of ABS composed of this salt and imidazolium-based ILs revealed to be acidic.⁷⁰ Nevertheless, in most of these systems,⁷⁰ there was not a fixed control of the pH of the systems which is a crucial issue regarding the type of salt and respective ion speciation that might take place. The previous study indicated that the salt (and IL) ions equilibrium lead to a change on the pH of the aqueous media.⁷⁰ Here, we additionally explore this feature by keeping the pH at a fixed value to evaluate the salt ions speciation in IL-based ABS.

The results obtained are presented in Figure 8 (and Figures S11–S14 in the Supporting Information) and depict the effect of pH on the formation of ABS composed of $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$, Na_2SO_4 , and water. It is observed that the increase

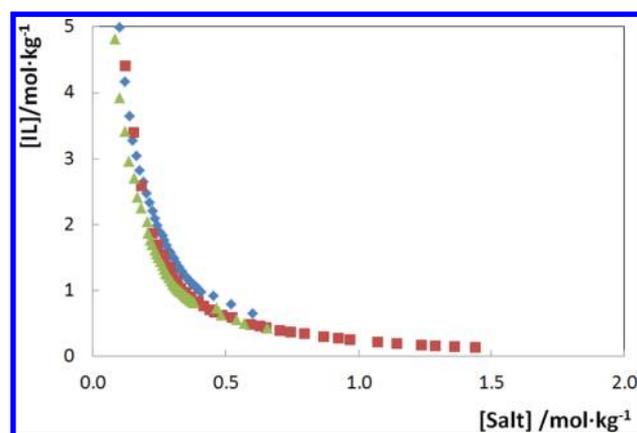


Figure 8. Phase diagrams for the systems composed of $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3] + \text{Na}_2\text{SO}_4 + \text{H}_2\text{O}$ at 298 K and atmospheric pressure. Symbols: \blacklozenge , pH 2; \blacksquare , neutral pH; \blacktriangle , pH 12.

of the pH from 2.0 to 12.0 leads to an increase on the biphasic region envelope. This behavior was also observed for the ternary system composed of Na_2SO_4 and other ILs, with the exception of $[\text{C}_4\text{mim}][\text{BF}_4]$ (cf. Figures S11–S14 in the Supporting Information). This inability further confirms the instability of $[\text{C}_4\text{mim}][\text{BF}_4]$ in the presence of acidic and alkaline solutions.⁷⁷

The trend for a more favorable phase separation from acidic to alkaline solutions can also be explained at the light of ion speciation and Na^+ and SO_4^{2-} compositions at different pH values (cf. Figure S16 in the Supporting Information). Moving from acidic to alkaline solutions decreases the number of individual Na^+ , while slightly increasing the concentration of SO_4^{2-} . The latter ion has higher hydration energy and thus more easily induces phase separation.

In addition, this set of data also allows the study of the effect of the IL anion at different pH values, as depicted in Figure 9. According to the obtained trends, the sequence for the ability of the various ILs for phase separation is as follows: $[\text{C}_4\text{mim}][\text{BF}_4] > [\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3] > [\text{C}_4\text{mim}][\text{TOS}] \approx [\text{C}_4\text{mim}][\text{SCN}] \approx [\text{C}_4\text{mim}][\text{N}(\text{CN})_2] > [\text{C}_4\text{mim}][\text{C}_2\text{H}_5\text{SO}_4] > [\text{C}_4\text{mim}][\text{CF}_3\text{CO}_2] \approx [\text{C}_4\text{mim}][\text{CH}_3\text{SO}_4] > [\text{C}_4\text{mim}]\text{Br}$. Although the rank is more pronounced at neutral pH, in general, the pH does not affect the sequence on the IL anion ability in promoting ABS. However, it is striking to see that $[\text{C}_4\text{mim}][\text{CH}_3\text{SO}_4]$, $[\text{C}_4\text{mim}][\text{C}_2\text{H}_5\text{SO}_4]$, and $[\text{C}_4\text{mim}][\text{CF}_3\text{CO}_2]$ could undergo liquid–liquid demixing with Na_2SO_4 at “neutral” pH but are unable to form ABS at pH 2.0 and 12.0. This phenomenon might be addressed to a little or no presence of $[\text{CH}_3\text{SO}_4]^-$ or $[\text{C}_2\text{H}_5\text{SO}_4]^-$ in the ternary system at pH 2.0 and 12.0. A recent work by Jacquemin et al.⁸⁷ showed that methyl sulfate- and ethyl sulfate-based ILs are not stable in the presence of water, since the hydrolysis of the $[\text{CH}_3\text{SO}_4]^-$ or $[\text{C}_2\text{H}_5\text{SO}_4]^-$ anions to methanol or ethanol and $[\text{HSO}_4]^-$ is observed. The presence of acidic and alkaline medium might accelerate the hydrolysis of the IL anion and could explain the inability of sulfate-based ILs to form ABS with Na_2SO_4 at pH 2.0 and 12.0.

One could very easily get the incorrect impression that alkaline pH drift toward easily phase separation. However, this is not always true. Figure 10 presents the phase diagram for magnesium-based salts with $[\text{C}_4\text{mim}][\text{CF}_3\text{SO}_3]$ at pH 2. The phase diagram corresponding to a pH of 12 could not be studied with the magnesium-based salt since it was observed

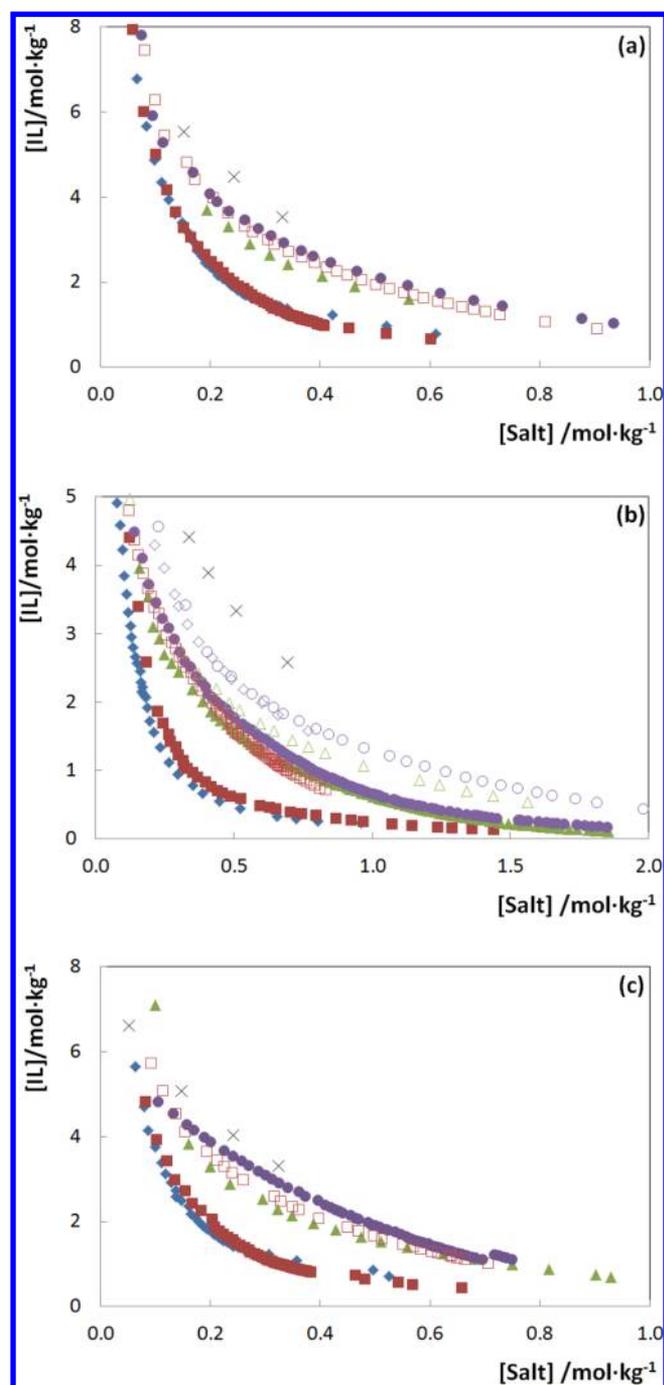


Figure 9. Phase diagrams for systems composed of IL + Na₂SO₄ + H₂O at 298 K and atmospheric pressure at (a) pH 2, (b) without controlling the pH, and (c) pH 12. Symbols: \blacklozenge , [C₄mim][BF₄]; \blacksquare , [C₄mim][CF₃SO₃]; \blacktriangle , [C₄mim][TOS]; \bullet , [C₄mim][N(CN)₂]; \circ , [C₄mim][CH₃SO₄]; \triangle , [C₄mim][C₂H₅SO₄]; \square , [C₄mim][SCN]; \diamond , [C₄mim][CF₃CO₂]; and \times , [C₄mim]Br.

the formation of precipitated Mg(OH)₂. While the pH seems to have no effect on the MgSO₄-based systems, the acidic pH leads to an easier phase separation for the systems formed by MgCl₂, contrarily to what has been observed with Na₂SO₄ and as discussed above. Unexpectedly, Mg(CH₃CO₂)₂ could not form ABS at pH 2. The reason for this fact is related with the concentration of “free” salting-out ions available. For example, at pH 2, the CH₃CO₂⁻ binds with H⁺ to form acetic acid (as easily identified by the characteristic smell during the

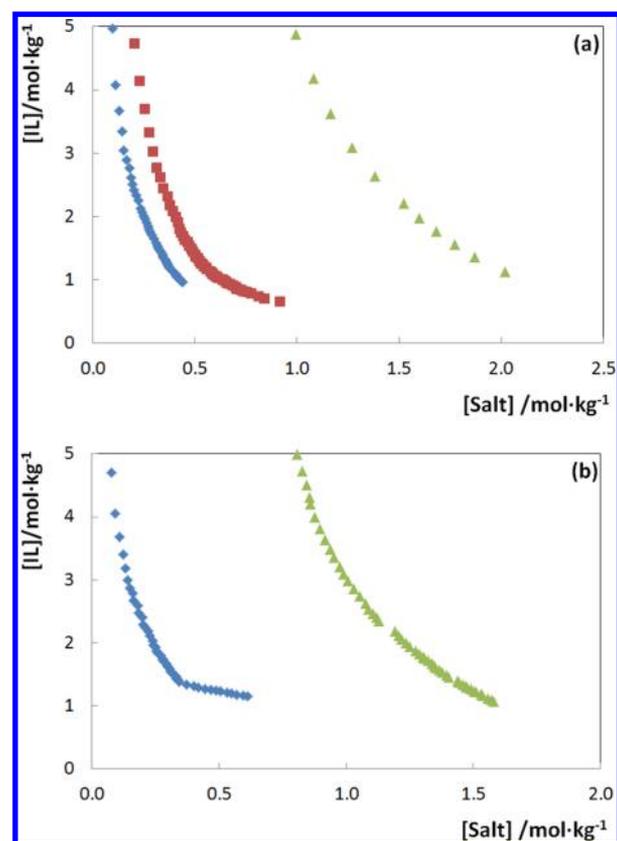


Figure 10. Phase diagrams for systems composed of [C₄mim]-[CF₃SO₃] + magnesium-based salts + H₂O at 298 K and different pH: (a) without controlling pH and (b) with controlling pH at 2. Symbols: \blacklozenge , MgSO₄; \blacksquare , Mg(CH₃CO₂)₂; and \blacktriangle , MgCl₂.

experiments). The Mg²⁺ binds with the remaining free CH₃CO₂⁻ and Cl⁻, forming MgCH₃CO₂⁺ and MgCl⁺, respectively (cf. Figure S17 in the Supporting Information). Therefore, this inherent ion speciation reduces the number of “free” and stronger salting-out inducers, namely Mg²⁺ and CH₃CO₂⁻, and as a consequence no ABS is formed.

The point to be made at this stage is that the ABS formation composed of ILs and salts are more complex than initially anticipated and are highly dependent on the presence of “free” ions. In fact, the trends observed can be well explained if the ion speciation is taken into account and the analysis is based on the amount of “free” salting-out ions available. Several salt ions work better at alkaline pH, while other performs better at acidic conditions.

In summary, the IL-based ABS formation ability strongly depends on the ions speciation and on interactions occurring between the salt ions that eventually lead to ion pairing. This understanding and a proper evaluation of the amount of each species in solution at given conditions will allow an appropriately tailoring of the corresponding phase diagrams of IL-based ABS.

4. CONCLUSIONS

IL-salt ABS are a promising media for the extraction and separation fields. Up to now, it is evident that the unique nature of the salt, as well as of the IL, is a crucial feature in determining their performance to induce the phase separation and ABS formation. It has been admitted so far that the IL-based ABS formation ability would follow the Hofmeister series and the

aptitude of each ion to be hydrated. However, it was here demonstrated that some deviations can occur to the well-established series and that mainly depend on the interactions occurring among the salt ions and on the ions speciation in aqueous media. This trend was confirmed with a large number of experimental phase diagrams where the IL and salt ions effects were evaluated, in addition to the pH influence. It should be pointed out that the knowledge of the salt ions speciation strongly contributes toward the understanding of their impact on IL-based ABS formation.

■ ASSOCIATED CONTENT

■ Supporting Information

Experimental weight fraction data along with the estimated ion speciation using VisualMINTEQ; additional representation of the remaining ABS and ions speciation of diverse salt; ^1H and ^{19}F NMR chemical shift deviations. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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