Studies on dissolution of carbohydrates in ionic liquids and extraction from aqueous phase†

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An extended study on the solubility of the carbohydrates glucose, fructose, sucrose and lactose in twenty eight different ionic liquids (ILs) was performed. These ILs were based on the combination of tetraalkylammonium, tetraalkylphosphonium, 1-methyl-3-alkylimidazolium and dimethyl-tetraalkylguanidinium cations containing alkyl and ether pendant substituent groups, and anions of chloride, dicyanamide, saccharine, acesulfame, acetate or thiocyanate. It was possible to achieve solubilities, at 35 °C, of each carbohydrate up to 43.9, 49.0, 17.1 and 16.6% (g of carbohydrate per 100 g of IL), respectively. The possibility to extract carbohydrates from an aqueous phase by hydrophobic ILs was also demonstrated. Besides, some selectivity for a mixture of two carbohydrates was also observed.

Introduction

Carbohydrates are chiral organic molecules readily available from natural and renewable resources and are relatively inexpensive. They play an important role in many biological processes, such as biological recognition and metabolic pathways, and also in the pharmaceutical and food industries.[1,2] Although most carbohydrates are soluble in protic solvents, such as water, they contain a high number of hydroxyl groups which hinder their dissolution in most common organic aprotic solvents, limiting some applications that require the use of aprotic solvents. The few organic aprotic solvents that can dissolve glucose, a simple and neutral monosaccharide, are pyridine, dimethylsulfoxide, and dimethylformamide.[3] However, most of the enzymes used in carbohydrate chemistry can be inactivated in these solvents.[4] In this context, it is relevant to discover new adequate media that can improve the dissolution of carbohydrates, allowing a better performance in carbohydrate chemistry. Ionic liquids (ILs) have been reported as new potential media to dissolve some carbohydrates.[3,5]

ILs are compounds that contain only ions: cations and anions that have a melting point below 100 °C. They are versatile compounds due to the possibility to tune the desired property such as polarity, conductivity, thermal and chemical stability, density, viscosity, melting point, and their solvent capacity just by combining different anions and cations.[6–10] ILs have been recognized as "greener" solvents compared with classic organic solvents mainly due to their negligible vapor pressure, high thermal and chemical stability, and their capacity for dissolving numerous polar and non-polar compounds. ILs have been reported not only as carbohydrates solvents but, for some reactions, also as catalysts.[11]

In 2000 Sheldon *et al.* were the first to connect ILs and carbohydrates by exploring their potential as media for carbohydrate transformations.[12] In 2001 two different research groups[13,14] reported the solubility of glucose in ILs based on the imidazolium unit. These ILs containing an ether pendant substituent are currently named "sugar-philic" ILs due to their capacity to establish hydrogen bonds with the hydroxyl groups of the carbohydrate. MacFarlane *et al.*[11,15] described the dicyanamide as an attractive anion to dissolve carbohydrates, due to its hydrogen bond acceptor properties, but only reported range values of solubility. Later, Sheldon *et al.*[16] reported the solubility of carbohydrates in several ILs containing, among others, dicyanamide anion and "sugar-philic" cation. This research group observed that the solubility was more significantly influenced by the nature of the anion (with the dicyanamide anion being the best for dissolution of carbohydrates) than the cation, where the [BMIM] was the best cation unit instead of the ether pendant substituent cation as predicted. Table 1 provides a comprehensive report of data regarding the dissolution of several low molecular weight carbohydrates in different ILs (shown in Fig. 1) collected at different temperatures. Here, we extend the reported carbohydrate solubility studies using some new ILs (Fig. 1) based on dimethylguanidinium and imidazolium cations combined with acesulfame, thiocyanate, saccharine and acetate anions. Particularly relevant are the observations that in some cases the cation also has a determinant role in the solubility capability and the ether pendant substituent in the cation can significantly improve the dissolution of carbohydrates. We also studied how the IL water content can influence the solubility of glucose in the IL.

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Table 1 Reported data on the dissolution of several low molecular weight carbohydrates in different ILs

Carbohydrate	Ionic liquid		Solubility/mg mL^{-1a}	Water content^b (wt%)	T^c/°C	Ref.
Glucose	[EMIM]	[DCA]	>100*	nd	75	17
		[MS]	~100*	nd	75	17
		[MS]	89.6	0.1	25	18a
			133.2		60	
		[BF$_4$]	1.1	0.1	25	18a
			4.8		60	
		[ACET]	600*	nd	60	18b
		[TfO]	6.1	0.1	25	18a
			27.8		60	
	[BMIM]	[DCA]	145	<0.05	25	16
			211		40	
			405		75	
		[DCA]	>100	nd	rt	11
		[PF$_6$]	<0.5	<0.05	25	16
			<1.0*	nd	55	13
		[BF$_4$]	<0.5	<0.05	25	16
		[BF$_4$]	0.9	0.1	25	18a
			2.7		50	
			3.5		60	
		[TfO]	4.8	0.1	25	18a
			14.2		50	
			18.1		60	
	[OMIM]	[BF$_4$]	0.7	0.1	25	18a
			1.5		60	
	[MOMMIM]	[Br]	450*	2.5	Heat	14
		[DCA]	66	<0.05	25	16
		[BF$_4$]	4.4	<0.05	25	16
		[TfO]	4.3	<0.05	25	16
		[Tf$_2$N]	0.5	<0.05	25	16
	[MOEMIM]	[Br]	450*	2.5	Heat	14
		[DCA]	91	<0.05	25	16
		[PF$_6$]	2.5	<0.05	25	16
		[BF$_4$]	2.8	<0.05	25	16
			~5*	nd	55	13
		[TfO]	3.2	<0.05	25	16
		[Tf$_2$N]	0.5	<0.05	25	16
	[EOEMIM]	[DCA]	70	<0.05	25	16
		[PF$_6$]	0.7	<0.05	25	16
		[BF$_4$]	2.8	<0.05	25	16
		[Tf$_2$N]	0.5	<0.05	25	16
	[Bt$_{14}$]	[DCA]	>100*	nd	75	17
		[MS]	~60*	nd	75	17
	[Bt$_{1Bn}$]	[DCA]	~60*	nd	75	17
		[Tf$_2$N]	~20*	nd	75	17
Fructose	[EMIM]	[BF$_4$]	7.7	0.1	25	18a
			25.7		60	
		[TfO]	32.8	0.1	25	18a
			123.9		60	
	[BMIM]	[Cl]	560*	nd	110	19
		[BF$_4$]	3.3	0.1	25	18a
			15.9		60	
		[TfO]	27	0.1	25	18a
			87.5		60	
	[BM$_2$IM]	[Cl]	400*	nd	120	19
Sucrose	[EMIM]	[DCA]	~100*	nd	75	17
		[MS]	12.4	0.1	25	18a
		[MS]	~80*	nd	75	17
		[BF$_4$]	0.6	0.1	25	18a
			0.6		60	
		[TfO]	3.1	0.1	25	18a
			7.1		60	
	[BMIM]	[Cl]	180*	nd	110	19
		[DCA]	195	<0.05	25	16
			282		60	
		[BF$_4$]	0.5	0.1	25	18a
			0.6		60	
		[TfO]	2.0	0.1	25	18a
			5.3	60		
	[BM$_2$IM]	[Cl]	140*	nd	120	19

Table 1 *(Contd.)*

Carbohydrate	Ionic liquid		Solubility/mg mL^{-1a}	Water content^b (wt%)	T^c/°C	Ref.
	[MOEMIM]	[DCA]	220	<0.05	25	16
		$[PF_6]$	0.7	<0.05	25	16
		$[BF_4]$	0.4	<0.05	25	16
		[TfO]	2.1	<0.05	25	16
		$[Tf_2N]$	0.13	<0.05	25	16
	[MOMMIM]	[DCA]	249	<0.05	25	16
			352		60	
	[EOEMIM]	[DCA]	50	<0.05	25	16
			240		60	
	$[Bt_{14}]$	[DCA]	~80*	nd	75	17
		[MS]	~80*	nd	75	17
	[MOEMIM]	[DCA]	220	<0.05	25	16
	$[Bt_{1Bn}]$	[DCA]	~20*	nd	75	17
		[MS]	~20*	nd	75	17
Lactose	[BMIM]	[DCA]	51	<0.05	25	16
			225		75	

[a] Solubility measured by UV except for those assigned (*) that were measured by weight. [b] nd–not defined [c] rt–room temperature

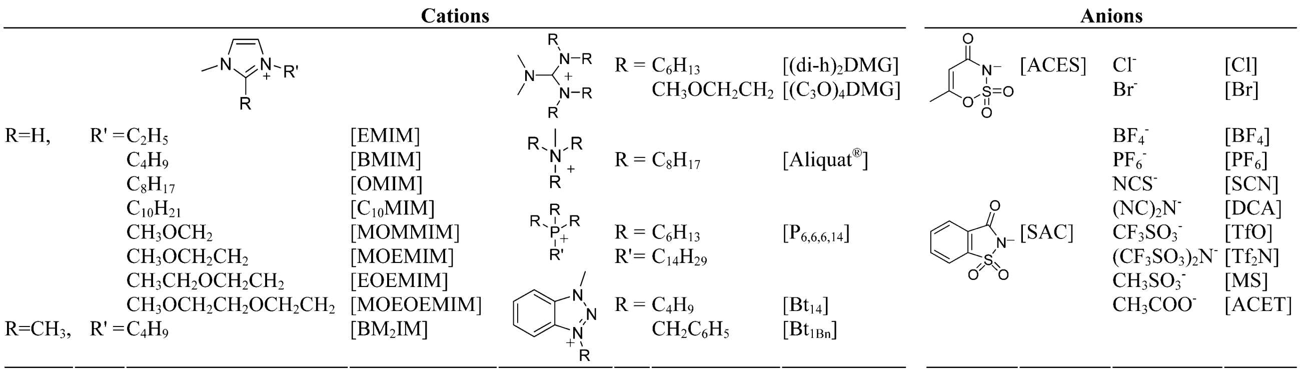

Fig. 1 Structures of the different new and previously reported ILs for the dissolution of carbohydrates.

The complete dissolution of carbohydrates using an adequate medium is an important factor in carbohydrate chemistry, and for specific cases the possibility to remove or recover these compounds from aqueous solutions is also relevant.[20] Carbohydrate extractions from aqueous solutions have been reported using quaternary ammonium salts and lipophilic boronic acids, which can form reversible covalent complexes with diol groups in carbohydrates moieties.[20,21] Hydrophobic ILs have been recently reported as potential extractors of metals[22,23] or polar organic compounds,[24] such as alcohols,[25] from the aqueous phase. Additionally to the dissolution of carbohydrates, studies were carried out to describe a simple method for the extraction of carbohydrates, where a hydrophobic IL can directly extract the carbohydrate from an aqueous solution without the need of a surfactant or a buffer solution in the aqueous phase.

Results and discussion

Solubilities of carbohydrates in ILs

As reported in the literature,[15,16] ILs based on the dicyanamide anion can dissolve a large quantity of carbohydrates, but remarkable results were also achieved with ILs based on different anions. For the first time ILs based on saccharine, acesulfame and thiocyanate anions are reported as media for carbohydrates dissolution, being an alternative for the ILs based on dicyanamide anion. Despite the higher viscosity of saccharine based ILs, Table 2 shows a comparable solubility behavior for glucose in these novel ILs and ILs based on the dicyanamide anion (19.01% in [MOEOEMIM][DCA] *vs.* 18.97% in [MOEOEMIM][SAC] *vs.* 18.38% in [MOEOEMIM][SCN]).

Since all our solubility experiments were made by multi-addition of a slight excess of carbohydrate to the IL at the studied temperature (35 °C), and not by prior dissolution at higher temperatures followed by cooling, the possibility of observing dissolution of carbohydrates under supersaturated[18a] conditions was avoided. The observation of [MOEOEMIM][Cl] and glucose solution under a microscope (200× magnification) also showed that no sample dispersion of sugar crystals in the IL is occurring (see ESI).† All the solubility results (Table 2 and Table 3) were obtained by HPLC analyses, and agreed with the expected range considering the overall amount of carbohydrate added. The water content in the IL was measured after the dissolution experiments.

Despite the high number of carbon atoms (27 for $[(\text{di-}h)_2\text{DMG}]$ cation) present in ILs based on the dimethylguanidinium cation unit, they have a low tendency to crystallize even in the presence of anions which persistently become solid when combined with different cations,[26] including chiral anions.[27] In this context we have synthesized two

Table 2 Observed glucose solubility in several novel ILs at 35 °C

Carbohydrate	Ionic liquid		Solubility (wt%)[a]	Water content (wt%)[b]
Glucose	[MOEOEMIM]	[Cl]	29.28	3.26
		[DCA]	19.01	0.80
		[SAC]	18.97	0.66
		[ACES]	14.39	0.62
		[SCN]	18.38	0.81
	$[(C_3O)_4DMG]$	[Cl]	38.58	1.29
		[DCA]	6.19[c]	6.48
		[SAC]	20.59	1.75
		[ACES]	8.44[c]	6.75
		[SCN]	11.34	0.94
		[ACET]	31.73[c]	3.18
	$[(di\text{-}h)_2DMG]$	[Cl]	6.61	2.95
		[DCA]	2.88	0.25
		[SAC]	3.66	0.41
		[ACES]	2.27	0.30
		[SCN]	1.95	0.29
		[ACET]	14.40[c]	5.66
	[BMIM]	$[NTf_2]$	0.59	0.12
		[DCA]	18.56	1.06
		[ACET]	39.41[c]	24.00
	[EMIM]	[ACET]	43.89[c]	14.58
	$[C_{10}MIM]$	$[BF_4]$	0.44	0.46
	$[P_{6,6,6,14}]$	[Cl]	4.69	6.43
		[DCA]	0.50	0.03
		[ACET]	4.90[c]	6.41
	[Aliquat®]	[Cl]	2.26	0.18
		[DCA]	1.25	0.05
		[ACET]	4.05[c]	4.10

[a] g of carbohydrate per 100 g of IL determined by HPLC analysis. [b] Observed water content after glucose dissolution. [c] g of carbohydrate per 100 g of IL determined by weight.

Table 3 Solubility of mono- and di-saccharides in ILs

Carbohydrate	Ionic liquid		Solubility[a] (wt%)	Water content[b] (wt%)
Glucose	[MOEOEMIM]	[Cl]	29.28	3.26
		[DCA]	19.01	0.80
Fructose	[MOEOEMIM]	[Cl]	14.10	2.69
		[DCA]	48.99	0.58
Sucrose	[MOEOEMIM]	[Cl]	17.11	0.7
		[DCA]	11.06	0.48
Lactose	[MOEOEMIM]	[Cl]	10.69	0.8
		[DCA]	16.55	1.0

[a] g of carbohydrate per 100 g of IL determined by HPLC analysis. [b] Observed water content after carbohydrate dissolution.

dimethylguanidinium cations, one of them with an ether pendant substituent, and combined them with several anions. Table 2 shows that the introduction of oxygen in the alkyl chain from the guanidinium cation unit could significantly improve the solubility of glucose when compared with the alkyl guanidinium cation, $[(di\text{-}h)_2DMG]$. In fact, at 35 °C, $[(C_3O)_4DMG][Cl]$ and $[(C_3O)_4DMG][ACET]$ can dissolve the impressive amount of 38.68 and 31.73%, respectively. ILs with imidazolium unit cations highlight the absence of this effect, [MOEOEMIM][DCA] and [BMIM][DCA], at 35 °C, can dissolve approximately the same amount of glucose (19.01 and 18.56% respectively, Table 2).

ILs based on acetate anions can dissolve a large quantity of glucose ($[(C_3O)_4DMG][ACET]$ 31.73%; [BMIM][ACET] 39.41%; [EMIM][ACET] 43.89%; reported for [EMIM][ACET] 60% at 60 °C) notwithstanding that these ILs are more hygroscopic than the other ILs analyzed, water content can be over 20%.

In order to observe how the IL water content influences the carbohydrate solubility behavior, we performed a study using different water content percentages for two hydrophilic ILs (Fig. 2) and four hydrophobic ILs (Fig. 3). The results for the two hydrophilic ILs are quite different: whereas a small amount of water (variation of 2% in the water content) increased the glucose solubility over 10.0% in the case of [MOEOEMIM][Cl], in contrast to [MOEOEMIM][DCA] in which the water effect is not so considerable.

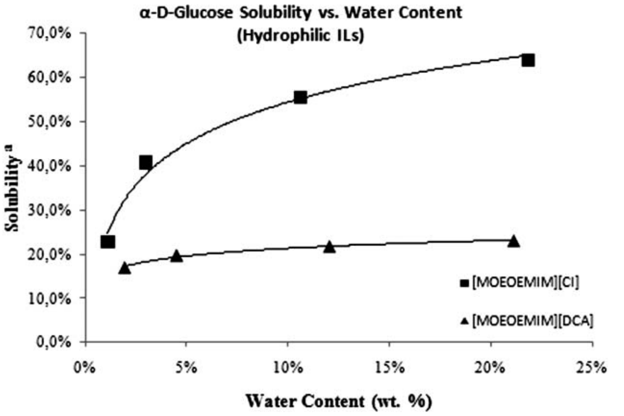

Fig. 2 Variation of glucose solubility with the water content in hydrophilic ILs at 35 °C. [a]Solubility of glucose wt%.

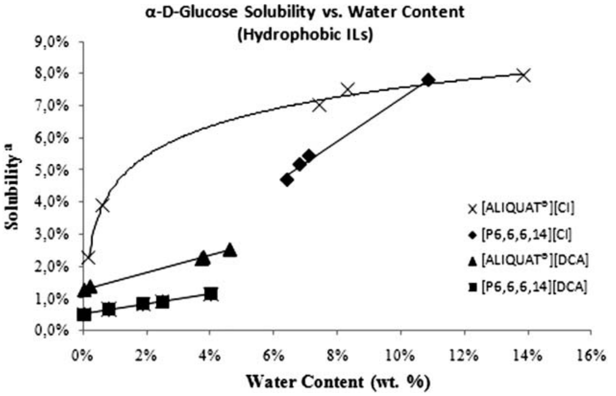

Fig. 3 Variation of glucose solubility with the water content in hydrophobic ILs at 35 °C. [a]Solubility of glucose wt%.

For hydrophobic ILs (Fig. 3) the type of anion also influences the water effect on the glucose solubility in the IL (Fig. 3). ILs based on chloride anions have a higher water content when saturated than those based on dicyanamide anions, and a small fluctuation on the water content of the IL can significantly change the solubility values. Dicyanamide based ILs can dissolve a lower amount of glucose, but are not so dependent of the water content of the IL than those based on chloride anions. Additionally, a slight increase of glucose solubility requires more water addition than for chloride based ILs. There is also a cation

Table 4 Extraction of glucose from a aqueous phase (500 mg mL^{-1}) by hydrophobic IL

Carbohydrate extracted	Ionic liquid		Quantity extracted (wt%)	Solubility [a] (wt%)	Water content[b] (wt%)
Glucose	$[(\text{di-}h)_2\text{DMG}]$	[DCA]	2.70 (cycle 1) 2.63 (cycle 2) 2.69 (cycle 3)	3.68	6.0
	[Aliquat®]	[Cl]	3.46	7.95	13.9
		[DCA]	2.25	2.52	4.6
	$[P_{6,6,6,14}]$	[Cl]	3.64	7.79	10.8
		[DCA]	4.23	1.14	4.0
	[BMIM]	$[NTf_2]$	1.19	1.10	1.6
	$[C_{10}MIM]$	$[BF_4]$	3.29	3.20	10.8

[a] Solubility of glucose in the IL previously saturated with water (g of glucose per 100 g of IL). [b] Maximum water contents in the IL (saturated IL).

Table 5 Extraction of a mixture of carbohydrates from an aqueous phase (500 mg mL^{-1}) to a hydrophobic IL

Mixture of carbohydrates extracted	Ionic liquid		Quantity extracted (wt%)	Selectivity[a] (wt.%)
Glucose/Fructose (G/F–50 : 50 wt%)	$[(\text{di-}h)_2\text{DMG}]$	[DCA]	5.78	71.6G/28.4F
	[Aliquat®]	[Cl]	2.31	80.2G/19.2F
		[DCA]	7.22	69.2G/30.8F
	$[P_{6,6,6,14}]$	[Cl]	1.68	82.5G/17.5F
		[DCA]	5.22	77.8G/22.2F
Sucrose/Lactose (S/L–50 : 50 wt%)	$[(\text{di-}h)_2\text{DMG}]$	[DCA]	1.52	53.8S/46.2L
	[Aliquat®]	[Cl]	3.76	—S/—L
		[DCA]	3.73	48.8S/51.2L
	$[P_{6,6,6,14}]$	[Cl]	2.83	—S/—L
		[DCA]	2.42	55.1S/44.9L
Fructose/Lactose (F/L–50 : 50 wt%)	$[(\text{di-}h)_2\text{DMG}]$	[DCA]	6.84	51.9F/48.1L
	[Aliquat®]	[Cl]	2.02	—F/—L
		[DCA]	1.08	54.6F/45.4L
	$[P_{6,6,6,14}]$	[Cl]	1.37	—F/—L
		[DCA]	2.68	47.3F/52.7L

[a] Ratios determined by ^{1}H NMR (for more information see ESI).

effect: ammonium based ILs can dissolve a larger quantity of glucose than phosphonium based ILs.

ILs with ether pendant groups can dissolve several other carbohydrates including mono and disaccharides (Table 3). Fructose can be two times more soluble in the IL [MOEOEMIM][DCA] than glucose. This result (48.99% at 35 °C) is the best result known for fructose, only comparable with [BMIM][Cl], 56.0% at 110 °C.[19]

Extraction of carbohydrates from an aqueous phase with ILs

$[(\text{di-}h)_2\text{DMG}][\text{DCA}]$ is a hydrophobic IL, not soluble in water, but still solubilizes a large quantity of glucose (Table 2), when compared with the hydrophobic IL, $[BMIM][PF_6]$ (Table 1)[16] (2.88% *vs.* <0.05%). To take advantage of this property, we performed extraction studies for glucose (Table 4), and glucose–fructose, lactose–sucrose, fructose–lactose mixtures (1 : 1 wt%) from an aqueous solution to the IL (Table 5). This study was complemented with different hydrophobic ILs.

The extraction method is simple: the sugar is dissolved in the aqueous solution, and mixed with the hydrophobic IL for one week. Then the two phases are separated and dichloromethane added to the organic layer in which sugar dissolved in the IL precipitate immediately. Following filtration and washing with dichloromethane, the sugar recovered shows no trace of IL. After evaporation of the solvent, the IL is recovered without any traces of carbohydrates, and can be recycled for, at least, three times (recycling experiments were made with $[(\text{di-}h)_2\text{DMG}][\text{DCA}]$, Table 4).

In Table 4 is shown the extraction values for glucose from an aqueous phase to several hydrophobic ILs. For $[BMIM][NTf_2]$, $[C_{10}MIM][BF_4]$ and [Aliquat®][DCA] the quantity extracted from the aqueous phase is similar to the solubility of glucose in the IL saturated with water. For ammonium and phosphonium chloride, the glucose extracted from the aqueous phase is much smaller than the IL can dissolve. Interestingly, $[P_{6,6,6,14}][DCA]$ can extract a much larger quantity than the IL can dissolve (4.23% *vs.* 1.14%). This result could be due to the formation of water microenvironments consisting of glucose solubilized in water inside the IL.[28,29]

The extraction results of carbohydrate mixtures from an aqueous phase (500 mg mL^{-1}) to several hydrophobic ILs are shown in Table 5. For the mixture of two monosaccharides (glucose–fructose), the ILs based on dicyanamide anions can extract a larger quantity than those ILs with chloride as anion. The five different ILs can extract this mixture with relative selectivity, extracting a higher amount of glucose than fructose. When a mixture of two disaccharides (sucrose and lactose) is extracted from an aqueous phase, the cation influences the quantity extracted. With the IL based on the $[(\text{di-}h)_2\text{DMG}]$ cation, a small amount of the mixture is extracted (Table 5), increasing with ILs based on the $[P_{6,6,6,14}]$ cation (either with dicyanamide or chloride as anion). ILs based on the [Aliquat®] cation can dissolve the biggest amount of the mixture of disaccharides (sucrose–lactose), although with almost no selectivity.

When a monosaccharide and a disaccharide (fructose and lactose, respectively) are mixed in an aqueous phase and extracted with five different hydrophobic ILs the results can be quite different. [(di-*h*)$_2$DMG][DCA] can extract a surprising amount of 6.84% (Table 5) of the mixture, while the other four ILs only extract 1.0 to 2.6% with no selectivity. In summary, [(di-*h*)$_2$DMG][DCA] is an efficient IL to extract monosaccharides (G/F), but not so appropriate for extracting disaccharide mixtures (S/L); [Aliquat®][Cl] and [$P_{6,6,6,14}$][Cl] can extract a large quantity of disaccharide mixtures (S/L), but are not so efficient at extracting monosaccharide mixtures (G/F).

Conclusions

We have demonstrated that introduction of ether functionality in the alkyl chain of the IL can improve the dissolution of carbohydrates in ILs based on dimethylguanidinium cations. Saccharine, thiocyanate and acetate anions can be an alternative to ILs based on dicyanamide and halide anions. Hydrophobic ILs can extract a large quantity of glucose from an aqueous solution by a simple method. For these extraction experiments, the ILs contain large amounts of water, since they are saturated, which should play an important role in the observed partitions. Interestingly, some selectivity in the partition studies was also observed.

Experimental

Materials

Commercially supplied reagents were used as supplied. All aqueous solutions were prepared with distilled water. NMR spectra were recorded on a Bruker AMX 400 Spectrometer. The water content of each IL was determined by a volumetric Karl–Fischer titration using HYDRANAL solvent and Tritant 2 reagents. The chloride contents were measured on a chloride electrode instrument. Elemental analysis (C, H, N, analyzer) of each synthesized ionic liquid was performed by the Laboratório de Análises at REQUIMTE, Portugal.

Solubility of carbohydrates in ionic liquids (ILs)

To a 1 mL seal vial was added 250 mg of IL. Several portions of 5 mg additions of carbohydrate were added at a controlled temperature of 35 °C until saturation. The sample was centrifuged and the supernatant was analyzed in an HPLC system with a reverse phase C_{18} column (Hichrom, Lichrosorb RP18–5, 25 cm × 4.6 mm id) and a refractive index detector; the mobile phase consisted of water (100%) at a 1.0 mL min^{-1} flow rate. The water content of all ILs was measured before and after solubility experiments.

Extraction of carbohydrates by ionic liquids (ILs) from aqueous phase

In a 10 mL vial was added 2 mL of a 500 mg mL^{-1} aqueous solution of carbohydrate, and then 2 g of the IL were added. The mixture was stirred for 8 days at 35 °C. The two phases were separated and 10 mL of dichloromethane was added to the organic phase. The carbohydrate was filtered and washed with 2 mL of dichloromethane. For [Aliquat®][Cl] a supplemental experiment was made with a large amount of IL: in a 20 mL vial was added 5 mL of a 500 mg mL^{-1} aqueous solution of carbohydrate, and then 5 g of the IL was added. The mixture was stirred for 8 days at 35 °C. The two phases were separated and 60 mL of dichloromethane was added to the organic phase. The carbohydrate was filtered and washed with 2 mL of dichloromethane. The carbohydrate or mixtures of carbohydrates were recovered without traces of the IL (by ^{1}H-NMR analysis). For [(di-*h*)$_2$DMG][DCA] the process of extraction was repeated three times with the same IL without lost of efficiency.

IL synthesis

The ionic liquids (ILs) tetrahexyldimethylguanidinium chloride [(di-*h*)$_2$DMG][Cl],[26] tetrahexyldimethylguanidinium dicyanamide [(di-*h*)$_2$DMG][DCA],[30] tetrahexyldimethylguanidinium saccharine [(di-*h*)$_2$DMG][SAC],[30] tetrahexyldimethylguanidinium thiocyanate [(di-*h*)$_2$DMG][SCN][30]and Aliquat® dicyanamide [Aliquat®][DCA][30] 1-(2-(2-methoxyethoxy)-ethyl)-3-methylimidazolium chloride [MOEOEMIM][Cl][31] were prepared following the reported procedures. Trihexyl(tetradecyl)phosphonium acetate [$P_{6,6,6,14}$][ACET][32] and Aliquat® acetate [Aliquat®][ACET][33] were prepared following the procedure for [$(C_3O)_4$DMG][ACET] described below. [C_{10}MIM][BF_4] and [BMIM][NTf_2] were purchased from Solchemar; [BMIM][ACET], [EMIM][ACET] and [Aliquat®][Cl] were purchased from Aldrich. [$P_{6,6,6,14}$][Cl] and [$P_{6,6,6,14}$] [DCA] were kindly donated by CYTEC. All ILs synthesized had a residual chloride content of less than 300 ppm.

[$(C_3O)_4$DMG][Cl]. To a suspension of phosgene iminium chloride 1 (2.0 g; 12 mmol) in anhydrous dichloromethane (20 mL) at 0 °C (ice bath) and argon atmosphere was added dropwise a mixture of bis(2-methoxyethyl)amine (3.81 mL, 2.1 equiv.) and triethylamine (8.8 mL, 2.2 equiv.) in anhydrous dichloromethane (30 mL). After 30 min at 0 °C the reaction was stirred at room temperature for 24 h. The solvent was removed under vacuum and an aqueous solution of NaOH (2 M; 20 mL) was added. The mixture was washed with diethyl ether (3 × 25 mL). The water was removed under vacuum, the residue extracted with dichloromethane (50 mL), dried ($MgSO_4$), the solvent evaporated and the product left under vacuum (<1 mm Hg) at 80 °C overnight. The guanidinium salt was obtained as a brown liquid with 92.5% yield. ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 3.43–3.1 (16 H, m); 3.03 (6H, s); 3.00 (6 H, s); 2.77 (6H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 165.04; 68.59; 58.53; 58.41; 49.16; 48.44; 40.11. Elemental analysis calc. (%) for $C_{15}H_{34}ClN_3O_4 \cdot 1.4\ H_2O$: C 47.27, H 9.73, N 11.03. Found: C 47.27, H 10.07, N 11.16.

[$(C_3O)_4$DMG][DCA]. To a solution of [$(C_3O)_4$DMG][Cl] (1 g, 2.8 mmol) in dichloromethane (10 mL) was added $NaN(CN)_2$ (0.348 g, 1.4 equiv.) and the mixture stirred at room temperature for 24 hours. The sodium chloride salt was removed by filtration and the organic phase evaporated under vacuum.

The residual oil was then purified by passing through a column with silica and activated carbon, and the solvent removed under vacuum. The residue was stirred under vacuum (<1 mmHg) at 60 °C overnight (1.02 g, 92.5%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 3.60–3.33 (16H, m); 3.29 (6H, s); 3.27 (6 H, s); 2.98 (6H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 165.27; 119.89; 68.64; 68.60; 58.75; 58.62; 49.39; 48.61; 40.10. Elemental analysis calc. (%) for $C_{17}H_{34}N_6O_4$: C 52.83, H 8.87, N 21.74. Found: C 52.89, H 8.96, N 21.99.

[$(C_3O)_4$DMG][SAC]. To a solution of [$(C_3O)_4$DMG][Cl] (1 g, 2.8 mmol) in dichloromethane (10 mL) was added sodium saccharin (0.80 g, 1.4 equiv.) and the mixture stirred at room temperature for 24 hours. The sodium chloride salt was removed by filtration and the organic phase evaporated under vacuum. The residual oil was then purified by passing through a column with silica and activated carbon, and the solvent removed under vacuum. The residue was stirred under vacuum (<1 mmHg) at 60 °C overnight (0.85 g, 60.5%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 7.80 (1H, m); 7.74 (1H, m); 7.51 (2H, m); 3.66–3.45 (16H, m); 3.34 (6H, s); 3.28 (6 H, s); 3.07 (6H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 165.33; 145.25; 135.44; 131.41; 130.69; 123.09; 119.46; 69.05; 58.75; 58.58; 49.55; 48.75; 40.28. Elemental analysis calc. (%) for $C_{22}H_{38}N_4O_7S\cdot0.7\ H_2O$: C 51.28, H 7.71, N 10.87, S 6.22. Found: C 51.76, H 7.79, N 10.95, S 5.57.

[$(C_3O)_4$DMG][ACES]. To a solution of [$(C_3O)_4$DMG][Cl] (1 g, 2.8 mmol) in dichloromethane (10 mL) was added potassium acesulfame (0.788 g, 1.4 equiv.) and the mixture stirred at room temperature for 24 hours. The potassium chloride salt was removed by filtration and the organic phase evaporated under vacuum. The residual oil was then purified by passing through a column with silica and activated carbon, and the solvent removed under vacuum. The residue was stirred under vacuum (<1 mmHg) at 60 °C overnight (1.298 g, 96.1%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 5.4 (1H, s); 3.62–3.32 (16H, m); 3.29 (6H, s); 3.27 (6 H, s); 3.00 (6H, s); 1.96 (3H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 169.54; 165.30; 160.19; 102.40; 68.84; 58.71; 58.56; 49.43; 48.63; 40.16; 19.90. Elemental analysis calc. (%) for $C_{19}H_{38}N_4O_8S$: C 47.29, H 7.94, N 11.61, S 6.64. Found: C 47.37, H 8.37, N 11.52, S 6.12.

[$(C_3O)_4$DMG][SCN]. To a solution of [$(C_3O)_4$DMG][Cl] (1 g, 2.8 mmol) in dichloromethane (10 mL) was added KSCN (0.38 g, 1.4 equiv.) and the mixture stirred at room temperature for 24 hours. The potassium chloride salt was removed by filtration and the organic phase evaporated under vacuum. The residual oil was then purified by passing through a column with silica and activated carbon, and the solvent removed under vacuum. The residue was stirred under vacuum (<1 mmHg) at 60 °C overnight (0.46 g, 43.7%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 3.60–3.37 (16H, m); 3.25 (6H, s); 3.22 (6 H, s); 3.02 (6H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 165.27; 130.67; 68.77; 58.69; 58.56; 49.42; 48.63; 40.18. Elemental analysis calc. (%) for $C_{16}H_{34}N_4O_4S\cdot0.7\ H_2O$: C 49.13, H 9.12, N 14.32, S 8.20. Found: C 49.47, H 9.23, N 14.56, S 7.73.

[$(C_3O)_4$DMG][ACET]. A solution of [$(C_3O)_4$DMG][Cl] (1 g, 2.8 mmol) in methanol (10 mL) was passed through a column with Amberlite IRA-400 (OH) resin. Acetic acid (1.1 eq) in methanol was slowly added to [$(C_3O)_4$DMG][OH] extracted from the column and the mixture stirred at room temperature for 30 minutes. The solvent was removed under vacuum. The residual acetic acid was removed by stirring under vacuum (<1 mmHg) at 60 °C overnight (0.988 g, 93.0%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 3.57–3.35 (16H, m); 3.24 (6H, s); 3.21 (6 H, s); 2.99 (6H, s); 1.96 (3H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 175.25; 165.21; 68.78; 58.68; 58.54; 49.40; 48.63; 40.24; 23.00. Elemental analysis calc. (%) for $C_{17}H_{37}N_3O_6\cdot2.5\ H_2O$: C 48.10, H 9.97, N 9.90. Found: C 48.44, H 10.24, N 10.64.

[(di-*h*)$_2$DMG][ACES]. To a solution of [(di-*h*)$_2$DMG][Cl] (1 g, 2.1 mmol) in dichloromethane (10 mL) was added potassium acesulfame (0.61 g, 1.4 equiv.) and the mixture stirred at room temperature for 24 hours. The potassium chloride salt was removed by filtration and the organic phase evaporated under vacuum. The residual oil was then purified by passing through a column with silica and activated carbon, and the solvent removed under vacuum. The residue was stirred under vacuum (<1 mmHg) at 60 °C overnight (0.83 g, 65.2%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 5.49 (1H, s); 3.17–3.03 (8H, m); 2.99 (6H, s); 1.99 (3H, s); 1.72–1.22 (32H, m); 0.83 (12H, m). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 170.17; 163.38; 161.20; 101.56; 49.89 and 49.30 (rotamers); 47.96; 31.48 and 31.35 (rotamers); 27.68 and 27.33 (rotamers); 26.44 and 26.31 (rotamers); 22.38; 19.83; 13.81. Elemental analysis calc. (%) for $C_{31}H_{62}N_4O_4S\cdot0.5\ H_2O$: C 62.48; H 10.66; N 9.40; S, 5.38. Found: C 62.50, H 10.93; N 9.27, S 5.30.

[(di-*h*)$_2$DMG][ACET]. A solution of [(di-*h*)$_2$DMG][Cl] (1 g, 2.1 mmol) in methanol (10 mL) was passed through a column with Amberlite IRA-400 (OH) resin. A solution of acetic acid (1.1 eq) in methanol was slowly added to [(di-*h*)$_2$DMG][OH] extracted from the column and the mixture stirred at room temperature for 30 minutes. The solvent was removed under vacuum. The residual acetic acid was removed by stirring under vacuum (<1 mmHg) at 60 °C overnight (0.9988 g, 98.2%). ^{1}H-NMR δ ($CDCl_3$, 400 MHz): 3.17–3.05 (8H, m); 2.86 (6H, s); 2.03 (3H, s); 1.68–1.29 (32H, m); 0.90 (12H, m). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 176.00; 163.41; 49.91 and 49.34 (rotamers); 47.5; 40.62; 31.31 and 31.23 (rotamers); 27.79 and 27.44 (rotamers); 26.56 and 26.44 (rotamers); 22.82; 22.49; 13.91. Elemental analysis calc. (%) for $C_{29}H_{62}N_3O_2\cdot2.5\ H_2O$: C 65.74, H 12.75, N 7.93. Found: C 65.20, H 12.70; N 7.60.

[MOEOEMIM][DCA]. [MOEOEMIM][DCA] was prepared from [MOEOEMIM][Cl] (1 g, 4.5 mmol) and $NaN(CN)_2$ (0.56 g, 1.4 equiv.) as described for [(di-*h*)$_2$DMG][DCA], and obtained as a yellow oil (1.05 g, 92.4%).^{1}H-NMR δ ($CDCl_3$, 400 MHz): 9.02 (1H, s); 7.49 (1H, s); 7.36 (1H, s); 4.35 (2H, t, J = 3.4 Hz); 3.93 (3H, s); 3.79 (2H, t, J = 3.4 Hz); 3.57 (2H, t, J = 1.7 Hz); 3.46 (2H, t, J = 1.7 Hz); 3.28 (3H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 136.50; 123.23; 122.99; 119.60; 71.28; 70.03; 68.24; 58.65; 49.66; 36.28. Elemental analysis calc. (%) for $C_{11}H_{17}N_5O_2\cdot0.5\ H_2O$: C 50.76; H 6.97; N 26.91. Found: C 50.74, H 7.04; N 28.13.

[MOEOEMIM][SAC]. [MOEOEMIM][SAC] was prepared from [MOEOEMIM][Cl] (1 g, 4.5 mmol) and sodium saccharin (1.30 g, 1.4 equiv.), as described for [$(C_3O)_4$DMG][SAC], and obtained as a yellow oil (1.52 g, 91.2%).^{1}H-NMR δ ($CDCl_3$, 400 MHz): 9.57 (1H, s); 7.75(1H, m); 7.69 (1H, m); 7.54 (2H, m); 7.46 (1H, s); 7.26 (1H, s); 4.44 (2H, t, $J = 4.5$ Hz); 3.95 (3H, s); 3.78 (2H, t, $J = 4.5$ Hz); 3.55 (2H, t, $J = 3.3$ Hz); 3.42 (2H, t, $J = 3.3$ Hz); 3.26 (3H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 169.47; 144.02; 137.62; 133.84; 132.13; 131.67; 123.29; 123.11; 122.74; 119.68; 71.74; 70.41; 68.80; 58.72; 49.53; 36.31. Elemental analysis calc. (%) for $C_{16}H_{21}N_3O_5S{\cdot}1.5\ H_2O$: C 48.72; H 6.13; N 10.65; S 8.13. Found: C 48.67, H 6.21; N 10.62; S 8.02.

[MOEOEMIM][ACES]. [MOEOEMIM][ACES] was obtained from [MOEOEMIM][Cl] (1 g, 4.5 mmol) and potassium acesulfame (1.28 g, 1.4 equiv.), as described for [(di-*h*)$_2$DMG][ACE], as a yellow oil (1.453 g, 92.5%).^{1}H-NMR δ ($CDCl_3$, 400 MHz): 9.39 (1H, s); 7.47 (1H, s); 7.29 (1H, s); 5.46 (1H, s); 4.41 (2H, t, $J = 4.5$ Hz); 3.93 (3H, s); 3.79 (2H, t, $J = 4.5$ Hz); 3.58 (2H, m); 3.46 (2H, m); 3.30 (3H, s); 1.99 (3H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 170.42; 161.98; 137.42; 123.16; 122.85; 101.39; 71.84; 70.43; 68.78; 58.77; 49.55; 36.29; 19.86. Elemental analysis calc. (%) for $C_{13}H_{21}N_3O_6S{\cdot}0.1\ H_2O$: C 44.71; H 6.12; N 12.03; S 9.18. Found: C 44.19, H 6.31; N 12.29; S 9.31.

[MOEOEMIM][SCN]. [MOEOEMIM][SCN] was obtained from [MOEOEMIM][Cl] (1 g, 4.5 mmol) and KSCN (0.68 g, 1.4 equiv.) as described for [(C_3O)$_4$DMG][SCN], as a yellow oil (0.99 g, 90.12%).^{1}H-NMR δ ($CDCl_3$, 400 MHz): 9.14 (1H, s); 7.53 (1H, s); 7.43 (1H, s); 4.41 (2H, t, $J = 3.3$ Hz); 3.97 (3H, s); 3.80 (2H, t, $J = 3.3$ Hz); 3.56 (2H, t, $J = 3.1$ Hz); 3.43 (2H, t, $J = 3.1$ Hz); 3.25 (3H, s). ^{13}C-NMR δ (100 MHz, $CDCl_3$): 136.65; 131.24; 123.13; 123.02; 71.27; 69.97; 68.45; 58.62; 49.64; 36.36. Elemental analysis calc. (%) for $C_{10}H_{17}N_3O_2S{\cdot}0.4\ H_2O$: C 47.94; H 7.16; N 16.77; S 12.80. Found: C 47.47, H 6.98; N 17.16; S 12.74.

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References

1 J. O. Duus, C. H. Gotfredsen and K. Bock, *Chem. Rev.*, 2000, **100**, 4589–4614.
2 G.-J. Boons and K. Hale, *Organic synthesis with carbohydrates*, Sheffield Academic Press, Sheffield, 2000.
3 S. Murugesan and R. J. Linhardt, *Curr. Org. Synth.*, 2005, **2**, 437–451.
4 F. Ganske and U. T. Bornscheuer, *Org. Lett.*, 2005, **7**, 3097–3098.
5 O. A. El Seoud, A. Koschella, L. C. Fidale, S. Dorn and T. Heinze, *Biomacromolecules*, 2007, **8**, 2629–2647.
6 J. Dupont, in *Green separation processes : fundamentals and applications*, ed. C. A. M. Afonso and J. G. Crespo, Wiley, Weinheim, Chichester, 2005.
7 *Ionic liquids : industrial applications for green chemistry* ed. R. D. Rogers and K. R. Seddon, American Chemical Society, Washington, D.C., 2002.
8 T. L. Greaves and C. J. Drummond, *Chem. Rev.*, 2008, **108**, 206–237.
9 M. A. P. Martins, C. P. Frizzo, D. N. Moreira, N. Zanatta and H. G. Bonacorso, *Chem. Rev.*, 2008, **108**, 2015–2050.
10 F. van Rantwijk and R. A. Sheldon, *Chem. Rev.*, 2007, **107**, 2757–2785.
11 S. A. Forsyth, D. R. MacFarlane, R. J. Thomson and M. von Itzstein, *Chem. Commun.*, 2002, 714–715.
12 R. M. Lau, F. van Rantwijk, K. R. Seddon and R. A. Sheldon, *Org. Lett.*, 2000, **2**, 4189–4191.
13 S. Park and R. J. Kazlauskas, *J. Org. Chem.*, 2001, **66**, 8395–8401.
14 N. Kimizuka and T. Nakashima, *Langmuir*, 2001, **17**, 6759–6761.
15 D. R. MacFarlane, J. Golding, S. Forsyth, M. Forsyth and G. B. Deacon, *Chem. Commun.*, 2001, 1430–1431.
16 Q. B. Liu, M. H. A. Janssen, F. van Rantwijk and R. A. Sheldon, *Green Chem.*, 2005, **7**, 39–42.
17 S. A. Forsyth and D. R. MacFarlane, *J. Mater. Chem.*, 2003, **13**, 2451–2456.
18 (*a*) S. H. Lee, D. T. Dang, S. H. Ha, W. J. Chang and Y. M. Koo, *Biotechnol. Bioeng.*, 2008, **99**, 1–8; (*b*) H. Zhao, G. A. Baker, Z. Y. Song, O. Olubajo, T. Crittle and D. Peters, *Green Chem.*, 2008, **10**, 696–705.
19 V. M. Egorov, S. V. Smirnova, A. A. Formanovsky, I. V. Pletnev and Y. A. Zolotov, *Anal. Bioanal. Chem.*, 2007, **387**, 2263–2269.
20 M. Matsumoto, K. Ueba and K. Kondo, *Sep. Purif. Technol.*, 2005, **43**, 269–274.
21 H. A. Aziz, A. H. Kamaruddin and M. Z. Abu Bakar, *Sep. Purif. Technol.*, 2008, **60**, 190–197.
22 N. Papaiconomou, J. M. Lee, J. Salminen, M. von Stosch and J. M. Prausnitz, *Ind. Eng. Chem. Res.*, 2008, **47**, 5080–5086.
23 D. Kogelnig, A. Stojanovic, M. Galanski, M. Groessl, F. Iirsa, R. Krachler and B. K. Keppler, *Tetrahedron Lett.*, 2008, **49**, 2782–2785.
24 J. McFarlane, W. B. Ridenour, H. Luo, R. D. Hunt, D. W. DePaoli and R. X. Ren, *Sep. Sci. Technol.*, 2005, **40**, 1245–1265.
25 A. Chapeaux, L. D. Simoni, T. S. Ronan, M. A. Stadtherr and J. F. Brennecke, *Green Chem.*, 2008, **10**, 1301–1306.
26 N. M. M. Mateus, L. C. Branco, N. M. T. Lourenco and C. A. M. Afonso, *Green Chem.*, 2003, **5**, 347–352.
27 L. C. Branco, P. M. P. Gois, N. M. T. Lourenco, V. B. Kurteva and C. A. M. Afonso, *Chem. Commun.*, 2006, 2371–2372.
28 R. Fortunato, C. A. M. Afonso, M. A. M. Reis and J. G. Crespo, *J. Membr. Sci.*, 2004, **242**, 197–209.
29 R. Fortunato, M. J. Gonzalez-Munoz, M. Kubasiewicz, S. Luque, J. R. Alvarez, C. A. M. Afonso, I. M. Coelhoso and J. G. Crespo, *J. Membr. Sci.*, 2005, **249**, 153–162.
30 P. S. Kulkarni, L. C. Branco, J. G. Crespo, M. C. Nunes, A. Raymundo and C. A. M. Afonso, *Chem.–Eur. J.*, 2007, **13**, 8478–8488.
31 L. C. Branco, J. N. Rosa, J. J. M. Ramos and C. A. M. Afonso, *Chem.–Eur. J.*, 2002, **8**, 3671–3677.
32 J. M. S. S. Esperança, H. J. R. Guedes, M. Blesic and L. P. N. Rebelo, *J. Chem. Eng. Data*, 2006, **51**, 237–242.
33 J. P. Mikkola, P. Virtanen and R. Sojholm, *1st International Conference on Ionic Liquids (COIL)*, Salzburg, Austria, 2005, pp. 250–255.