

University of South Bohemia in České Budějovice

Faculty of Science

**Biomolecular interactions at the surfaces in aqueous and
non-aqueous solutions**

Ph. D. Thesis

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České Budějovice 2023

This thesis should be cited as:

Aryafard, M., 2023: Biomolecular interactions at the surfaces in aqueous and non-aqueous solutions. Ph.D. Thesis Series, No. 8. University of South Bohemia, Faculty of Science, České Budějovice, Czech Republic, 179 pp.

Annotation

Knowledge of interactions in solvents helps to choose a good solvent, save time and costs to find a solution, and improve the efficiency of reactions. Understanding adding a co-solvent to another solvent is important as well because of their needs in several biological and chemical applications. This becomes more difficult when one of the solvents is an ionic solvent (DESs, ILs) which consists of several components.

MD simulation is a powerful technique to understand the physical nature of some interactions at the molecular levels in complex media. As well, solvatochromic parameters present useful knowledge of interactions by experimental methods.

Three famous DESs named reline, ethaline, and glyceline were chosen to measure their interactions with green co-solvents (water, PEG 400). Also, amino acid ionic liquids were studied as well.

This research was a combined experimental and theoretical study to see the agreement between the experimental and computational results.

Solvent-solvent, solute-solvent, solvatochromic parameters, preferential solvation model, and ions solvations were investigated in the binary mixtures of DESs/ILs with organic solvents.

Moreover, our knowledge resulted in synthesizing novel ILs and DESs with good benefits in several applications and some of usages were investigated.

Declaration

I hereby declare that I am the author of this thesis and that I have used only those sources and literature detailed in the list of references.

České Budějovice, 5. 5. 2023

Meysam Aryafard

This thesis originated from Faculty of Science, University of South Bohemia.



List of publications:

1. Aryafard, M.; Abbasi, M.; Řeha, D.; Harifi-Mood, A. R.; Minofar, B. Experimental and theoretical investigation of solvatochromic properties and ion solvation structure in DESs of reline, glyceline, ethaline, and their mixtures with PEG 400. *J. Mol. Liq.* **2019**, *284*, 59–67. <https://doi.org/10.1016/j.molliq.2019.03.149>, IF = 6.63. Percentage of contribution around 55%. MA performed the MD simulations, analysed the results, combined the experimental and theoretical studies, and wrote the paper.
2. Aryafard, M.; Jahanshahi, M. J.; Harifi-Mood, A. R.; Minofar, B.; Kuta Smatanova, I. Experimental and Theoretical Studies of Preferential Solvation of 4-Nitroaniline and 4-Nitroanisole in an Amino Acid Ionic Liquid with Molecular Solvents. *J. Chem. Eng. Data* **2019**, *64*, 5755-5764. <https://doi.org/10.1021/acs.jced.9b00719>, IF = 3.11. Percentage of contribution around 75%. MA synthesized the ionic liquids, and calculated the preferential solvation parameters, performed the MD simulations, combined the experimental and theoretical studies, and wrote the paper.
3. Aryafard, M.; Karimi, A.; Harifi-Mood, A. R.; Minofar, B. Molecular Dynamics Simulations, Solvatochromism and Preferential Solvation in Aqueous Solutions of Ethaline (DES), Ethylene glycol and Choline chloride. *J. Chem. Eng. Data.* **2020**, *65*, 4556-4566. <https://doi.org/10.1021/acs.jced.0c00381>, IF = 3.11. Percentage of contribution around 65%. MA offered the idea of aqueous mixtures of ethaline and its components, performed the MD simulations, combined the experimental and theoretical studies, and wrote the paper.
4. Borthakur, P.; Aryafard, M.; Zara, Z.; Reha, D.; Minofar, B.; Das, M.; Vithanage, M. Computational and experimental assessment of pH and specific ions on the solute solvent interactions of clay-biochar composites towards tetracycline adsorption: Implications on wastewater treatment. *J. Env. Man.* **2021**, *283*, 111989. <https://doi.org/10.1016/j.jenvman.2021.111989>, IF = 8.91. Percentage of contribution around 30%. MA did the MD simulations and wrote the computational part.
5. Aryafard, M.; Minofar, B.; Cséfalvay, E.; Malinova, L.; Řeha, D. Novel Room Temperature Ionic Liquids and Low Melting Mixtures Based on Imidazolium: Cheap

Ionic Solvents for Chemical and Biological Applications. *J. Mol. Liq.* **2021**, *344*, 117877. <https://doi.org/10.1016/j.molliq.2021.117877>, IF = 6.63. Percentage of contribution around 90%. MA had the idea of novel ionic solvents, synthesized the new ionic liquids and deep eutectic solvents based on imidazolium, and wrote the paper.

Co-author agreement

Babak Minofar, the supervisor of this Ph.D. thesis and co-author of papers fully acknowledges the stated contribution of Meysam Aryafard to these manuscripts.

České Budějovice,

Babak Minofar, Ph.D.

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List of Abbreviations used in this thesis.

Complete name	abbreviation	Complete name	abbreviation
Organic solvents	OS	Molecular Dynamics	MD
Ionic liquids	ILs	Visual molecular dynamics	VMD
Deep eutectic solvents	DESs	Monte Carlo	MC
Reichardt's dye	RC	Quantum mechanics	QM
4-nitroaniline	ANI	Density functional theory	DFT
4-nitroanisole	ANS	Kamlet-Taft	KT
Hydrochloric acid	HCl	Preferential solvation	PS
Ethylene glycol	EG	Radial distribution function	RDF
Glycerol	Gly	Root mean square deviation	RMSD
Polyethylene Glycol 400	PEG 400		
Acetonitrile	ACN	Nuclear magnetic resonance	NMR
Ethanolamine	ETA	Melting temperature	T_m
n-Hexane	n-H	Glass transition temperature	T_g
Cyclohexane	C-H	Decomposition temperature	T_d
Tetrahydrofuran	THF	Solvatochromic properties	SP
Glucose	Glc	Hydrogen bond acidity	α
Cellulose	Cel	Hydrogen bond basicity	β
Cellobiose	Clb	Polarizability	π^*
Choline	CHL	Normalized solvent polarity	E_T^N
Chloride	Cl ⁻	Biochar	B7, B17
First solvent	S1	Dielectric constant	ϵ_s
Second solvent	S2	Dipole moment	μ
Mixed solvents	S12	Acceptor normal	AN
Imidazolium chloride	ImCl	Donor normal	DN

CHAPTER 1

Solvents

1.1 Introduction

Outline of this thesis:

Deep eutectic solvents (DESs) and ionic liquids (ILs) have been interested in the most of reactions due to more efficiently and novelty compared to common organic solvents.

Although ILs and DESs are designer solvents, their interactions are not known, and it is needed to have knowledge of them before choosing the kind of solvent.

To have a good selection of ILs or DESs for a desired reaction, it is critical to know the features of ILs based on the structures and interactions. The lack of knowledge from these interactions is the limitation of ILs and DESs as sustainable solvents in industries and new laboratories research.

Variety of cations and anions in the structures of ILs and DESs cause them to be unpredictable. Moreover, their mixtures with organic solvents for some goals increase these interactions much more complex.

To understand some of these interactions in ILs and DESs, solute-solvent and solvent-solvent interactions in ILs and DESs and their mixtures with organic solvents were investigated. It was done by experimental and computational research. Moreover, a new series of ILs and DESs were synthesized, and some reactions were done in these solvents.

1.2 Solvents

Solutions consist of two parts: solutes and solvents. Solvents can be found in different phases such as liquid, gas, supercritical fluids, etc. [1-4]. The most common solvents are in the liquid phase. These liquids classify to different groups to be able to know their effects on reactions. Classification of solvents based on their structures and features is one of the fundamental methods. In this categories, different physical or chemical features can be considered. Melting point, boiling point, density, viscosity, volatility, and on top of them polarity are the most ways to categorize solvents. Each method follows different principles. Here, we focus on the polarity as the major applicable method.

1.2.1 Polarity of solvents

Polarity can be described in different ways; some methods are using dielectric constant (ϵ_s), dipole moment (μ), and acceptor normal (AN) or donor normal (DN) for pair of electrons compared to SbCl_5 and Et_3PO as references [3-9]. These parameters are shown in Table 1 for some organic solvents (OS). The amount of AN for water is more than the other solvents displayed in Table 1, but the amount of DN is not in the same trend and it is less than alcohols. Each method includes a different order for classifications of solvents. E.g., by considering either ϵ_s or μ , the order changes and some solvents are in the different trends (Table 1). Hence, a method which involves more parameters to introduce solvents properties can solve this problem in classification of solvents [10-15].

1.2.2 Solvatochromic properties

The most common method to classify solvents and especially to calculate polarity is determination the solvatochromic properties (SP). SP includes empirical polarity and Kamlet–Taft parameters. These parameters are E_T^N , normalized solvent polarity; π^* , dipolarity/polarizability; α , hydrogen bond acidity; β , hydrogen bond basicity. The SP can be calculated from the wavelengths shifts of different solvatochromic probe dyes. The most famous dyes are 2,6-Diphenyl-4-(2,4,6-triphenylpyridinium-1-yl) phenolate (Reichardt's dye) (Figure 1), 4-Nitroaniline and 4-nitroanisole (Figure 2), [9-11, 16-23].

Table 1. Dipole moment (μ), dielectric constant (ϵ_s), donor normal (DN) and acceptor normal (AN) constants, melting point (mp) and boiling point (bp) for some OS [3-5].

Solvents	AN	DN	ϵ_s	μ	mp(°C)	bp(°C)
Water	54.8	0.46	78.3	1.82	0	100
Methanol	41.5	0.77	32.7	1.70	-98	65
Ethanol	37.9	0.82	24.5	1.69	-114	78
Acetonitrile	18.9	0.36	35.9	3.45	-44	82
Acetone	12.5	0.44	20.7	2.85	-95	56
Ethyl acetate	9.3	0.44	6.0	1.88	-84	77
Tetrahydrofuran	8.0	0.52	7.6	1.75	-109	66
Diethyl ether	3.9	0.49	4.2	1.30	-117	35
Dichloromethane	20.4	0.03	8.9	1.55	-95	40
Chloroform	23.1	0.10	4.8	1.15	-64	61
Benzene	8.2	0.01	2.3	0.0	5	80
Cyclohexane	0.0	0.00	2.0	0.0	6	81
Hexane	0.0	0.00	1.9	0.0	-94	69

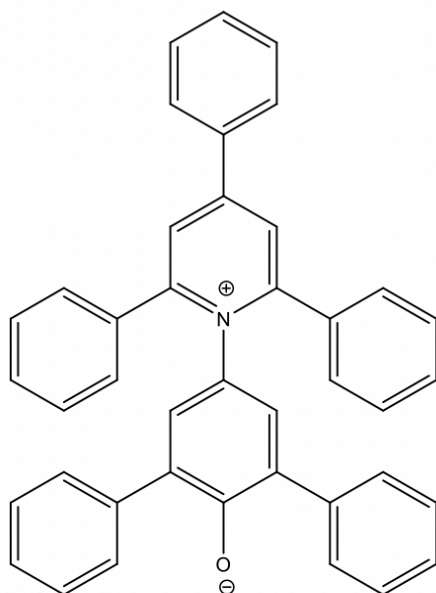


Fig. 1. The Reichardt's dye (Betaine 30) as a famous probe for measuring the polarity of solvents.

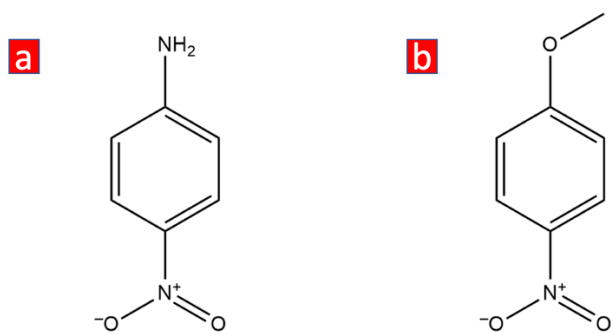


Fig. 2. Structures of 4-nitroaniline (a), and 4-nitroanisole (b) as probe dyes.

When solutes (probes in Figures 1 and 2) experience different microsphere solvations, result in change of their spectra (UV-Vis region). In some case (especially for Reichardt's dye), the shifts of wavelengths are large, and probes have different colors by changing the solvents. Therefore, this phenomenon is named solvatochromism [20-26].

Changes of the polarity and hydrogen bond ability of solvents have the major effects on shifting the wavelengths of solutes by affecting on their ground/excited electronic states.

Here, it is mentioned how SP are calculated by the wavelengths.

$E_T(30)$, also it is called the empirical polarity parameter of solven, is extremely sensitive to the hydrogen bond donor ability of solvents [20-26], $E_T(30)$ in kcal.mol⁻¹ can be calculated according to equation 1:

$$E_T(30) / \text{kcal.mol}^{-1} = 2.8591\vartheta_B \quad (1)$$

where ϑ_B is the wavenumber of the maximum absorption related to the charge transfer energy of Reichardt's dye. The amount of $E_T(30)$ is normalized by utilizing of two solvents as references: water ($E_T^N = 1$) and tetramethylsilane ($E_T^N = 0$).

Moreover, E_T^N is easier than $E_T(30)$ to be uses because it is a unitless factor and indicates both the dipolarity/polarizability and the HBD ability of the media (equation 2).

$$E_T^N = \frac{E_T(\text{solvent}) - E_T(\text{TMS})}{E_T(\text{water}) - E_T(\text{TMS})} = \frac{E_T(\text{solvent}) - 30.7}{32.4} \quad (2)$$

Kamlet-Taft parameters:

The empirical Kamlet-Taft parameters involve π^* , β , and α parameters [20-26]. They show the normalized values like E_T^N , were calculated from the wavenumbers of maximum absorption of 4-nitroanisole (ϑ_{ANS}), 4-nitroaniline (ϑ_{ANI}), and Reichardt's dye (ϑ_B), respectively in solvent mixtures according to equations 3-5:

$$\pi^* = 0.427(34.12 - \vartheta_{\text{ANS}}) \quad (3)$$

$$\beta = \frac{31.10 - 3.14\pi^* - \vartheta_{\text{ANI}}}{2.79} \quad (4)$$

$$\alpha = 0.186(10.91 - \vartheta_B) - 0.72\pi^* \quad (5)$$

Solvents polarities which are calculated by the SP have the most trustable amounts between all methods. Table 2 shows some of the Kamlet-Taft parameters related to the OS [20-26].

Table 2. The solvatochromic parameters for some OS [4, 20-25].

Solvents	α	β	π^*	$E_T(30)$
Water	1.17	0.47	1.09	6.31
Methanol	0.98	0.66	0.60	5.54
Ethanol	0.86	0.75	0.54	5.19
n-Propanol	0.84	0.90	0.52	5.07
Dimethyl sulfoxide	0.00	0.76	1.00	4.51
Acetonitrile	0.19	0.40	0.75	4.56
Acetone	0.08	0.43	0.71	4.22
Ethyl acetate	0.00	0.45	0.55	3.81
Tetrahydrofuran	0.00	0.55	0.58	3.74
Dichloromethane	0.13	0.10	0.82	4.07
n-Hexane	0.00	0.00	- 0.04	3.10
C-Hexane	00	0.00	0.00	3.09
triethylamine	00	0.71	0.14	3.21
Chloroform	0.20	0.10	0.58	3.91
Benzene	0.00	0.10	0.59	3.43
Toluene	0.00	0.11	0.54	3.39
Formic acid	1.23	0.38	0.65	5.77
Acetic acid	1.12	0.45	0.64	5.52

1.3 Preferential solvation model

Preferential solvation (PS) model parameters in terms of solute-solvent interactions are being determined by the measuring hypsochromic or bathochromic shifts of the chromophore probes (Figure 3) [27-33]. In binary mixtures of ILs and DESs with molecular solvent, the solvent-solvent interactions are much complicated than binary OS. Therefore, they affect solute-solvent interaction and PS [27-33]. Hence, synergism behaviors in binary mixtures of DESs are more probable than ordinary mixtures. These deviations arise because of the difference between the microsphere solvation of the solute and bulk compositions.

PS model is based on a simple exchange of solvents in solvation shells of probe dyes according to the following equations



where I stand for the probes (Reichardt's dye, 4-nitroaniline, and 4-nitroanisole), S1 (the first solvent), S2 (the second solvent), and S12 the composite structure of solvents (ILs/DESs + an organic solvent). I(S1), I(S2) and I(S12) display the probes solvated by each solvent. Eq. 6 reflects the total exchange of the first solvent by the second one in the solvation shell of the probes, and eq. 7 comes to the exchange by the mixed solvents. PS parameters are obtained based on the solvatochromic equilibrium constants of solvent exchange molecules according to eqs 8-10.

$$f_{2/1} = \frac{x_2^s/x_1^s}{(x_2^0/x_1^0)^2} \quad (8)$$

$$f_{12/1} = \frac{x_{12}^s/x_1^s}{x_2^0/x_1^0} \quad (9)$$

$$f_{12/2} = \frac{f_{12/1}}{f_{2/1}} \quad (10)$$

where x_1^0 and x_1^s refer to the mole fraction of each solvent in bulk and microsphere solvation of the solute respectively. Therefore, the wavenumber of maximum absorption of solvatochromic probes in the solvent mixtures can be calculated as a function of PS parameters. PS model was used for the mixtures of DESs or ILs with organic solvents and the results are explained comprehensively in the literature [27-33]. In the next sections, ILs and DESs were explained.

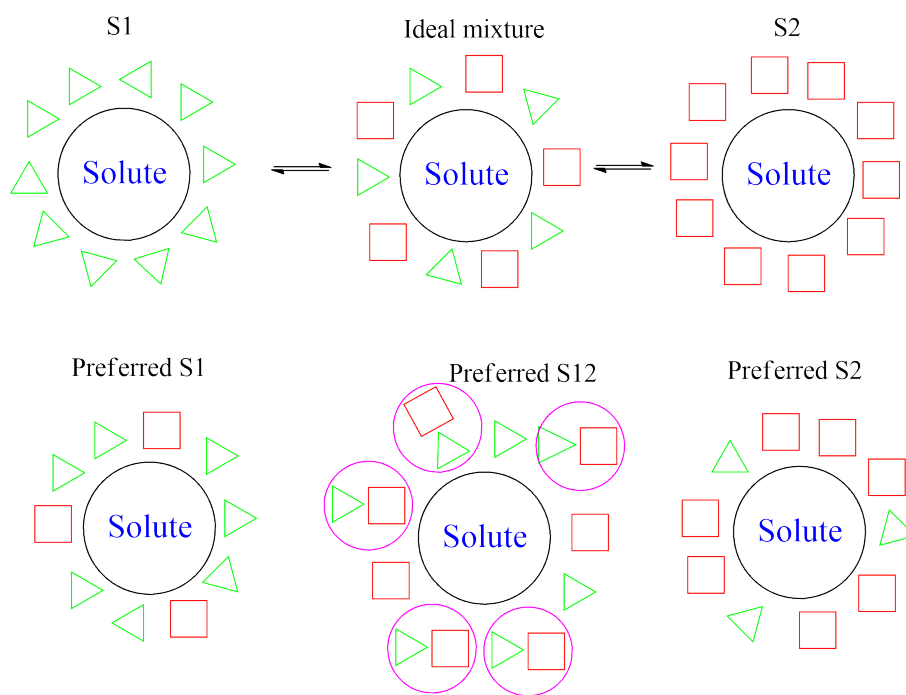


Fig. 3. Showing the preferential solvation model in binary solvents. The presence of first solvent (triangle), second solvent (square), and combination of first and second solvents (circle). Coordination numbers of each solvent at the microsphere solvation of probes were calculated by MD simulations [33].

1.4 Ionic Liquids

Ionic liquids (ILs), organic molten salts, are salts with the melting points lower than 100 °C. They have been used widely as sustainable solvents [34-42]. Not only currently ILs are using in industries and laboratories, but they are also utilizing in environment protection, global warming, and air pollution [43-49]. Hence, they can be sustainable and designer solvents for future. ILs consist of organic cations or anions (Figure 4). The first IL synthesized by Gabriel in 1888 and it was ethanolanmonium nitrate with the melting point 52 °C [50-52]. ILs with melting points near to 25 °C are called room temperature ionic liquids (RTILs). The first RTIL was ethylammonium nitrate, synthesized by Walden (1914), with the melting point 12 °C [50-52].

ILs have shown considerable performance as solvents because of their remarkable properties (high thermal stability, no vapor pressure, high electrical conductivity, polarity, etc.) [52-57]. ILs have been used in various applications such as organic synthesis [58], catalysts [58-61], biocatalysis [62], extraction, separation [63,64], green solvents, electrolytes (to improve the thermal stability of batteries instead of OS), lubricants, and additives in a variety of usages (Figure 5) [65-71]. Also, they have been used for biomass. In this context, ILs have been shown to dissolve cellulose more efficiently than molecular solvents [72-79].

Among ILs, dialkyl imidazolium acetate is one of the most efficient ILs for cellulose dissolution [77], that is because of acetate anion which can break the hydrogen bond interactions between hydroxyl groups of cellulose. Therefore, it is a selective IL for this goal, and it is explained in the next section comprehensively. ILs have been described as designer solvents; by choosing the kind of cation or anion that is possible to tune an IL for practical applications [76-79].

Interest in ILs was developed by the discovery of ILs based on dialkyl imidazolium cations [80-83]. Due to low degree of symmetry, good distribution of charge, low intermolecular interactions of cations and anions, the lattice energy of the crystal salt reduces. Therefore, the melting points of these salts (ILs) decreases.

A simple change to the structure of the ions causes to alter the properties such as melting point, viscosity, density, hydrophobicity, etc. and makes them favorable for the reactions [84-89]. For example, the melting points of 1-alkyl-3-methylimidazolium tetrafluoroborates [90] and hexafluorophosphates [91] depend on the length of the alkyl groups. Another important thing that changes with structures is the miscibility of water in these ionic liquids. E.g., 1-alkyl-3-methylimidazolium tetrafluoroborate ILs are miscible with water at 25 °C where the alkyl chain

length is less than 6, but more than 6 carbon atoms, they are immiscible. This behavior can be of substantial benefit when carrying out solvent extractions or product separations, as the relative solubilities of the ionic and extraction phase can be adjusted to make the separation as easy as possible.

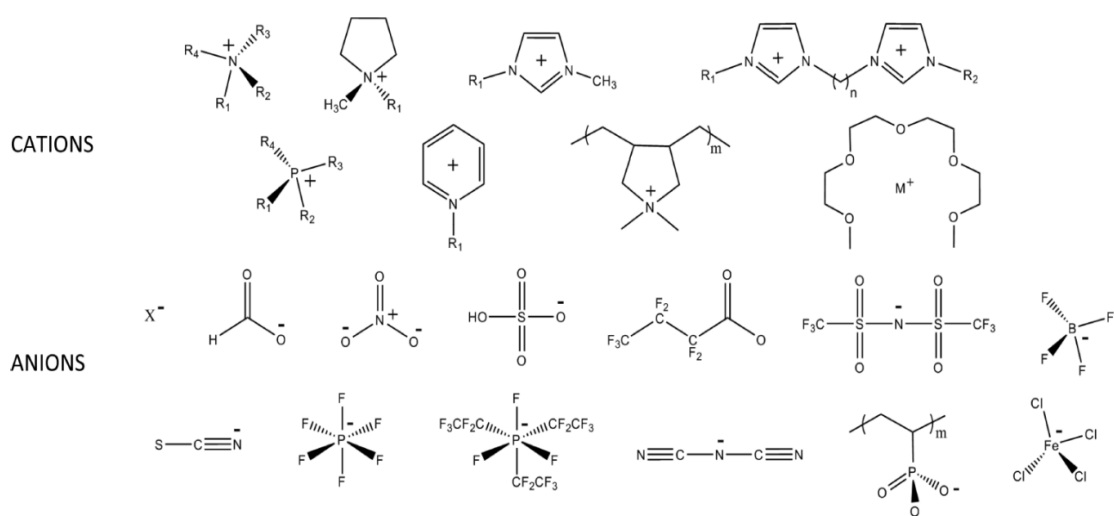


Fig. 4. Shows some common cations and anions in the structures of ILs. From left to right, the cations (top row) include: ammonium, pyrrolidinium, 1-methyl-3-alkylimidazolium, 1,3-bis[3-methylimidazolium-1-yl]alkane; (second row) phosphonium, pyridinium, poly(diallyldimethylammonium), metal (M⁺) tetraglyme. The anions include (third row) halides, formate, nitrate, hydrogen sulfate, heptafluorobutyrate, bis(perfluoromethylsulfonyl)imide, tetrafluoroborate, (bottom row) thiocyanate, hexafluorophosphate, tris(pentafluoroethyl)trifluorophosphate, dicyanamide, poly(phosphonic acid), and tetrachloroferrate [92].

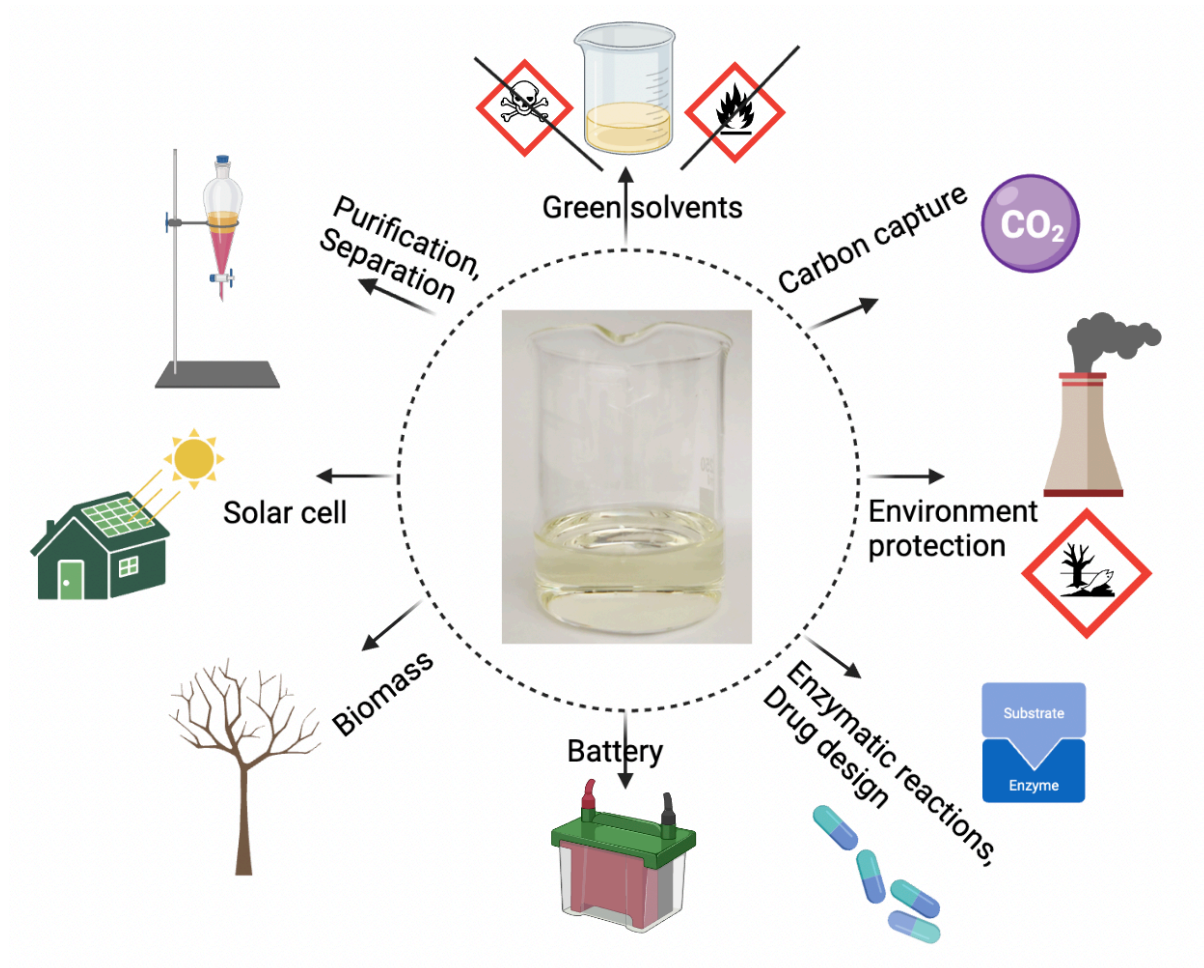


Fig. 5. Application of ILs in several processes.

1.5 Deep eutectic solvents

Deep eutectic solvents (DESs) have been applied in close research works like ILs because of near properties such as non-flammability, low toxicity, low vapor pressures, wide temperature usage, biodegradable, and good solubility for materials [93-99]. Due to these close properties of DESs to ILs, they are also described as a new category of ILs and have been used in the same applications (Figure 5) [100-104]. It is necessary to point out that these are two different kinds of solvents, and they are not same. ILs are liquid salts composed of anion and cation (they were introduced in previous section) but DESs are the mixtures of some components which can be neutral or ionic (Figure 6).

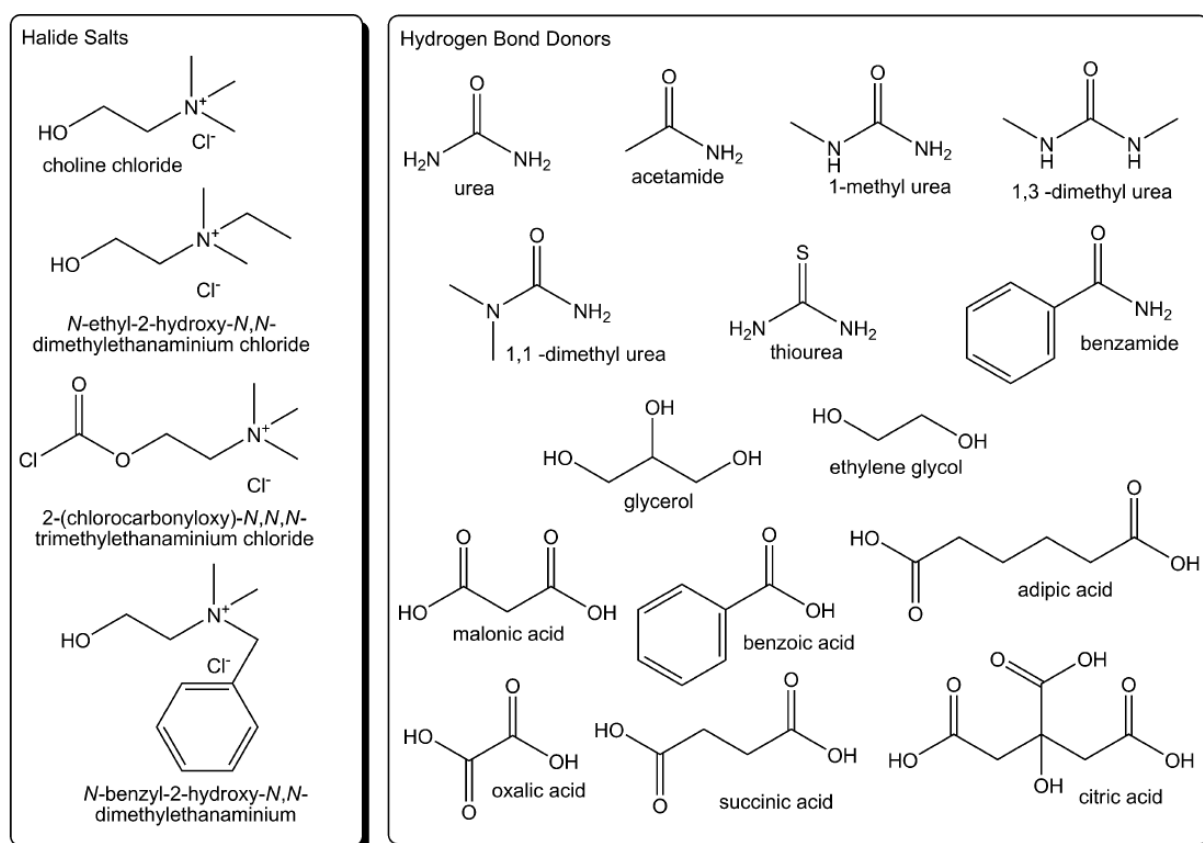


Fig. 6. Structures of some halide salts and hydrogen bond donors used in the formation of deep eutectic solvents [93].

DESs have been synthesized with ionic and non-ionic components and they can be classified based on their components [101-103].

- Salts + metal halides
- Salts + metal halide hydrates
- Salts + hydrogen bond donors
- Non-ionic component + non-ionic component

Although DESs have the possibility to be a mixture of different components, it is important to notice the most of mixtures does not provide any homogenous liquid with a eutectic point. Hence, there are some restrictions for having a desirable DES by choosing the components. So far, most of DESs have been prepared with quaternary ammonium salts and HBDs (Figure 6). Abbott et al. were the pioneer group in designing and synthesizing new DESs. They tried several components to find a new DES (Table 3). One of the fantastic DESs (reline) was the mixture of choline chloride and urea with the mole fraction of 1:2 which has a eutectic point 12 °C; the melting point of choline chloride is 303 °C and urea 134 °C [93].

Due to low toxicity, and cheap source of choline chloride, it was the most interested compound between salts in the structures of DESs [105,106]. Also, it can provide DESs with a wide range of HBDs such as amides, carboxylic acids, and alcohols (Figure 6).

The charge delocalization between a halide ion and the hydrogen donor component is responsible for decreasing the melting point of the mixture relative to the melting points of the individual components; also, hydrogen bond interactions is another reason [93, 107]. A study by Abbott et al. in 2001, a range of quaternary ammonium salts were heated with ZnCl₂ and the melting points of the resulting liquids measured. It was found that the lowest melting point, 23–25 °C, was obtained when choline chloride was used as the ammonium salt [107-111].

As it was explained for ILs, DESs have the possibility to tune their properties by choosing their components.

Mixtures of menthol and thymol with the mole fractions of 1:1 or 1:2 show a eutectic point. These DESs are hydrophobic DESs which are very useful as non-aqueous media [112-114]. Vies-versa, DESs based on choline chloride are hydrophilic DESs which are very useful as aqueous mixtures for proteins applications.

Table 3. The melting points (°C) of some DESs and their components [93].

Halide salt	salt	molar		DES (°C)
		HBD	HBD	
ChCl	303	urea	134	12
ChCl	303	thiourea	175	69
ChCl	303	1-methyl urea	93	29
ChCl	303	1,3-dimethyl urea	102	70
ChCl	303	1,1-dimethyl urea	180	149
ChCl	303	acetamide	80	51
ChCl	303	banzamide	129	92
ChCl	303	ethylene glycol	-12.9	1:2
ChCl	303	glycerol	17.8	1:2
ChCl	303	adipic acid	153	1:1
ChCl	303	benzoic acid	122	1:1
ChCl	303	citric acid	149	1:1
ChCl	303	malonic acid	134	1:1
ChCl	303	oxalic acid	190	1:1
ChCl	303	phenylacetic acid	77	1:1
ChCl	303	phenylpropionic acid	48	1:1
ZnCl ₂	293	urea	134	9
ZnCl ₂	293	acetamide	81	-16
ZnCl ₂	293	ethylene glycol	-12.9	-30
ZnCl ₂	293	hexanediol	42	-23

Moreover, some physical and chemical properties can be changed by the kind of components. These changes are beneficial to be used in different application e.g., CO₂ capture, extraction, etc. [115-121].

1.6 Future solvents

Ionic liquids and deep eutectic solvents have extremely desirable properties which make them better than organic solvents. These solvents have been tested, applied, and granted in different research areas (energy storage, biosensors, devices, removal of glycerol from biodiesel, processing of metal oxides and the synthesis of cellulose derivatives). Indeed, they are sustainable future solvents as the research in ILs and DESs has been growing significantly. Due to close applications of ILs and DESs in old research they were considered as the same solvent while it is clear now that they are two different kinds of solvents with incredible properties. All these properties need to be known more and more in microscopic level to know what is happening and have a better idea for synthesizing new ILs.

We used computational methods to study the interactions in DESs and ILs and finally a good knowledge in this area led to discover novel ILs and DESs.

CHAPTER 2

Simulation theory

2.1 Simulation Theory

Molecular Dynamics (MD) and Monte Carlo (MC) simulations have become the strong tools which are connecting experimental and theoretical studies. In general, MD and MC methods deal with the study of materials in a different ranges of size scales from micrometer to larger scales [122-130]. Generally, both these methods are being used to analyze the the simulated system to find dynamic and thermodynamic properties (e.g., energy, pressure, volume, diffusion constant, thermal conductivity etc.) [128-135]. Although there some difference between the methods and procedures, the results of these methods are comparable.

In MD simulations, phase space is achieved by solving the Newton's equations of motion. The positions of atoms/molecules in the simulation box are connected to find the trajectories of the atoms/molecules. These positions are calculated as a function of time. While in MC, the phase space is generated by random changing of coordinates of the system. It does not have any deal with Newton's equations, the trajectories, and function of time. MC calculate the properties based on Boltzmann factor.

$$\rho = \frac{e^{-\varepsilon_i/kT}}{\iint e^{-\varepsilon_i/kT} dpdr} \quad (11)$$

The trial movements are considered to make the future configuration of the system if the energy of new configuration is less than the old one. If not, the temperatures and energies should be considered to know the new configuration is accepted or rejected [122].

In the other words, the new movement is accepted if $E_{n+1} < E_n$.

If the $E_{n+1} > E_n$, we have two possibility to accept or reject the new position.

In this case a random number, R, is generated which has the value between zero and one

$$0 < R < 1.$$

If $R < \exp(-(E_{n+1} - E_n)/kT)$, results this movement is accepted.

If $R > \exp(-(E_{n+1} - E_n)/kT)$, results this movement is rejected.

There are some comparisons to know the abilities of MC and MD simulations. The advantages of MC to MD are no need to evaluate the forces and sampling based on Boltzmann distribution. In contrast, time independent of MC to calculate the properties related to time make it less

efficient compared to MD. Moreover, there is a bit change in the ensembles of MC and MD simulations [122, 128-132].

Molecular simulations showed good correlations between the macroscopic properties of materials from microscopic level statistical thermodynamics [136-140].

These properties from molecular simulations can decrease the costs and difficulty of experiments [136-140]. Also, molecular simulations showed good results for calculating the properties of solvents (DESSs, ILs, OS) such as density, diffusion coefficients, viscosity, surface tensions [141-158], and the structures [159-163].

Because of success of MD simulations to find these properties of ILs and DESSs, this method was used in our studies to calculate the properties of DESSs, ILs, and OS.

2.2 Molecular Dynamics Simulation

Using MD simulations as a major tool for computational research in various fields have been increased (biology, chemistry, physics, material science, etc.) [164-171].

For doing MD simulations, different software packages are available such as GROMACS, NAMD, LAMMPS, and etc [172-176]. In our works, we used GROMACS package [172- 174]. To find the trajectories and phase space with any MD software we need to have an algorithm of movements.

2.3 Equations of Motion

In MD simulation, a time-dependent trajectory is generated with coordinates and velocities of all particles in the system by solving the Newton's equation:

$$F = ma, \quad m \frac{d^2x}{dt^2} = -\nabla U, \quad \frac{d^2r}{dt^2} = \frac{F_i}{m_i}, \quad F = -\nabla U \quad (12)$$

where F_i is the force acts on the particle i , m_i is its mass, and 2nd derivative ratio of r to t is the acceleration on particle i , a_i .

For the present positions of particles, MD examines the interactions and calculate the forces by gradient of energies (equation 12). Then, we need to solve the equation of motions to find the

next coordinates and velocities/momenta of particles. MD repeats these steps to reach the time of simulations.

Various algorithms have been developed and used to integrate the equations of motions.

The famous algorithms are Verlet algorithm, Leap frog algorithm, and Gear's predictor corrector.

There are some differences between them which are calculating based on coordinates, velocities, and accelerations that are estimated by a Taylor's expansion (equation 13) [177-179].

$$f(x) = \sum_{k=0}^{\infty} \frac{f^{(k)}(x_0)}{k!} (x - x_0)^k \quad (13)$$

Regarding the differences of algorithms, the fast process achieved by Verlet algorithm. The explicitly of velocities is in Leap frog algorithm and lack of velocities in Verlet algorithm. Also, the possibility to calculate large time step can get by Gear's predictor corrector.

In our simulations, we used the Verlet algorithm [177]:

$$r(t + \delta t) = r(t) + v(t)\delta t + \frac{1}{2}a(t)\delta t^2 + \dots \quad (14)$$

$$r(t - \delta t) = r(t) - v(t)\delta t + \frac{1}{2}a(t)\delta t^2 - \dots \quad (15)$$

Sum of these two equations 14 and 15 gives:

$$r(t + \delta t) = 2r(t) - r(t - \delta t) + a(t)\delta t^2 \quad (16)$$

The equations 14-16 show MD simulations process the coordinates derived from the previous ones in the trajectory with a time step. The choice of time step (δt) is an important part in any MD simulation. If δt be too short, the simulations will be so slowly and time demanding. If δt be too long, we will have errors. The reasonable δt considers the maximum δt as possible with acceptable errors in order the integration algorithm conserves the total energy of the system.

Therefore, to achieve numerical stability and to avoid errors in the calculation of forces in simulations, it is recommended that δt corresponds to 1/10 of the fastest vibration motion of

the system. In the most of systems, the fastest vibration are C-H vibrations with the periodicity of 10 fs; dividing this amount by 10 gives the time step of 1 fs.

$\delta t \leq 1\text{fs}$ is recommended for investigations the vibrations of hydrogens. A larger time step of $\delta t = 2\text{fs}$ can be achieved if the vibrations of hydrogen is not interested (by constraining the position of hydrogen atoms to the equilibrium bond lengths with the corresponding heavy atoms) [174,180].

2.4 Molecular Mechanics Force Fields

As it mentioned before, in MD simulations, the next state of the system is generated by its present state by solving the Newton's equations of motions. These particles (atoms/molecules) are interacting each other with a potential energy function which is called force field. Therefore, force fields describe the energy of a system as a function of coordinates. Forces are calculated as the gradient of the potential energy ($F = -\nabla U$).

(It is good to mention that without the Born-Oppenheimer approximation, it is impossible to solve the Schrodinger equation to calculate the energy as a function of the nuclear coordinates). By using this approximation, the total energy equals the sum of the nuclear energy and the electronic energy. In the force field method, just energy of nuclear are being integrated [181]. Forcefields have been developed from the earliest force field (Figure 7) to the advanced ones.

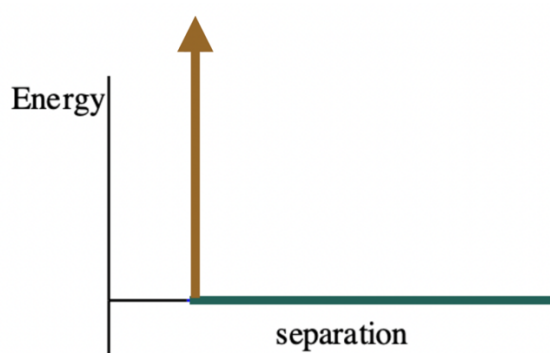


Fig. 7. The earliest force field (hard sphere) included the interactions only in collisions. It was not included the van der Waals and electrostatic interactions.

Due to the lack of some interactions in primary force fields and needs to develop MD simulations for some applications, force fields have been improved. AMBER, CHARMM, OPLS, MM3, MMFF94 are some famous applied force fields [182-189]. In our simulations, we used AMBER force field (equation 17).

$$\begin{aligned}
 E(r^N) = & \underbrace{\sum_{\text{bonds}} \frac{k_i}{2} (l_i - l_{i,0})^2 + \sum_{\text{angles}} \frac{k_i}{2} (\theta_i - \theta_{i,0})^2 + \sum_{\text{torsions}} \frac{V_n}{2} (1 + \cos(nw_i - \gamma_i))}_{\text{Bonding interactions}} \\
 & + \underbrace{\sum_{i=1}^N \sum_{j=i+1}^N 4 \epsilon_{ij} \left(\left(\frac{\delta_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\delta_{ij}}{r_{ij}} \right)^6 \right) + \sum_{i=1}^N \sum_{j=i+1}^N \frac{q_i q_j}{4\pi \epsilon_0 r_{ij}}}_{\text{Non-bonding interactions}}
 \end{aligned}$$

Stretching Angles Dihedrals
 Van der Waals Electrostatics

(17)

All these force fields include two parts: bonding and non-bonding interactions.

Bonding interactions consist of stretching, angles, and dihedral bonds. Non-bonding interactions involve electrostatic and Lennard-Jones interactions.

Most of these force fields are based on harmonic approximation and there is a bit difference in dihedral angles or non-bonding interactions. AMBER force field shows energy of the system, $E(r^N)$, as the sum over all bonded and non-bonded interactions. It consists of the summation of stretching, angle, torsion, van der Waals and Coulomb interactions. In the equation 17, δ_{ij} and ϵ_{ij} are the Lennard-Jones parameters between atoms i and j , the distance between atoms i and j is r_{ij} , ϵ_0 (the dielectric constant), q_i and q_j are the partial charges of atom i and j . Non-bonding interactions are the most time-demanding parts of MD simulations because it calculates the interaction of inter and intra for all atoms of particles in a system. As the number of particles in a system increase, the time increase as well.

This part of interactions takes the most of CPU for doing MD simulations. Although graphics processing units (GPUs) can speed the performance of simulations [190-193], the necessary of using the cut off for the interactions are still desirable. The first reason is no possibility to

consider unlimited interactions in a system especially when we are using a periodic boundary condition (PBC). In PBC, it is possible to perform the simulations with a few numbers of particles (a unit cell) like a huge real system. PBC consist of infinite numbers of unit cells (Figure 8). All necessary algorithms regarding PBC were included in the GROMACS package [194-196]).

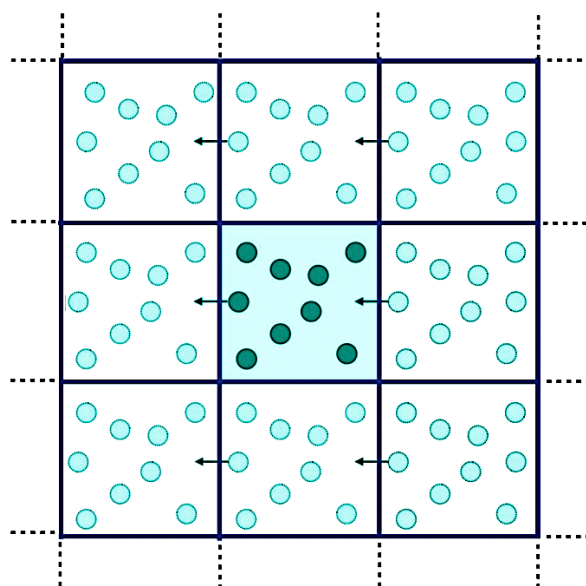


Fig. 8. The periodic boundary condition; leaving a particle in the cell from one side and entering to the cell from the opposite side.

The second reason is nature of reactions which is not needed to consider in very long distances. Therefore, it is critical to cut them and increase the speed of MD simulations.

In most of reported MD simulations, favorable nonbonded interactions have distance cutoffs between 8-15 Å. These cutoffs help to reduce the number of pairwise interactions and increase the speed of calculating the forces [197-199], In our simulations, we considered distances cutoffs ≥ 10 Å.

Although simple functions are used to show the interactions in a system, they can estimate the potential energy well for a system. Moreover, it is possible to improve some parts of these force fields depend on the desirable properties.

As it was mentioned before, in force fields, we ignore the energy of electrons and calculate the energy of nuclear positions. Hence, it speeds calculating the energy and makes it possible to perform simulations for millions of atoms.

In contrast, quantum mechanics (QM) calculate the energy of electrons by solving the Schrodinger equation [200]. QM gives more accurate energy compared to MM for a few numbers of atoms. [122, 201–206]. Although QM cannot be used to calculate the energy of a large system with thousands of atoms, it helps to improve force field parameters such as equilibrium bond lengths (l_i), force constants (k_i), the atomic charge of particles [207]. Using QM or MM depends on the favorable properties. In some cases, it is possible to benefit from the advantages of molecular mechanics (MM) and QM by the hybrid of QM/MM.

This hybrid works well for the mechanism of some enzyme reactions [208-210]. Also, for using this hybrid method some tricks for non-bonded, truncated, and neighbor interactions are needed [211,212]. The comparison between the QM and MM methods is not the goal of this thesis and it was only explanation of supportive effects of QM for doing MD simulations. The final part of any MD simulation is a trajectory file which include information of the system to be analyzed. For visualization of MD simulations trajectories, it is needed to have a graphics program [213,214]. For our simulations, we used the VMD (visual molecular dynamics) program as it is a free and the most common program for MD simulations [214].

Commands which are commonly used in GROMACS for doing MD simulations, and analyzing the trajectories are in the appendix.

Radial distribution function (RDF) and root mean square deviation (RMSD) are the most common tools to analyze the trajectories of MD simulations.

RMSD shows the average distance between two atoms or molecules, and it can easily represent by the equation 18.

$$\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad (18)$$

In the equation 18, d_i shows the distances between two desired atoms/molecules. The number of pairs represent by n .

RDF makes it possible to understand the solvation structures of molecules and ions in MD simulations. Its function works by calculating the average number of particles contained in a spherical shell from any reference particle (spherical shell with thickness δr and distance r) [215-218].

$$4\pi n \int_r^{r+\delta r} r^2 g(r) dr \quad (19)$$

where n shows the ion number density. In RDFs, at far distance the integration goes to one. By considering $g(r) = 1$, then:

$$\frac{4}{3} \pi n [(r + \delta r)^3 - r^3] \quad (20)$$

It means, if $g(r) = 1$, the number of expected ions in the shell equals $n \times V_{\text{shell}}$ (number density multiplied by the volume of the spherical shell).

CHAPTER 3

Results and discussion

3.1 Published results

Solute-solvent, solvent-solvent interactions, ion delocalization, hydrogen bond interactions, and solvation structures.

My studies included the finding of the interactions in complex media. The presences of different cations, anions, and HBDs in the structures of DESs/ILs, and variety intermolecular interactions make DESs/ILs very complicated. Adding reactants to these media and understanding what are happening are impossible without any background and knowledge of their interactions. Solvents components, and solute-solvent interactions give a comprehensive insight of these complicated solvents.

MD simulations were applied to find ion delocalization, hydrogen bond interactions, solute-solvent, and solvent-solvent interactions, PS model, and shifts of solvatochromic parameters [33, 219,220].

To analyze some of these interested features, RDF is a strong tool.

RDFs have been used for understanding the solvation structures, and ions delocalization in DESs of reline, ethaline, and glyceline. In DESs, it was found out although Cl^- ions can make contact ion pair with choline ammonium, interactions with hydroxyl of choline are more probable (Figure 9). Also, the Cl^- interactions with functional groups of HBDs are another highlighted factor on changing and tuning properties of DESs. All these DESs with choline chloride showed a similar trend which can be used to have a glue for the other DESs with the same HBA (salt) but different HBDs.

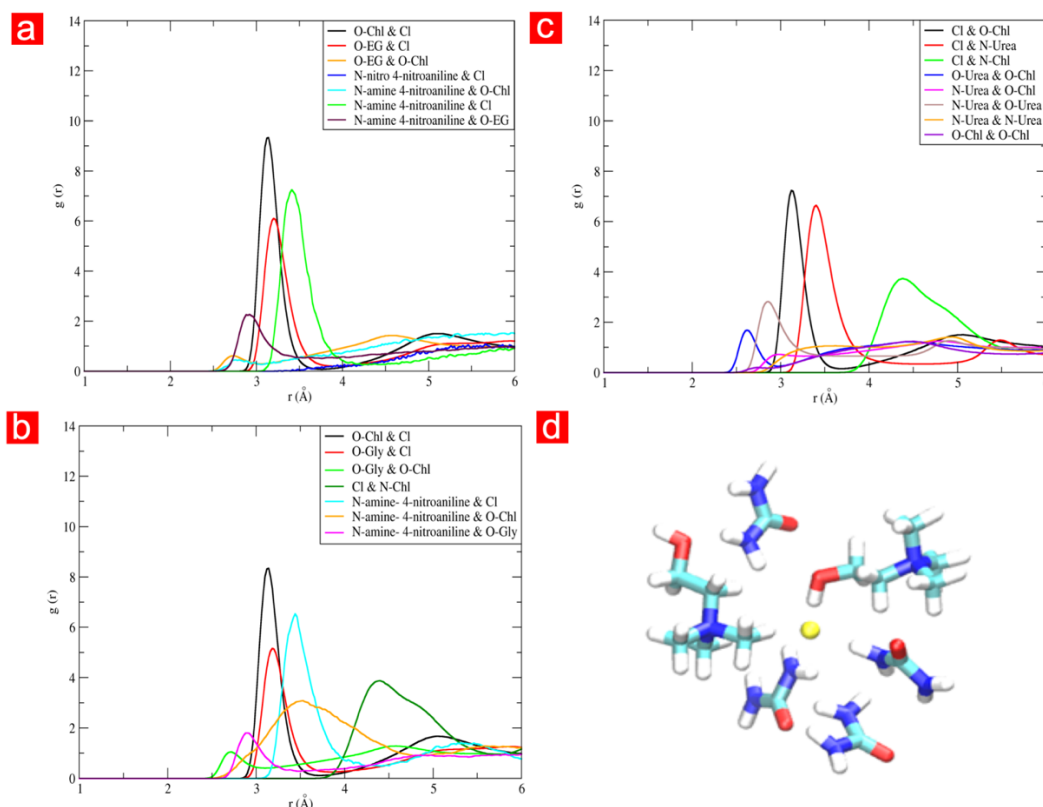


Fig. 9. RDFs of functional groups in ethaline (a), glycine (b), and reline (c). Snapshot from MD simulation showing the coordination shell of Cl^- ion (yellow color) by urea and choline in the DES of reline (d) [219].

Also, RDFs of DESs in Figure 9 confirm that the interaction of Cl^- ion on hydroxyl groups of choline is slightly more probable than the hydroxyl groups of ethylene glycol, glycerol and amine groups of urea.

The hydroxyl of choline and Cl^- has an intense correlation peak at $\sim 3.1 \text{ \AA}$. This shows that the hydrogen bonding between Cl^- and hydroxyl hydrogen of choline are the most probable interactions. The correlation peak from RDF for Cl^- and N-urea in reline is at $\sim 3.4 \text{ \AA}$, for Cl^- and O-Gly or O-EG in glycine and ethaline are at $\sim 3.2 \text{ \AA}$. RDFs in Figure 9 show distances of Cl^- with components of DESs are in this order $(\text{Cl}^- \text{ \& \; N-Chl}) > (\text{Cl}^- \text{ \& \; N-Urea}) \sim (\text{Cl}^- \text{ \& \; O-Gly}) \sim (\text{Cl}^- \text{ \& \; O-EG}) > (\text{Cl}^- \text{ \& \; O-Chl})$.

In addition of DESs components, all these RDFs have been calculated for ILs and probes solvation structures (Figure 10) which are discussed in detail in our published works [33, 219,220].

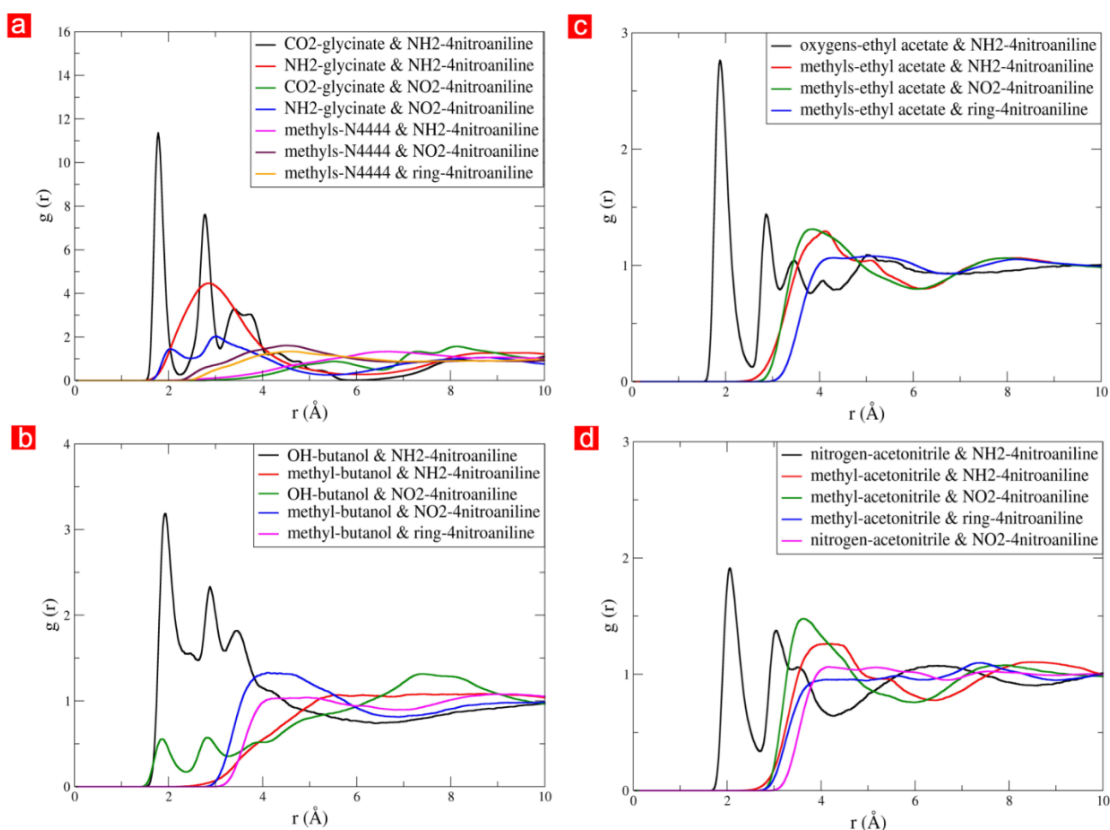


Fig. 10. RDFs of 4-nitroaniline in $[N_{4444}][Gly]$ (a), butanol (b), ethyl acetate (c), and acetonitrile (d) [220].

As DESs have been interested as green solvents, their mixtures with some organic solvents increase their applications and attentions. Water and polyethylene glycols are desired solvents for biological and chemical reactions. All these solvent-solvent interactions were investigated for the DESs (reline, ethaline, and glyceline). Tables 4 and 5 show how these hydrogen bond interactions have changed between potential groups over different mole fractions of PEG 400. By adding the mole fraction of PEG 400, the solvent-solvent interactions increased more and more which resulted in decreasing the hydrogen bond interactions in DESs components. Hydrogen bond interactions in ethaline and glyceline with PEG 400 showed approximately the same behavior which was a bit different with reline. It can be confirmed by focusing on the structures of HBDs and the presence of functional groups. Not only DESs, but also adding OS (alcohols/acetonitrile/ethyl acetate) to ILs were discussed in our studies [33, 219,220]. Also, PS model based on the response of probe dyes (Reichardt's dye 30, 4-Nitroaniline and 4-nitroanisole) were introduced as well.

Table 4. The calculated HBA (β') parameters in reline and it's binary mixtures at the mole fractions of 0.3 and 0.9 PEG 400 [219].

HBA (β')	HBD components	Mole fraction		
		0.9 PEG 400	0.3 PEG 400	Reline
O-Urea	NH-Urea	0.072	0.696	0.112
	OH-PEG	1.001	0.380	-
	OH-Chl	0.013	0.075	0.114
$\sum \beta'$ O-Urea		1.085	1.151	0.226
O-t-PEG*	OH-PEG	0.987	0.389	-
	NH-Urea	0.035	0.314	-
	OH-Chl	0.009	0.034	-
$\sum \beta'$ O-t-PEG		1.031	0.737	-
O-c-PEG*	OH-PEG	0.067	0.027	-
	NH-Urea	0.011	0.118	-
	OH-Chl	0	0.001	-
$\sum \beta'$ O-c-PEG		0.078	0.146	-
O-Chl	NH-Urea	0.017	0.162	0.267
	OH-PEG	0.106	0.052	-
	OH-Chl	0.001	0.000	0.000
$\sum \beta'$ O-Chl		0.124	0.214	0.267
N-Urea	OH-PEG	0.037	0.011	-
	OH-Chl	0.000	0.001	0.003
	NH-Urea	0.000	0.006	0.000
$\sum \beta'$ N-Urea		0.037	0.018	0.003

*O-t-PEG relates to terminal oxygens of PEG 400, and O-c-PEG relates to oxygens of PEG 400 except for O-t-PEG.

Table 5. The calculated HBA (β') parameters in glyceline and its binary mixtures at the mole fractions of 0.3 and 0.9 PEG 400 [219].

HBA (β')	HBD components	Mole fraction		
		0.9 PEG 400	0.3 PEG 400	Glyceline
O-Gly	OH-Gly	0.180	0.532	0.760
	OH-PEG	0.376	0.163	-
	OH-Chl	0.009	0.030	0.051
$\sum \beta'$ O-Gly		0.565	0.725	0.811
O-tails-PEG	OH-Gly	0.030	0.245	-
	OH-PEG	0.986	0.389	-
	OH-Chl	0.009	0.034	-
$\sum \beta'$ O-t-PEG		1.025	0.668	-
O-chain-PEG	OH-Gly	0.004	0.031	-
	OH-PEG	0.067	0.026	-
	OH-Chl	0.000	0.002	-
$\sum \beta'$ O-c-PEG		0.071	0.059	
O-Chl	OH-Gly	0.003	0.056	0.135
	OH-PEG	0.102	0.042	-
	OH-Chl	0.000	0.003	0.019
$\sum \beta'$ O-Chl		0.105	0.101	0.154

PS model by MD simulations

Solvatochromism and PS parameters directly depend on changes of molecules in microsphere solvation of probes (Figure 3). PS parameters have been calculated for the different DESs/ILs with OS. Here, it is explained for the DES of ethaline with water as an important applicable co-solvent.

In the experimental work, we measured PS for the aqueous solutions of ethaline. Aqueous solutions of ethylene glycol and choline chloride were investigated to have more information of DESs components and their abilities to change PS parameters (Figure 11). Changes in the numbers of each molecule (ethaline, EG, water) which solvated the probes caused the experimental results to alter over the mole fractions (Table 6) (the formula and experimental measurements were discussed in the related section).

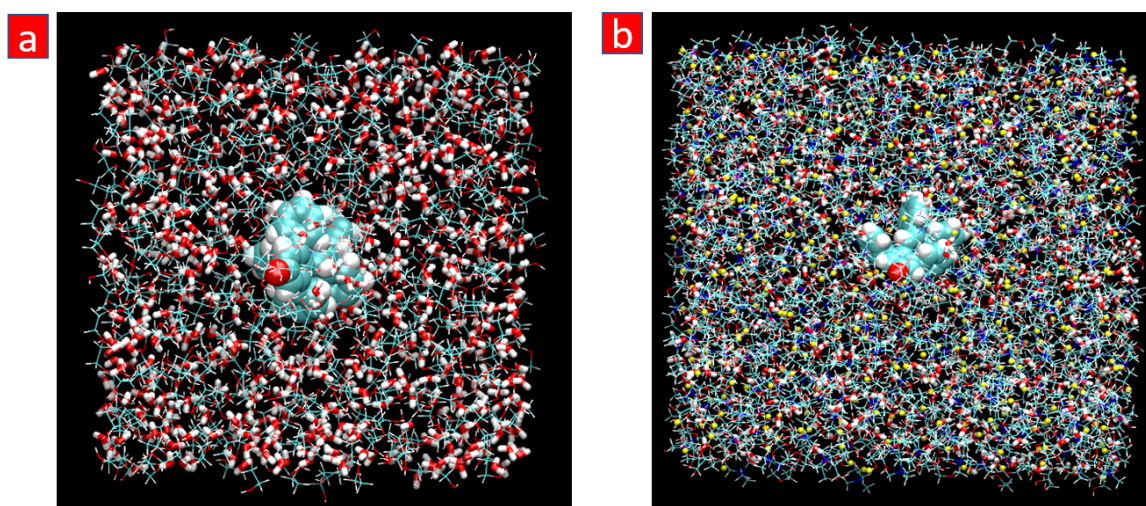


Fig. 11. Snapshots from MD simulations showing the solvation shell of RC in moderate mole fraction of ethylene glycol + water (a), and ethaline + water (b) [33].

Hence, the numbers of molecules around probes is the key role to confirm experimental results. RDF, probabilities of finding a particle from a reference particle over distances, is a powerful tool in MD simulations to understand the solvation structures. After simulations and producing phase trajectories, in order to analyze preferential solvation by RDFs, `gmx make_ndx` command was used. Choline (CHL), chloride (Cl), and ethylene glycol (EG) were placed in a group in an index file to make ethaline (f'_2), water (f'_1), and a combination of f'_2 and f'_1 was performed to create a group as f'_{12} in the index file. RDFs for PS parameters (f'_1, f'_2, f'_{12}) with probe dyes were obtained.

PS parameters were showed with the apostrophe symbol to confirm they have not the same amount with experimental results.

In all RDFs, it was realized that how probabilities, $g(r)$, of f'_2 and f'_{12} , and f'_1 changed over all mole fractions. Also, Cumulative number RDFs were determined, and they confirmed how coordination numbers (CN) obtained by MD simulations can strongly describe PS parameters over selective distances. For example, coordination numbers of O-RC (oxygen of Reichardt's probe is extremely sensitive to microsphere shells and changing PS parameters) and f'_1, f'_2, f'_{12} over 0-3 Å were 0.43, 6.43, 6.86 in aqueous solution of ethaline (0.5 ethaline + 0.5 water). In aqueous solution of ethylene glycol (0.5 EG + 0.5 water), coordination numbers of O-RD and f'_1, f'_2, f'_{12} were 2.10, 4.97, 7.07 over 0-3 Å. CNs obtained by each RDF (f'_1, f'_2, f'_{12}) confirmed that the solvation is governed by the mixed solvents. Also, these numbers display that probes prefer ethaline + water or ethylene glycol + water much more than pure water. The CNs amount of ethaline or ethylene glycol for solvation of probes in these mixtures are significant. In addition, to find more details and effect of components, the CN of each component of DES (choline, chloride, and ethylene glycol) is very valuable. The CN of selected species a and b is described by eq 21:

$$CN_{ab} = 4\pi \int_0^R \frac{N_b}{V} r^2 g_{ab}(r) dr \quad (21)$$

R , a distance between 2 species a and b, V the volume of box, and N_b , the numbers of species b in the box. In our calculations, R was taken 4 Å in order to involve the first microsphere solvation shells of interested groups over all mole fractions. The CNs were calculated between selected groups (each component of solvents and probes). For this purpose, the CNs were obtained by integrating the corresponding RDFs. The CNs revealed that the existence of

ethylene glycol and choline in microsphere solvation of probe dyes are remarkable (Tables 7 and 8). Even in the rich mole fraction of water (0.1 ethaline/EG + 0.9 water), the numbers of ethylene glycol or choline are approximately half of water. In some mole fractions of binary mixtures, the CNs reached to 10 times variation in numbers of EG to water which strongly confirmed that probes prefer to be solvated by ethaline/EG. Data collected by CNs show that the accumulations at the microsphere solvation of probes in aqueous solutions of ethaline are in this trend EG > choline > water > chloride; in aqueous solutions of ethylene glycol EG > water.

Table 6. PS parameters obtained by applying eqs 6-10 to the experimental wavenumbers of the probes (ANS, ANI, and RC), in binary mixtures of ethaline (2) or ethylene glycol (2) + water (1). N , r^2 , and σ are the numbers of experimental data, regression coefficient, and standard deviation respectively [33].

indicator	solvents	$Y_1(\overline{\vartheta}_1)$	$Y_2(\overline{\vartheta}_2)$	$Y_{12}(\overline{\vartheta}_{12})$	$f_{2/1}$	$f_{12/1}$	N	r^2	σ
ANS	ethaline/water	31.45	31.61	31.42	3.50	2.40	11	0.941	0.002
	EG/water	31.55	31.76	31.74	3.12	2.44	11	0.965	0.002
ANI	ethaline/water	26.32	25.90	25.54	14.60	3.95	11	0.993	0.001
	EG/water	26.29	26.27	25.50	2.63	3.72	11	0.972	0.007
RC	ethaline/water	21.99	20.17	20.21	2.56	2.42	11	0.967	0.132
	EG/water	21.89	19.77	19.69	2.41	1.84	11	0.983	0.097

Table 7. Determined CNs in aqueous solutions of ethylene glycol. All CNs have been obtained by integrating the corresponding RDF over range 0 – 4 Å via eq 20 [33].

x_w^a	RC		O-RC		N-RC	
	EG	water	EG	water	EG	water
0	10.85	-	20.95	-	1.85	-
0.1	10.53	0.27	20.26	0.59	1.75	0.02
0.3	9.66	1.04	18.19	2.29	1.62	0.13
0.5	8.67	1.93	15.75	4.32	1.49	0.20
0.7	7.08	3.37	12.12	7.40	1.30	0.35
0.9	4.33	5.85	6.99	11.75	0.91	0.64
1.0	-	9.86	-	17.17	-	1.21

x_w^a	ANI		NH ₂ -ANI		NO ₂ -ANI	
	EG	water	EG	water	EG	water
0	15.77	-	19.98	-	17.15	-
0.1	15.22	0.55	19.18	0.77	16.63	0.57
0.3	13.73	1.87	16.99	2.73	15.11	1.90
0.5	12.19	3.29	14.72	4.74	13.51	3.41
0.7	9.60	5.64	11.17	7.94	10.69	6.02
0.9	4.97	9.89	5.08	13.41	5.68	10.68
1.0	-	14.52	-	18.02	-	16.08

x_w^a	ANS		OCH ₃ -ANS		NO ₂ -ANS	
	EG	water	EG	water	EG	water
0	14.75	-	16.72	-	17.14	-
0.1	14.23	0.46	15.98	0.62	16.59	0.47
0.3	13.09	1.53	14.59	1.94	15.26	1.72
0.5	11.35	3.12	12.41	3.96	13.27	3.56
0.7	9.00	5.23	9.62	6.49	10.56	6.04
0.9	4.95	8.94	4.91	10.80	5.70	10.61
1.0	-	13.58	-	15.42	-	16.06

^a x_w is the mole fraction of water.

Table 8. Determined CNs in aqueous solutions of ethaline. All CNs have been obtained by integrating the corresponding RDF over range 0 – 4 Å via eq 20 [33].

x_w^a	RC				O-RC				N-RC			
	CHL	Cl	EG	water	CHL	Cl	EG	water	CHL	Cl	EG	water
0	3.54	0.16	7.19	-	13.74	0.00	8.03	-	0.25	0.01	1.55	-
0.1	4.72	0.12	5.85	0.07	15.78	0.00	6.92	0.02	0.26	0.00	0.36	0.00
0.3	5.35	0.14	5.55	0.19	15.31	0.00	5.93	0.44	0.88	0.00	0.52	0.06
0.5	4.34	0.13	6.12	0.47	9.20	0.00	11.83	0.76	0.43	0.00	1.22	0.04
0.7	3.29	0.08	6.49	1.11	9.34	0.00	9.91	1.87	0.31	0.00	1.25	0.09
0.9	2.33	0.04	5.33	3.17	5.13	0.00	8.42	6.41	0.31	0.00	1.20	0.27
1	-	-	-	9.86	-	-	-	17.17	-	-	-	1.21

x_w^a	ANI				NH ₂ -ANI				NO ₂ -ANI			
	CHL	Cl	EG	water	CHL	Cl	EG	water	CHL	Cl	EG	water
0	8.75	0.38	6.66	-	9.70	0.98	8.41	-	10.01	0.05	8.11	-
0.1	6.01	0.33	8.81	0.28	7.45	0.88	10.02	0.25	8.73	0.03	9.08	0.12
0.3	8.55	0.47	5.97	0.53	10.48	1.26	5.87	0.72	10.16	0.08	7.24	0.47
0.5	6.17	0.31	8.28	0.92	8.02	0.89	8.32	1.58	8.60	0.03	8.65	0.56
0.7	5.05	0.24	8.35	1.97	6.14	0.66	8.60	3.55	7.12	0.03	9.37	1.26
0.9	4.48	0.14	5.42	5.66	4.93	0.37	5.71	8.11	6.26	0.01	6.20	5.13
1	-	-	-	14.52	-	-	-	18.02	-	-	-	16.08

x_w^a	ANS				OCH ₃ -ANS				NO ₂ -ANS			
	CHL	Cl	EG	water	CHL	Cl	EG	water	CHL	Cl	EG	water
0	5.42	0.21	9.03	-	5.99	0.26	10.08	-	9.93	0.03	8.20	-
0.1	5.48	0.26	8.68	0.02	5.35	0.32	10.56	0.02	10.51	0.11	7.05	0.00
0.3	6.36	0.26	7.96	0.32	6.97	0.33	8.97	0.39	9.84	0.06	8.11	0.27
0.5	5.01	0.21	8.91	0.63	4.86	0.24	10.55	0.92	8.59	0.06	8.58	0.44
0.7	5.51	0.17	7.40	1.77	5.73	0.24	8.04	2.67	9.05	0.04	7.33	1.32
0.9	3.33	0.08	5.97	5.35	3.41	0.13	6.12	6.93	5.63	0.02	6.57	5.27
1	-	-	-	13.58	-	-	-	15.42	-	-	-	16.06

^a x_w is the mole fraction of water.

In aqueous solutions of ethaline (Table 8), however the CNs of ethylene glycol are remarkable, but they are less than 2 times that are for choline. For instance, in the moderate mole fraction (0.5 ethaline + 0.5 water), the CNs of ethylene glycol for RC, NLE, NAS are 6.12, 8.28, 8.91; the CNs of choline are 4.34, 6.17, 5.01 for RD, NLE, NAS respectively. It means that even though the numbers of EG are two times more than choline in binary mixtures, the numbers are not same at local solvation shell (the microsphere solvation of probe dyes). It can be helpful to clear the effect of DES components. The CN in the aqueous solution of choline chloride (0.1 choline chloride + 0.9 water) were 5.24, 7.31, 6.55 for choline and RC, NLE, NAS sequentially and 5.77, 8.38, 8.30 for water and probes. By comparing the CN in the aqueous solution of choline chloride (0.1 choline chloride + 0.9 water) with the aqueous solution of ethaline (0.1 ethaline + 0.9 water), it was found out that ethylene glycol and choline are serious competitors for solvating the probes (the CN for each of them increases in absence of the other one).

Moreover, different sides (functional groups) of probes were examined to discover the preferred sides of probes. The CNs data (Tables 7 and 8) showed that selective side of RC is oxygen atom. In aqueous solutions of ethaline, the presence of different species causes different preferential for probes. Oxygen of RC was more surrounded by choline. Probably this oxygen has the major effect on shifting wavelengths of RC in solvatochromism. Amine group of 4-nitroaniline and methoxy group of 4-nitroanisole prefer to be solvated by ethylene glycol more than others. Nitro group of these dyes (NLE, and NAS) prefers choline a bit more than ethylene glycol in low mole fractions of water. It is probably because of positive charge of choline. Presence of chloride was just seen around the amine group of 4-nitroaniline. In case of the other probes, there is not probability of chloride at near distances. The obtained CN from different aqueous solutions (ethaline, ethylene glycol, and choline chloride) but the same mole fraction of water (0.1 ethaline/EG/ChCl + 0.9 water) were concluded that choline was a potent rival for ethylene glycol to solvate the probe dyes and both these components are considerably more preferred than water.

Solvation shells of probes as an important reason for turning UV-Vis spectra were discussed. The other reason for either red or blue shifts in probes spectra is hydrogen bond interaction between probes and solvents. 4-nitroaniline and 4-nitroanisole have different side to have hydrogen bond interactions with surrounding molecules. Hence, these two probes make confusion to understand the effect of hydrogen bond interactions. RC has only one oxygen which makes it suitable to overcome this goal. Numbers of hydrogen bonds were calculated between functional groups of probes and surrounded molecules which are explained in the literature [33, 219, 220].

In order to better understand the solvatochromism and effect of microsphere solvation on shifting wavelengths, quantum calculations were used. Coordinates of different number molecules in the vicinity of probes were extracted from their trajectories in MD simulations files. The DFT/B3LYP functional using a 6-31G* basis set was used to optimize the geometries of probes and corresponding solvents in Gaussian 09 program. The optimized geometries with different numbers of solvents were applied by time dependent density functional theory (TD-DFT) with the CAM-B3LYP functional using a TZVP basis set. Molden program was used for visualization of the UV–Vis spectra of QM calculations. All these calculations were done for the probes in the DESs/ILs mixtures. Figures 12 and 13 show the optimized geometries and obtained UV-Vis spectra of these calculations in gas phase for ILs + molecular solvents. All the information of these spectra and their accordance with experimental finding can be found in the literature [33, 219, 220].

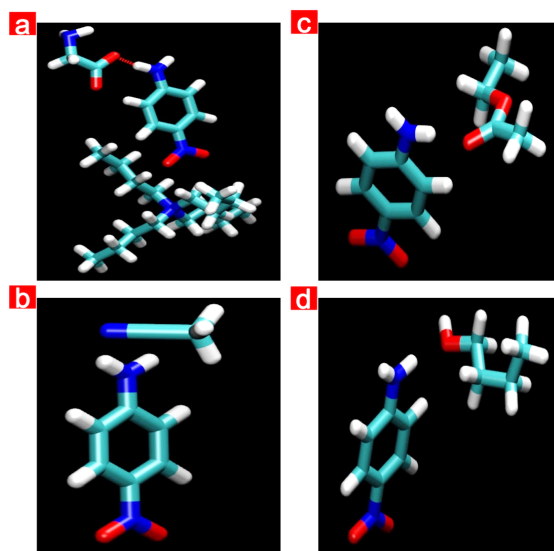


Fig. 12. Optimized geometry of 4-nitroaniline with one molecule of [N₄₄₄₄][Gly] (a), acetonitrile (b), ethyl acetate (c), and butanol (d), by DFT/B3LYP [220].

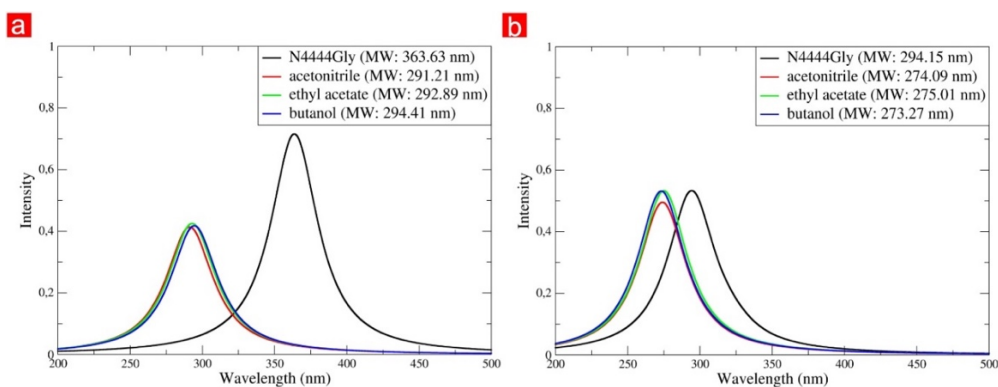


Fig. 13. Obtained UV-Vis spectra of 4-nitroaniline (a), and 4-nitroanisole (b), with one molecule of different solvents [220].

3.1. a. Conclusion

As a brief, DESs, ILs, and their binary mixtures were studied [33, 219, 220]. Several experimental and computational methods were done to find the microsphere solvation of probes, interactions in DESs, and ions solvation. We made a simple method to understand the PS parameters and effect of different species in binary mixtures by using RDF and CNs. It is worthwhile to find which combination of solvents is preferred at the microsphere solvation of probes in complex systems by calculating CNs. They provided to find out how the accumulation of different components causes the synergism in experimental data. E.g., The presences of ethylene glycol and choline were remarkable in all binary mixtures of ethaline + water. Finally, DFT method was used to improve our knowledge of solvation shell effects on absorbance spectra; by increasing the number of molecules in solvation shells of probes, shifting in the absorbance spectra of the probes were seen. Based on our findings, MD simulations and DFT calculations are very practical to have a perspective of the nature of solvatochromism and PS.

MD simulations in aqueous solutions of biochar for tetracycline sorption

MD Simulations were applied to find the interactions of biochar in aqueous solutions and its sorption for tetracycline as a water pollutant. Biochar is an effective adsorbent in the wastewater/soil media which has received attention due to its high capacity to adsorb various ions and compounds, organic compounds, drugs, and other pollutants.

Two kinds of biochar with the abbreviation names B7 and B17 were modeled in our study (Figure 14).

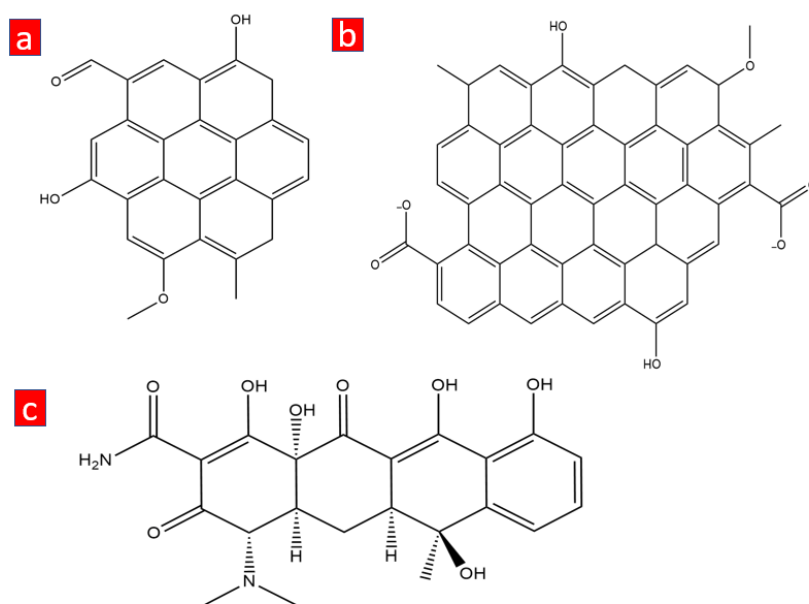


Fig. 14. The structures of B7 (a), B17 (b) in basic aqueous solutions, and tetracycline (c) [223].

The presence of different inorganic salt solutions changes solute-solvent interactions and influences zeta potential. In addition of Na^+ salt solutions, the Na^+ ions undergo electrostatic interaction with the negatively charged biochar and form a double layer at the interface of biochar and ionic solution. Molecular dynamics simulations have been employed to understand experimental findings, ions adsorption and solute-solvent interactions at the molecular level of two biochar B7 and B17 in aqueous solutions (Figure 15). The results confirm that hydroxyls and carboxylate groups of biochar are responsible for solute-solvent interactions. This study confirms that interactions between amide and hydroxyl groups of tetracycline with hydroxyl and carboxylate groups of biochar play the key role in the adsorption process. The solution and presence of different background electrolytes effectively influence the process of solute-solvent interactions as well as adsorption efficacy towards tetracycline adsorption [223].

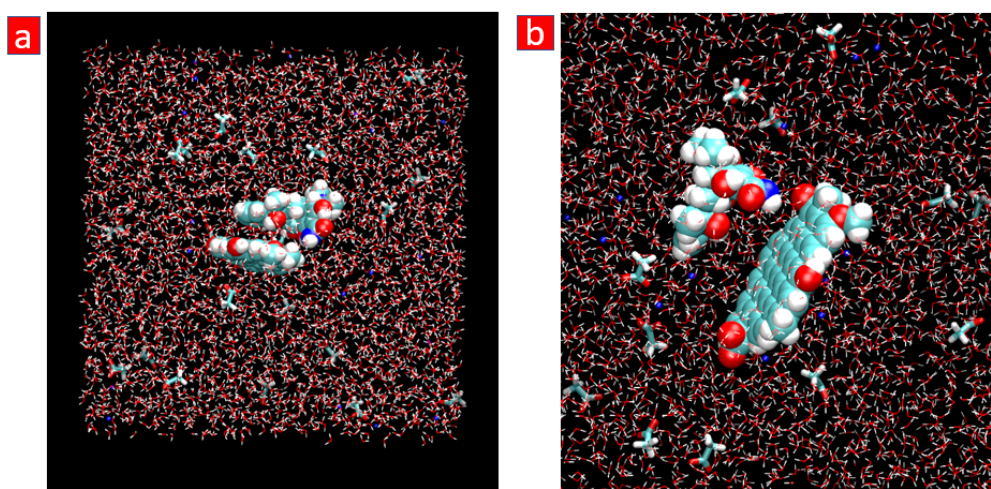


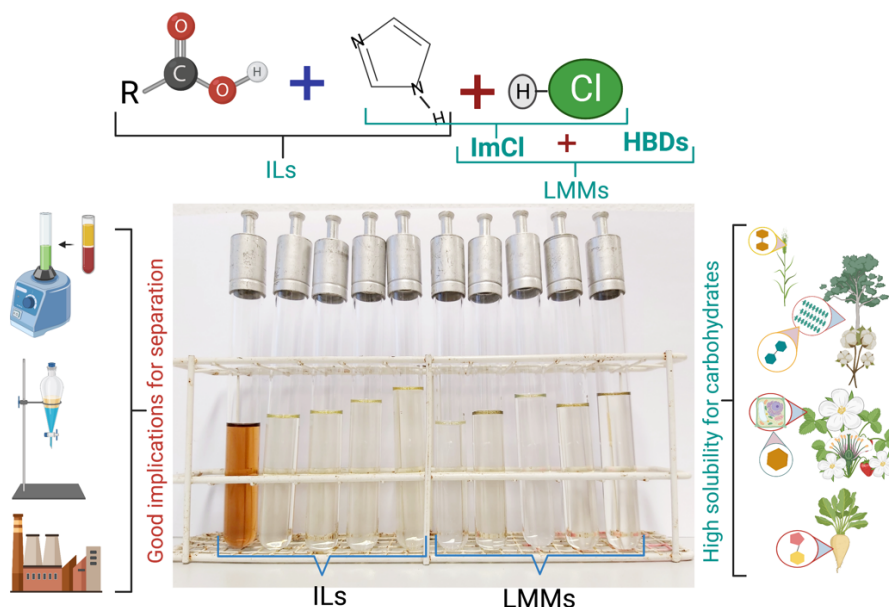
Fig. 15. Snapshot from tetracycline adsorption by B7 (a), and B17 (b) in NaCH_3COO solution [223].

Ionic liquids (ILs) and low melting mixtures (LMMs)

Novel protic ionic liquids (PILs) and low melting mixtures (LMMs) have been synthesized based on green components, the cheap sources, high purity, and easy way of preparation [222].

PILs include [Im][For], [Im][Ace], [Im][Pro], [Im][But], and [Im][Pen]. LMMs include [ImCl][EG], [ImCl][Gly], [ImCl][PEG], [ImCl][ETA], and [ImCl][carbohydrate] + DMSO.

These solvents contain imidazolium/imidazolium chloride as a cation/salt. NMR spectroscopy was used to analyze the structures of solvents. Melting points, and thermal stabilities were measured via thermal analyses. We were looking to synthesize new DESs with imidazolium chloride (ImCl); Due to lack of observation the melting points for mixtures of ImCl + hydrogen bond donors (HBDs), these mixtures were called low melting mixtures (LMMs) in this work. The mixtures of PILs/LMMs with molecular solvents showed good implications for homogenous and heterogenous systems which can be used for separation goals. Solubilities of carbohydrates, and some amino acids were tested in pure and mixed of ILs with molecular liquids. Adding DMSO to ILs/LMMs increased the dissolution of carbohydrates. As well, adding water to ILs had a remarkable effect for increasing the solubility of amino acids.



Left to right: ILs: [Im][For], [Im][Ace], [Im][Pro], [Im][But], [Im][Pen]; LMMs: [ImCl][EG], [ImCl][Gly], [ImCl][PEG 400], [ImCl][ETA], [ImCl][Glucose] + DMSO [222].

Ionic liquids (ILs) and deep eutectic solvents (DESs) have been emerged in the most of scientific and industrial applications as potential green solvents due to their unique properties which were discussed in the previous section.

Until now, amongst ILs, imidazolium ILs have been more attracted than the other ILs based on ammonium, phosphonium, sulfonium, and pyridinium cations. Despite imidazolium ILs are very practicable in most of applications, the cost of preparation of these ILs limits them in some enforceable areas. The reasons come out of the price of materials and procedures to synthesize ILs with high purity. Deprotonation of imidazole, materials (for instance alkyl halides, silver oxide, etc.) and separations steps lead to increase the costs and impurities of ILs. Hence, the cheap pure ILs need to pass a few steps to be synthesized. Moreover, the simple method makes new solvents to be more accessible. E.g., DESs based on the choline chloride salt reported by Abbott et. al have been remarkable interested between DESs because of the simple method to prepare, and the inexpensive low toxic material [93].

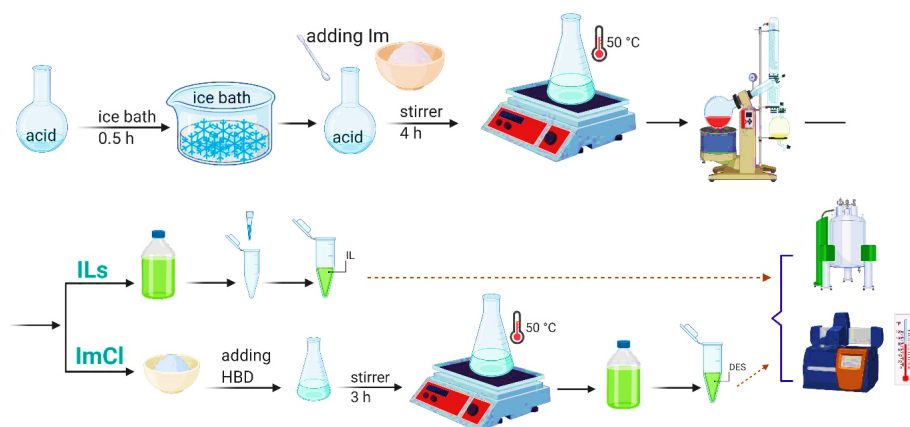
The economic synthesis, favorite imidazolium structure, green sources, purity, and easy way of preparation were our guidelines to achieve novel solvents. Accordingly, our goal was to offer a new class of solvents that benefit of the mentioned advantages. Further, miscibility of ionic solvents with organic solvents for separation, and physicochemical applications were investigated. Also, dissolution of carbohydrates in ionic solvents were measured.

Experimental

Primary materials were purchased in high qualities and were used without further purification. ILs and low melting mixtures (LMMs) were synthesized as it is shown in Scheme 1.

The procedure was done by adding each carboxylic acid (formic/acetic/propionic/butanoic/pentanoic acid) in a round-bottom flask, then the flask was placed in an ice bath for 0.5 h. An equimolar of imidazole (solid) was added to each acid and the reaction was stirred for 4 h under slowly increasing the temperature (up to 50 °C) to reach the target ILs (see Supporting Information). Imidazolium chloride (ImCl) was prepared in the same way but an excess equimolar of hydrochloric acid (the molar ratio of HCl to imidazole was 1.1:1) was used in the first step (Scheme 1).

Scheme 1. Procedures for the synthesis of ILs and LMMs.



After stirring, the excess of HCl and water were evaporated with a rotary evaporator. At the end, the residue, ImCl, was placed in a vacuum oven (pressure~6 kPa) for 5 h at 80 °C and the amount of water by Karl Fischer titration (0.54%) was measured. Hydrogen bond donors including ethylene glycol, glycerol, polyethylene glycol 400, ethanolamine, urea, imidazole, and maleic acid were added to ImCl and homogeneous liquids were formed to reach the target LMMs (Table 9). The same protocol was used to reach low melting mixtures for liquid and solid HBDs; the only difference in the method was the temperature of stirring after mixing ImCl with HBD. In case of liquid HBDs, the temperature was 50 °C but for solid HBDs the temperature reached up to 140 °C. NMR spectrometer 700 MHz Bruker was used to analyze the structures of samples at 25 °C.

Thermal analyses of samples (melting temperature (T_m), glass transition temperature (T_g) and decomposition temperature, the temperature at which the substance decomposes chemically (T_d)) were measured by DSC250 Auto (TA Instruments, USA) in the range of -90 °C till 100 °C under the nitrogen atmosphere (nitrogen flow 50 mL/min), and TGA550 Auto Advanced (TA Instruments, USA) in the range of room temperature till 400 °C under the nitrogen atmosphere (nitrogen flow 60 mL/min). Thermal analyses were measured by using 7-10 mg of each sample with a heating rate of 10 °C . min⁻¹. Decomposition temperature was determined as the peak top of the derivative value.

Solubility of ILs/LMMs + molecular solvents

Solubility was tested by mixing 2.0 g of IL/LMM with 2.0 ml of each molecular solvent (acetonitrile, acetone, THF, ethyl acetate, ethanol, water, n-hexane, and cyclohexane). Then, three times the mixtures were shaken for 60 s every 4 min at 25 °C.

Solubility of carbohydrates and amino acids in ILs/LMMs

Solubility of carbohydrates (glucose, sucrose, cellobiose, and maltose) and some amino acids (Glycine, L-Alanine, L-Valine, and L-Tryptophan) were tested in ILs and LMMs. As a brief, 20.0 g of ILs/LMMs was put in a flat bottom flask or beaker. It followed by adding carbohydrates/amino acids in the range of 0.1-1.0 g. The solutions were stirred at 25 °C for 0.5 h. Adding water and temperature up to 70 °C for increasing the solubility were noticed.

Results and discussion

PILs were synthesized through the neutralization reaction of a carboxylic acid and imidazole as a base (Scheme 1). The reactions were done under the solvent-free condition. Therefore, they did not have any impurity of solvent and other materials in synthesized ILs which is a good point for every IL. Nuclear magnetic resonance (NMR) spectroscopy was used to analyze the structures of ILs and LMMs; NMR results confirmed that ILs and LMMs did not have any unwanted reaction. (Figures 16 and 17. See Supporting Information).

^{13}C NMR was used to identify our ILs based on imidazolium. Presence of two peaks in ^{13}C NMR spectra at δ (ppm)~ 118.90, 133.31 proved the protonated ring (imidazolium) in the structures of ILs and LMMs. Also, no evidence of impurity peaks for unreacted carboxylic acids confirmed the high purity of synthesized ILs. Chemical shifts of imidazolium in the structure of ImCl (118.89, 133.32), [Im][For] (118.83, 133.26), [Im][Ace] (118.91, 133.31), [Im][Pro] (118.98, 133.37), [Im][But] (118.99, 133.35), [Im][Pen] (119.03, 133.41) are similar. This is a strong reason for protonation of imidazole in ILs (Figures 16 and 17. See Supporting Information). These chemical shifts of imidazolium are different with imidazole (121.60, 135.63) [222].

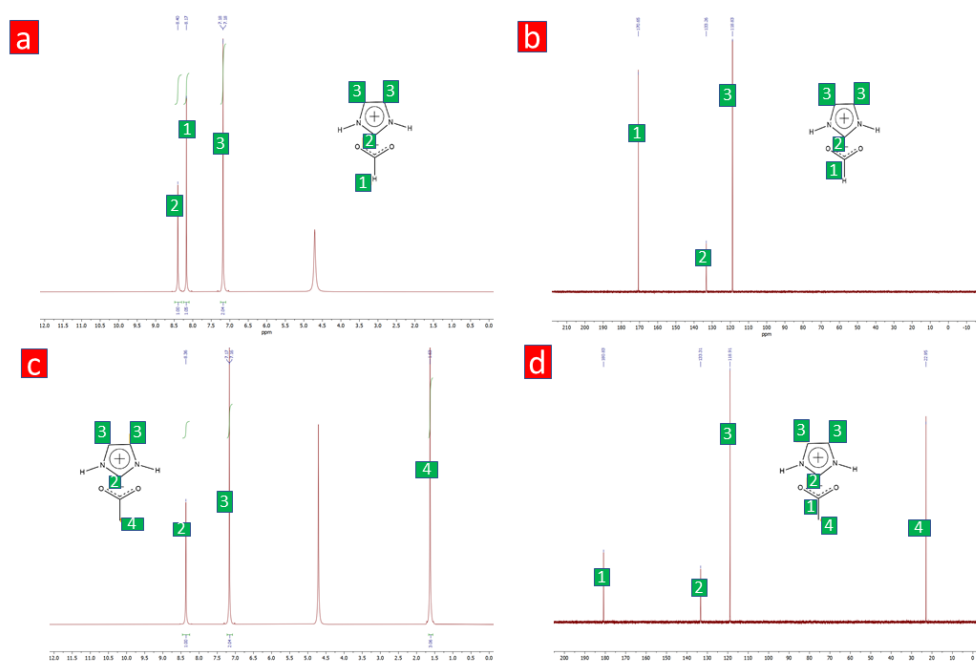


Fig. 16. *Imidazolium Formate* (a, b): ^1H NMR (700 MHz, D_2O , 25°C): $\delta(\text{ppm}) = 7.18$ (2H, d), 8.17 (1H, s), 8.40 (1H, s); ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 118.83, 133.26, 170.65. *Imidazolium Acetate* (c, d): ^1H NMR (700 MHz, D_2O , 25°C): $\delta(\text{ppm}) = 1.63$ (3H, s), 7.16 (2H, d), 8.36 (1H, s); ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 22.95, 118.91, 133.31, 180.83.

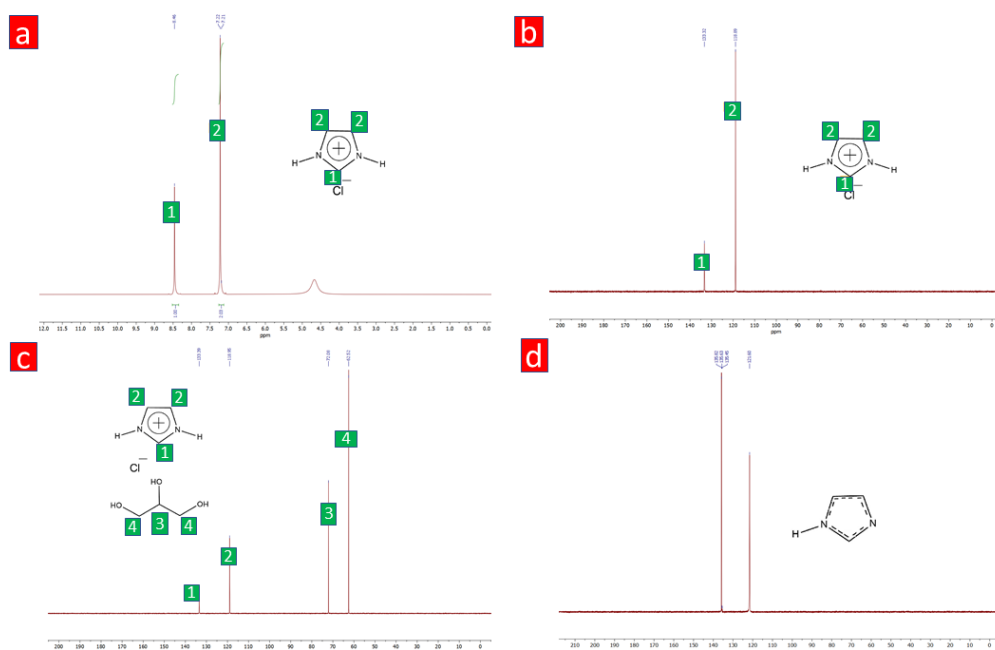


Fig. 17. *Imidazolium Chloride* (a, b): ^1H NMR (700 MHz, D_2O , 25°C): $\delta(\text{ppm}) = 7.21$ (2H, d), 8.46 (1H, s); ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 118.89, 133.32. *Imidazolium Chloride Glycerol* (c): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 62.52, 72.08, 118.95, 133.39. *Imidazole* (d): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 121.60, 135.63.

Thermal analyses of ILs, ImCl, and LMMs:

Table 9 and Figure 18 present thermal analyses of ILs, ImCl, and LMMs. Comparison and effects of the cation, anions, and HBDs can be found in the literature [222].

3.1. b. Conclusion

In summary, for the first time, a series of PILs and LMMs based on imidazolium without any alkyl chain were synthesized. Because of non-observation the melting points for mixtures of ImCl + HBDs, it was not possible to plot the phase diagrams and find the eutectic points. Hence, the mixtures of ImCl + HBDs were named low melting mixtures. These solvents solve the cost, purity, and difficulty of preparation ILs and DESs based on imidazolium, and they can be used in several applications. These solvents have good potential as industrial solvents. It is possible to design a homogenous/heterogenous system of IL/LMMs with water/n-hexane for separation or purification usages. Binary mixtures of PILs/LMMs with molecular solvents have significant implications to tune some physicochemical properties in future studies. The major difference in the structures of ILs and LMMs is the kind of anion in this work. If the presence of chloride anion is annoying or an anion with alky chain is desirable, and/or pure ionic solvents are interested, ILs will be suggested. As a hint, choosing an IL or LMM depends to conditions of reactions. These solvents open up multi tool uses that can be investigated for future applications.

Table 9. Synthesized ILs and LMMs in this work with thermal properties: melting temperature (T_m), glass transition temperature (T_g) and decomposition temperature (T_d) [222].

ILs	Cation	Anion	Molar ratio	T_g (°C)	T_m (°C)	T_d (°C)
[Im][For]	Imidazolium	Formate	1: 1	- 80.3	14.7	192.0
[Im][Ace]	Imidazolium	Acetate	1: 1	- 69.8	5.0	179.0
[Im][Pro]	Imidazolium	Propionate	1: 1	- 41.8	33.8	175.7
[Im][But]	Imidazolium	Butanoate	1: 1	- 75.2	16.4	173.6
[Im][Pen]	Imidazolium	Pentanoate	1: 1	- 78.2	NO	170.6
[ImCl]	ImCl	-	-	-	137.3	291.6
LMMs	HBA	HBD	Molar ratio	T_g (°C)	T_m (°C)	T_d (°C)
[ImCl][EG]	ImCl	Ethylene glycol	1: 1.5	NO	NO	258.0
[ImCl][Gly]	ImCl	Glycerol	1: 1	NO	NO	277.7
[ImCl][PEG]	ImCl	PEG 400	1: 1	NO	- 25.8	334.8
[ImCl][Urea]	ImCl	Urea	1: 1	- 53.0	60.6	253.8
[ImCl][ETA]	ImCl	Ethanolamine	1: 1	- 71.1	NO	283.1

NO: the melting temperature or glass transition temperature was not observed (DSC were measured in the range of -90 °C till 100 °C).

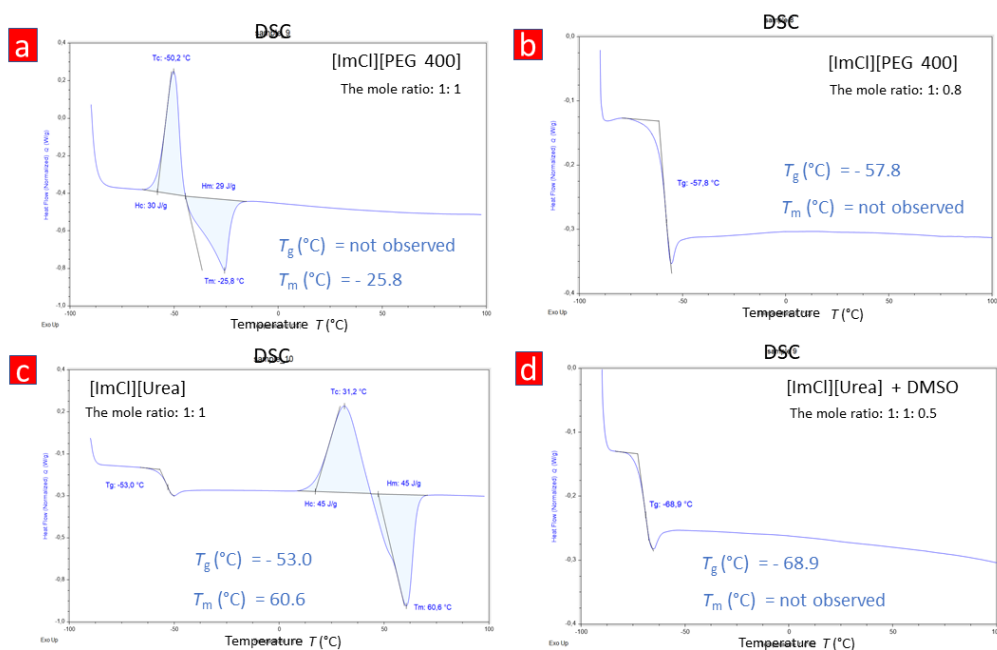


Fig. 18. The DSC spectra of LMMs [222].

3.2 Cellulose dissolution

3.2.1 Introduction

Cellulose is the most abundant organic polymer with endless resources. It can be used for producing many compounds (derivatives like cellulose ethers, and esters) in environmentally friendly way [72, 224-242]. One of the cheap sources of cellulose is biomass. Recycling cellulose of biomass is very challenging as cellulose is not soluble in water and green organic solvents. The use of ionic liquids for the dissolution of cellulose is not a new method these days. ILs have been considered for cellulose dissolution because of their advantages compared to conventional aqueous solutions. Several studies have been made to find out which kinds of ILs are good for this goal and how it is possible to improve the efficiency of ILs [72-79, 243, 244]. Strong hydrogen bond interactions in cellulose, make it insoluble in common organic solvents (Figure 19) [72, 241].

It is a long-time scientist have been trying to find and improve a good solvent for cellulose dissolution [243]. Before ILs, aqueous and non-aqueous solvents for different sources of cellulose have been applied for this goal [244–247]. The mainly agreement is on the solvents which have good hydrogen bond acceptor ability to break the hydrogen bond interactions between cellulose chain. Other factors like the hydrophobicity of solvents for reassembly of cellulose are in the second order [248-251].

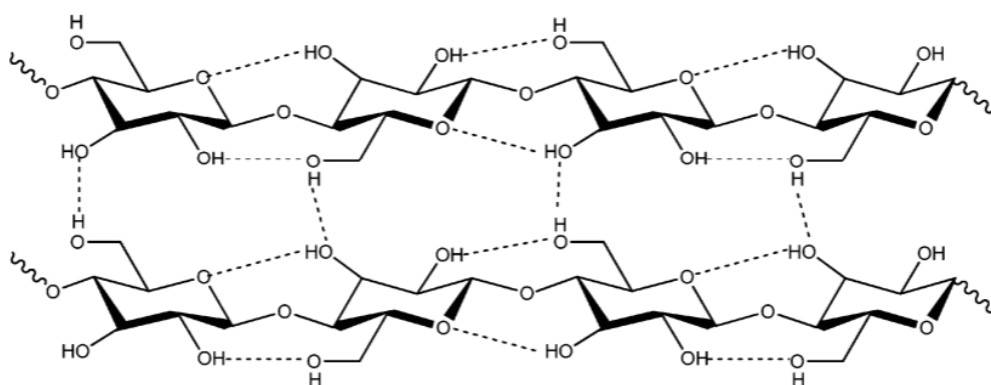


Fig. 19. Inter and intramolecular hydrogen bond interactions in cellulose [242].

Some alkaline solutions, acidic solvents, and hydrophobic have been investigated for the dissolution of cellulose [251-255]. Although some of these solvents are not safe and have toxicity, they made a point of view for the potential solvents.

Therefore, a good solvent should have all advantages to be a good candidate for dissolution of cellulose. In this context, ILs have been shown to dissolve cellulose more efficiently than molecular solvents [74, 79, 225, 255]. Several factors such as kind of cations, anions, and temperature have been investigated [256-258] Lu et al. examined some ILs with different alkylated imidazolium cation but the same anion ([OAc]). They reported that by increasing the temperature the solubility improved and there is no relation between the kind of cations and the dissolution (Table 10) [257].

Moreover, they found incredible relations between the KT parameters of ILs and solubility of cellulose (Table 11). They revealed that ILs with high hydrogen bond basicity and cations without high electronegativity atoms (like oxygen or nitrogen) in the alkyl chain were more successful candidate.

Table 10. Solubility of microcrystalline cellulose (g/mol) in the ILs at different temperatures [257].

ENTRY	IL	40°C	50°C	60°C	70°C	80°C	90°C	100°C	110°C
1	[C ₄ mim][CH ₃ COO]	23	25	26	31	36	49	54	56
2	[C ₁ OC ₂ mim][CH ₃ COO]	8	17	21	23	29	39	44	49
3	[C ₂ OHmim][CH ₃ COO]	a	1	18	22	26	30	33	34
4	[C ₄ dmim][CH ₃ COO]	a	5	18	24	27	29	32	35
5	[phC ₁ mim][CH ₃ COO]	a	1	14	17	20	22	24	30
6	[C ₂ mmor][CH ₃ COO]	a	a	1	3	6	18	21	28
7	[C=C ₂ mmor][CH ₃ COO]	a	1	2	4	12	17	21	24
8	[C=C ₂ mpip][CH ₃ COO]	a	a	a	a	a	10	14	16
9	[C ₄ mpip][CH ₃ COO]	a	a	a	a	1	2	3	4
10	[C ₄ mpyr][CH ₃ COO]	a	a	a	a	a	a	1	2
11	[C ₄ ebim][CH ₃ COO]	a	a	a	a	a	a	a	a
12	[C ₂ ebim][CH ₃ COO]	a	a	a	a	a	a	a	a
13	[C ₄ ebt][CH ₃ COO]	a	a	a	a	a	a	a	a

^a Insoluble at given temperature.

Table 11. Values of α , β and π^* parameters for the ILs at different temperatures [257].

IL		25°C	35°C	45°C	55°C	65°C
[C ₄ MIM][CH ₃ COO]	α	0.61	0.61	0.61	0.60	0.60
	β	1.14	1.14	1.14	1.14	1.14
	π^*	1.02	1.02	1.02	1.02	1.02
[C ₁ OC ₂ MIM][CH ₃ COO]	α	0.51	0.50	0.50	0.50	0.49
	β	1.10	1.10	1.10	1.10	1.10
	π^*	1.06	1.06	1.06	1.06	1.06
[PHC ₁ MIM][CH ₃ COO]	α	0.44	0.43	0.42	0.41	0.41
	β	1.05	1.05	1.05	1.05	1.05
	π^*	1.09	1.09	1.09	1.09	1.09
[C ₂ MMOR][CH ₃ COO]	α	0.36	0.35	0.35	0.35	0.34
	β	1.10	1.10	1.10	1.10	1.10
	π^*	1.17	1.17	1.17	1.17	1.17
[C=C ₂ MMOR][CH ₃ COO]	α	0.25	0.25	0.25	0.24	0.24
	β	1.12	1.12	1.12	1.12	1.12
	π^*	1.15	1.15	1.15	1.15	1.15
[C ₂ OHMIM][CH ₃ COO]	α	b	b	b	b	0.54
	β	b	b	b	b	0.97
	π^*	b	b	b	b	1.06

^b Can not be measured.

Subsequently to experimental attempts on cellulose dissolution, computational studies were examined to find what is happening at the microsphere level of cellulose to have a better idea for the choose of solvents. MD simulation was a powerful tool between the computational methods which were used. Youngs, et al. carried out MD simulations for glucose as it is a smallest unit cell of cellulose in the IL of 1,3 dimethyl imidazolium chloride [259]. Their results were in a good accordance with experimental detection which confirmed the chloride makes hydrogen bond interaction with glucose, while the interactions of cations are negligible. Bala et al. did MD simulations for a bigger unit cell than glucose, cellobiose, in ILs with [bmim] as a cation and different kinds of anions: [OAc]⁻, [NO₃]⁻, [Cl]⁻, [BF₄]⁻, [PF₆]⁻, [CF₃SO₃]⁻, and [NTf₂]⁻ [260]. They found that acetate and chloride are the best protentional anions to have

the interactions with cellobiose. Figure 20 shows the RDFs for different anions and hydroxyl hydrogen of cellobiose.

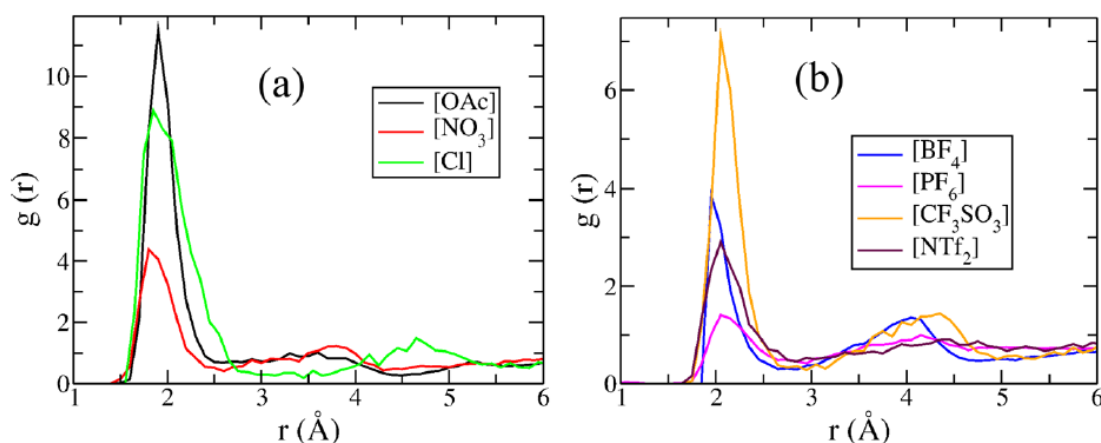


Fig. 20. Radial distribution functions between the hydroxyl hydrogen of cellobiose and the hydrogen bonding sites of anions [260].

Another prominent research was done by Zhao et al. [261]. They considered the effect of adding co-solvents to the IL on the cellulose dissolution.

[C4mim][OAc] was the selected IL and aprotic and protic co-solvents (DMSO, DMF, CH₃OH and H₂O) were chosen. They found in binary mixtures, the cellulose dissolution is governed by the electrostatic and hydrogen bond interactions between cellulose and [OAc]⁻. They revealed that the dissolution in the IL was improved by adding the aprotic co-solvents (DMSO and DMF). The reason can be supposed on the increasing distances between the cations and anions in ILs by adding aprotic co-solvents. Freer the anions, more interactions with cellulose (Figure 21). Reverse was seen in the protic co-solvents (CH₃OH and H₂O). It is assumed that protic co-solvents make the hydrogen bond interactions with [OAc]⁻.

Also, the effects of adding DMSO as a co-solvent to 1-ethyl-3-methylimidazolium acetate was studied by Hawkins et al. [262]. They found the equal binary mixtures of IL + DMSO had the maximum dissolution.

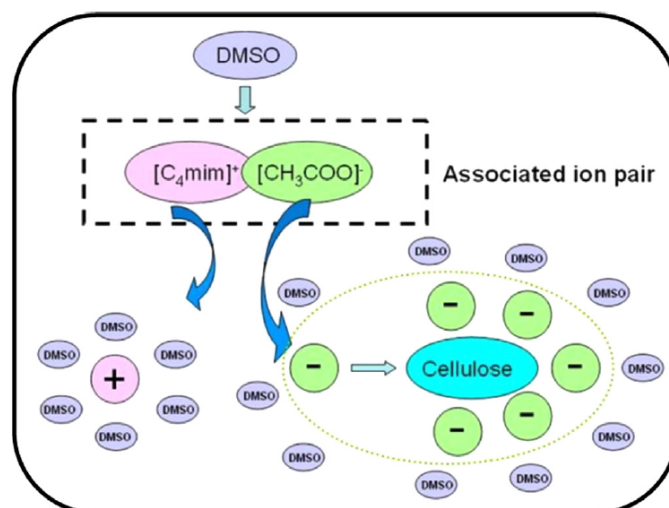


Fig. 21. Adding co-solvent on cellulose dissolution in $[C_4mim][OAc]$ as an IL [261].

There are several successful research on using different kinds of ILs for cellulose, and its derivatives [262-268]. As it was examined and tested by the experimental and computational studies, 1-ethyl-3-methylimidazolium acetate and chloride are the most powerful ILs for cellulose dissolution. Therefore, in our simulations, 1-ethyl-3-methylimidazolium acetate ($[C_2mim][OAc]$) was used as the best IL for dissolution.

3.2.2 MD Simulations of Glucose/Cellobiose/Cellulose

Cellulose is an organic compound and a poly saccharide that consists of many D-glucose units linked to each other in a linear chain (Figure 22) [263,264].

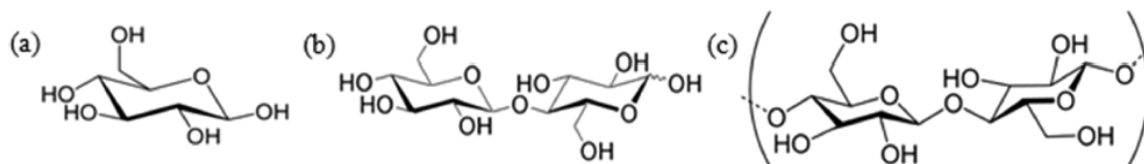


Fig. 22. Structure of (a) glucose, (b) cellobiose, and (c) cellulose [263].

MD simulations have been used to understand the solvation structure of glucose, cellobiose and cellulose with different concentrations in 1-ethyl-3-methylimidazolium acetate ([C₂mim][OAc]). The cellulose chain in this work consists of 6 unit cells of glucose. The solutions were prepared by random dissolution of 1, 5, 10, and 15 molecules of glucose, cellobiose and cellulose in a cubic box which contained 500 molecules of ionic liquid. All MD simulations were performed by Gromacs program package [172-174], with General Amber Force Field for all molecules and ions [183,189].

$$E(\mathbf{r}^N) = \sum_{bonds} \frac{k_i}{2} (l_i - l_{i,0})^2 + \sum_{angles} \frac{k_i}{2} (\theta_i - \theta_{i,0})^2 + \sum_{torsions} \frac{V_n}{2} (1 + \cos(n\phi_i - \gamma_i))$$

$$+ \sum_{i=1}^N \sum_{j=i+1}^N 4 \epsilon_{ij} \left(\left(\frac{\delta_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\delta_{ij}}{r_{ij}} \right)^6 \right) + \sum_{i=1}^N \sum_{j=i+1}^N \frac{q_i q_j}{4\pi \epsilon_0 r_{ij}}$$

After preparation of each system, energy minimization procedure were used to remove all unexpected and unfavorable contacts due to random solvation of molecules in the box. All MD simulations were run in the NVT (canonical ensemble) at 300 K and then NPT (isothermal–isobaric ensemble) simulations. Simulations were run for 50 ns or 100 ns depends to the necessity. Equations of motion were integrated using the leap-frog algorithm. VMD program was used for visualizations and preparation of snapshot.

Studies showed that the anions play an important role in the dissolution of cellulose in ionic liquids. Figure 23 shows the RDFs of acetate anion around the cellulose in the solution containing one chain of cellulose. RDFs prove that acetate can enter to the microsphere solvation of cellulose, however the bulky [C₂mim] cation cannot get so close to the cellulose. The first correlation peaks of acetate with all saccharides are approximately at 1.7 Å and the second are at 2.6 Å. In case of imidazolium, they start solvating saccharides after the 2 Å distance. This behavior was independent of saccharides concentrations in [C₂mim][OAc].

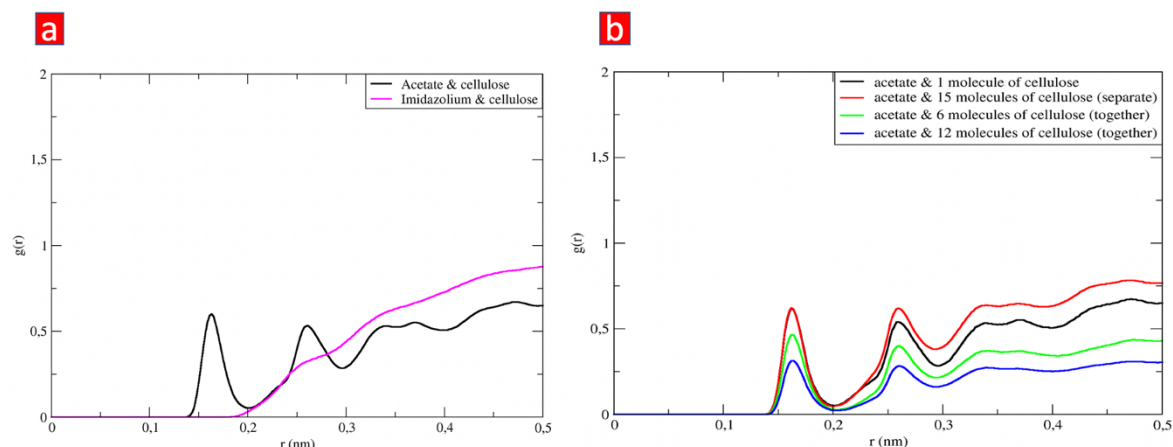


Fig. 23. RDFs of solvation one cellulose chain with acetate and imidazolium ions in $[C_2mim][OAc]$ (a), different concentrations of cellulose in $[C_2mim][OAc]$ (b).

RDFs in Figure 23, show for different concentrations of cellulose which are randomly put in $[C_2mim][OAc]$ the same numbers of acetate and imidazolium at microsphere solvation shells are seen. Moreover, they prove cellulose prefer to be solvated by anions more than cations.

To have a deeper knowledge of solvation shells, the systems in which cellulose chains have not been separated and solved and have the connection were performed. It was found out the ions solvate the cellulose in same distance when they are randomly solvated in the solutions. The results also show that the number of cations and anions of ILs per each chain of the cellulose in the solution of ionic liquid has a trend in which:

Separated 1, 5, 10 and 15 cellulose chains > non-separated cellulose with 6 chains > non-separated with 12 cellulose chains. It confirms the difficulty of cellulose dissolution and importance of anions effects on breaking the hydrogen bond interactions by replacing with the new ones.

Tables 12 and 13 show the number of hydrogen bonds between acetate ions and different hydroxyl groups of saccharides in the systems containing 1, 6 and 12 chains of cellulose molecules. It can be seen that the number of hydrogen bonds per each OH groups (OH groups of CH_2OH groups and other hydroxyl groups of cellulose with acetate ions is almost the same. However, by increasing the number of chains of cellulose which are close to each other (6 and 12 chains), the number of hydrogen bonds decreased it is assumed that the number of available hydroxy groups decreased. To better understand the solvation structures of acetate and its freedom to make hydrogen bond interaction, the structure of ionic liquid is also important.

Figure 24 shows the RDFs of oxygen atoms of acetate ions with C1, C2, C3, C4, C5 and C6 atoms of imidazolium cations.

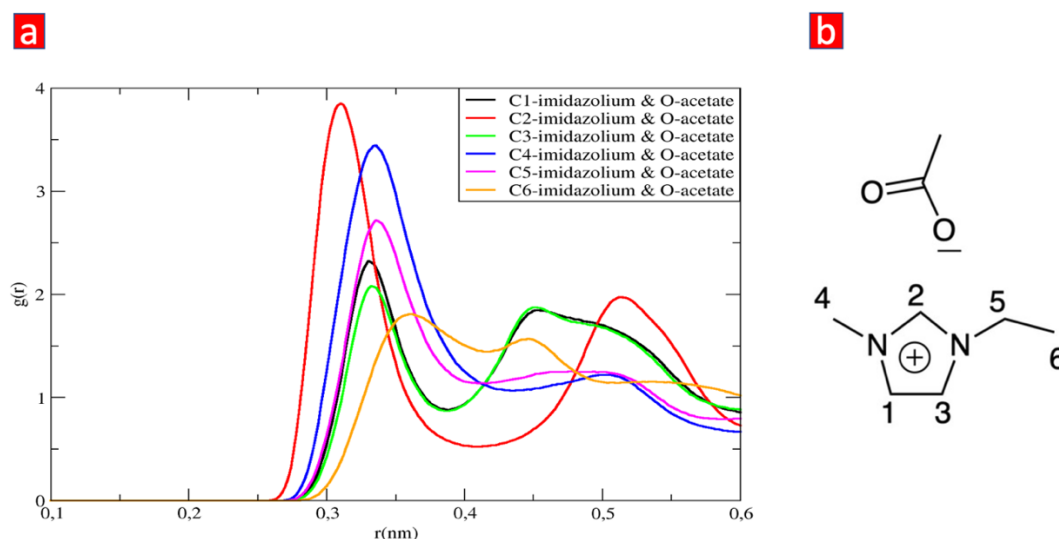


Fig. 24. RDFs of acetate around different carbons of imidazolium in $[C_2mim][OAc]$.

The RDFs show the distances and probabilities of acetate around carbons of imidazolium which are related to charges of different carbon atoms of imidazolium. The distances are in this order $C2 > C1 \sim C3 \sim C5 \sim C4 > C6$. Therefore, the most probable hydrogen bond interactions of acetate ions with imidazolium in $[C_2mim][OAc]$ is related to H(C2) of imidazolium cation. Also, Figure 24 shows that the oxygen of acetate ion prefers interact with hydrogen atom of C2 atom of imidazolium which is in good agreement with NMR results. These results were in a good accordance with Bowron et al. findings [265]. They studied the structure of $[C_2mim][OAc]$ ionic liquid by MD simulations and neutron diffraction. Also, they analyzed the solvation structure of acetate ions around the imidazolium and found acetate anions interact with three hydrogen atoms of imidazolium ring.

Figure 25 shows the interaction of acetate with hydroxyl groups of cellulose, cellobiose, and glucose via making hydrogen bonds.

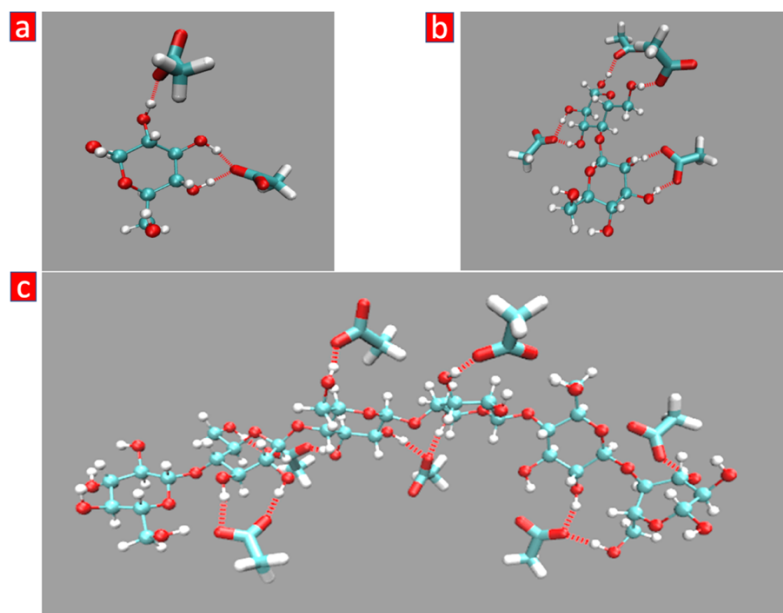


Fig. 25. Snapshots from MD simulations, showing the hydrogen bonds between acetate ions and glucose/cellobiose/cellulose at 2A resname of cellulose.

After anions, the cations can improve the dissolution of cellulose by hydrophobic interactions (Figure 26).

Table 12. The number of hydrogen bonds of cellulose, cellobiose, and glucose with acetate in [C₂mim][OAc] as an IL.

Carbohydrate	F. G	N
Cellulose-1 chain	OH-CH ₂ OH	0.99
Cellulose-1 chain	OH-hydroxyls	1.07
Cellulose-6 chain	OH-CH ₂ OH	0.73
Cellulose-6 chain	OH-hydroxyls	0.77
Cellulose-12 chain	OH-CH ₂ OH	0.53
Cellulose-12 chain	OH-hydroxyls	0.51
Glucose	OH-CH ₂ OH	0.99
Glucose	OH-hydroxyls	1.06
Cellobiose	OH-CH ₂ OH	1.01
Cellobiose	OH-hydroxyls	1.03

3.2 Conclusion

These findings show that cations and anions together disrupt the strong hydrogen bonding network of cellulose and make it soluble in $[\text{C}_2\text{mim}][\text{OAc}]$ ionic liquid. The reasonable mechanism of cellulose dissolution assumed that the anions make strong hydrogen bonds with OH groups of cellulose, and break the intra hydrogen bonds. Then, cations improve the dissolutions via hydrophobic interactions and preventing the accumulation.

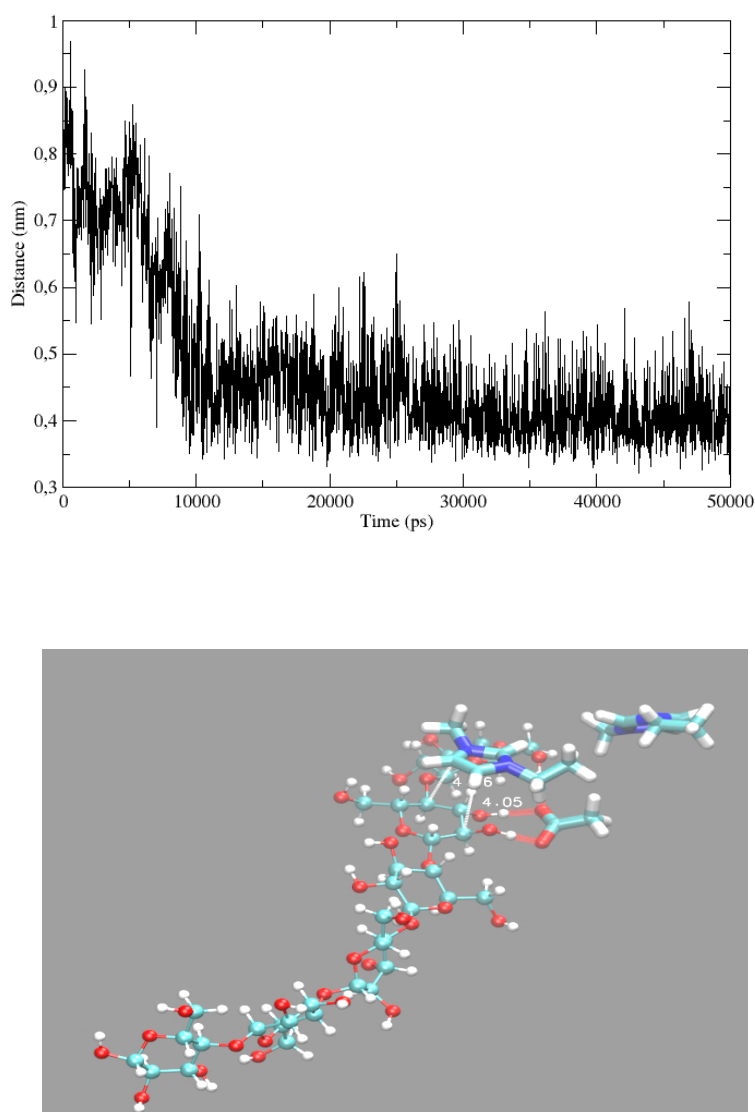


Fig. 26. The distance between methyl of alkyl chain of imidazolium cation with hydrophobic CH_3 group of acetate (top) and snapshot from MD simulation (bottom).

Table 13. The number of acetate and imidazolium ions around chains of cellulose, glucose, and cellobiose in [C₂mim][OAc] solutions by g_select, it writes out basic data about dynamic selections and the numbers are based on mass centers, the result are in different distances, average over steps 10 ns-50 ns.

Carbohydrate	Ions	1.5 Å	2 Å	2.5 Å	3 Å	3.5 Å	4 Å	4.5 Å	5 Å
Cellulose-1 chain	Acetate	0	0	4	10	11	12	15	17
Cellulose-1 chain	Imidazolium	0	0	0	2	6	13	21	27
Cellulose-6 chain	Acetate	0	0	15	44	47	50	54	56
Cellulose-6 chain	Imidazolium	0	0	0	4	18	37	52	66
Cellulose-12 chain	Acetate	0	0	22	62	64	65	68	73
Cellulose-12 chain	Imidazolium	0	0	0	6	27	50	72	90
Glucose	Acetate	0	0	1	3	3	4	4	5
Glucose	Imidazolium	0	0	0	0	1	3	5	8
Cellobiose	Acetate	0	0	2	5	6	7	8	9
Cellobiose	Imidazolium	0	0	0	1	3	6	10	11

CHAPTER 4

References

4.1 References

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CHAPTER 5

Original papers

5.1 Article 1

Journal of Molecular Liquids 284 (2019) 59–67



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Experimental and theoretical investigation of solvatochromic properties and ion solvation structure in DESs of reline, glyceline, ethaline and their mixtures with PEG 400



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Participation of Meysam Aryafard:

MA performed the MD simulations, analysed the results, combined the experimental and theoretical studies, and wrote the paper.

Aryafard, M.; Abbasi, M.; Řeha, D.; Harifi-Mood, A. R.; Minofar, B. Experimental and theoretical investigation of solvatochromic properties and ion solvation structure in DESs of reline, glyceline, ethaline, and their mixtures with PEG 400. *J. Mol. Liq.* **2019**, 284, 59–67.

<https://doi.org/10.1016/j.molliq.2019.03.149>



Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

Experimental and theoretical investigation of solvatochromic properties and ion solvation structure in DESs of reline, glyceline, ethaline and their mixtures with PEG 400

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ARTICLE INFO

Article history:

Received 4 December 2018

Received in revised form 15 March 2019

Accepted 26 March 2019

Available online 30 March 2019

ABSTRACT

Deep eutectic solvents (DESs) are a new class of ionic liquids which have been applied in many chemical reactions therefore, the investigation of their physicochemical properties such as hydrogen bond property and ion delocalization, are important. We measured solvatochromic parameters of three different DESs, namely urea-choline chloride (reline), ethylene glycol-choline chloride (ethaline), and glycerol-choline chloride (glyceline) and their binary mixtures with different mole fractions of poly ethylene glycol (PEG 400) as co-solvent. Solvatochromic results showed that the reline has the biggest polarity in these three DESs, but the lowest in hydrogen bond donor and acceptor abilities. In binary mixtures of DESs with PEG 400, π^* and α values are decreasing with increasing the mole fraction of PEG 400 which is in good agreement with these parameters in mixed solvents. Molecular dynamic simulations confirmed that there are hydrogen bonds between urea, ethylene glycol, glycerol and choline chloride in pure DESs, and their amount calculated in all DESs and also with some mole fractions of PEG 400. Moreover, delocalization of chloride in DESs, were calculated for all compositions by MD simulations analysis. Also, MD simulations confirmed result of the experimental finding and preferential solvation model.

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1. Introduction

Investigation of the properties of deep eutectic solvents (DESs) is a growing research area. DESs can be simply prepared via mixing of a quaternary ammonium salts with hydrogen bond donor (HBD) compounds. DESs were reported in many industrial applications as attractive alternatives to ionic liquids (ILs). DESs share with ILs many of their intrinsic merits such as their biodegradable components, non-flammability due to their low or none measurable vapor pressure, and low toxicity [1–3]. Additionally, DESs are much cheaper than ILs which makes them readily available for large scale industrial applications. The majority of studies have focused on choline chloride (ChCl) as an organic salt in eutectic mixtures in combination with HBDs. The first effort on these compounds was reported by Abbott et al. based on choline chloride and urea in a 1:2 M ratio [4,5]. Nevertheless, most of the studies in the literature are about ChCl-based DESs in combination with different types of

HBDs [6]. Other salts, such as imidazolium [7], ammonium [8,9] and phosphonium based [10,11] DESs have also been studied but to a minor extent in comparison with ChCl based DESs. ChCl-base DESs are suitable platform for DES development considering their environmental, economic, and technological viewpoints. The diversity of possible combinations of the starting materials provides a powerful tool to control the physical properties of DESs. Besides, DESs exhibit physicochemical properties similar to those of ILs which, along with their advantages, allows DESs to replace or improve ILs in many applications. In this sense, several review works have focused on the wide range of applications of DESs such as organic synthesis, catalysis, electrochemistry, nanotechnology, and separation technologies [12–14]. DESs not only have special properties compared to traditional organic solvents but also their mixtures with ordinary organic solvents may show improvement and favorable characteristics [15–17]. Due to the fact that they have several practical applications, the study of aqueous solutions of DESs has widely increased in recent years [18–20]. Therefore, selection of the suitable co-solvent is an important part of every process. Poly ethylene glycols (PEGs) are liquids or low-melting solids, depending on their molecular weights. As DESs are composed of mixtures of quaternary ammonium salts and HBD components so that by choosing PEG 400 which has same functional groups to the ethylene glycol and

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Table 1

The measured solvatochromic parameters in DESs–PEG 400 mixtures at 25 °C.

x_1^a	Ethaline				Reline				Glyceline			
	A	B	π^*	E_T^N	α	β	π^*	E_T^N	α	β	π^*	E_T^N
0	0.63	0.73	1.02	0.66	0.63	0.73	1.02	0.66	0.63	0.73	1.02	0.66
0.1	0.63	0.73	1.05	0.67	0.60	0.67	1.11	0.68	0.64	0.76	1.02	0.67
0.2	0.65	0.73	1.06	0.69	0.60	0.67	1.11	0.68	0.68	0.78	1.02	0.69
0.3	0.67	0.73	1.06	0.70	0.59	0.67	1.12	0.68	0.69	0.78	1.02	0.69
0.4	0.68	0.73	1.08	0.71	0.58	0.67	1.14	0.68	0.70	0.78	1.02	0.70
0.5	0.68	0.73	1.09	0.71	0.57	0.66	1.17	0.69	0.71	0.78	1.02	0.70
0.6	0.70	0.73	1.09	0.72	0.59	0.66	1.17	0.70	0.73	0.78	1.02	0.71
0.7	0.72	0.73	1.10	0.73	0.59	0.66	1.17	0.70	0.75	0.78	1.02	0.72
0.8	0.75	0.73	1.10	0.75	0.63	0.66	1.17	0.72	0.78	0.78	1.04	0.74
0.9	0.78	0.72	1.11	0.77	0.69	0.66	1.18	0.75	0.82	0.77	1.06	0.77
1	0.89	0.55	1.14	0.83	0.82	0.45	1.25	0.83	0.93	0.60	1.08	0.82

^a x_1 is the mole fraction of DESs.

glycerol a series of new mixed solvents are close to DESs can be synthesized. Moreover, PEG 400 is soluble in water, alcohols, and aromatic hydrocarbons also partly in aliphatic hydrocarbons [21] therefore, it can be used as one of the best co-solvent for DESs.

As new effects arise from mixture formation of pure DESs with organic solvents because of synergic effects or hydrogen bond acceptor–donor (HBA–HBD) interactions thus binary mixtures of DESs with other solvents can show new physicochemical properties compared to pure DESs. Solute–solvent interactions are presented as solvatochromic properties of the media such as empirical polarity and Kamlet–Taft parameters [22–25]. Solute–solvent interactions are much more complex in mixed solvents than in pure solvents owing to the possibility of preferential solvation of each component of solvents present in the mixture [26]. Moreover, the solvent–solvent interactions in solvent mixtures can affect the solute–solvent interactions therefore affects preferential solvation [26,27]. In this work, in order to obtain information on physicochemical properties of binary mixtures of DESs with molecular

solvents, we have investigated the behaviors of solvatochromic probes in different mixtures. On the basis of these probes' responses, four solvatochromic parameters (i.e., E_T^N normalized solvent polarity parameter; π^* , dipolarity/polarizability; β , HBA basicity; α , HBD acidity) were determined in binary mixtures of urea–choline chloride (reline), ethylene glycol–choline chloride (ethaline), and glycerol–choline chloride (glyceline) as three DESs with PEG 400. A preferential solvation model has been used in order to interpret the ideal or non-ideal behavior of solvatochromic parameters in these mixtures.

Moreover, molecular dynamics (MD) simulations have been used to examine hydrogen bond interaction between molecules and ions as well as ion solvation structure in pure DESs and mixtures with PEG 400. MD simulations have been used to study many chemical and biological systems, covering a range of size and scales [28]. MD simulation can predict many thermodynamic and structural properties of systems based on statistical mechanics [29] therefore, it provides complementary information to experimental methods. Also, MD simulations allow to investigate the inter-molecular interactions in molecular level which is not easily accessible for some experimental techniques. In recent years, MD simulations have been used for analysis of interactions at molecular level for understanding a large variety of processes such as ion transport and solute–solvent interactions [30–33]. Moreover, MD simulations can target specific ion localization, solvent–solvent and solute–solvent interactions which occur during the solvation and can be compared to experimental results.

2. Experimental

2.1. Materials

2,6-Diphenyl-4-(2,4,6-triphenylpyridinium-1-yl) phenolate (Reichardt's dye 30) and Urea (>99%) were purchased from Sigma-

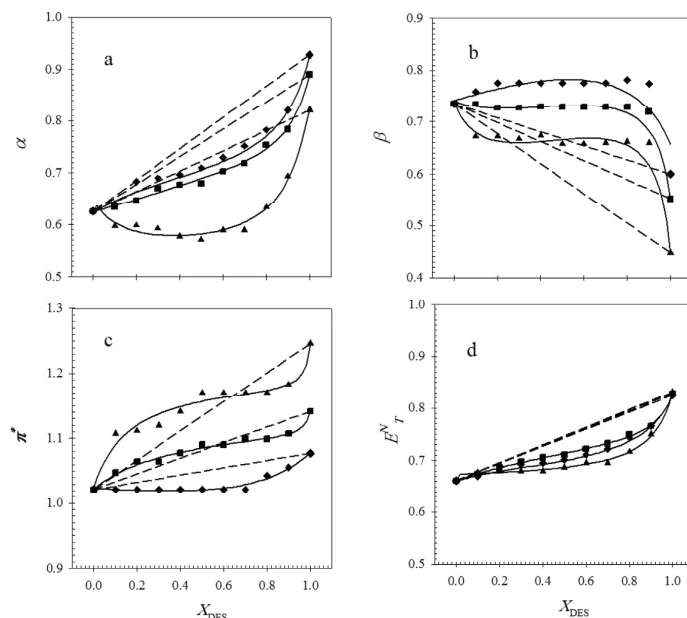


Fig. 1. The plots of α (a), β (b), π^* (c) and E_T^N (d) in the DESs (ethaline (■), glyceline (◆), and reline (▲)) mixed with PEG 400. The solid curves have been calculated from coefficients of Eq. (6) given in Table 2 and the dashed lines show the ideal behavior.

Table 2

Preferential solvation parameters obtained by applying Eq. (6) on solvatochromic data in binary mixtures of DESs (2) with PEG 400 (1). N , r^2 , and σ are number of experimental data, regression coefficient, and standard deviation, respectively.

Indicator	Solvents	Y_1	Y_2	Y_{12}	$f_{2/1}$	$f_{12/1}$	$f_{12/2}$	N	r^2	$10^3 \times \sigma$
4-Nitroanisole	Ethaline/PEG 400	31.72	31.45	31.54	0.10	3.60	36.00	11	0.989	0.10
	Reline/PEG 400	31.72	31.20	31.37	0.17	7.16	42.11	11	0.967	0.91
	Glyceline/PEG 400	31.72	31.59	31.77	0.26	1.05	4.04	11	0.971	0.10
4-Nitroaniline	Ethaline/PEG 400	25.82	25.97	25.47	0.11	1.11	10.09	11	0.982	0.46
	Reline/PEG 400	25.83	25.94	25.37	0.11	1.06	9.64	11	0.977	0.63
	Glyceline/PEG 400	25.83	26.04	25.64	0.41	3.19	7.78	11	0.988	0.26
Betaine dye	Ethaline/PEG 400	18.24	20.12	18.99	0.18	2.18	12.11	11	0.999	0.55
	Reline/PEG 400	18.32	20.16	18.47	0.18	2.00	11.11	11	0.992	3.8
	Glyceline/PEG 400	18.23	20.08	18.56	0.69	4.81	6.97	11	0.990	4.8

Aldrich and were used without further purification. 4-Nitroaniline and 4-nitroanisole (Merck, 99%) were recrystallized multiple times with water/ethanol and water/acetone before use. Choline chloride (>98%), purchased from Sigma-Aldrich, was dried for 4 days at 313 K in a vacuum oven. PEG 400, ethylene glycol (99.8%, anhydrous), and glycerol (>99.5% spectrophotometric grade) were supplied from Merck. All liquid materials were dried by 3 Å molecular sieve. The water content of the dried compounds was determined by coulometric Karl Fischer titration (Metrohm 899 Coulometer) yielding <400 ppm residual water for PEG 400, <100 ppm for ethylene glycol and glycerol, and <600 ppm for choline chloride.

2.2. Methods

In order to prepare ethaline, glyceline, and reline, choline chloride was mixed with ethylene glycol, glycerol, and urea, respectively, in a molar ratio of 1:2 followed by stirring under heating (near 80 °C) until homogeneous colorless liquids were formed. All probe stock solutions were prepared in high purity ethanol and stored in dark glass vials at 4 °C. An appropriate aliquot of the indicator solution was transferred into 1 cm quartz cuvette, including pure solvent or mixed system, to achieve the desired probe concentration. The mixtures of DESs with PEG-400 at different compositions were gravimetrically prepared with a precision of ± 0.1 mg. The solutions were vigorously stirred with a magnetic stirrer to obtain homogeneous solutions. Then it was transferred into the quartz cuvette. A GBC UV-vis Cintra 101 spectrophotometer with a thermocell coupled to it was used for recording the UV-vis absorbance spectra of the solutions at 25 ± 0.1 °C. All of the measurements were recorded three times and averaged.

3. Computational section

DESs can be described by the general formula of $\text{Cat}^+ \text{X}^- zY$ [34], here Cat^+ refers to choline, X^- chloride, and zY refers to the number (z) of molecules (Y) such as ethylene glycol, glycerol, urea or co solvents. In the mixture of DESs and PEG 400, chloride ion interacts with components of DES-PEG 400 mixtures, therefore the knowledge of the hydrogen bond interactions and ion solvation structure are important for understanding the physicochemical properties of DESs-PEG 400 mixtures. It would be interesting to investigate the ion solvation structure and the interaction between solute-solvent molecules as well as solvent-solvent molecules in order to understand the HBA and HBD abilities of DESs in presence of different mole fractions of PEG 400 in molecular level. Classical molecular dynamics simulations have been used to study the solutions containing one molecule of 4-nitroaniline and 4-nitroanisole separately with exact ratios of choline chloride to urea, ethylene glycol and glycerol over the entire range of PEG 400 mol fractions in DES-PEG 400 mixtures according to experimental work. The solutions were made in the cubic box with a dimension of 120 Å. All MD simulations were performed by Gromacs 5.0 program

package [35–37] with General Amber Force Field (GAFF) [38] for all molecules and ions of the solutions. In the Eq. (1),

$$E(r^N) = \sum_{\text{bonds}} \frac{k_i}{2} (l_i - l_{i,0})^2 + \sum_{\text{angles}} \frac{k_i}{2} (\theta_i - \theta_{i,0})^2 + \sum_{\text{torsions}} \frac{V_n}{2} (1 + \cos(n\omega_i - \gamma_i)) + \sum_{i=1}^N \sum_{j=i+1}^N 4\epsilon_{ij} \left(\left(\frac{\delta_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\delta_{ij}}{r_{ij}} \right)^6 \right) + \sum_{i=1}^N \sum_{j=i+1}^N \frac{q_i q_j}{4\pi\epsilon_0 r_{ij}} \quad (1)$$

The total potential energy of the system, $E(r^N)$, is given as the sum over all bonded and non-bonded interactions. The former consists of the summation of harmonic interaction potentials for any bond, angle, or torsion, and the latter represents van der Waals and Coulomb interaction energies of all atom pairs separated by three or more covalent bonds.

After preparation of each system, energy minimization procedure was used to remove all unexpected and unfavorable contacts due to random solvation of molecules in the box. All MD simulations were run in the NVT (canonical ensemble) at 298 K [39] for 100 ps and then NPT (isothermal-isobaric ensemble) simulations for 500 ps. All simulations were run for 50 ns and collected data were analyzed and compared with experimental data. Equations of motion were integrated using the leap-frog algorithm [40] and VMD program was used for visualizations [41] and preparation of snapshots.

Table 3

The calculated HBA (β') parameters in neat reline and its binary mixtures at the mole fractions of 0.3 and 0.9 PEG 400.

HBA (β')	HBD components	Mole fraction		
		0.9 PEG 400	0.3 PEG 400	Reline
O-Urea	NH-Urea	0.072	0.696	0.112
	OH-PEG	1.001	0.380	–
	OH-Chl	0.013	0.075	0.114
$\sum \beta'$ O-Urea		1.085	1.151	0.226
O-t-PEG ^a	OH-PEG	0.987	0.389	–
	NH-Urea	0.035	0.314	–
	OH-Chl	0.009	0.034	–
$\sum \beta'$ O-t-PEG		1.031	0.737	–
O-c-PEG ^a	OH-PEG	0.067	0.027	–
	NH-Urea	0.011	0.118	–
	OH-Chl	0	0.001	–
$\sum \beta'$ O-c-PEG		0.078	0.146	–
O-Chl	NH-Urea	0.017	0.162	0.267
	OH-PEG	0.106	0.052	–
	OH-Chl	0.001	0.000	0.000
$\sum \beta'$ O-Chl		0.124	0.214	0.267
N-Urea	OH-PEG	0.037	0.011	–
	OH-Chl	0.000	0.001	0.003
	NH-Urea	0.000	0.006	0.000
$\sum \beta'$ N-Urea		0.037	0.018	0.003

^a O-t-PEG relates to terminal oxygens of PEG 400, and O-c-PEG relates to oxygens of PEG 400 except for O-t-PEG.

Table 4

The calculated HBA (β') parameters in neat glyceline and its binary mixtures at the mole fractions of 0.3 and 0.9 PEG 400.

HBA (β')	HBD components	Mole fraction		
		0.9 PEG 400	0.3 PEG 400	Glyceline
O-Gly	OH-Gly	0.180	0.532	0.760
	OH-PEG	0.376	0.163	–
	OH-Chl	0.009	0.030	0.051
$\sum \beta'$ O-Gly		0.565	0.725	0.811
O-tails-PEG	OH-Gly	0.030	0.245	–
	OH-PEG	0.986	0.389	–
	OH-Chl	0.009	0.034	–
$\sum \beta'$ O-t-PEG		1.025	0.668	–
O-chain-PEG	OH-Gly	0.004	0.031	–
	OH-PEG	0.067	0.026	–
	OH-Chl	0.000	0.002	–
$\sum \beta'$ O-c-PEG		0.071	0.059	–
O-Chl	OH-Gly	0.003	0.056	0.135
	OH-PEG	0.102	0.042	–
	OH-Chl	0.000	0.003	0.019
$\sum \beta'$ O-Chl		0.105	0.101	0.154

4. Results and discussion

4.1. Behavior of 2,6-diphenyl-4-(2,4,6-triphenylpyridinium-1-yl) phenolate and E_T^N

The empirical parameter of solvent polarity, $E_T(30)$, which is strongly sensitive to the HBD ability of solvents [22,23] in $\text{kcal} \cdot \text{mol}^{-1}$ can be calculated according to Eq. (2):

$$E_T(30)/\text{kcal} \cdot \text{mol}^{-1} = 2.8591 \phi_B \quad (2)$$

where ϕ_B is the wavenumber of the maximum absorption attributed to the charge transfer energy of Reichardt's dye. $E_T(30)$ is normalized by using tetramethylsilane (TMS) as an extreme nonpolar and water as a high polar solvents. Moreover, E_T^N is easier to use as it is dimensionless factor and indicates both the dipolarity/polarizability and the HBD ability of the media.

$$E_T^N = \frac{E_T(\text{solvent}) - E_T(\text{TMS})}{E_T(\text{water}) - E_T(\text{TMS})} = \frac{E_T(\text{solvent}) - 30.7}{32.4} \quad (3)$$

Experimentally obtained E_T^N of binary mixtures of ethaline, glyceline and reline with PEG-400 are given in Table 1. Data show that the neat PEG 400 has lower normalized polarity than those of pure DESs.

Table 5

The calculated HBA (β') parameters in neat ethaline and its binary mixture at the mole fraction of 0.3 PEG 400.

HBA (β')	HBD components	Mole fraction	
		0.3 PEG 400	Ethaline
O-EG	OH-EG	0.279	0.426
	OH-PEG	0.165	–
	OH-Chl	0.026	0.033
$\sum \beta'$ O-EG		0.470	0.459
O-tails-PEG	OH-EG	0.162	–
	OH-PEG	0.447	–
	OH-Chl	0.048	–
$\sum \beta'$ O-t-PEG		0.657	–
O-chain-PEG	OH-EG	0.021	–
	OH-PEG	0.031	–
	OH-Chl	0.002	–
$\sum \beta'$ O-c-PEG		0.054	–
O-Chl	OH-EG	0.046	0.079
	OH-PEG	0.039	–
	OH-Chl	0.004	0.009
$\sum \beta'$ O-Chl		0.089	0.088

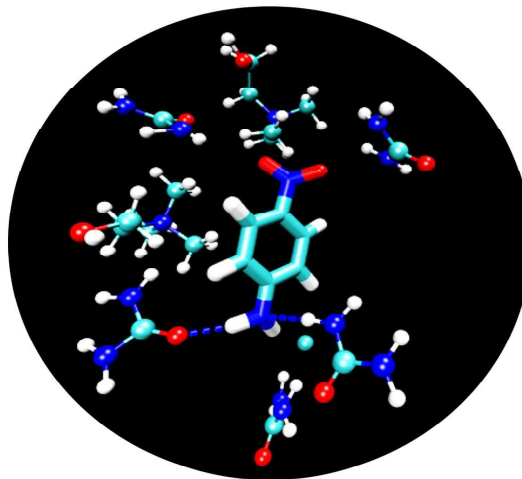


Fig. 2. Snapshot from MD simulation showing the distribution of solvent molecules around 4-nitroaniline in reline. 4-Nitroaniline acts as both HBD and HBA by amine group.

Incrementing behavior with a negative deviation from ideality can be observed for E_T^N in all investigated binary mixtures when the mole fraction of ethaline increases (Fig. 1d). The present data of this work is in excellent agreement with recently published [42,43] E_T^N of pure ethaline. The higher E_T^N values of DES in comparison with the neat PEG 400 can be attributed to the presence of large anion as polarizable species and the hydrogens of ammonium cation which can readily participate in specific and non-specific interactions with Reichardt's dye.

4.2. Kamlet–Taft parameters

The Empirical Kamlet–Taft parameters [23–25] were calculated for all mixtures. The π^* , β , and α parameters, that show the normalized

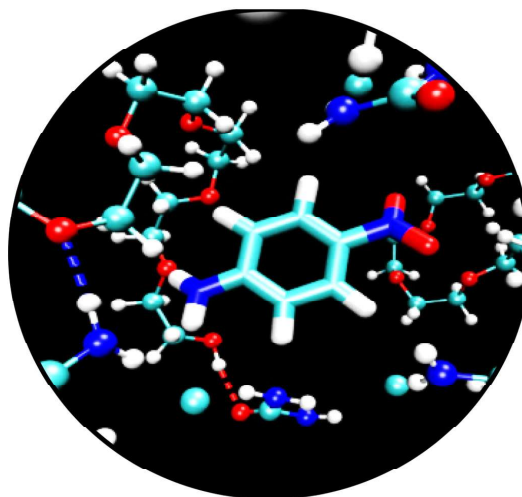


Fig. 3. Snapshot from MD simulation showing the distribution of solvent molecules around 4-nitroaniline in the binary mixture of reline-PEG 400 at the mole fraction of 0.3 PEG 400.

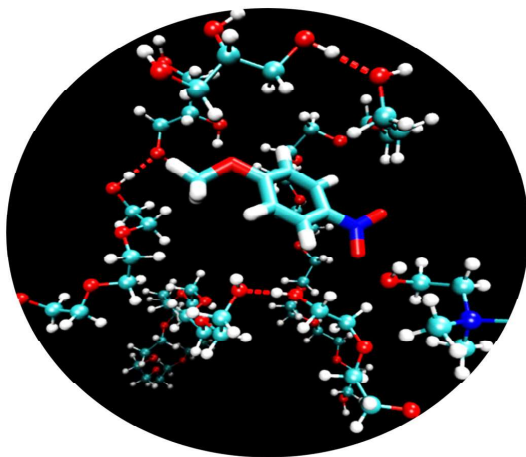


Fig. 4. Snapshot from MD simulation showing the distribution of solvent molecules around 4-nitroanisole in the binary mixture of glycine-PEG 400 at the mole fraction of 0.3 PEG 400.

values like E_T^N , were calculated from the wavenumbers of maximum absorption of 4-nitroanisole (ϕ_{ANS}), 4-nitroaniline (ϕ_{ANI}), and Reichardt's dye (ϕ_B), respectively, in solvent mixtures according to Eqs. (4)–(6):

$$\pi^* = 0.427(34.12 - \phi_{ANS}) \quad (4)$$

$$\beta = \frac{31.10 - 3.14\pi^* - \phi_{ANI}}{2.79} \quad (5)$$

$$\alpha = 0.186(10.91 - \phi_B) - 0.72\pi^* \quad (6)$$

Since there are several method to calculate the π^* parameter, the scale mentioned in Eq. (4) is so-called N-scale. The values of π^* , α , and β of the binary mixtures of reline, ethaline, and glycine with PEG 400 in different mole fractions are summarized in Table 1. It can be seen that by addition of glycine to PEG 400, the π^* value is moderately constant corresponding with its value in neat PEG 400 and then increases after 0.7 mol fraction of glycine to the value of pure glycine.

In PEG 400–reline and PEG 400–ethaline mixtures, the increase in π^* is continuously observed with increasing of DES in whole mole fraction range (Fig. 1c).

An interesting result was observed in β values which show approximately constant values in all solvent compositions. The β values in solvent mixtures and pure PEG 400 are close to each other which reveal HBA ability of PEG 400 is the determining HBA ability of the media. It can be easily inferred that each PEG molecule offers many more hydrogen bond accepting centers (two HOCH_2CH_2 and oxyethylene chains ($\text{CH}_2\text{CH}_2\text{OCH}_2\text{CH}_2$) of PEG 400) than those of reline, ethaline, and glycine. Following mole fraction of 0.9 with respect to DESs, the β values decrease suddenly to its corresponding value in DESs. It confirms that the solutes with HBD ability are solvated preferentially by PEG 400 in the mixture systems so that the dominant solute-solvent interaction is HBD-HBA interactions. In this solvation structure, solvent acts as a HBA molecule.

Fig. 1 exhibits a negative deviation from ideal behavior for α values in the mixtures of ethaline, glycine, and reline with PEG 400. The α value of PEG 400 has been found to be lower than that of DESs. PEG 400 molecules have two terminal hydroxyl groups as hydrogen bond donor groups while DESs molecules include various hydrogen bond donating groups such as hydroxyl groups in glycine, ethaline, and choline cation and NH_2 groups in reline. Therefore, the difference in α value between DESs and PEG 400 can be attributed to their structures.

The normalized polarity parameter (E_T^N) is a blend of π^* and α abilities of media. Thus the behavior of the plots is also related and the plot of E_T^N is combination of the plots of π^* and α . Since the variation of π^* is

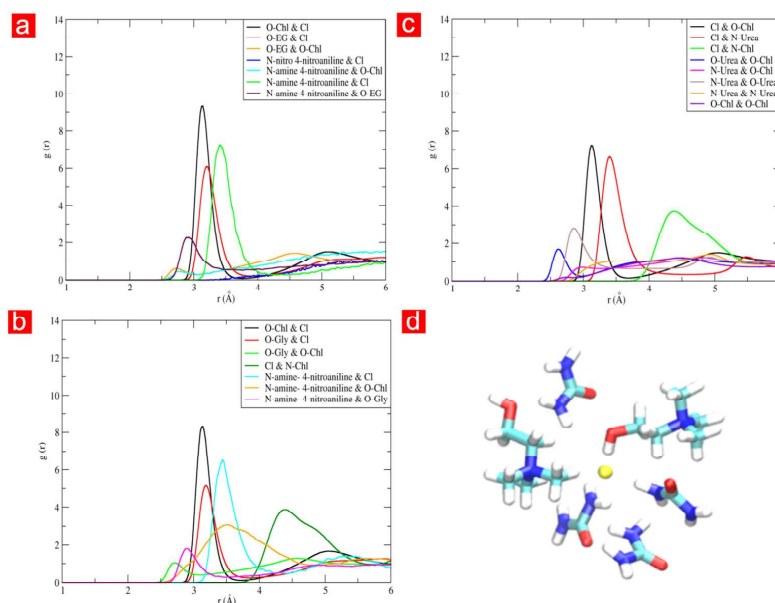


Fig. 5. Radial distribution functions of functional groups in ethaline (a), glycine (b), and reline (c). Snapshot from MD simulation showing the coordination shell of Cl^- ion (yellow color) by urea and choline cation in DES of reline (d).

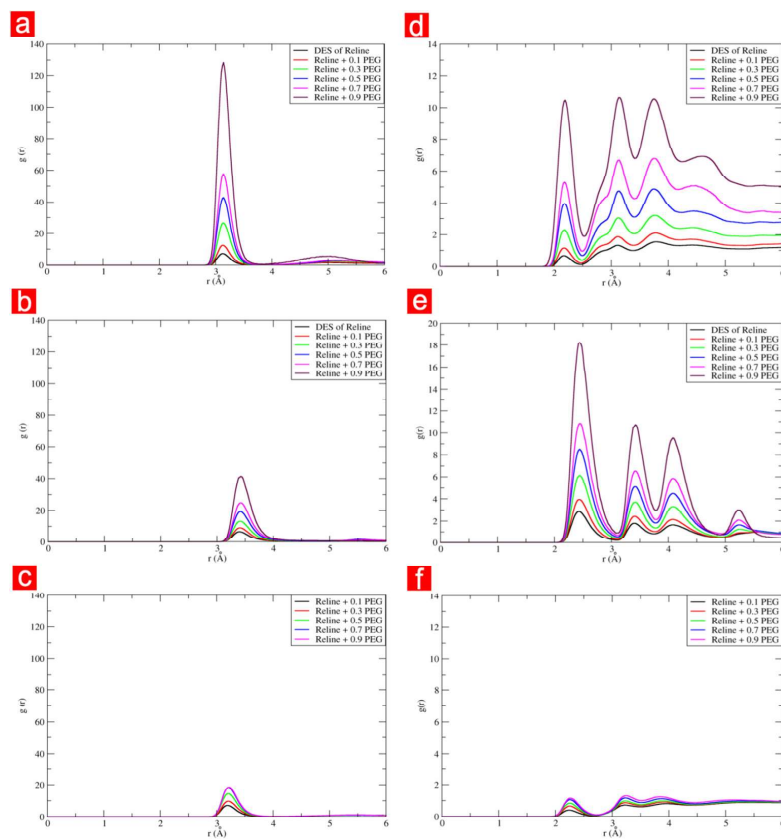


Fig. 6. Radial distribution functions in different mole fractions of reline; O-choline and Cl^- (a), N-urea and Cl^- (b), O-terminals PEG 400 and Cl^- (c), choline and Cl^- (d), urea and Cl^- (e), PEG 400 and Cl^- (f).

negligible in solvent mixtures, the changes in E_N^N value depend on α variation. Therefore, a similarity is obvious in the trend of E_N^N and α .

The most known probes for measuring solvatochromic parameters have low solubility in short alkyl chain alcohols and solubility of these probes depend on functional groups and number of benzene rings. For example nitrobenzene is insoluble in water and ethanol

but aniline is soluble in them. The most DESs have hydrophilic functional groups, thus it seems that solvatochromic probes should have low solubility in DESs; in order to tuning the behavior of the probes, PEG 400 has been used as it is soluble in these DESs. Moreover, PEGs have both hydrophobic and hydrophilic character as either liquid or low-melting solids depending on their molecular weights so that can

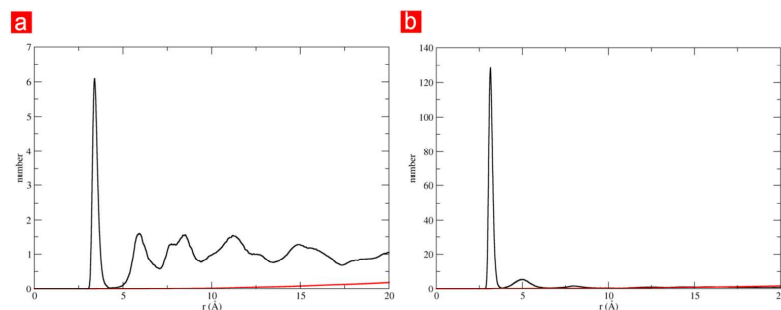


Fig. 7. Radial distribution functions (black curves) and cumulative sums of them (red curves) which show the coordination numbers of radial distributions, for N-amine 4-nitroaniline and Cl^- in reline (a), O-choline and Cl^- in reline + the mole fraction of 0.9 PEG 400 (b).

Table 6

Determined coordination numbers for each partial RDF shown in Fig. 5. All coordination numbers have been obtained by integrating the corresponding RDF over range 2–4 Å.

Components	Components	DESs		
		Reline	Ethaline	Glyceline
Cl	Chl	15.18	14.35	12.85
	EG	–	13.22	–
	Gly	–	–	14.88
	Urea	11.95	–	–
	O-Chl	0.78	0.77	0.70
	O-EG	–	2.85	–
	O-Gly	–	–	3.28
O-Chl	N-Urea	4.58	–	–
	O-Chl	0.34	0.27	0.27
	O-EG	–	0.29	–
	O-Gly	–	–	0.28
	N-Urea	0.37	–	–
	O-Urea	0.46	–	–
	O-EG	–	1.21	–
O-EG	O-Gly	–	–	1.90
N-Urea	N-Urea	1.85	–	–
O-Urea	N-Urea	2.23	–	–

be good co-solvents for DESs. Solvatochromic results revealed that the dipolarity/polarizability of reline shows the high value among studied DESs while HBD and HBA abilities of DESs demonstrate the sequence of glyceline > ethaline > reline. α values decrease with increasing the mole fraction of PEG 400. The data are in good agreement with mixed solvents, whereas β values increase with increase of mole fractions of PEG 400 (Fig. 1a and b). Since ethylene glycol and glycerol have similar structure as PEG 400, their solvatochromic behaviors are similar and solvatochromic parameters of mixtures are close to those of ethaline and glyceline. In order to understand the solvation behavior of experimentally studied DESs with and without co-solvent at the molecular level, classical molecular dynamics (MD) simulations have been performed.

4.3. Preferential solvation model

Interest on preferential solvation model for studying the solvent-solute and solute-solute interactions and describing the synergism behavior of the solvent mixtures has been increased [44–46] therefore to understand the solvation microsphere, preferential solvation model has been used. According to literature [43–46], the physical properties (Y), such as the wavenumber of maximum absorption of solvatochromic probes in the solvent mixtures, are calculated as an average of these properties in pure and mixed solvents (Y_1 , Y_2 , and Y_{12} , respectively) according to the mole fractions of each solvent (DES component) in the mixture (x_2^0) as followed:

$$Y = \frac{Y_1(1-x_2^0)^2 + Y_2f_{2/1}(x_2^0)^2 + Y_{12}f_{12/1}(1-x_2^0)x_2^0}{(1-x_2^0)^2 + f_{2/1}(x_2^0)^2 + f_{12/1}(1-x_2^0)x_2^0} \quad (7)$$

Table 7

Determined coordination numbers of solvated 4-nitroaniline and 4-nitroanisole in some mole fraction of reline-PEG 400 and glyceline-PEG 400 mixtures, respectively. All coordination numbers have been obtained by integrating the corresponding RDF over range 2–4 Å.

Probe	Components	The mole fraction of DES		
		0.1	0.7	1.0
4-Nitro aniline	Choline	0.08	3.44	8.12
	Urea	0	2.24	7.43
	PEG 400	15.38	8.82	0
4-Nitro anisole	Choline	0	3.62	5.93
	Glycerol	0.53	1.95	9.36
	PEG 400	14.65	9.27	0

where $f_{2/1}$ and $f_{12/1}$ are the preferential solvation parameters based on the thermodynamic equilibrium constants of solvent exchange molecules in microsphere solvation of the solute [35].

Table 2 shows parameters which have been achieved by preferential solvation model. The low values of $f_{2/1}$ confirm the weak attendance of DES in the microsphere solvation of the solvatochromic probes. The solvatochromic parameters which are extracted from the wavenumber of maximum absorption of solvatochromic probes according to Eqs. (2)–(6) show the clear deviation from ideal behavior (Fig. 1). Compared with pure PEG 400, negligible changes in parameters were observed in mixtures up to high mole fractions of DESs. It is in agreement with $f_{2/1}$ values which prove the preferential solvation of probes with PEG 400 in all mixtures. On the other hand, $f_{12/1}$ values show that all probes have strong tendency to be solvated by mixed solvents compared with DESs separately. Also, $f_{12/1}$ are lower than $f_{12/2}$ because mixed solvents behave like pure PEG 400. Positive or negative synergism observed in Fig. 1a and b are attributed to the preferential solvation of probes with composite molecules of solvents which show lower HBD or higher HBA abilities, respectively, compared with each components.

4.4. Computational details

Numbers of hydrogen bonds were calculated in DESs with the increasing mole fraction of PEG 400. In this computational work, hydrogen bond interaction parameter (β'), refer to relations between the components of solvent mixtures while in Experimental section, it refers to the ability of solvent for having interactions with probes (β). Tables 3–5 show the hydrogen bond acceptor (β') for all components of pure DESs and with 0.3 and 0.9 mol fractions of PEG 400. Urea, ethylene glycol, glycerol and choline can be both HBA and HBD as they have amine and hydroxyl groups. The number of hydrogen bonds in Tables 3–5 was calculated for HBA per one molecule of acceptor. The β' values for solvent's components (Tables 3–5) confirm that by adding PEG 400, β' values for urea are bigger than glycerol and ethylene glycol, and urea molecules have HBA property with both ketone and amines functional groups. Table 3 shows that β' values with ketone functional group are larger than amine groups. Moreover, all hydrogen bond interactions between oxygen atoms and hydrogen atoms of same molecules (O-Urea & NH-Urea, O-Glycerol & OH-Glycerol, O-ethylene glycol & OH-ethylene glycol) decrease while interactions between different molecules (O-Urea & OH-PEG 400, O-Glycerol & OH-PEG 400, O-ethylene glycol & OH-PEG 400) increase with increasing PEG 400 mol fraction.

In the case of hydrogen bond interaction of solvatochromic probes, amine group of 4-nitroaniline can act both as HBD and HBA with DESs as shown in Fig. 2. By addition of PEG 400 to the solution, PEG 400 molecules which act as hydrogen bond acceptors interacting with hydroxyl groups of DESs molecules and 4-nitroaniline behaves preferentially as HBD molecule (Fig. 3). Since there are strong hydrogen bond interactions between components of DES, the solvated probes cannot make enough hydrogen bonds with solvent (Fig. 4) thus their wavelengths of maximum absorption are just slightly changed during spectrophotometric measurements with increasing the mole fractions of PEG 400.

Radial distribution function (RDF) as a powerful tool from MD simulations has been used for understanding of the solvation structure around molecules and ions in solutions. Cl^- ions can make contact ion pair with choline cation but it is observed that the ion pair formation pattern is not increased noticeably by increasing the mole fraction of PEG 400. Fig. 5 shows that Cl^- ions are not strongly solvated by ammonium part of choline (Cl & N-Chl) compare to another solvent's components, therefore chloride solvation structure is very important factor on changing the physicochemical properties of pure DESs and the mixture of DESs with PEG 400. In reline, ethaline, and glyceline, RDFs of Cl^- ion with choline showed similar behavior with increasing of the mole fraction of PEG 400, therefore, the Fig. 6 just shows the RDFs of Cl^- ion and choline for reline over all mole fractions with PEG 400. RDFs in Fig. 6

show that the location of Cl^- ion around DESs components are on functional groups, and the peak corresponding to the first solvation shell of Cl^- ion, with respect to the hydroxyl group of choline increases with increasing the PEG 400 more than Cl^- ion with respect to the other components of the solution and it's because, β' in the solutions increase by addition of PEG 400 to the solution in which all components of the solutions have tendency for hydrogen bond interactions with PEG 400.

Also, RDFs of DESs in Fig. 5 confirm that the interaction of Cl^- ion on hydroxyl groups of choline is slightly stronger than the hydroxyl groups of ethylene glycol, glycerol and amine groups of urea. This property strongly depends on proton of each component of the solutions which can make hydrogen bonds. The RDFs of DESs between choline and Cl^- ions demonstrate a significant level of ordering in Figs. 5–7. The hydroxyl of choline has an intense correlation peak at ~ 3.1 Å, which shows that the hydroxyl hydrogen of choline is participating in strong hydrogen bonding with chloride as the most preferential interaction with 0.77 chloride ions coordinated on average Table 6. The correlation peak from RDF for Cl^- and N-urea in reline is at ~ 3.4 Å, for Cl^- and O-Gly or O-EG in glyceline and ethaline are at ~ 3.2 Å. Also the protons of amine group of 4-nitroaniline show strong interaction as it has been shown in RDF in Fig. 7a with the first correlation peak for Cl^- and N-amine 4-nitroaniline is at ~ 3.4 Å. RDFs in Fig. 5 show distances of Cl^- ion with components of DESs in order of $(\text{Cl}^- \& \text{N-Chl}) > (\text{Cl}^- \& \text{N-Urea}) \sim (\text{Cl}^- \& \text{O-Gly}) \sim (\text{Cl}^- \& \text{O-EG}) > (\text{Cl}^- \& \text{O-Chl})$.

Table 6 involves coordination numbers that are obtained by integrating the corresponding RDF for first microsphere solvation shell of DESs components, and also Table 7 involves coordination numbers for probes.

In experimental work, solvatochromic parameters calculated by three probes (see above). They are based on the hypsochromic or bathochromic shift of their UV–vis spectra which depend on the microsphere solvation of the probes. When a co-solvent is added to media, changes occur in the composition of microsphere solvation. The number of solvent molecules have been calculated around the 4-nitroaniline and 4-nitroanisole (as more responsible probes for HBA and HBD abilities) in some different solvent compositions and summarized in Table 7. It confirmed that by increasing the PEG 400, as co solvent, the number of this molecule increases in microsphere solvation of solvatochromic probes whereas DES components decrease. It is in good agreement with experimental analysis that showed probes were preferentially solvated by PEG 400 even in its low mole fractions.

The local structure around functional groups (NH_2 or NO_2) of solvatochromic dyes is the area which is defined by the distance of maximum peak in the radial distribution function (RDF). The wavelength of probes in different mixtures of DESs that was measured in the experiment was compared with the properties of local structures which were calculated by molecular dynamics simulations. In order to correlate the different measured wavelengths with local structures from MD simulations, the UV–vis spectra and maximum wavelengths were calculated by ab initio quantum chemical calculations.

For calculations of UV spectra of ethylene glycol, glycerol and PEG 400 in the vicinity of 4-nitroanisole from the solutions extracted from MD simulations, were optimized by DFT method with B3LYP functional using 6-31G* basis set in Gaussian09 [47] program. The UV–vis spectra were calculated by time dependent density functional theory (TD-DFT) with CAM-B3LYP functional using TZVP basis set. Maximum wavelength of calculated UV–vis spectra of system containing one molecule of 4-nitroanisole and one molecule of ethylene glycol, glycerol and PEG 400 were compared with the measured experimental wavelengths. According to the Frank–Condon principle, the maximum absorption peak λ_{max} corresponds in an UV–Vis spectrum to vertical excitation. Time-dependent density functional predicted maximum wavelength for ethylene glycol (280.7 nm), glycerol (283.4 nm) and PEG 400 (281.6 nm). Experimental maximum wavelength of UV–vis spectra of 4-nitroanisole in ethylene glycol (315.5 nm), glycerol (317.6 nm) and PEG 400 (315.2 nm) have similar trend with quantum chemical calculated

maximum wavelength of UV–vis. Of course it must take to account that the calculations have been performed in gas phase and experimental measurements in liquid state but we can observe qualitatively similar trend for systems in gas phase as experimental data in liquid phase.

5. Conclusions

Experimental finding showed that glyceline, ethaline, and reline have higher E_{N}^{H} values than neat PEG 400 which is related to the presence of large anion as polarizable species and the hydrogen atoms of ammonium cation which can readily participate in specific and non-specific interactions with Reichardt's dye. Also, it was experimentally shown that the β values in solvent mixtures and pure PEG 400 were close to each other which shows that HBA donor and acceptor ability of PEG 400 was the determining HBA donor and acceptor ability of the media. Experimental findings showed negative deviation from ideal behavior for α values in the mixtures of ethaline, glyceline, and reline with PEG 400. The α value of PEG 400 has been found to be lower than that of DESs. PEG 400 molecules have two terminal hydroxyl groups as hydrogen bond donor groups while DESs molecules include various hydrogen bond donating groups such as hydroxyl groups in glyceline, ethaline, and choline cation and NH_2 groups in reline. Therefore, the difference in α value between DESs and PEG 400 can be attributed to their structures. These results supported by MD simulations data which showed that PEG 400 as co-solvent can make strong hydrogen bond with DESs and bring them to the solvation sphere of solvatochromic probes. MD simulations also confirmed preferential solvation model introduced by solvatochromic parameters by analyses of RDFs and hydrogen bond for solute–solvent and solvent–solvent interactions in mixture of DESs and PEG 400. Time-dependent density functional was used to predict the maximum wavelength in the solutions which showed the same trend with experimental data.

Acknowledgments

A. R. Harifi-Mood gratefully acknowledges the financial support of Kharazmi University (Grant Number: D/2043). M. Aryafard gratefully acknowledges the support from grant Grantová agentura Jihočeská Univerzita v Českých Budějovicích, (GAJU, 04-017/2019/P). B. Minofar acknowledges access to modelling facilities supported by the Czech research infrastructure for systems biology C4SYS (project no. LM2015055) and computational resources provided by the CESNET LM2015042 and the CERIT Scientific Cloud LM2015085, provided under the program “Projects of Large Research, Development, and Innovations Infrastructures”.

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5.2 Article 2

Experimental and Theoretical Studies of Preferential Solvation of 4-Nitroaniline and 4-Nitroanisole in an Amino Acid Ionic Liquid with Molecular Solvents

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Participation of Meysam Aryafard:

MA synthesized the ionic liquids, and calculated the preferential solvation parameters, performed the MD simulations, combined the experimental and theoretical studies, and wrote the paper.

Aryafard, M.; Jahanshahi, M. J.; Harifi-Mood, A. R.; Minofar, B.; Kuta Smatanova, I. Experimental and Theoretical Studies of Preferential Solvation of 4-Nitroaniline and 4-Nitroanisole in an Amino Acid Ionic Liquid with Molecular Solvents. *J. Chem. Eng. Data* **2019**, *64*, 5755-5764. <https://doi.org/10.1021/acs.jced.9b00719>

Experimental and Theoretical Studies of Preferential Solvation of 4-Nitroaniline and 4-Nitroanisole in an Amino Acid Ionic Liquid with Molecular Solvents

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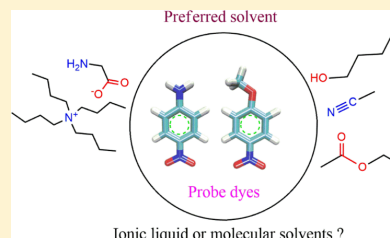
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ABSTRACT: Amino acid ionic liquids (AAILs) are a new green class of ILs. Maximum wave numbers of 4-nitroaniline and 4-nitroanisole based on the solvatochromic method were calculated in binary mixtures of tetra butyl ammonium glycinate ([N₄₄₄₄][Gly]) with both protic and aprotic molecular solvents to understand the microsphere solvations and preferred solvents. These investigations showed that the effects of glycinate in [N₄₄₄₄][Gly] led to high hydrogen-bond basicity (β) and polarizability (π^*), and they illustrated that normalized polarity (E_T^N), π^* , and β of [N₄₄₄₄][Gly] are more than those of molecular solvents. The preferential solvation model presented that the probes prefer to be solvated by either IL or mixed solvents. Molecular dynamic (MD) simulations confirmed the preferential solvation model results and were used to analyze the microsphere solvation of dyes. It has been found out that the glycinate attend the microsphere solvation of 4-nitroaniline to have hydrogen bond interactions with amine group, but the same behavior was not seen for 4-nitroanisole. Therefore, shift wavelengths of 4-nitroaniline in binary mixtures are noticeable, which were seen in experimental works. In addition, MD simulations were applied to understand the structural analysis of [N₄₄₄₄][Gly] and solvent–solvent interactions and it showed the distances and good probabilities for hydrogen bond interactions between the glycinate and butanol. Finally, QM calculations confirmed both the experimental and MD simulation findings.



1. INTRODUCTION

Ionic liquids (ILs) have shown considerable performance as organic solvents because of their remarkable properties,^{1–3} and they are used in various applications such as organic synthesis,⁴ catalysis,^{5,6} extraction, separation,^{7,8} and also they have been used for biomass. In this context, ILs have been shown to dissolve cellulose more efficiently than molecular solvents.^{9–11} ILs has been described as designer solvents, by choosing the kind of cation or anion that is possible to tune a IL for practical applications.^{12–14} This means that their properties can be tuned so that properties such as melting point, viscosity, hydrophobicity, polarity, and hydrogen bond acidity/basicity can be varied by simple changes to the structure of the ions. After Fukumoto et al. (in 2005) synthesized amino acid ILs (AAILs), many AAILs have been synthesized including amino acids as anions.^{15–17} Because of amino acids, AAILs are more biodegradable and provide a variety of usages, such as in chiral solvents, pharmaceutical chemistry, and drug delivery.¹⁸ In some cases, adding molecular solvents to ILs is beneficiary such as the cost of preparation of ILs and in some progresses such as separation and cellulose dissolution as well. Lu et al. calculated

Kamlet–Taft parameters for some ILs with various cations but the same acetate anion (Table 1). They measured the solubility of cellulose in their ILs and they found out that the cations can restrict the anions; for cellulose dissolution, anions with strong hydrogen bond basicity are needed to design a new IL.¹⁹ Effects of adding molecular solvents to ILs were examined by Zhang et al. and they found out that cellulose dissolution in IL/molecular solvent mixtures was governed by the hydrogen bond interactions between cellulose solutes and acetate ions. It was revealed that the dissolution was improved by using the aprotic solvents because the aprotic molecular solvents separate the cations and anions, and by solvating the cations, the anions can have more hydrogen bonds with cellulose.²⁰ Therefore, it is important to know solvent properties for understanding chemical reactions that occur in solvents. Solvatochromic properties are beneficial to understand physicochemical properties of solvents. Until now, the most commonly practiced

Received: July 23, 2019

Accepted: November 6, 2019

Published: November 15, 2019

Table 1. Measured Solvatochromic Parameters for Some ILs

Solvent	β	α	π^*	E_T^N	refs	Name
[N ₄₄₄₄][Gly]	1.26	0.78	1.14	0.77	this work	tetrabutylammonium glycinate
[N ₄₄₄₄][Ala]	1.33	0.79	1.09	0.76	this work	tetrabutylammonium alaninate
[Bmim][OAc]	1.14	0.61	1.02		19	1- <i>n</i> -butyl-3-methylimidazolium acetate
[PhC ₄ mim][OAc]	1.05	0.44	1.09		19	1-benzyl-3-methylimidazolium acetate
[C ₂ mmor][OAc]	1.10	0.36	1.17		19	<i>N</i> -ethyl- <i>N</i> -methylmorpholium acetate
[C≡C ₂ mmor][OAc]	1.12	0.25	1.15		19	<i>N</i> -allyl- <i>N</i> -methylmorpholium acetate
[Bmim]Cl	0.87	0.47	1.10		46	1-butyl-3-methylimidazolium chloride
[Hmim]Cl	0.94	0.48	1.02		46	1-hexyl-3-methylimidazolium chloride
[Bmim][N(Tf) ₂]	0.24	0.62	0.98	0.64	47	1- <i>n</i> -butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide
[Bmim][TfO]	0.46	0.62	1.01	0.66	47	1- <i>n</i> -butyl-3-methylimidazolium trifluoromethane sulfonate
[Bmim][BF ₄]	0.59	0.75	0.89	0.67	49	1-butyl-3-methylimidazolium tetrafluoroborate
[Bmim][PF ₆]	0.21	0.64	1.03	0.66	43	1-butyl-3-methylimidazolium hexafluorophosphate
[OPYR][N(Tf) ₂]	0.28	0.51	0.99	0.59	45	1-octylpyridinium bis(trifluoromethylsulfonyl)imide
[4MBPYR][N(Tf) ₂]	0.29	0.51	0.98	0.59	45	1-butyl-4-methylpyridinium bis(trifluoromethylsulfonyl)imide
[HMIM][PF ₆]	0.22	0.62	1.01	0.65	43	1-hexyl-3-methylimidazolium hexafluorophosphate
[OH-C ₂ NH ₃][For]	0.59	0.99	1.14	0.91	44	2-hydroxyethylammonium formate

Table 2. Information of Used Materials

Component	CAS reg. no.	suppliers	mass fraction	molar mass/g·mol ⁻¹	analysis method
4-nitroaniline	100-01-6	Sigma-Aldrich	0.99	138.12	
4-nitroanisole	100-17-4	Sigma-Aldrich	0.97	153.14	
Reichardt's dye 30	10081-39-7	Sigma-Aldrich	0.90	551.68	
glycine	56-40-6	Merck	0.99	75.07	
1-butanol	71-36-3	Sigma-Aldrich	0.99	74.12	GC ^a
acetonitrile	75-05-8	Sigma-Aldrich	0.99	41.05	GC
ethyl acetate	141-78-6	Sigma-Aldrich	0.99	88.11	GC
ethanol	64-17-5	Sigma-Aldrich	0.99	46.07	GC
tetra- <i>n</i> -butylammonium hydroxide	2052-49-5	Merck	0.20	259.48	

^aGas chromatography.

method to study the polarity and hydrogen bond basicity of solvents is solvatochromic method based on the interactions of probe molecules with solvent molecules. Solute–solvent interactions are introduced as solvatochromic properties of the media such as empirical polarity and Kamlet–Taft parameters.^{21–23} Because of solvent–solvent interactions in mixed solvents, solute–solvent interactions are more complicated in binary solvents than in pure solvents owing to the possibility of preferential solvation of each component of solvents present in the mixture.²⁴ Moreover, the solvent–solvent interactions in solvent mixtures can affect the solute–solvent interactions which affect preferential solvation.²⁵

In this study, the solvatochromic parameters (i.e., E_T^N , normalized solvent polarity; π^* , dipolarity/polarizability; β , HBA basicity; and α , HBD acidity) have been measured for pure solvents at 25 °C; also β and π^* values have been measured for mixed solvents of [N₄₄₄₄][Gly]/acetonitrile, ethyl acetate, and 1-butanol, but it was impossible for α and E_T^N because of dual peaks of Reichardt's betaine dye in mixed solvents.²⁶ The preferential solvation model has been used to understand the preferred solvents and microsphere solvations of 4-nitroaniline and 4-nitroanisole. Although there is good experimental knowledge of solvatochromic behaviors, there are few reports on theoretical studies in mixed solvents. Computational simulation is a powerful tool to discover the nature of molecular interactions. Molecular dynamic (MD) simulation allows the investigation of molecular regions and interactions at a size resolution that is not accessible to experimental techniques^{27–30} and it can confirm the reason of the experimental result. Besides, it is a useful

method to analyze the properties of solvents and features describing their structural and dynamic properties. Therefore, MD simulations have been employed to understand the experimental findings, solute–solvent interactions, and preferential solvation results at the molecular level of 4-nitroaniline and 4-nitroanisole.

2. EXPERIMENTAL SECTION

2.1. Materials. 2,6-Diphenyl-4-(2,4,6-triphenylpyridinium-1-yl) phenolate (Reichardt's dye 30), acetonitrile, ethyl acetate, ethanol, and 1-butanol are tabulated in Table 2 and were used without further purification. Glycine and tetra-*n*-butylammonium hydroxide were supplied from Merck, and 4-nitroaniline and 4-nitroanisole were recrystallized multiple times with water/ethanol and water/acetone before use.

2.2. Methods. The synthesis of [N₄₄₄₄][Gly] was performed by following the procedure that has been described in the literature.^{31,32} In brief, tetra-*n*-butylammonium glycinate was prepared by adding a slight excess amount of an aqueous solution of the glycine amino acid to an aqueous solution of tetra-*n*-butylammonium hydroxide under a nitrogen atmosphere at room temperature with vigorous stirring for 6 h. Water was evaporated to generate a residual solution that contained the required IL. After being further dried at 60 °C under vacuum, the excess glycine was removed by adding ethanol and by filtration, and then ethanol was removed by vacuum evaporation. Finally, the product was dried at 60 °C under vacuum for 48 h; the amount of water (0.04 w/w %) was determined by coulometric Karl Fischer titration (Metrohm 899

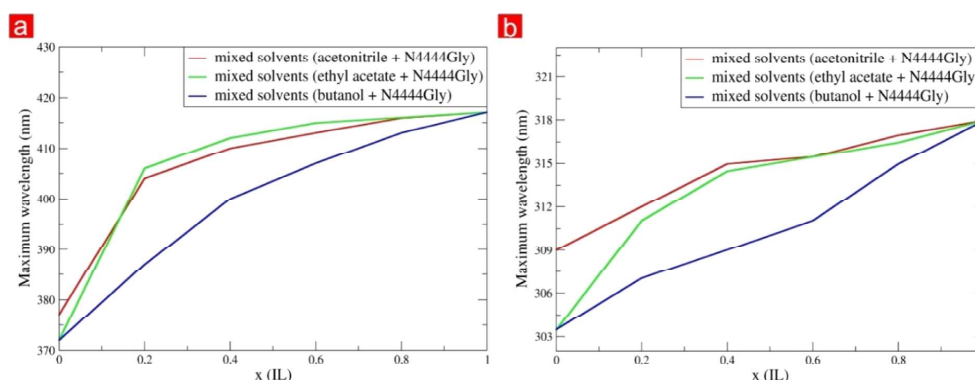


Figure 1. Maximum wavelength absorptions (uncertainty ~ 0.5 nm) of 4-nitroaniline (a) and 4-nitroanisole (b) in binary solvent mixtures of $[N_{4444}][Gly]$ with molecular solvents.

Coulometer), and the purity of $[N_{4444}][Gly]$ ($\geq 96\%$) was determined by NMR spectrum.

2.2.1. Tetrabutylammonium Hydroxide. 1H NMR (300 MHz, D_2O , 25 $^{\circ}C$): δ (ppm) 0.82 (12H, t, $J = 7.0$ Hz), 1.20–1.27 (8H, m), 1.47–1.57 (8H, m), 3.07 (8H, t, $J = 8.0$ Hz); ^{13}C NMR (75 MHz, D_2O): δ (ppm) 12.4, 18.7, 22.7, 57.6.

2.2.2. Tetrabutylammonium Glycinate. 1H NMR (300 MHz, D_2O , 25 $^{\circ}C$): δ (ppm) 0.79 (12H, t, $J = 7.0$ Hz), 1.14–1.26 (8H, m), 1.43–1.54 (8H, m), 3.00–3.11 (10H, m); ^{13}C NMR (75 MHz, D_2O): δ (ppm) 12.4, 18.7, 22.6, 43.1, 57.6, 177.8.

All probe stock solutions were prepared in high purity ethanol. An appropriate aliquot of the indicator solution was transferred into a 1 cm quartz cuvette and its solvents were evaporated by vacuum to include pure or mixed solvents with desired probe concentration. The mixtures of $[N_{4444}][Gly]$ with acetonitrile, ethyl acetate, and 1-butanol at different compositions were gravimetrically prepared with a precision of ± 0.1 mg. Solutions were vigorously stirred with a magnetic stirrer to obtain homogeneous solutions, and then they were transferred into the quartz cuvette. A GBC UV–vis Cintra 101 spectrophotometer with a thermocell coupled to it was used for recording the UV–vis absorbance spectra of the solutions at 25 ± 0.1 $^{\circ}C$. All of the measurements were recorded by repeating and averaged. Wave numbers of maximum absorptions of 4-nitroanisole (ϑ_{ANS}), 4-nitroaniline (ϑ_{ANI}), π^* , and β were measured according to the literature (Figure 1, Table 3).^{21,23,27}

3. COMPUTATIONAL SECTION

Solvatochromic properties depend on the microsphere solvations of probe dyes (Figure 2). MD simulations were used to understand the solvation structures of probe dyes in pure tetrabutylammonium glycinate, acetonitrile, ethyl acetate, 1-butanol, and the moderate mole fraction of binary mixtures (0.5 IL + 0.5 molecular solvents) in a cubic box with the specific molecules for each solvent. All MD simulations were performed by using GROMACS package^{33–35} with a general amber force field.³⁶ In eq 1, the terms describe bonded (stretch vibration, bond bending, and torsion angle rotation) and nonbonded interactions (Lennard-Jones potential and Coulomb electrostatics).

Table 3. Maximum Wave Numbers of Adsorbance (in kK) of the Solvatochromic Dyes, Hydrogen-Bond Acceptor (β), and Dipolarity/Polarizability (π^*) in Mixed Solvents

x_{IL}	ϑ_{ANS}/kK	ϑ_{ANI}/kK	β	π^*
Acetonitrile/$[N_{4444}][Gly]$				
0.0	32.36	26.52	0.794	0.750
0.2	32.05	24.75	1.279	0.883
0.4	31.75	24.39	1.262	1.013
0.6	31.70	24.21	1.301	1.035
0.8	31.55	24.04	1.292	1.099
1	31.45	23.98	1.265	1.141
Ethyl Acetate/$[N_{4444}][Gly]$				
0.0	32.95	26.88	0.948	0.499
0.2	32.15	24.63	1.372	0.839
0.4	31.80	24.27	1.329	0.992
0.6	31.70	24.10	1.343	1.035
0.8	31.60	24.04	1.316	1.077
1	31.45	23.98	1.265	1.141
1-Butanol/$[N_{4444}][Gly]$				
0.0	32.95	26.88	0.948	0.499
0.2	32.57	25.84	1.140	0.660
0.4	32.36	25.00	1.340	0.750
0.6	32.15	24.57	1.394	0.839
0.8	31.75	24.21	1.326	1.013
1	31.45	23.98	1.265	1.141

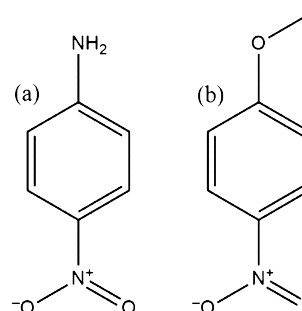
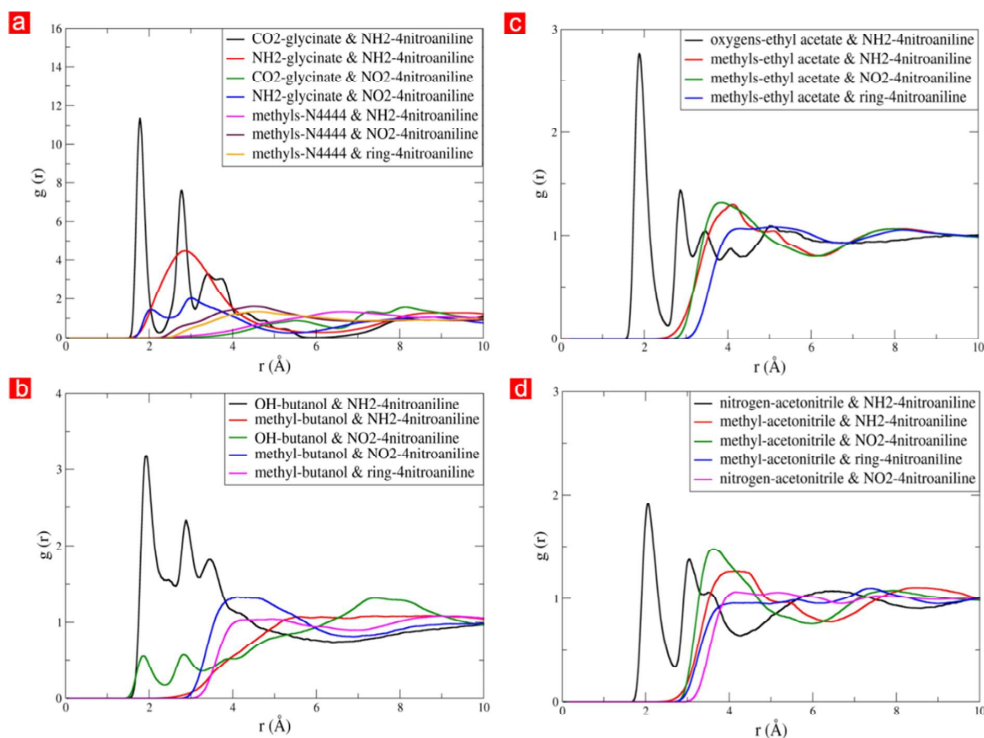


Figure 2. Structures of 4-nitroaniline (a) and 4-nitroanisole (b), as probe dyes.

Table 4. Preferential Solvation Parameters Obtained by Applying eqs 4–7 on Solvatochromic Data in Binary Mixtures of [N₄₄₄₄][Gly] (2) with Molecular Solvents (1), r^2 is the Regression Coefficient

solvents	indicator	Y_1	Y_2	Y_{12}	$f_{2/1}$	$f_{12/1}$	$f_{12/2}$	r^2
[N ₄₄₄₄][Gly]/acetonitrile	4-nitroanisole	33.36	31.46	32.02	9.06	5.78	0.64	0.999
	4-nitroaniline	26.52	23.98	24.12	2.56	9.82	3.84	0.999
[N ₄₄₄₄][Gly]/ethyl acetate	4-nitroanisole	32.95	31.47	31.69	2.32	5.85	2.52	0.996
	4-nitroaniline	26.88	23.98	24.10	8.61	14.32	1.66	0.999
[N ₄₄₄₄][Gly]/1-butanol	4-nitroanisole	32.94	31.43	32.54	3.4	6.57	1.93	0.996
	4-nitroaniline	26.88	23.99	25.16	4.48	3.36	0.75	0.999

**Figure 3.** RDFs of 4-nitroaniline in [N₄₄₄₄][Gly] (a), butanol (b), ethyl acetate (c), and acetonitrile (d).

$$\begin{aligned}
 E(r^N) = & \sum_{\text{bonds}} \frac{k_i}{2} (l_i - l_{i,0})^2 + \sum_{\text{angles}} \frac{k_i}{2} (\theta_i - \theta_{i,0})^2 \\
 & + \sum_{\text{torsions}} \frac{V_n}{2} (1 + \cos(n\omega_i - \gamma_i)) \\
 & + \sum_{i=1}^N \sum_{j=i+1}^N 4\epsilon_{ij} \left(\left(\frac{\delta_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\delta_{ij}}{r_{ij}} \right)^6 \right) \\
 & + \sum_{i=1}^N \sum_{j=i+1}^N \frac{q_i q_j}{4\pi\epsilon_0 r_{ij}}
 \end{aligned} \quad (1)$$

For preparation of the solution boxes, packmol package was used and probes had been placed in the center of the cubic box.^{37,38} After preparation of each system, the energy minimization procedure was used to remove all unexpected and unfavorable contacts because of random solvation of molecules in the box, then NVT (canonical ensemble)

simulations were run at 300 K,³⁹ followed by NPT (isothermal–isobaric ensemble) simulations and a time step of 2 fs was used for all simulations, and the production phase was performed for 50 ns. Equations of motion were integrated using the leap-frog algorithm,⁴⁰ and the visual molecular dynamics (VMD) program was used for visualizations of the trajectory and preparation of snapshots.⁴¹

4. RESULTS AND DISCUSSION

The hydrogen bond basicity of ILs is mainly dominated by the nature of anions.⁴² The anions of AAILs have much stronger hydrogen bond basicity in comparison with the molecular solvents and some of ILs (Table 1) because of carboxylates of amino acids. By adding [N₄₄₄₄][Gly] to molecular solvents, initially β values increased rapidly but then became relatively constant at the higher mole fractions of IL. The variations of polarizability in mixtures show an increasing trend over the whole range mole fraction of IL. By comparing solvatochromic results with those of our previous work,²⁷ it was found that β of

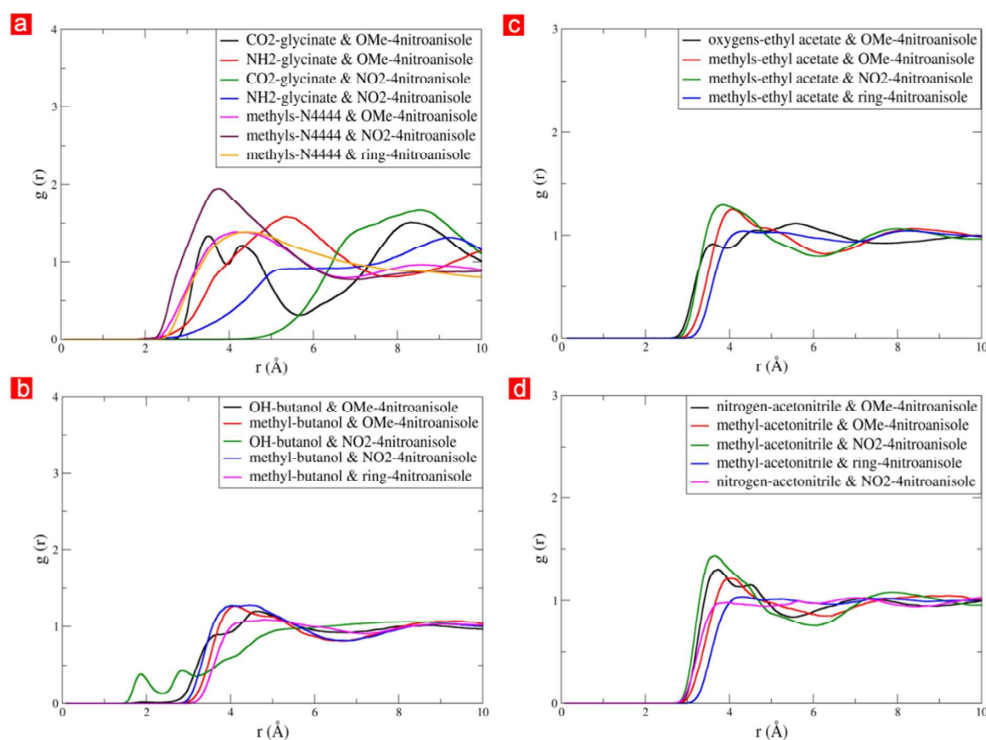
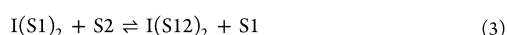
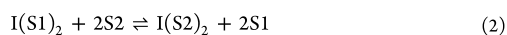


Figure 4. RDFs of 4-nitroanisole in [N₄₄₄₄][Gly] (a), butanol (b), ethyl acetate (c), and acetonitrile (d).

[N₄₄₄₄][Gly] has a remarkable difference with that of deep eutectic solvents (DESs) because the glycinate anion in [N₄₄₄₄][Gly] is more free than the chloride anion and acceptor sides in DESs, but they have close values for other parameters (π^* , α , and E_{H}^{N}). The high β values of these tetraalkylammonium-based AAILs can label them for some processes such as cellulose dissolution. It has been realized that ILs with high β can break the hydrogen bond interaction between cellulose chains and make them more soluble compared to other ILs.^{19,43–47} Table 1 shows the solvatochromic parameters of some ILs that were used for cellulose dissolution. By comparison of β values, it seems that tetraalkylammonium-based AAILs can be a good candidate for this goal. The additional benefits of these AAILs compared to imidazolium-based AAILs are cheaper primary sources, being greener, and the possibility to opt the length of alkyl chains for the amphiphilic nature of AAILs and diffusion purpose.

4.1. Preferential Solvation Model. Interest on the preferential solvation model for studying the solute–solvent and solvent–solvent interactions and describing the synergism behavior of the solvent mixtures has been increased. Hence, to understand the solvation microsphere of probes, the preferential solvation model has been used. The preferential solvation model in binary mixtures of solvents is based on a simple exchange of solvents in the microsphere solvation of probe dyes according to the following equations



where I stands for the probes (4-nitroaniline and 4-nitroanisole), S1 and S2 for the pure solvents (acetonitrile, ethyl acetate, butanol, and [N₄₄₄₄][Gly]), and S12 for the solvents formed by the interactions of [N₄₄₄₄][Gly] and molecular solvents. I (S1), I (S2), and I (S12) represent the probes solvated by pure molecular solvents, IL, and mixed solvents. Equation 2 reflects the total exchange of molecular solvents by [N₄₄₄₄][Gly] in the solvation sphere of the probes, and eq 3 corresponds to the exchange by the mixed solvents. According to the literature,^{27,44,48} the physical properties (Y), such as the wave number of maximum absorption of solvatochromic probes in the solvent mixtures, are calculated as an average of these properties in pure and mixed solvents (Y_1 , Y_2 , and Y_{12} , respectively) according to eq 4.

$$Y = \frac{Y_1(1 - x_2^0)^2 + Y_2f_{2/1}(x_2^0)^2 + Y_{12}f_{12/1}(1 - x_2^0)x_2^0}{(1 - x_2^0)^2 + f_{2/1}(x_2^0)^2 + f_{12/1}(1 - x_2^0)x_2^0} \quad (4)$$

Preferential solvation parameters obtained by applying eqs 5–7.

$$f_{2/1} = \frac{x_2^s/x_1^s}{(x_2^0/x_1^0)^2} \quad (5)$$

$$f_{12/1} = \frac{x_{12}^s/x_1^s}{x_2^0/x_1^0} \quad (6)$$

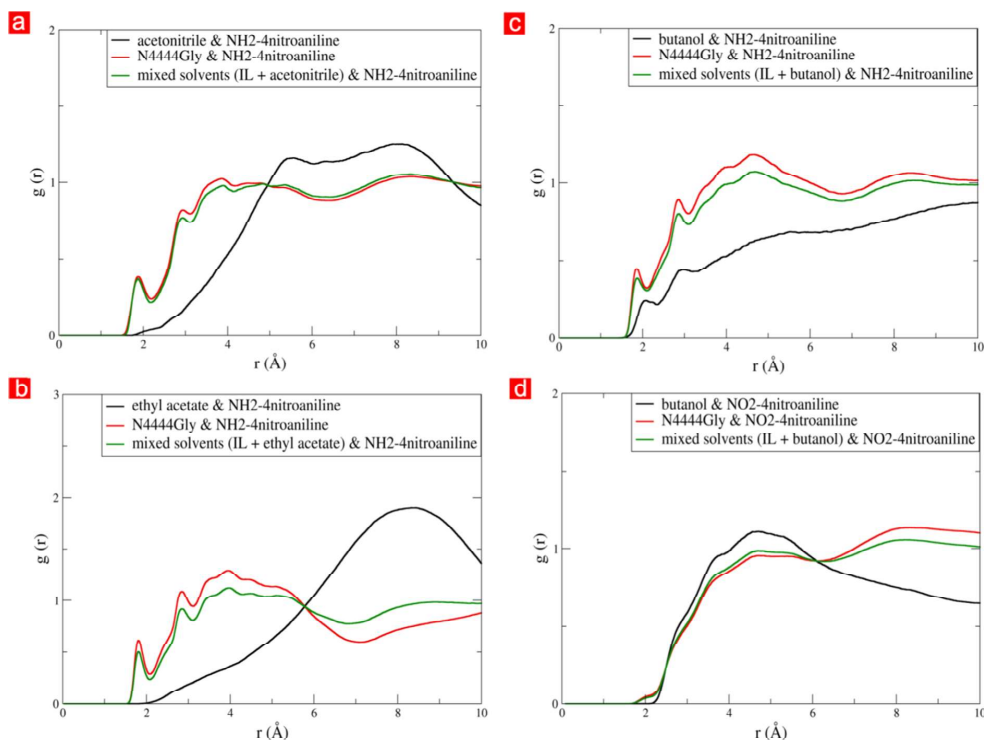


Figure 5. RDFs of 4-nitroaniline in pure and mixed solvents of [N₄₄₄₄][Gly] with acetonitrile (a), ethyl acetate (b), and butanol (c,d).

$$f_{12/2} = \frac{f_{12/1}}{f_{2/1}} \quad (7)$$

Table 4 shows parameters which have been achieved by the preferential solvation model. Values of $f_{2/1}$ and $f_{12/1}$ confirm the weak attendance of molecular solvents in the microsphere solvation of the solvatochromic probes. In other words, preferential solvation parameters show that all probes have a strong tendency to be preferentially solvated by mixed solvents ([N₄₄₄₄][Gly] + molecular solvents).

4.2. Computational Results. For analyzing MD simulations, a radial distribution function (RDF) was used as it describes the distribution of solvent molecules around one specific molecule or atom. Therefore, it can give good knowledge about the microsphere solvation of probe dyes. Figure 3 shows RDFs of solvents around 4-nitroaniline and they confirm that solvents have tendency to solvate the amine group of 4-nitroaniline by their functional groups. In Figure 3a, RDFs show that glycinate prefers to solvate amine dye by the carboxylate group, and its probability $g(r)$ is considerable, but in the case of nitro group dye, amine of glycinate is preferred. The tetrabutylammonium cation has a different trend and prefers to solvate the nitro group of dye more than the amine group because of the positive charge of this cation. RDFs in Figure 3 confirm that butanol, acetonitrile, and ethyl acetate solvate amine of 4-nitroaniline by their functional groups, but they solvate nitro group dye by their alkyl groups. The exception is just for butanol that the hydroxyl group is preferred for both the amine and nitro groups of the dye. Figure 4 illustrates the

same trend as 4-nitroaniline for solvating the nitro group of 4-nitroanisole by solvents, but for solvating the methoxy group of 4-nitroanisole, there are no differences between the hydrophilic or hydrophobic groups of solvents. RDFs in Figures 3 and 4 confirmed that 4-nitroanisole was solvated less than 4-nitroaniline by glycinate of [N₄₄₄₄][Gly] which is the reason that maximum wave numbers of 4-nitroaniline shift more than 4-nitroanisole by adding IL to molecular solvents. These findings are in good agreement with UV-vis results. Figure 5 shows that the amine group of 4-nitroaniline prefers to be solvated by either ILs/co-solvents or IL, and it is not interested in being solvated by pure molecular solvents. These differences for the aprotic molecular solvents (acetonitrile and ethyl acetate) are more than the protic solvent (butanol), as shown by RDFs. Figure 6 presents the distribution of the mixed solvent around probe dyes. In addition to abovementioned terms of solute-solvents interactions, solvent-solvent interactions are important to have knowledge of binary mixtures. In pure solvents, the structure of liquids can be studied by either X-ray or neutron scattering. RDFs from MD simulations can provide good information in both the pure and mixed solvents which is not easy to be gained from an experiment. Bowron et al. studied the structure of 1-ethyl-3-methylimidazolium acetate [C₂mim][OAc], via neutron diffraction and MD simulations.⁵⁰ They used RDFs to analyze the structure of [C₂mim][OAc] and recognized that RDFs of both methods are in good accordance. They also revealed the solvation structure of acetate ions around imidazolium, in which the anions interact with three hydrogen atoms of imidazolium rings. The structures of AAILs based on imidazolium cations

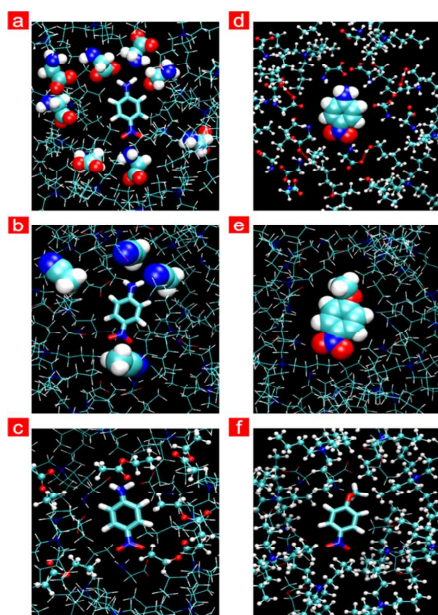


Figure 6. Snapshots from MD simulations showing the distribution of solvents around 4-nitroaniline in $[N_{4444}][Gly]$ (a), mixed solvents of $[N_{4444}][Gly]$ /acetonitrile (b), $[N_{4444}][Gly]$ /ethyl acetate (c), and $[N_{4444}][Gly]$ /butanol (d). Distribution of solvents around 4-nitroanisole in $[N_{4444}][Gly]$ (e) and mixed solvents of $[N_{4444}][Gly]$ /ethyl acetate (f).

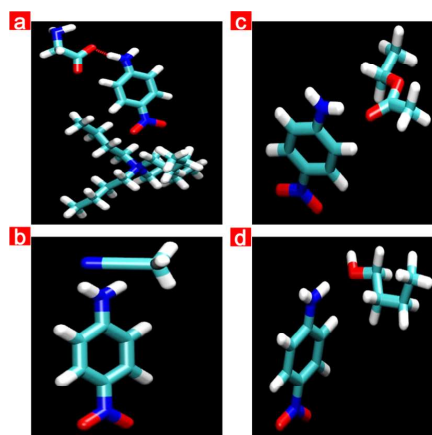


Figure 8. Optimized geometries of 4-nitroaniline with one molecule of $[N_{4444}][Gly]$ (a), acetonitrile (b), ethyl acetate (c), and butanol (d) by DFT/B3LYP.

were studied via MD simulations by Herrera et al. and they discovered hydrogen bond interactions between amino acids and imidazolium cations.⁵¹ Figure 7 demonstrates that the RDFs of pure $[N_{4444}][Gly]$, and pure butanol were calculated from MD simulations. The average separation of cation–anion is at ~ 4.8 Å, glycinate nitrogen and glycinate oxygens (N-glycinate & oxygens-glycinate) at ~ 3.0 Å, and also the same distance for glycinate nitrogen and glycinate nitrogen (N-glycinate & N-glycinate) at ~ 3.0 Å, but more probability with nitrogens compared to oxygens. They confirm that hydrogen bond

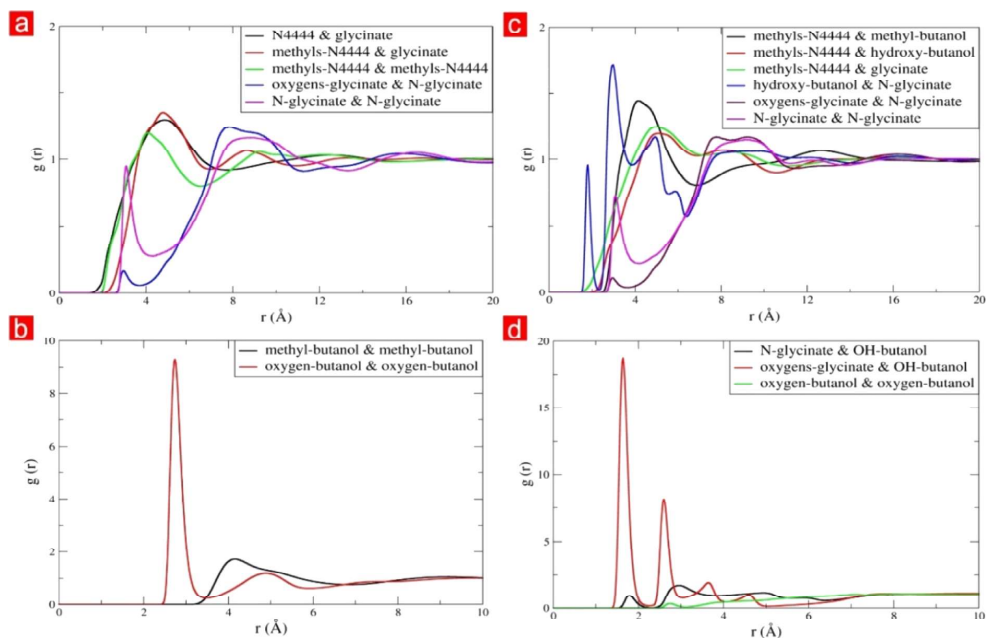


Figure 7. RDFs in pure $[N_{4444}][Gly]$ (a), pure butanol (b), and mixed of solvents ($0.5 [N_{4444}][Gly] + 0.5$ butanol) (c,d).

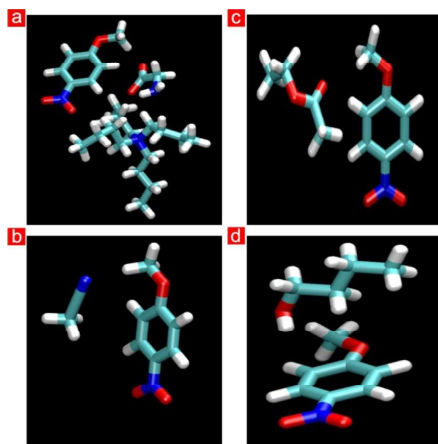


Figure 9. Optimized geometries of 4-nitroanisole with one molecule of $[N_{4444}][Gly]$ (a), acetonitrile (b), ethyl acetate (c), and butanol (d) by DFT/B3LYP.

interactions between amine sides of glycinate are more probable. Figure 7 verifies the distance and good probability of being hydrogen bond interactions between the hydroxy groups of butanol molecules (O-butanol and O-butanol, with a correlation peak at ~ 2.8 Å). By adding butanol to $[N_{4444}][Gly]$, the remarkable changes relate to probability decreases of intra-interactions (N-glycinate and N-glycinate and O-butanol and O-butanol), while the probabilities of inter-interactions increase (OH-butanol and oxygens-glycinate, OH-butanol and N-glycinate, and methyls- N_{4444} and methyl-butanol) (Figure 7). The most interactions in binary mixtures relate to hydrogen bond interactions between glycinate oxygens and butanol. As a result, there are more interactions in the protic solvent compared to other aprotic solvents with $[N_{4444}][Gly]$. Thus, the protic solvents have more solvent–solvent interactions and solute–solvent interactions which shows that butanol has a hinder effect for glycinate to attend the microsphere solvation of 4-nitroanisole. In experimental work, β values for mixtures of IL/butanol increased gradually in comparison with acetonitrile or ethyl acetate.

In order to better understand the experimental findings and MD simulation results, quantum theoretical calculations were used. Coordinates of each solvent in the vicinity of probes (4-nitroanisole and 4-nitroanisole) in their solutions were extracted from MD simulations. Each system contained one molecule of probes and one molecule of solvents, and then the DFT/B3LYP functional using a 6-31G* basis set was used to optimize the geometries of probes and solvents in Gaussian 09 program.⁵² Figures 8, and 9 illustrate the optimized geometries of one molecule of the solvent around probe dyes. These optimized figures confirm the orientation of the solvent by hydrophilic groups around amine, methoxy, and nitro groups of probes. These optimized geometries were used by time-dependent density functional theory (DFT) with the CAM-B3LYP functional using a TZVP basis set to calculate maximum wavelengths of UV–vis spectra. UV–vis spectra of these calculations in the gas phase are shown in Figure 10. There is a noticeable difference between UV–vis spectra of $[N_{4444}][Gly]$ and molecular solvents, and also a similar trend was seen in experimental wavelength measurements (Figure 1). In both the experimental and theoretical calculations, maximum wavelengths of probes in $[N_{4444}][Gly]$ are in longer wavelengths (bathochromic shift) and maximum wavelengths of molecular solvents are close to each other.

5. CONCLUSIONS

Adding a cosolvent to AAILs is useful in many reactions in order to reduce the cost of preparing AAILs, and it also increases the efficiency of the process. In order to understand how adding cosolvents affects the physicochemical properties, $[N_{4444}][Gly]$ was prepared, and the addition of acetonitrile, ethyl acetate, and butanol as cosolvents was studied. This IL demonstrated a high β value that remarks it for some reactions. In addition, solvatochromic and preferential solvation behaviors showed that these probes prefer to be solvated by either $[N_{4444}][Gly]$ or mixed solvents. MD simulations verified that probes prefer mixed solvents. In the case of 4-nitroanisole, presence of glycinate in the microsphere solvation is more than other solvent components which is in a good agreement with experimental results. MD simulations showed that the orientation of solvents around probe dyes depends on the hydrophilic sides of dyes which is also in a good agreement with QM calculation results. Based on our findings, we estimate that other AAILs probably would have close solvatochromic parameters. As a result, these

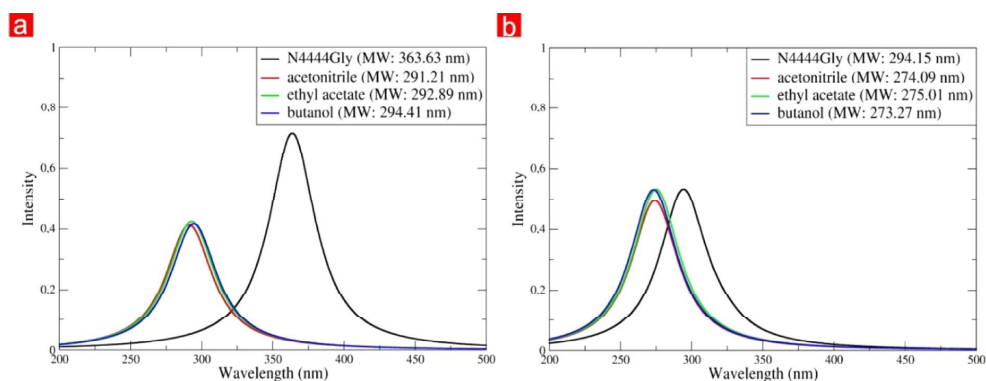


Figure 10. Obtained UV–vis spectra of 4-nitroanisole (a) and 4-nitroanisole (b) with one molecule of different solvents (gas phase).

findings can be used to understand solvation structures of probe dyes in future studies.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

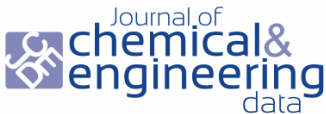
M.A. gratefully acknowledges the support from the Czech Science Foundation grant (ERDF CZ.02.1.01/0.0/0.0/15_003/0000441 and GAJU 017/2019/P) and the University of South Bohemia. Authors acknowledge access to computational resources provided by the CESNET LM2015042 and the CERIT Scientific Cloud LM2015085, provided under the program "Projects of Large Research, Development, and Innovations Infrastructures".

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5.3 Article 3



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Molecular Dynamics Simulations, Solvatochromic Parameters, and Preferential Solvation in Aqueous Solutions of Ethaline, Ethylene Glycol, and Choline Chloride

Meysam Aryafard,* Anis Karimi, Ali Reza Harifi-Mood,* and Babak Minofar

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Participation of Meysam Aryafard:

MA offered the idea of aqueous mixtures of ethaline and its components, performed the MD simulations, combined the experimental and theoretical studies, and wrote the paper.

Aryafard, M.; Karimi, A.; Harifi-Mood, A. R.; Minofar, B. Molecular Dynamics Simulations, Solvatochromism and Preferential Solvation in Aqueous Solutions of Ethaline (DES), Ethylene glycol and Choline chloride. *J. Chem. Eng. Data*. 2020, 65, 4556-4566. <https://doi.org/10.1021/acs.jced.0c00381>

Molecular Dynamics Simulations, Solvatochromic Parameters, and Preferential Solvation in Aqueous Solutions of Ethaline, Ethylene Glycol, and Choline Chloride

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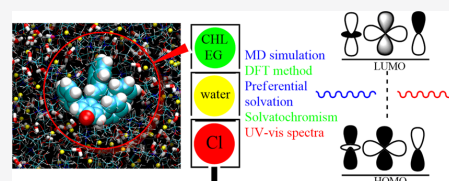
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ABSTRACT: Deep eutectic solvents (DESs) are recent solvents that have the basic characteristics close to ionic liquids, and they have been applied in several reactions. Adding molecular solvents especially water to DESs is beneficial in some cases such as biophysics and biochemistry. Therefore, understanding the effect of different solvents and preferred solvent is critical in binary mixtures. This work describes the principles to investigate the preferential solvation of probe dyes (4-nitroaniline, 4-nitroanisole, and Reichardt's dye 30) in complex mixed solvents in detail. Experimental and theoretical studies were used to seek the preferential solvation of probes in aqueous solution of ethylene glycol–choline chloride (ethaline) and its components (aqueous solutions of ethylene glycol and choline chloride). Results confirmed that probes prefer to be solvated by ethaline and ethylene glycol. In detail, the microsphere solvation of probe dyes was analyzed, which confirmed fundamental roles of choline and ethylene glycol for synergism effects from ideal mixtures. In most of the mole fractions, probes prefer to be solvated in the order of components, namely, ethylene glycol and choline > water > chloride. Moreover, aggregation of solvents components around probes was calculated profoundly. Molecular dynamics simulations made it possible to understand which combinations of components in mixed solvents display preferential solvation. Also, as a minor goal, solvatochromic parameters in mentioned mixtures were discussed in the related section. Finally, density functional theory (DFT) calculations showed either bathochromic or hypsochromic shifts coming from changes in microsphere solvation and hydrogen bonding of probes with solvents.



1. INTRODUCTION

The application of deep eutectic solvents (DESs) has recently increased as potential green replacements for volatile organic solvents due to their unique properties.^{1–3} Primary DESs were synthesized by Abbott et al. with quaternary ammonium salt and hydrogen bond donor (HBD) or metal components.^{4–6} Hydrogen bond interactions between DES components as well as halide delocalization play key roles in formation of DESs. These phenomena were discussed in the literature.^{7–11} Like ionic liquids (ILs), DESs contain ionic species. Therefore, they share some characteristics such as low volatility, chemically and physically stability, wide range of temperature usage, and solubility in organic and inorganic compounds.^{8–11} Inasmuch as DESs are cheaper and easier to prepare, they have been noticed as serious alternatives to ILs. This can make them more favorable than ILs for large-scale industrial applications. These applications include broad areas such as organic synthesis, catalysis, and separation.^{12–14} Adding organic solvents to DESs shows desirable characteristics.^{15–17} Also, aqueous solutions of DESs as binary solvents have been widely considered in recent years.^{18–20} Binary mixtures of DESs with water are beneficial in biochemical and pharmaceutical reactions. Changes in hydrogen bond abilities, polarity, hydrophilicity, hydrophobicity, etc. cause the different

solvation shells in proteins and drugs to alter their structures, active sites, and features.^{21–25}

The effects of adding cosolvents, Kamlet–Taft parameters, and preferential solvation on solubilities of drugs, fragrances, and chemical materials have been studied recently.^{26–29} Bao et al. revealed that for understanding the solubilities of materials, the advanced preferential solvation method is needed in binary mixtures.²⁹ Preferential solvation (PS) is a useful method to understand the effect of each solvent when reactions pass through binary mixtures. Results of this method are more significant when solvents do not contribute equally at the solvation shell of solutes.^{30–35} The PS model can easily be described in Figure 1. It shows how the PS model works in ideal mixtures and synergisms get the preferred solvent. Several attempts have been used to understand the PS and solute–solvent interactions in simple binary mixtures (molecular solvents) by UV–vis measurement of probe dyes.^{36–42} However, few works have been made in complex binary

Received: April 25, 2020

Accepted: July 20, 2020

Published: August 6, 2020



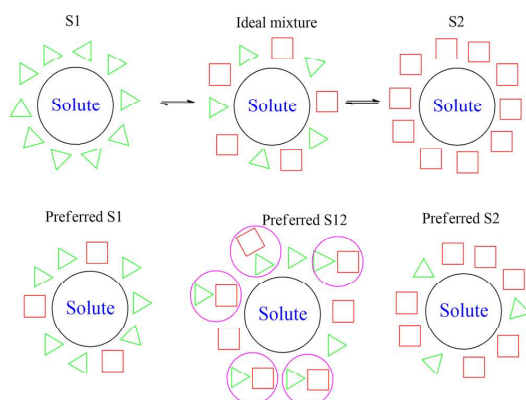


Figure 1. Preferential solvation model in binary solvents. The presence of first solvent (triangle), second solvent (square), and combination of first and second solvents (circle). Coordination numbers of each solvent at the microsphere solvation of probes were calculated and are shown in Tables 2 and 3 by MD simulations.

systems including ILs or DESs.^{11,30,41–43} The most common method to overcome the PS is based on shifting UV–vis spectra of probes. By changing the solvent–solvent interactions, solute–solvent interactions (maximum wavelengths of probe spectra calculated using a UV–vis spectrophotometer) are affected; hence, PS outputs change. Some attempts have been concentrated to find the effects of PS and cosolvents on solubility and interactions of biomolecules in mixed solvents.^{29,44–47} Although the PS model is a simple method to get experimental data, there is no knowledge at the microsphere solvation of probe dyes and the number of molecules that perform it in complicated solvents. The main goal of this work is to understand the nature of PS in binary mixtures. Understanding the effect of each component in binary complex mixtures of solvents is difficult by experimental methods. Molecular dynamics (MD) simulation can assist to find many properties of complicated systems based on statistical mechanics, which makes it a worthwhile method for features characterized through structural and dynamic properties.^{11,48} Accordingly, MD simulations were applied to understand PS parameters earned by probe dyes. They garner knowledge of solvation shells of probe dyes in detail, which is not accessible by experimental methods. In this work, MD simulation results offer simple interpretation of PS by radial distribution functions and coordination numbers. MD simulation results were confirmed by experimental data of preferential solvation determined using a UV–vis spectrophotometer. Additionally, on the basis of these probes' responses, four solvatochromic parameters (i.e., E_T^N normalized solvent polarity parameter; π^* , dipolarity/polarizability; β , hydrogen bond acceptor (HBA); α , hydrogen bond donor (HBD) abilities) were determined in binary mixtures of ethaline + water. In order to determine the effect of each DES component on the solvation parameters, the aqueous solutions of ethylene glycol and choline chloride were also investigated. Finally, density functional theory (DFT) was used to understand how the maximum absorbances of probe dyes change by increasing the number of molecules in solvation shells.

2. EXPERIMENTAL SECTION

2.1. Materials. Choline chloride (>98%), purchased from Sigma-Aldrich, was dried for 48 h at 313 K in a vacuum oven. Ethylene glycol (99.8%, anhydrous) was supplied from Merck and dried with a 3 Å molecular sieve. The water content of the dried compounds was determined by coulometric Karl Fischer titration yielding <100 ppm for ethylene glycol and <600 ppm for choline chloride. Probes were purchased from Sigma-Aldrich. 2,6-Diphenyl-4-(2,4,6-triphenylpyridinium-1-yl) phenolate (Reichardt's dye 30) was used without further purification. 4-Nitroaniline and 4-nitroanisole were recrystallized multiple times with water–ethanol and water–acetone before use (Table S1).

2.2. Methods. In order to prepare ethaline, choline chloride was mixed with ethylene glycol in a molar ratio of 1:2 and stirred under heating (near 80 °C) until a homogeneous colorless liquid was formed. Stock solutions of the Reichardt's dye, 4-nitroanisole, and 4-nitroaniline were prepared in ethanol and stored in a dark glass vial at 4 °C. In every measurement, an appropriate aliquot of the solvatochromic probe primary solution was transferred into 1 cm quartz cuvettes, and its solution, ethanol, was evaporated in vacuum. Following, the aqueous solution of DES at a defined mole fraction was gravimetrically prepared and was transferred into the quartz cuvette including the solvatochromic probe. The solution was vigorously stirred with a magnetic stirrer so that a steady-state solution was produced. UV–vis absorption spectra of the solutions were recorded using a GBC UV–vis Cintra 101 spectrophotometer with a thermocell coupled to it. The temperature was maintained at 25 °C, and all measurements were made in triplicate and averaged.

3. COMPUTATIONAL SECTION

Molecular dynamics simulations have been used to prove preferential solvation results in binary mixtures. Systems containing pure solvents (ethaline, ethylene glycol, and water) and binary mixtures of solvents over all odd mole fractions were prepared (Table S2). Only were they performed in the 0.1 mole fraction of choline chloride because of low solubility of choline chloride in water. Every system that included proper numbers of each solvent depends on the mole fraction. It means that the numbers of ethylene glycol should be 2 times that of choline chloride in each mole fraction of ethaline. Afterward, one molecule of probe dyes (4-nitroaniline, 4-nitroanisole, and Reichardt's dye) was placed in the center of boxes. Cubic boxes, periodic boundary conditions, and Packmol program were used to build systems.^{49,50} All MD simulations were performed using the GROMACS program package.^{51–53} Parameterizations of all the ions and molecules were performed with the general amber force field (GAFF)⁵⁴ represented by eq 1.

$$E(r^N) = \sum_{\text{bonds}} \frac{k_i}{2} (l_i - l_{i,0})^2 + \sum_{\text{angles}} \frac{k_i}{2} (\theta_i - \theta_{i,0})^2 + \sum_{\text{torsions}} \frac{V_n}{2} (1 + \cos(n\omega_i - \gamma_i)) + \sum_{i=1}^N \sum_{j=i+1}^N 4 \epsilon_{ij} \left(\left(\frac{\delta_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\delta_{ij}}{r_{ij}} \right)^6 \right) + \sum_{i=1}^N \sum_{j=i+1}^N \frac{q_i q_j}{4\pi \epsilon_0 r_{ij}} \quad (1)$$

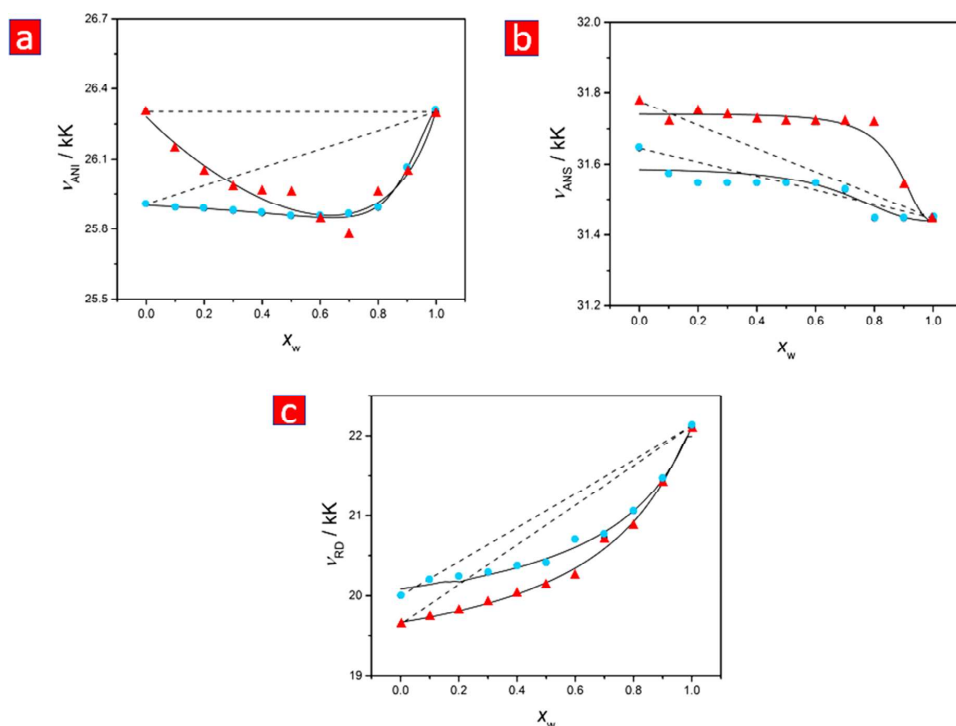


Figure 2. Wavenumbers of ANI (a), ANS (b), and RD (c) in aqueous solutions of ethaline (blue bullet) and ethylene glycol (red triangle). The solid curves have been calculated from our measurements, and the dashed lines show the ideal behavior. The maximum uncertainties of $\bar{\nu}_i$ are ± 0.06 kK. Standard uncertainty u for temperature is $u(T) = \pm 0.1$ °C.

Simulations were run for 50 ns with a time step of 2 fs. Preceding phase produce, energy minimization, simulations in the NVT (canonical ensemble) and in the NPT (isothermal-isobaric ensemble) were performed at 298 K and 1 bar.⁵⁵ Equations of motion were integrated using the leap-frog algorithm.⁵⁶ Observing the trajectories and preparing snapshots were done using the VMD program.⁵⁷

4. RESULTS AND DISCUSSION

4.1. Solvatochromic Parameters. The values of solvatochromic parameters (E_T^N , π^* , β , and α) have been determined in aqueous solutions of ethaline and ethylene glycol from the wavenumbers of maximum absorptions of the corresponding chemical probes at 25 °C (Figures 2 and 3, Table S3). These parameters were calculated over the whole range of mole fractions according to the procedure reported before.^{11,58–61} The relationships connecting the solvatochromic parameters and UV–vis spectra are shown in eqs 2–6

$$\alpha = 0.186(10.91 - \vartheta_B) - 0.72\pi^* \quad (2)$$

$$\beta = \frac{31.10 - 3.14\pi^* - \vartheta_{\text{ANI}}}{2.79} \quad (3)$$

$$\pi^* = 0.427(34.12 - \vartheta_{\text{ANS}}) \quad (4)$$

$$E_T(30) \text{ (kcal mol}^{-1}\text{)} = 2.8591 \vartheta_B \quad (5)$$

$$E_T^N = \frac{E_T(\text{solvent}) - E_T(\text{TMS})}{E_T(\text{water}) - E_T(\text{TMS})} = \frac{E_T(\text{solvent}) - 30.7}{32.4} \quad (6)$$

α , β , π^* , and E_T^N parameters were calculated based on the maximum wavenumbers of 4-nitroanisole (ϑ_{ANS}), 4-nitroaniline (ϑ_{ANI}), and Reichardt's dye (ϑ_B), in the unit of kilo Kaser (kK).

$E_T(30)$, the empirical solvent polarity, was normalized by utilizing of two solvents as references: water ($E_T^N = 1$) and tetramethylsilane (TMS) with ($E_T^N = 0$).

Figure 3 and Table S3 show that the experimental data in this work are compatible with those in the literature.⁶² Differences between the π^* and β data relate to different probe dyes applied to measuring these parameters. Figure 3 shows that there are no changes in the π^* values of aqueous solutions of ethaline or ethylene glycol. This parameter is moderately constant in the whole range of solvent mole fractions. Identical behaviors are observed in the E_T^N and α trend in which the solvent–solvent interaction controls these variations. Since E_T^N has a linear dual correlation with α and π^* , it is common to see identical behavior between E_T^N and α . By adding water to ethaline or ethylene glycol, these parameters change slowly at low concentrations of water. E_T^N and α increase sharply at the high mole fractions of water. This different behavior in the range of solvent composition causes negative behavior from ideality in the parameter trend. It seems that a solute will

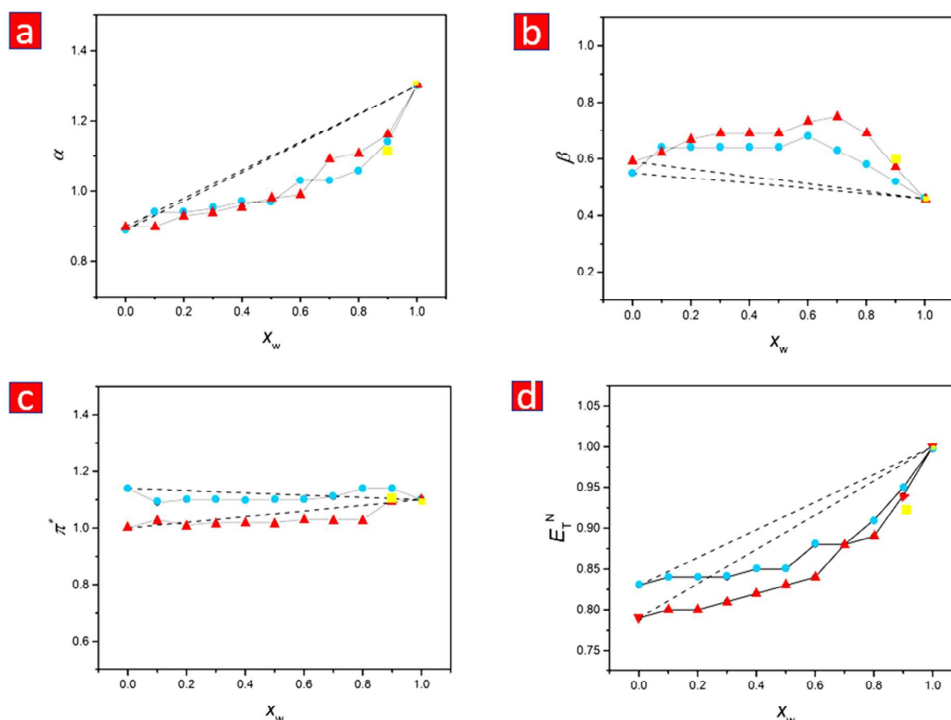


Figure 3. Measured solvatochromic parameters in mixtures of ethaline + water (blue bullet), ethylene glycol + water (red triangle), and choline chloride + water (yellow square) at 25.0 °C. The maximum uncertainties related with α , β , π^* , E_T are ± 0.02 . Standard uncertainty u for temperature is $u(T) = \pm 0.1$ °C.

Table 1. PS Parameters Obtained by Applying eqs 9–11 to the Experimental Wavenumbers in kK (1 kK = 10^3 cm $^{-1}$) of the Probes (ANS, ANI, and RD), in Binary Mixtures of Ethaline (2) or Ethylene Glycol (2) + Water (1)^a

indicator	solvents	Y_1 ($\bar{\theta}_1$)	Y_2 ($\bar{\theta}_2$)	Y_{12} ($\bar{\theta}_{12}$)	$f_{2/1}$	$f_{12/1}$	N	r^2	σ
ANS	ethaline/water	31.45	31.61	31.42	3.50	2.40	11	0.941	0.002
	EG/water	31.55	31.76	31.74	3.12	2.44	11	0.965	0.002
ANI	ethaline/water	26.32	25.90	25.54	14.60	3.95	11	0.993	0.001
	EG/water	26.29	26.27	25.50	2.63	3.72	11	0.972	0.007
RD	ethaline/water	21.99	20.17	20.21	2.56	2.42	11	0.967	0.132
	EG/water	21.89	19.77	19.69	2.41	1.84	11	0.983	0.097

^a N , r^2 , and σ are the numbers of experimental data, regression coefficient, and standard deviation, respectively. The maximum uncertainties of $\lambda_{\max}$ and $\bar{\theta}_i$ are ± 0.3 nm and 0.06 kK, respectively. Standard uncertainty u for temperature is $u(T) = \pm 0.1$ °C.

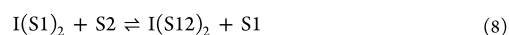
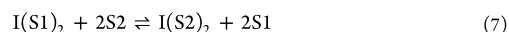
preferentially be solvated by DES and ethylene glycol in the aqueous solutions of ethaline and ethylene glycol, respectively.

In a different trend, β values show a positive deviation from ideal behavior along with a synergistic effect in both binary mixtures. It confirms that the binary mixtures of ethaline + water and ethylene glycol + water will be new media with higher hydrogen bond acceptor abilities than their pure components. Solvent–solvent interactions cause an identical composite molecule consisting of two different molecules, which shows special physicochemical properties.

4.2. Preferential Solvation Model. PS parameters in terms of solute–solvent interactions are determined by measuring hypsochromic or bathochromic shifts of the chromophore probes.^{63–65} In binary mixtures of ILs and DESs with molecular solvent, the solvent–solvent interactions

are more complicated than binary molecular solvents. Therefore, they affect solute–solvent interaction and PS.^{63–65} Hence, synergism behaviors in binary mixtures of DESs are more probable than those in ordinary mixtures. These deviations arise because of the difference between the microsphere solvation of the solute and bulk compositions.

The PS model is based on a simple exchange of solvents in solvation shells of probe dyes according to the following equations



where I stands for the probes (Reichardt's dye, 4-nitroaniline, and 4-nitroanisole), S1 (water), S2 (ethaline/EG), and S12 are the composite structures of solvents (ethaline/EG + water).

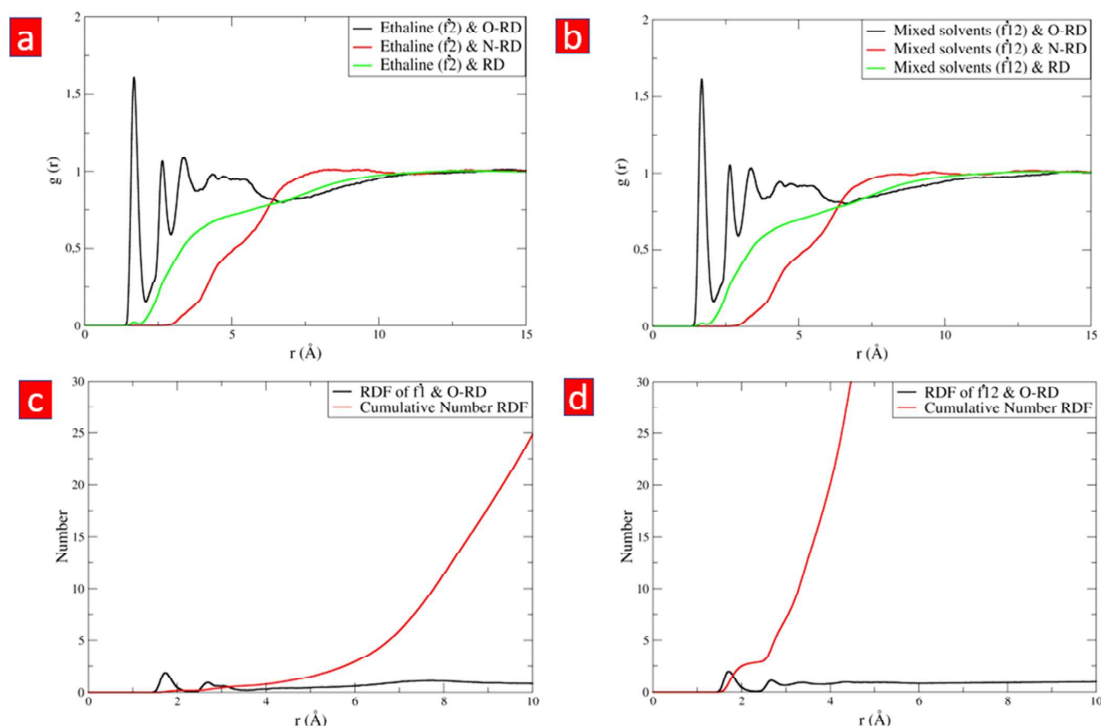


Figure 4. RDFs of the RD probe showing PS parameters, f_2 (a), f_{12} (b), f_1 and its cumulative number (c), and f_{12} with its cumulative number (d) in an aqueous solution of ethaline (0.5 ethaline + 0.5 water).

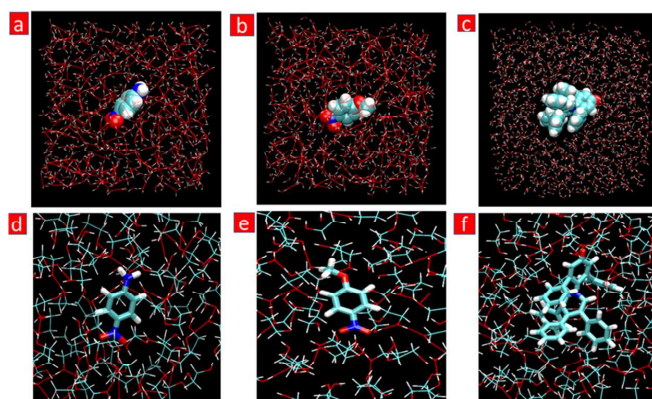


Figure 5. Snapshots from MD simulations showing the solvation shell of probes in water (a–c) and in ethylene glycol (d–f).

$I(S1)$, $I(S2)$, and $I(S12)$ display the probes solvated by each solvent. Equation 7 reflects the total exchange of water by ethaline/ethylene glycol in the solvation shell of the probes, and eq 8 comes from the exchange by the mixed solvents. PS parameters are obtained based on the solvatochromic equilibrium constants of solvent exchange molecules according to eqs 9–11.

$$f_{2/1} = \frac{x_2^s/x_1^s}{(x_2^0/x_1^0)^2} \quad (9)$$

$$f_{12/1} = \frac{x_{12}^s/x_1^s}{x_2^0/x_1^0} \quad (10)$$

$$f_{12/2} = \frac{f_{12/1}}{f_{2/1}} \quad (11)$$

where x_i^0 and x_i^s refer to the mole fraction of each solvent in bulk and microsphere solvation of the solute, respectively. Therefore, the wavenumber of maximum absorption of

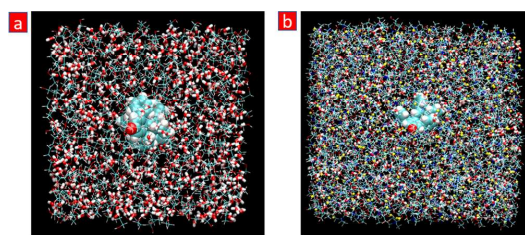


Figure 6. Snapshots from MD simulations showing the solvation shell of RD in a moderate mole fraction of ethylene glycol + water (a) and ethaline + water (b).

Table 2. Determined CNs for Probes (Reichardt's dye (RD), 4-nitroaniline (ANI), and 4-nitroanisole (ANS)) in Aqueous Solutions of Ethylene Glycol^a

x_w^b	RC		O-RC		N-RC	
	EG	water	EG	water	EG	water
0	10.85		20.95		1.85	
0.1	10.53	0.27	20.26	0.59	1.75	0.02
0.3	9.66	1.04	18.19	2.29	1.62	0.13
0.5	8.67	1.93	15.75	4.32	1.49	0.20
0.7	7.08	3.37	12.12	7.40	1.30	0.35
0.9	4.33	5.85	6.99	11.75	0.91	0.64
1.0		9.86		17.17		1.21

x_w^b	ANI		NH ₂ -ANI		NO ₂ -ANI	
	EG	water	EG	water	EG	water
0	15.77		19.98		17.15	
0.1	15.22	0.55	19.18	0.77	16.63	0.57
0.3	13.73	1.87	16.99	2.73	15.11	1.90
0.5	12.19	3.29	14.72	4.74	13.51	3.41
0.7	9.60	5.64	11.17	7.94	10.69	6.02
0.9	4.97	9.89	5.08	13.41	5.68	10.68
1.0		14.52		18.02		16.08

x_w^b	ANS		OCH ₃ -ANS		NO ₂ -ANS	
	EG	water	EG	water	EG	water
0	14.75		16.72		17.14	
0.1	14.23	0.46	15.98	0.62	16.59	0.47
0.3	13.09	1.53	14.59	1.94	15.26	1.72
0.5	11.35	3.12	12.41	3.96	13.27	3.56
0.7	9.00	5.23	9.62	6.49	10.56	6.04
0.9	4.95	8.94	4.91	10.80	5.70	10.61
1.0		13.58		15.42		16.06

^aAll CNs have been obtained by integrating the corresponding RDF over the range of 0–4 Å via eq 12. ^b x_w is the mole fraction of water.

solvatochromic probes in the solvent mixtures can be calculated as a function of PS parameters.

Table 1 shows PS parameters that have been obtained by the PS model. For all probes in the mixtures, data show that $f_{2/1}$ values are more than unity. It means that these indicators are preferentially solvated by ethaline and ethylene glycol in ethaline–water and ethylene glycol–water mixtures, respectively. On the other hand, high $f_{12/1}$ values demonstrate that the indicators can be preferentially solvated by the composite solvents compared to each component. The composite structures of solvents can be produced due to strong interactions between DES (or ethylene glycol) and water molecules. Figure 2 shows that the maximum absorption of solvatochromic probes in solvents demonstrates a pronounced

negative deviation from ideal behavior. It can be attributed to the PS of the probes mentioned before.

4.3. Computational Results. Solvatochromism and PS parameters depend on changes of molecules in microsphere solvation of probe and solvent abilities to have interactions with probes Figure 1. In the experimental work, we measured PS by increasing the amount of water; therefore, changes in the numbers of each molecule (ethaline, EG, and water) that surrounded the probes caused the experimental results to shift over the mole fractions (by stabilizing of ground/excited electronic states of probes).

Hence, the number of molecules around probes is the key role to confirm experimental results. The radial distribution function (RDF), the probability of finding a particle from a reference particle over distances, is a powerful tool in MD simulations to understand the solvation structures. In our previous work,¹¹ RDFs were used to find the structural analyses of three DESs (reline, glyceline, and ethaline). It was found out that DESs have very close characteristic features, which is helpful to have knowledge of others by understanding some of them. After simulations and producing phase trajectories, in order to analyze preferential solvation by RDFs, the `gmx make_ndx` command was used. Choline (CHL), chloride (Cl), and ethylene glycol (EG) were placed in a group in an index file to make ethaline (f_2) and water (f_1), and a combination of f_2 and f_1 was performed to create a group as f_{12} in the index file (f_1 , f_2 , and f_{12} are representatives for each solvent at the microsphere solvation of probes in order to calculate probability or coordination number of each solvent around probes). RDFs for PS parameters (f_1 , f_2 , and f_{12}) with probe dyes were obtained. In all RDFs, it was realized that probabilities, $g(r)$, of f_2 and f_{12} are much more than that of f_1 . Figure 4 illustrates these differences between PS parameters depicted for the RD probe. Cumulative number RDFs were determined, and they confirmed how coordination numbers (CNs) obtained by MD simulations can strongly describe PS parameters over selective distances. For example, coordination numbers of O-RD and f_1 , f_2 , and f_{12} (CNs of Reichardt's dye oxygen with water, ethaline, and mixed solvents) over 0–3 Å were 0.43, 6.43 and 6.86 and those over 0–4 Å were 0.77, 21.03, and 21.80 in an aqueous solution of ethaline (0.5 ethaline + 0.5 water), respectively. In an aqueous solution of ethylene glycol (0.5 EG + 0.5 water), coordination numbers of O-RD and f_1 , f_2 , and f_{12} were 2.10, 4.97, and 7.07 over 0–3 Å and 4.32, 15.74, and 20.07 over 0–4 Å, respectively; the CN obtained by each RDF (f_1 , f_2 , and f_{12}) confirmed that the solvation is governed by mixed solvents. On the other hand, these numbers display that probes prefer ethaline + water or ethylene glycol + water much more than pure water. The CN amounts of ethaline or ethylene glycol for solvation of probes in these mixtures are significant. Moreover, to find more details and effect of DES components, the CN of each component of DES (choline, chloride, and ethylene glycol) is very valuable. The CN of selected species a and b is described by eq 12

$$CN_{ab} = 4\pi \int_0^R \frac{N_b}{V} r^2 g_{ab}(r) dr \quad (12)$$

R is a distance between two species a and b, V is the volume of the box, and N_b is the number of species b in the box. In our calculations, R was taken to be 4 Å in order to involve the first microsphere solvation shells of the groups of interest over all mole fractions (Figures 4–6). The CNs were calculated

Table 3. Determined CNs in Aqueous Solutions of Ethaline^a

x_w^b	RC				O-RC				N-RC			
	CHL	Cl	EG	water	CHL	Cl	EG	water	CHL	Cl	EG	water
0	3.54	0.16	7.19		13.74	0.00	8.03		0.25	0.01	1.55	
0.1	4.72	0.12	5.85	0.07	15.78	0.00	6.92	0.02	0.26	0.00	0.36	0.00
0.3	5.35	0.14	5.55	0.19	15.31	0.00	5.93	0.44	0.88	0.00	0.52	0.06
0.5	4.34	0.13	6.12	0.47	9.20	0.00	11.83	0.76	0.43	0.00	1.22	0.04
0.7	3.29	0.08	6.49	1.11	9.34	0.00	9.91	1.87	0.31	0.00	1.25	0.09
0.9	2.33	0.04	5.33	3.17	5.13	0.00	8.42	6.41	0.31	0.00	1.20	0.27
1				9.86				17.17				1.21
x_w^b	ANI				NH ₂ -ANI				NO ₂ -ANI			
	CHL	Cl	EG	water	CHL	Cl	EG	water	CHL	Cl	EG	water
0	8.75	0.38	6.66		9.70	0.98	8.41		10.01	0.05	8.11	
0.1	6.01	0.33	8.81	0.28	7.45	0.88	10.02	0.25	8.73	0.03	9.08	0.12
0.3	8.55	0.47	5.97	0.53	10.48	1.26	5.87	0.72	10.16	0.08	7.24	0.47
0.5	6.17	0.31	8.28	0.92	8.02	0.89	8.32	1.58	8.60	0.03	8.65	0.56
0.7	5.05	0.24	8.35	1.97	6.14	0.66	8.60	3.55	7.12	0.03	9.37	1.26
0.9	4.48	0.14	5.42	5.66	4.93	0.37	5.71	8.11	6.26	0.01	6.20	5.13
1				14.52				18.02				16.08
x_w^b	ANS				OCH ₃ -ANS				NO ₂ -ANS			
	CHL	Cl	EG	water	CHL	Cl	EG	water	CHL	Cl	EG	water
0	5.42	0.21	9.03		5.99	0.26	10.08		9.93	0.03	8.20	
0.1	5.48	0.26	8.68	0.02	5.35	0.32	10.56	0.02	10.51	0.11	7.05	0.00
0.3	6.36	0.26	7.96	0.32	6.97	0.33	8.97	0.39	9.84	0.06	8.11	0.27
0.5	5.01	0.21	8.91	0.63	4.86	0.24	10.55	0.92	8.59	0.06	8.58	0.44
0.7	5.51	0.17	7.40	1.77	5.73	0.24	8.04	2.67	9.05	0.04	7.33	1.32
0.9	3.33	0.08	5.97	5.35	3.41	0.13	6.12	6.93	5.63	0.02	6.57	5.27
1				13.58				15.42				16.06

^aAll CNs have been obtained by integrating the corresponding RDF over the range of 0–4 Å via eq 12. ^b x_w is the mole fraction of water.

Table 4. Average Numbers of Hydrogen Bond Acceptor Ability (β') of the RD Probe with Components in Aqueous Solutions of Ethaline and Ethylene Glycol

x_w^a	ethaline			ethylene glycol		
	CHL	EG	water	$\Sigma\beta'$	EG	water
0	0.91	0.65		1.56	2.72	2.72
0.1	0.83	0.66	0.00	1.49	2.61	0.13
0.3	0.74	0.62	0.11	1.47	2.31	0.49
0.5	0.29	1.57	0.18	2.04	1.93	0.89
0.7	0.53	1.12	0.44	2.09	1.38	1.48
0.9	0.33	0.82	1.41	2.56	0.72	2.21
1			3.06	3.06		3.06

^a x_w is the mole fraction of water.

between selected groups (each component of solvents and probes). For this purpose, the CNs were obtained by integrating the corresponding RDFs and are shown in Tables 2 and 3. The CNs reveal that the existence of ethylene glycol and choline in microsphere solvation of probe dyes is remarkable. Even in the rich mole fraction of water (0.1 ethaline/EG + 0.9 water), the numbers of ethylene glycol or choline are approximately half of water. In some mole fractions of binary mixtures, the CN reached 10 times variation in numbers of EG to water, which strongly confirmed that probes prefer to be solvated by ethaline/EG. Data collected by the CN show that the accumulations at the microsphere solvation of probes in aqueous solutions of ethaline are in this trend: EG > choline > water > chloride, and in aqueous solutions of ethylene glycol: EG > water.

In aqueous solutions of ethaline, however, the CNs of ethylene glycol are remarkable, but they are less than 2 times those for choline. For instance, in the moderate mole fraction (0.5 ethaline + 0.5 water), the CNs of ethylene glycol for RD, NLE, and NAS are 6.12, 8.28, and 8.91; the CNs of choline are 4.34, 6.17, and 5.01 for RD, NLE, and NAS respectively. It means that even though the numbers of EG are two times more than those of choline in binary mixtures, the numbers are not the same at the local solvation shell (the microsphere solvation of probe dyes). It can be helpful to clear the effect of DES components. The CNs in the aqueous solution of choline chloride (0.1 choline chloride + 0.9 water) were 5.24, 7.31, and 6.55 for choline and RD, NLE, and NAS sequentially and 5.77, 8.38, and 8.30 for water and probes. By comparing the CN in the aqueous solution of choline chloride (0.1 choline chloride + 0.9 water) with the aqueous solution of ethaline (0.1 ethaline + 0.9 water), it was found out that ethylene glycol and choline are serious competitors for solvating the probes (the CN for each of them increases in the absence of the other one).

Moreover, different sides (functional groups) of probes were examined to discover the preferred sides of probes. The CN data in Tables 2 and 3 show that the selective side of RD is the oxygen atom. In aqueous solutions of ethaline, the presence of different species causes different preferential for probes. Oxygen of RD was more surrounded by choline. Probably, this oxygen has the major effect on shifting wavelengths of RD in solvatochromism. The amine group of 4-nitroaniline and methoxy group of 4-nitroanisole prefer to be solvated by ethylene glycol more than others. The nitro group of these dyes (NLE and NAS) prefers choline a bit more than ethylene glycol in low mole fractions of water. It is probably because of

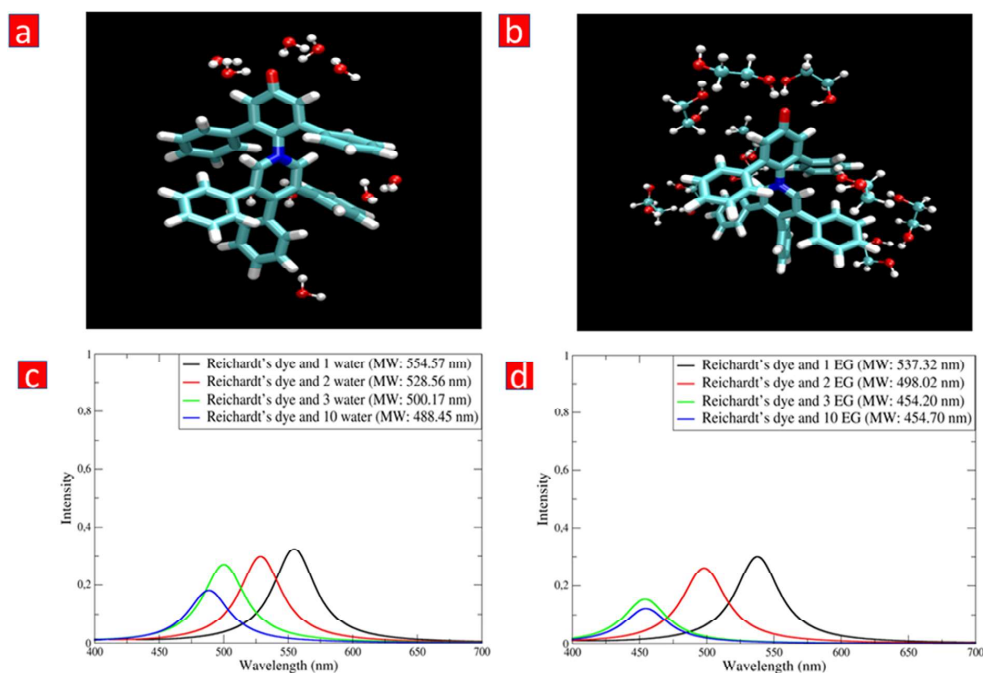


Figure 7. Optimized geometries of RD with 10 molecules of water (a) and ethylene glycol (b). Obtained UV-vis spectra of RD with 1, 2, 3, and 10 molecules of water (c) and ethylene glycol (d) in the gas phase.

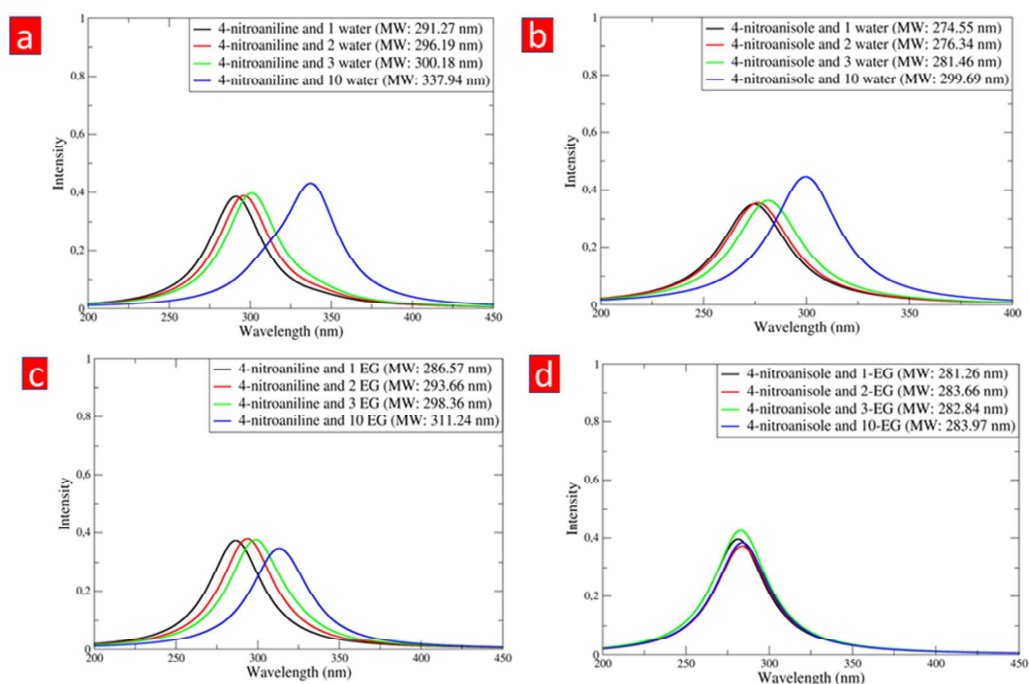


Figure 8. Obtained UV-vis spectra of 4-nitroaniline and 4-nitroanisole with 1, 2, 3, and 10 molecules of water (a,b) and ethylene glycol (c,d) in the gas phase.

the positive charge of choline. The presence of chloride was just seen around the amine group of 4-nitroaniline. In the case of the other probes, there is no probability of chloride at near distances. The obtained CNs from different aqueous solutions (ethaline, ethylene glycol, and choline chloride) but the same mole fraction of water (0.1 ethaline/EG/ChCl + 0.9 water) were concluded that choline was a potent rival for ethylene glycol to solvate the probe dyes and both these components are considerably more preferred than water.

Solvation shells of probes as an important reason for turning UV-vis spectra were discussed. The other reason for either red or blue shifts in probe spectra is hydrogen bond interaction between probes and solvents. 4-Nitroaniline and 4-nitroanisole have different sides to have hydrogen bond interactions with the surrounding molecules. Hence, these two probes make confusion to understand the effect of hydrogen bond interactions. RD has only one oxygen, which makes it suitable to overcome this goal. The numbers of hydrogen bonds were calculated between RD oxygen as the hydrogen bond acceptor and hydroxyl groups of ethylene glycol, choline, and water in different mole fractions. Data in Table 4 show that by increasing the mole fractions of water in binary aqueous solutions, the number of hydrogen bonds (β') of RD with water increased. The reverse trend of β' was observed for choline by increasing the mole fraction of water. In the case of ethylene glycol in aqueous solutions of ethaline, there was a maximum in moderate mole fraction and after that decreased. The total number of hydrogen bonds ($\sum\beta'$) in each mole fraction confirmed that by adding water to binary solutions, $\sum\beta'$ increased. It can be interpreted that water causes a shifting effect by making hydrogen bond interaction. In the same mole fractions of ethaline and ethylene glycol, $\sum\beta'$ values of ethylene glycol were more than those of ethaline; this is because of the choline existence in ethaline solutions, which occupies some sites around RD oxygen. Calculated β' values are in good accordance with the CNs in Tables 2 and 3.

In order to better understand the solvatochromism and effect of microsphere solvation on shifting wavelengths, quantum calculations were used. Coordinates of 1, 2, 3, and 10 molecules of water and ethylene glycol in the vicinity of probes were extracted from their trajectories in MD simulations files. The DFT/B3LYP functional using a 6-31G* basis set was used to optimize the geometries of probes and corresponding solvents in the Gaussian 09 program.⁶⁶ Figure 7 illustrates the optimized geometries of 10 molecules of water (a) and ethylene glycol (b) surrounding the RD probe. The optimized geometries with different numbers of solvents were used by time-dependent density functional theory (TD-DFT) with the CAM-B3LYP functional using a TZVP basis set. The Molden program was used for visualization of the UV-vis spectra of QM calculations. Figures 7 and 8 show the obtained UV-vis spectra of these calculations in the gas phase. Figure 8 illustrates how adding the number of molecules (1 $\rightarrow$ 10) in microsphere solvation of 4-nitroaniline and 4-nitroanisole causes bathochromic shifts. The shifts of 4-nitroaniline are more remarkable than those of 4-nitroanisole (in experimental work, 4-nitroaniline has a wider spectral range than 4-nitroanisole). Figure 7 shows that RD has a different trend, which means that by adding molecules hypsochromic shifts were observed.

5. CONCLUSIONS

Aqueous solutions of ethaline, ethylene glycol, and choline chloride were studied. A novel measurement of PS parameters by experimental and theoretical studies has been presented. The effects of ethylene glycol, choline chloride, and water were realized by measuring PS and solvatochromic parameters in aqueous solutions of components. MD simulations were applied to understand the microsphere solvation of each probe. They made a simple method to understand the PS parameters and effect of different species in binary mixtures by using RDF and CN. It is worthwhile to find which combination of solvents is preferred at the microsphere solvation of probes in complex systems by calculating the CN. This method was in good accordance with UV-vis data. Moreover, they provided insight into how the accumulation of different components causes the synergism in experimental data. The presence of ethylene glycol and choline was remarkable in all binary mixtures. Finally, the DFT method was used to improve our knowledge of solvation shell effects on absorbance spectra; by increasing the number of molecules in solvation shells of probes, shifting in the absorbance spectra of the probes was seen. Based on our findings, MD simulations and DFT calculations are very practical to have a perspective of the nature of solvatochromism and PS. As a result, these findings suggest a computational method to find which combination of components in mixed systems affects PS.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.jced.0c00381>.

Chemicals used in the study; numbers of solvent components in each box used for MD simulations; measured solvatochromic parameters for studied mixtures (PDF)

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<https://pubs.acs.org/doi/10.1021/acs.jced.0c00381>

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

M.A. acknowledges Dr. Habib Aghababaei Dehkordi for helpful suggestions and the support from the Czech Science Foundation grant (ERDF CZ.02.1.01/0.0/0.0/15_003/0000441 and GAJU 017/2019/P). Authors acknowledge access to computational resources provided by the CESNET LM2015042 and the CERIT Scientific Cloud LM2015085, provided under the program "Projects of Large Research, Development, and Innovations Infrastructures".

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5.4 Article 4

Journal of Environmental Management 283 (2021) 111989

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: <http://www.elsevier.com/locate/jenvman>

Computational and experimental assessment of pH and specific ions on the solute solvent interactions of clay-biochar composites towards tetracycline adsorption: Implications on wastewater treatment

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MA did the MD simulations and wrote the computational part.

Borthakur, P.; Aryafard, M.; Zara, Z.; Reha, D.; Minofar, B.; Das, M.; Vithanage, M. Computational and experimental assessment of pH and specific ions on the solute solvent interactions of clay-biochar composites towards tetracycline adsorption: Implications on wastewater treatment. *J. Env. Man.* **2021**, *283*, 111989. <https://doi.org/10.1016/j.jenvman.2021.111989>



Computational and experimental assessment of pH and specific ions on the solute solvent interactions of clay-biochar composites towards tetracycline adsorption: Implications on wastewater treatment

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ARTICLE INFO

Keywords:

Adsorption

Biochar

Computational chemistry

Pharmaceutical and personal care products

Zeta potential

ABSTRACT

Experimental and computational investigations have been conducted in this study to assess the influence of municipal waste pyrolyzed biochar impregnated clay composites on antibiotic removal as a material for wastewater treatment and simultaneous value-addition for waste. The surface potential (zeta potential) of the pristine biochar and composite samples are found to be within the range ~ 10 to ~ -40 mV in the pH range 2–10. The presence of different inorganic salt solutions influences the electrophoretic mobility of the dispersed phase in a suspension, as well as its zeta potential. In addition of Na^+ salt solutions, the Na^+ ions undergo electrostatic interaction with the negatively charged biochar samples and form a double layer at the interface of biochar and ionic salt solution. Molecular dynamics simulations have been employed to understand experimental findings, ions adsorption and solute-solvent interactions at the molecular level of two biochar B7 (seven benzene rings, one methoxy, one aldehyde and two hydroxyls groups) and B17 (seventeen benzene rings, one methoxy, two hydroxyls and two carboxylic acid groups) in salts aqueous solutions. The results confirm that hydroxyls and carboxylate groups of biochar are responsible for solute-solvent interactions. Successful removal of tetracycline antibiotics is observed with 26 mg/g maximum adsorption capacity with montmorillonite biochar composite. This study confirms that interactions between amide and hydroxyl groups of tetracycline with hydroxyl and carboxylate groups of biochar play the key role in the adsorption process. The solution pH and presence of different background electrolytes effectively influence the process of solute-solvent interactions as well as adsorption efficacy towards tetracycline adsorption.

1. Introduction

Biochar is an effective adsorbent in the wastewater/soil media which has received recent desirability over the past decade due to its high capacity to adsorb various ions and compounds, degradation and immobilization potential of hydrophobic organic compounds, drugs, and other persistent organic contaminants (Ahmad et al., 2014; Huang et al., 2019; Inyang and Dickenson 2015). However, compared to activated carbon, biochar still desires improvements for its capacity because

of its relatively low surface area and the influence of abiotic and/or biotic processes on its properties and adsorption capacity for certain contaminants and hence, most recent research has focused on preparing designer biochar (Premarathna et al., 2019b; Rajapaksha et al., 2016). Impregnation of organic compounds or carbonaceous materials, such as graphene oxide, carbon nanotubes and polysaccharides, clays, metal oxides to modify the surface properties of the biochar has been one of the most common ways of assembling engineered biochar (Mandal et al., 2020; Ramanayaka et al., 2020; Tan et al., 2016). The readily available

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<https://doi.org/10.1016/j.jenvman.2021.111989>

Received 4 October 2020; Received in revised form 24 December 2020; Accepted 11 January 2021

Available online 27 January 2021

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fine-grained clay has been effectively used for the adsorption of different toxic metal ions and molecules in the aqueous medium due to their low-cost, non-toxic nature, efficient adsorption properties, high specific surface area and potential in ion exchange (Uddin 2017). Montmorillonite (MMT) is an aluminosilicate clay mineral in which aluminum and silicon are the main components. In MMT, one aluminum octahedral sheet is stacked between two tetrahedral silicon sheets (Krupskaya et al., 2017). Cations (Na^+ , Ca^{2+} , Mg^{2+}) present in the interlayer space of MMT can exchange with positively charged contaminants by cation exchange. Thus, the guest ions or molecules can occupy the interlayer space of MMT by replacing the hydrated cations through the cation exchange mechanism (Ashiq et al., 2019; Li et al., 2010). Natural red earth clay (RE) mainly consists of silica (SiO_2) coated with considerable concentrations of Al_2O_3 and Fe_2O_3 (Vithanage et al. 2006, 2007). In RE both aluminum and iron ($>\text{AlOH}$ and $>\text{FeOH}$) act as active surface sites. As a result, the variation of pH in the surrounding environment can affect the surface charge of RE. Although RE does not have a porous or layered structure, it shows high adsorption efficiency for both organic and inorganic pollutants (Vithanage et al., 2006). Impregnating biochar with MMT and RE can, therefore, provide a surface with more reactive sites and lead to an increase of adsorption capacity of biochar-clay composite for pollutant mitigation applications.

Biochar assists as a porous structure to host the assemblage within its matrix and this characteristic feature has been exploited for the development of clay-biochar composites, which has been successfully applied in environmental remediation (Yao et al., 2014). During adsorptive removal of contaminants, the surface charge of biochar samples plays a key role in its adsorption efficiency towards remediating organic pollutant molecules (Banik et al., 2018). The extent of carbonization dictates the overall charge of biochar, keeping in mind the solution conditions such as pH of the media and the presence of different inorganic salts present in the media. Ideally, biochar surfaces are negatively charged (Ahmad et al., 2014). Therefore, positively charged ions are easily attracted by the biochar surface through electrostatic interactions of delocalized electrons cloud of aromatic rings present on the surface of carbonaceous biochars, forming cation- π electrons interactions with the $\text{C}=\text{C}$ aromatic bonds (Tan et al., 2020). This mode of adsorption onto biochar makes it more viable for a certain kind of pollutants that are positively charged and therefore, effortlessly remediates by electrostatic interactions. Biochar composites has proven advantageous to adsorb a wider range of pollutants, equalizing the charges for adsorbing both cationic and anionic species on to its surface. Based on it, the technique used for investigating the variation of surface charge (zeta potential) of the adsorbent materials with varying solution conditions are quite limited in this line of research. In addition, the counter effects on the adsorption efficiency of organic pollutants with the presence of different inorganic salts in the media, is also remotely studied (Borthakur et al., 2016; Das et al., 2010; Zhang et al., 2018).

Furthermore, cations of the inorganic salts can bind with the biochar surface and the surface becomes positive. The polarizability of the counter anions like Cl^- , SO_4^{2-} , NO_3^- , CH_3COO^- , Br^- , I^- can, in turn, play an essential role in the variation of the surface charge of biochar samples (Banik et al., 2018; Keiluweit et al., 2010; Zhao et al., 2017). Molecular dynamics (MD) simulation allows the analysis of molecular regions at a size resolution that is not available to experimental techniques (Aryafard et al. 2019a, 2019b; Borthakur et al., 2016; Makarov et al., 1998). Based on the previous reports, the solution conditions such as pH and presence of inorganic salts in the media that constitutes the background electrolytes adversely affects the surface properties (zeta potential) of biochar samples and its counter-effects on the adsorption of organic molecules has become an essential field of research and have received inadequate attention. Therefore, combining MD with surface potential data may describe the governing factors for antibiotic, such as tetracycline (TC), adsorption on biochar. Particularly the effect of salts on the remediation of tetracycline present in the aqueous media through the use of MD do not exist in the field of biochar science (Hong et al., 2019;

Tong et al., 2019). The main objective of the research is to understand the effect of solution pH and different inorganic ions on the surface potential of the biochar sample collected from municipal solid waste from Gohagoda, Sri Lanka, influence by montmorillonite and natural red earth clays. We have also studied the impact of variation of surface potential of modified biochar samples on the adsorption of Tetracycline molecules. Molecular dynamic simulations study has been carried out to better understanding the experimental findings which is not widely explored.

2. Experimental section

2.1. Preparation of biochar and its composites

The compostable organic portion was selected as the Municipal Solid Waste (MSW) feedstock for the production of parent biochar. Biomass feedstocks were pyrolyzed under slow pyrolysis at 500°C for 30 min under an oxygen-limited environment (MTI, Richmond, CA). Stable clay suspensions of Montmorillonite (MMT) from Sigma Aldrich, USA and Natural Red Earth (RE) from Aruwakkalu, Sri Lanka, were used to prepare independent slurries. A 50 g of each clay was mixed with 2 L deionized water, and mixture was sonicated for 30 min using an Ultrasonicator (Rocker). These two clays were selected based on the presence of Al and Fe in their composition (Mahatantila et al., 2012; Premarathna et al., 2019a). Then 250 g of MSW feedstock were added to each clay suspension and then mixtures were shaken for 2 h. Clay-feedstock suspensions were filtered and dried at 80°C overnight in an oven. Clay treated biomass feedstocks were pyrolyzed at 500°C for 30 min under the same pyrolysis conditions. Two biochar samples were washed, then dried in an oven at 80°C and finally sealed in a container for further testing. The as-obtained clay-biochar composite samples were henceforth referred to as MSW-MMT, MSW-RE, and MSW-BC, respectively.

2.2. Characterization of the biochar samples

The surface morphology of the modified biochar sample's surface was analyzed by the field-emission scanning electron microscope (FESEM), with the help of ZEISS Gemini scanning electron microscope (Germany) operated at an accelerating voltage of 9–7 kV. The specific surface area of the biochar samples was determined through nitrogen gas adsorption study at 77 K by using an Autosorb-iQ Station 1 (Quantachrome, USA) and applying Brunauer-Emmett-Teller (BET) calculations. Before performing the experiments, the samples were degassed at 200°C for 3 h.

The surface potential of the biochar samples was evaluated through the electrophoresis method in which the particle movements are monitored in an applied electric field. The zeta potential of the suspensions of biochar samples was determined by measuring the electrophoretic mobilities with the help of Zetasizer analyzer (Model: Nano ZS, Malvern, UK) instrument and applying Smoluchowski equation (Das et al., 2010). Eqn 1

$$\zeta = 4\pi\eta/D_t \times \mu \quad (1)$$

Where ζ is the zeta potential, η is the viscosity of the medium, μ is electrophoretic mobility at a particular temperature and D_t is the dielectric constant of the medium. The electrophoretic mobility of the biochar samples was also investigated as a function of pH in the presence of different monovalent and divalent salts. The effect of solution pH and the presence of 0.01 M different ionic species on the zeta potential of biochar suspension were studied by taking the suspension of biochar materials (1.00 mg/L in DI water) prepared by ultrasonication. The pH of the suspension was adjusted, adding 0.1 M of HCl and NaOH solution by using pH meter. Stock solutions (1.00 M) of the different electrolytes (NaCl, KCl, NaBr, NaNO_3 , Na_2SO_4 , CH_3COONa , CaCl_2 and MgCl_2) were prepared by dissolving an accurate amount of salt in DI water. All the experiments were performed in triplicates.

In addition, moisture content, mobile matter, ash and residual matter contents (proximate analysis) were performed at standard methods and reported in our previous studies. The study was also supported further with the elemental composition of the MSW biochar, prepared at the same conditions to obtain the C, H, N, S and O contents respectively (Jayawardhana et al., 2019).

2.3. Adsorption experiments

The effect of pH on the sorption was studied by adjusting the pH in the range of 3.0–9.0. Biochar and composite dosage was kept at 2.00 g/L of solutions containing TC 20.00 mg/L. Then pH was adjusted with 0.1 M HNO₃ or NaOH. After 12 h of contact time, the final pH of samples was measured. All the experiments and sampling were performed in triplicates. Thereafter, samples were filtered and the remaining TC concentrations in the solutions were measured by a spectrophotometer (Shimadzu UV160A) at 268.6 nm wavelength. Adsorption isotherms were determined with TC solution with different concentrations ranging from 0.25 to 50.00 mg/L for 12 h. Adsorbent dosage was kept at 2 g/L in pH 7.0–8.0 throughout the experiment.

The adsorbate TC transferring process from the liquid face to the solid phase is controlled by more than one process and therefore, individual modelling was performed on the experimental data. The models were made to fit through non-linear ((2) and (3)). regression in Origin Ver. 6.1. The right fit is decided based on the statistical parameters such as the correlation coefficient and the Chi-square values. Based on that, the best fits were pointed out as the results of this study. Freundlich isotherm:Eqn 2

$$q_e = K_f C_e^n \quad (2)$$

Langmuir isotherm:Eqn 3

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} \quad (3)$$

Where C_e is equilibrium concentration (mg/L), q_e is the adsorption of OTC per gram of adsorbents used (mg/g), q_m is the Langmuir constant associated with adsorption capacity at its maximum adsorption capacity (mg/g) and K_L is the Langmuir equilibrium constant (L/g) and n and K_f are Freundlich constant wherein they are indicators of adsorption capacity and intensity, respectively (Subramanyam and Das 2009).

2.4. Molecular dynamic modelling

Molecular Dynamics simulations have been employed to understand experimental findings, ions adsorption and solute-solvent interactions at the molecular level of two biochar (B7 and B17) in salts aqueous solutions. For the construction of biochar, B7 was built with seven benzene rings, one methoxy, one aldehyde and two hydroxyls groups. In the case of B17, seventeen benzene rings, one methoxy, two hydroxyls and two carboxylic acid groups were applied as functional groups Fig. 1.

MD simulations of B7 and B17 molecules have been performed in aqueous solutions with the presence of different salts like experimental work, NaNO₃, NaCl, NaBr, Na₂SO₄, NaCH₃COO, MgCl₂, and CaCl₂. For the preparation of the solution boxes, Packmol package was used. B7 and B17 molecules have been placed in the center of the cubic box (Martínez and Martínez 2003; Martínez et al., 2009). The General amber force field (GAFF) was used for all molecules and ions (Wang et al., 2004). After doing energy minimization, (to remove unfavorable contacts in the solutions), NVT (canonical ensemble) simulations were run at 300 K and then followed by NPT (isothermal–isobaric ensemble) simulations. The production phase was performed for 50 ns (ns) by employing Gromacs package. The conformations in trajectories were dumped with an interval of 2 fs (fs) for further analysis. Visual Molecular Dynamics (VMD) program was used for visualizations of the trajectory and preparation of snapshots (Humphrey et al., 1996).

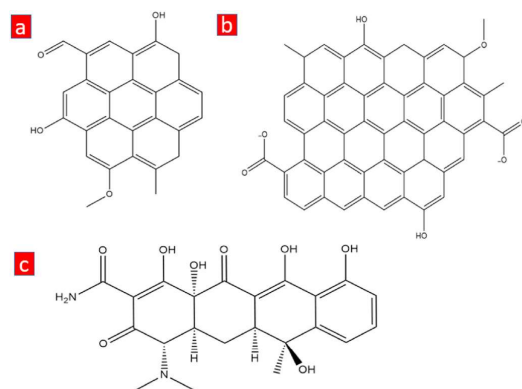


Fig. 1. The structures of B7 (a), B17 (b) in aqueous solutions, and tetracycline (c).

3. Results and discussions

3.1. FESEM analysis of the biochar samples

It is observed from FESEM images (Fig. 2a and b) that the surface of Pristine biochar prepared by municipal solid waste (MSW-BC) at 500 °C, possesses cracks and porosity on its surface. FESEM images of the other two materials like Biochar-montmorillonite composite (MSW-MMT) (Fig. 2c and d) and Biochar-natural red earth composite (MSW-RE) (Fig. 2e and f) display the adhering of the clay particles on the biochar surface.

The presence of pore on the clay modified biochar signifies that clay particles cover biochar surface partially, which makes the pores of biochar accessible to the adsorbate molecules. Energy-dispersive X-ray spectroscopy (EDS) analysis indicates the C and O contents present in the three biochar samples are (86.38 and 13.62%), (88.05 and 11.95%) and (86.54 and 13.46%), respectively. Thus, the carbon content in the biochar samples is following the order as MSW-MMT > MSW-RE > MSW-BC. Here the carbon content of modified biochar samples is higher than that of the pristine biochar. These results illustrate the higher adsorptive capacity of the clay modified biochar in comparison to raw biochar.

3.2. Surface area analysis of the biochar samples

The BET surface area of MSW-BC, MSW-MMT and MSW-RE were found to be 8.631, 7.703, 18.711 m²/g, respectively. The average pore volume and pore radius are listed in Table 1. It is observed that the biochar sample modified with natural red sand has the highest specific surface area and average pore volume due to the deposition of RE clay on the biochar surface. In the case of MSW-MMT, the surface area and volume are found to be lower than that of MSW-BC. This may be due to the decrease in the interlayer space of montmorillonite by loss of structural water from the clay mineral at high pyrolysis temperatures.

3.3. Zeta potential analysis of biochar samples

The point of zero charges (pzc) of the three biochar samples is presented in Fig. 3. The pzc values of MSW-BC, MSW-MMT and MSW-RE were found at pH values 2.8, 2.4 and 2.8, respectively. The pzc of our modified biochar samples has a lower value than the earlier reported calcium-rich biochar (CRB) obtained from pyrolysis of the natural nanostructured organic/inorganic composite (i.e., crab shell) (pH 6.7) (Dai et al., 2018), Chitosan-Modified fast pyrolysis Biochar (CMBC) (pH

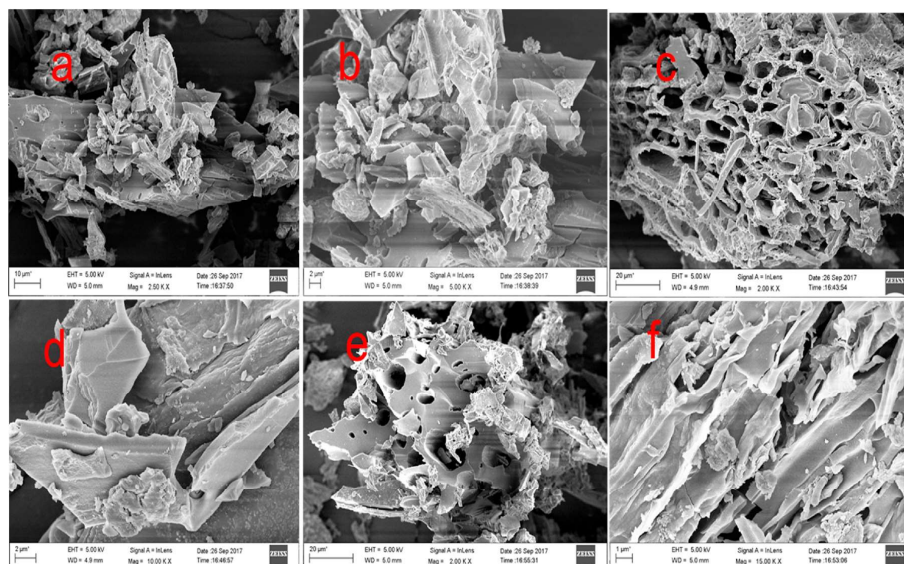


Fig. 2. FESEM images of Pristine biochar prepared by municipal solid waste at 500 °C (MSW-BC) (a, b), Biochar-montmorillonite composite (MSW-MMT) (c, d), Biochar-natural red earth composite (MSW-RE) (e, f).

Table 1
Specific surface area, pore volume and pore radius of biochar samples.

Sample	Surface area (m ² /g)	Pore volume (cc/g)	Pore radius (Å)
MSW-BC	8.631	0.022	17.708
MSW-MMT	7.703	0.020	22.513
MSW-RE	18.711	0.056	17.737

9.5) (Bombuwala Dewage et al., 2018). Low pzc value of the biochar samples indicates that the synthesized materials have negative potential in high pH range. Thus, the positively charged adsorbate molecules will undergo strong electrostatic interactions in acidic as well as in alkaline condition. At pH > pzc, the surface charge is negative and at pH < pzc, the surface charge is positive. At lower pH value, the solution is enriched with H⁺ ions, which can undergo adsorption on the active sites of the materials. Additionally, in more acidic medium, protonation of the surface functional groups like (C=O, -COOH) of biochar samples takes place (Liang et al., 2016). At higher pH, the functional groups of biochar materials undergo ionization in the presence of OH⁻ ions and the surface charge becomes negative.

Fig. 3 also demonstrates that the surface charge (zeta potential) of the three biochar samples are found to be within the range ~10 mV to ~-40 mV in the pH range 2–10. In presence of 0.01 M different salt solutions of Na⁺ ions, the surface charge of the three biochar samples tends towards positive than in the absence of the salt solutions and found to be within the range ~30 mV to ~-30 mV in the pH range 2–10. On addition of Na⁺ ions salt solutions, the Na⁺ ions undergo electrostatic interaction with the negatively charged biochar samples and form a double layer. However, the polarizability of the counterions has an adverse effect on the cations adsorption on the negatively charged biochar samples. As seen in Fig. 3, at lower pH range, the hydrophobic biochar surface adsorbs a smaller number of cations (Na⁺) and the resting Na⁺ ions and the counter anions are dispersed around the fixed layer of adsorbed cations on the biochar surface.

The anions with high polarizability can undergo more electrostatic attraction by the hydrophobic surface in comparison to the anions with

low polarizability. Thus, the zeta potential of the biochar surface tends towards more positive (in comparison to without salt) in the presence of larger anions than in the case of the smaller anions. Thus, the polarizability of the counter ions has a significant influence on the variation of the zeta potential of the biochar samples in the presence of inorganic salt solutions. Therefore, the zeta potential of the three biochar samples in presence of aqueous solutions of different Na⁺ salts within the pH range 2–10 follows the order as; without salt < Na₂SO₄ < NaBr < NaNO₃ < NaCl < CH₃COONa. In the presence of KCl solution, the zeta potential of the biochar samples is higher than the zeta potential value in the presence of NaCl solution. Because low hydrated larger size K⁺ ions can easily accumulate on the biochar surface than the highly hydrated Na⁺ ions.

Moreover, the zeta potential value of the three biochar samples is found to be more positive in presence of Cl⁻ ion salt solutions of divalent cations than in the presence of NaCl. Both the polarizability effect and the hydration of the cations play the key role in the variation of zeta potential of the biochar samples in presence of both MgCl₂ and CaCl₂. The effect of background electrolytes on the surface potential of MSW-BC is found to follow as; in acidic medium CaCl₂ (25.05 mV) > MgCl₂ (24.30 mV) > CH₃COONa (18.06 mV) > KCl (17.10 mV) > NaCl (17.00 mV) > NaNO₃ (15.76 mV) > NaBr (14.55 mV) > Na₂SO₄ (13.88 mV) > without salt (13.52 mV). Similarly, in neutral and alkaline medium the surface charge value of MSW-BC is found to be followed the similar order as shown in Fig. 3a. In case of MSW-MMT, the surface potential is found as CaCl₂ (25.40 mV) > MgCl₂ (24.85 mV) > CH₃COONa (21.89 mV) > KCl (21.47 mV) > NaCl (18.87 mV) > NaNO₃ (17.14 mV) > NaBr (16.29 mV) > Na₂SO₄ (16.16 mV) > without salt (15.32 mV) at pH 2; whereas the surface potential of MSW-RE is found as CaCl₂ (15.35 mV) > CH₃COONa (15.23 mV) > MgCl₂ (14.33 mV) > KCl (14.20 mV) > NaNO₃ (13.63 mV) > NaBr (10.21 mV) > NaCl ≈ Na₂SO₄ (9.77 mV) > without salt (8.42 mV). It is seen from the experimental findings that the surface properties of the biochar sample are changed when incorporated with montmorillonite clay and natural red earth composites.

It is also observed from Fig. 3 that the isoelectric point (IEP) of the three biochar samples is shifted to high pH value in the presence of

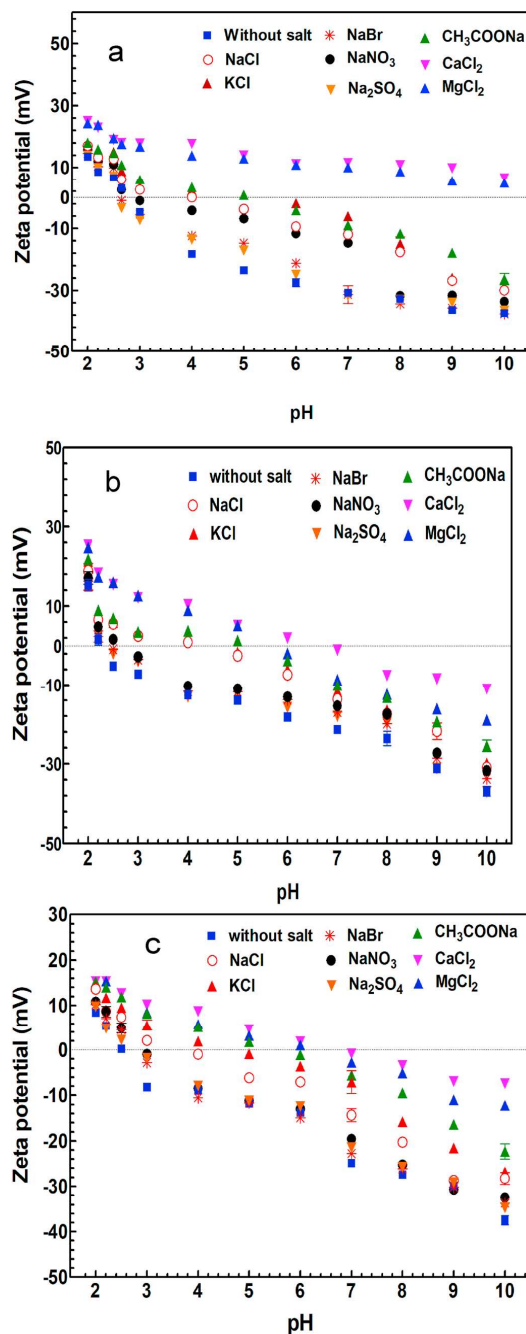


Fig. 3. Variation of zeta potential of MSW-BC (a), MSW-MMT (b) and MSW-RE (c) in the presence of 0.01 M different salt solutions at different pH.

different ions in comparison to that of raw biochar suspensions. It is reported previously that the shifting of IEP is salt specific and the salts containing smaller cations and more abundant anions shifted the IEP to a greater extent than other salts (Kosmulski et al., 2002). We observed that in the presence of CH_3COONa , the IEP value of the three biochar samples is found to be higher than that of other Na^+ ion salt solutions at pH (~5). According to Johnson and his group, the cations of the salts have a greater effect on the shifting of IEP than the anions (Johnson et al., 1999). In our study, we have found that the presence of divalent cations (Ca^{2+} and Mg^{2+}) caused more shifting of IEP (pH ~ 6) for MSW-BC and MSW-MMT and the value of the surface potential of MSW-RE is positive within the pH range 2–10. This is because of more electrostatic interactions between the divalent cations and negatively charged biochar surfaces after modification with red earth composite materials. Thus the surface properties of the biochar samples are significantly affected by the incorporation of foreign materials as well as by the background electrolytes. The catalytic efficiency of the biochar adsorbent materials can be affected by the different parameters. The IEP values of the three biochar samples in the presence of different background salt solutions are presented in Table 2. A significant experimental finding has been achieved in a variation of IEP in the presence of divalent cations (Ca^{2+} and Mg^{2+}) of the biochar samples when modified with montmorillonite clay and red earth composites. In the case of raw biochar materials, the surface potential is found to be positive in the pH range 2–10 due to the more accumulation of cations around the surface. Whereas, in the case of modified biochar materials, the surface charge is found to be in the negative range in alkaline medium (pH > 6). In the presence of Na_2SO_4 salt solution, the IEP of the three biochar samples is found in a low pH value than that of the absence of salt solutions. Here the bivalent anions (SO_4^{2-}) with high polarizability can undergo more accumulation around the positively charged surfaces and thus, the surface charge of the biochar samples becomes negative even in acidic media.

3.4. Adsorption edge and isotherm

As reported removal of chemotherapeutic agents from the environment depend largely on their structural orientation, environmental factors, and degree of ionization (Mukherjee et al., 2021). pH of the reaction mixture is one of the major governing factors that control TC adsorption on to MSW-BC and biochar composites as per the experimental data. TC speciates based on the pH of the media; pH 4–7 where zwitterionic form dominates whereas > pH 7 is cationic (Premarathna et al., 2019a). According to Fig. 4a, TC adsorption gradually increased with an increase in pH; the highest adsorption was exhibited at the pH range of 6–8. In that pH range, zwitterionic and positive charged species of TC dominates the solution; hence, adsorbed into biochar functional groups and negatively charged clay through electrostatic interactions. BC-RE composite demonstrated the lowest adsorption, even slightly less than that of the pristine MSW-BC (Fig. 4a). The highest adsorption was shown by BC-MMT, which was observed at pH 6.5–7.5, with a maximum of 11 mg/g. Then with a further increase of pH the adsorption capacity was decreased. The enhanced adsorption capacity of BC-MMT composite may be governing through high ion exchange capacity of MMT clay, which facilitates the removal of TC via intercalation interactions.

Isotherm experimental data exhibited the least adsorption capacity for MSW-BC and the highest for BC-MMT (Fig. 4b); the trends obtained for both the adsorbent, are in unanimous with the study obtained for the remediation of another quinolinone-type antibiotic-ciprofloxacin (Ashiq et al., 2019). The data were modelled with Langmuir and Freundlich isotherms, where the best fit was observed for Langmuir for the 3 different adsorbents, with maximum adsorption capacities of 13.7, 17.5, 25.98 mg/g for MSW-BC, BC-RE and BC-MMT respectively (Table 3). Data modelling indicated fitting for Langmuir, Freundlich and Hill isotherms are relatively close in R^2 describing the involvement of both chemisorption and physisorption mechanisms. At low concentrations of

Table 2

Effect of background salt solutions on the IEP of biochar samples.

Sample	IEP								
	Without salt	CH ₃ COONa	Na ₂ SO ₄	NaCl	NaNO ₃	NaBr	KCl	MgCl ₂	CaCl ₂
MSW-BC	2.8	5	2.6	4	2.9	2.8	4	No IEP	No IEP
MSW-MMT	2.4	5.2	2.3	4.2	2.6	2.4	4.5	5.6	6.4
MSW-RE	2.8	5.6	2.8	3.7	3	2.8	4.7	6.3	6.7

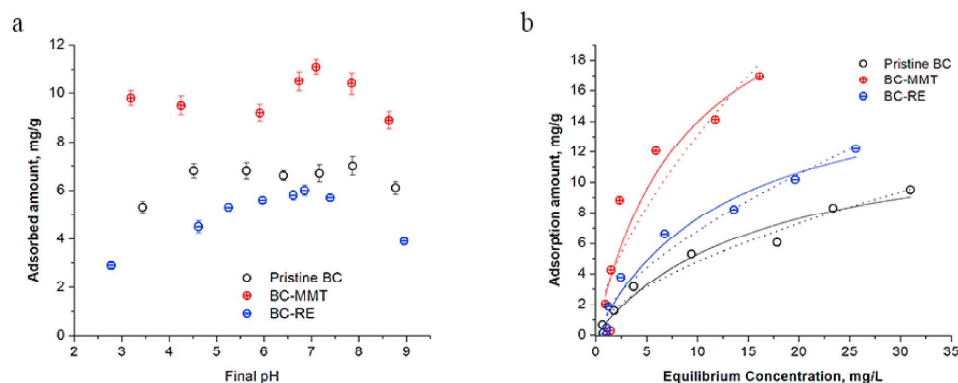


Fig. 4. MSW-BC, BC-MMT and BC-RE interactions with the solution pH (a) and isotherm experimental data and modelling using Langmuir and Freundlich equations. Symbols represent experimental data and lines represent model predictions. The solid line is for Langmuir, whereas the dotted line represents Freundlich predictions.

Table 3

Isotherm modelling data obtained through experimental data modelling of solid solution interaction of TC with MSW-BC, BC-MMT and BC-RE.

Adsorbent	Isotherm model and parameters							
	Langmuir				Freundlich			
	k	Q _{max}	R ²	Chi ²	K	n	R ²	Chi ²
MSW-BC	(L/mg)	(mg/g)			(mg/g)/(mg/L) ^{1/n}			
	0.06	13.66	0.973	0.377	1.18	0.609	0.975	0.36
BC-MMT	0.11	25.98	0.888	5.62	2.98	0.643	0.855	7.34
BC-RE	0.07	17.56	0.967	0.808	1.59	0.630	0.954	1.12

TC, monolayer interactions may be governing the mechanism of sorption. With more TC concentration, the solid-solution interface may become weak and follow through van der Waals, $\pi - \pi$, or hydrogen bonding physisorption interactions.

3.5. Molecular dynamics results

Both B7 and B17 biochar molecules have hydrophobic (benzene rings) and hydrophilic groups (functional groups) Fig. 1. Thus, the surfaces of biochar molecules can interact with each other via the π - π stacking interaction of aromatic rings, which is shown in Fig. 5 for B7 biochar molecules. Therefore, more solute-solvent interactions relate to functional groups of biochar. The radial distribution function (RDF) confirms that hydroxyls and carboxyl groups of biochar are more responsible for solute-solvent interactions. Hydroxyl and carboxyl groups are protonated in low pH values (acidic solutions); therefore, the zeta potential increases as it is observed in experimental measurements (Peiris et al., 2017). In basic solutions, these functional groups can act as a hydrogen bond donor or acceptor. Hydrogen bond interactions of functional groups and water are shown in Figs. 5 and 6. They confirmed that for B7, water molecules have a higher probability of being found around the aldehyde group. Fig. 6 shows a higher accumulation of water around carboxylate groups of B17 as it can have strong hydrogen bonds

with water molecules. Same trend has been observed for interaction of cations with functional groups for: cations-carboxylate > cations-alcohols > cations-methoxy Fig. 7.

There are noticeable differences between the interactions of different cations with carboxylate groups, whereby increasing the charge of cations ($\text{Na}^+ \rightarrow \text{Ca}^{2+}$), the probability of finding the cations close to the carboxylate groups is increased as seen in RDF plots (Figs. 5–7). This finding is in good agreement with experimental work where the zeta potentials in the solutions containing Ca^{2+} are more positive compare to Na^+ solutions because of the charge of Ca^{2+} cations. In the case of B7, we can observe that cations prefer to be around hydroxyl and aldehyde oxygen atoms and there is a lower probability of anions (compare to cations) to be found around functional groups and most of them are surrounding the hydroxyl groups Figs. 5–7. In addition, anions can form hydrogen bonds with the water molecules; therefore, they are found less around the microsphere solvation shell of biochar molecules.

Hence, anions are strongly hydrated with water molecules rather than biochar molecules; therefore, there are no remarkable differences between anions with the same cation in zeta potentials (NaCl, NaNO_3 , NaBr, NaCH_3COO). Hydrogen bond formation of anions with functional groups of biochar can increase the absorption of nutrients such as phosphate on the surface of biochar (Maroušek et al., 2020). Hydrogen bond calculations between water and functional groups are in good

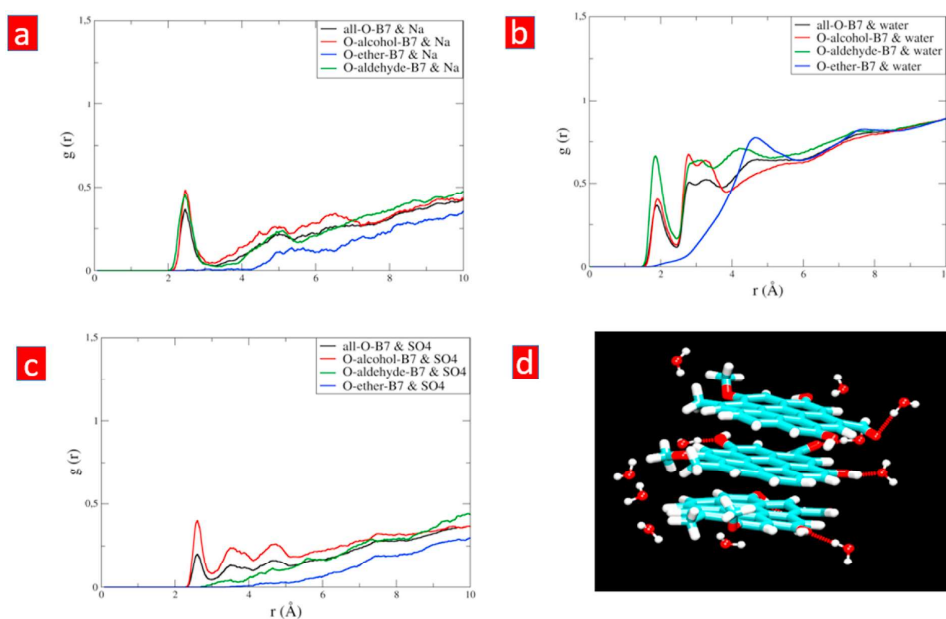


Fig. 5. Radial distribution functions of Na^+ ions around the functional groups of B7 (a), water (b), SO_4^{2-} ions (c) and hydrogen bond interaction with water molecules (d) in the aqueous solutions of Na_2SO_4 .

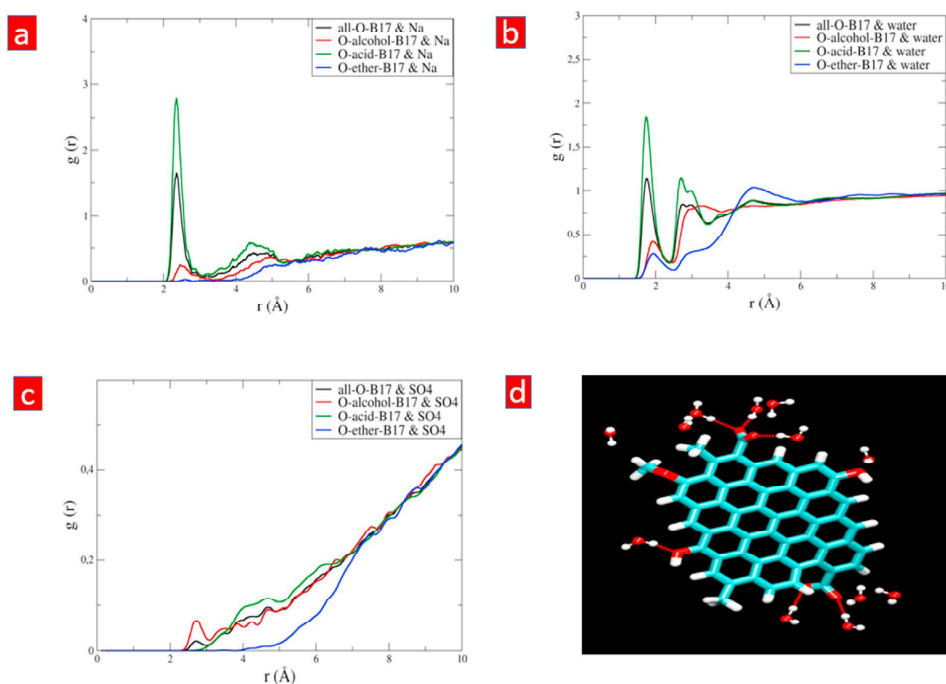


Fig. 6. RDFs of Na^+ ions around the functional groups of B17 (a), water (b), SO_4^{2-} ions (c) and hydrogen bond interactions with water molecules (d) in the aqueous solutions of Na_2SO_4 .

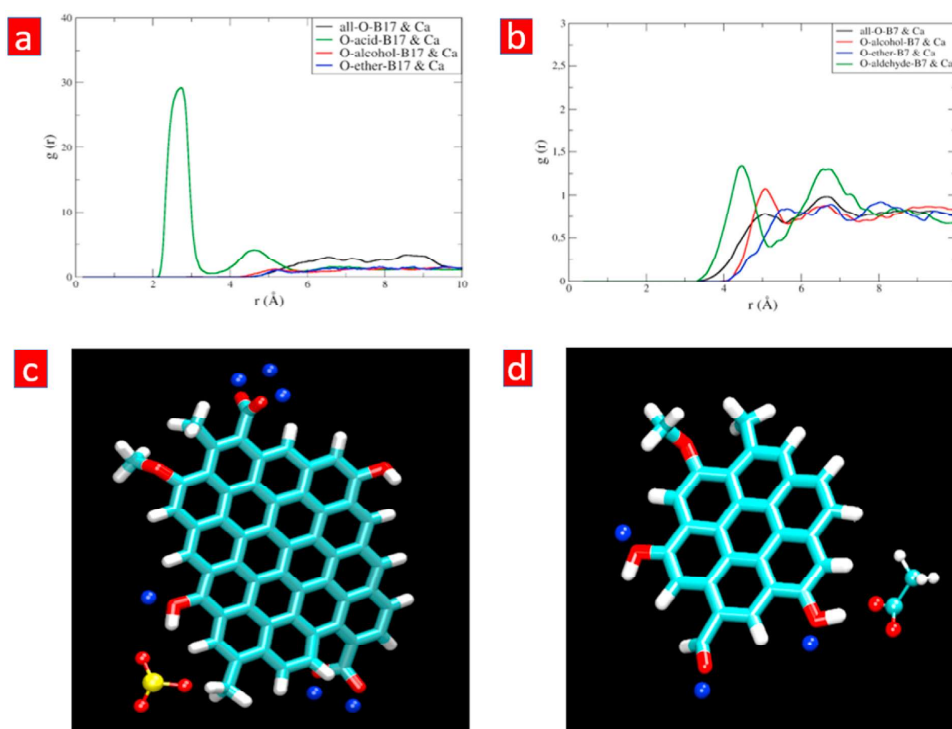


Fig. 7. RDFs of Ca^{2+} ions around the functional groups of B17 (a), and B7 (b) in the aqueous solutions of CaCl_2 . Snapshot from MD simulations of B17 in NaSO_4 solution, showing Na^+ and SO_4^{2-} ions around functional groups of B17 (c), and B7 in NaCH_3COO solution, showing Na^+ and CH_3COO^- ions around functional groups of B7 (d).

agreement with RDFs results, where the lowest number of a hydrogen bond between functional groups belongs to the oxygen of methoxy and the highest to carboxylate groups. RDFs in Figs. 5 and 6 confirmed that the presence of anions in the microsphere solvation of biochar is not noticeable compare to cations. Provided information from molecular dynamics simulations it can be concluded that the main interactions involved in the adsorption process can be divided to weak non-covalent interactions such as van der Waals forces, π - π stacking, hydrogen bonding interactions and strong electrostatic interactions play essential roles in this study. These findings are in good agreement with low pzc values of biochar that showed they have negative potential charges and cations can adsorb to the functional groups of biochar molecules.

3.6. Tetracycline sorption on biochar in aqueous salt solutions

Biochar derived from MSW consist of high-aromatic content that provides for the electron-rich surface for the TC to bind with the BC surface. Most prominent mechanism postulated for electron-rich surface is through π -cationic bonds between the MSW biochar and the cationic portion of TC at a lower pH, enhancing the adsorption further. Functional group on OTC containing oxygen has a strong tendency to get protonated at acidic environment and thereby, electrostatic attractions co-exists between the protonated moiety of TC and highly aromatic surface on MSW biochar, cumulatively contributing to the adsorption (Ashiq et al., 2019; Peng et al., 2016).

Biochar has been applied in water and wastewater treatment as an eco-friendly adsorbent for the removal of pesticides, dyes, and antibiotics (Ashiq et al., 2019; Ramanayaka et al., 2020). Different functional

groups at the surface and pore of the biochar are essential factors for the adsorption process. Besides, preparation conditions of biochar are the most important factors to alter surface properties of biochar, therefore their applications. Different aspects of tetracycline adsorption on biochar, such as porosity, pH conditions, temperature, and surface area, have been discussed extensively (Fan et al., 2018; Jang and Kan, 2019; Premaratna et al., 2019a). In this context, surface and functional groups of biochar are more responsible for factors of adsorption. It is revealed that there are interactions between functional groups of biochar and tetracycline, where interactions between amide and hydroxy groups of tetracycline with hydroxyl and carboxylate groups of biochar are the most critical interactions. The hydrophobic character of biochar also has a significant effect on tetracycline sorption and plays an important role. It found that B17 molecule which has higher surface area per molecule than B7, therefore can present more space for hydrophobic interactions for adsorption of tetracycline molecule which is shown in Fig. 8 where the surfaces are making π - π stacking interactions. Besides, biochar functional groups of biochar molecules interact with tetracycline functional groups where the interactions with amide and hydroxyl groups the most important interaction, which reveals the changes of adsorption by pH.

4. Conclusions

This present work demonstrates the adsorptive behaviour of biochar samples synthesized from municipal solid waste and its clay-treated composites towards tetracycline in the presence of different electrolytes. Enhanced adsorption comes from the combined effect of both

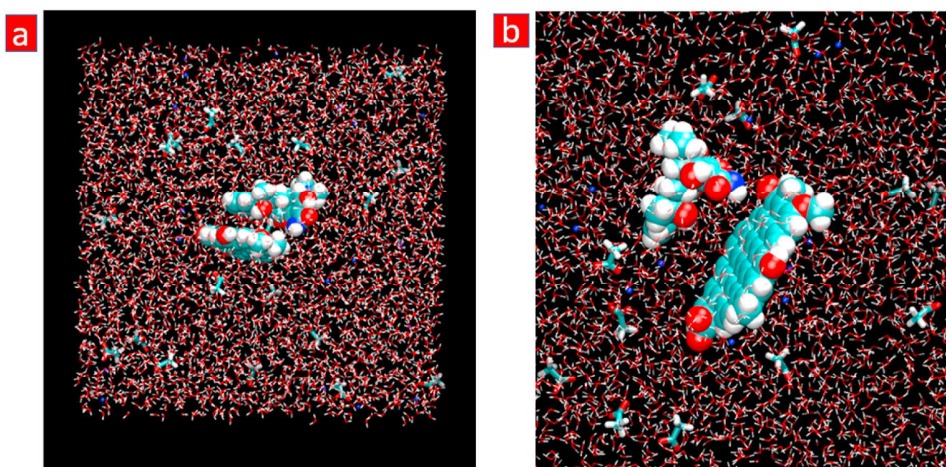


Fig. 8. Snapshot from tetracycline adsorption by B7 (a), and B17 (b) in NaCH_3COO solution.

biochar and the natural materials with the influence of solution pH and the existence of zwitterionic nature of TC in aqueous media. The major interactions are electrostatic interactions in the TC-adsorbent interfaces. The variation of morphological structure, surface area and surface potential of different clay treated biochar samples has been investigated and it is noticed that the surface properties of the biochar samples are considerably affected by the incorporation of different clay materials, solution pH, as well as by the background electrolytes. The surface potential (zeta potential) of different biochar samples are mainly affected by the size and charge of the cations and counter anions of the background electrolytes. Radial distribution functions (RDFs) confirmed that hydroxyls and carboxylate groups of biochar are the most responsible factors for solute-solvent interactions. MD simulation states that during tetracycline adsorption on hydrophobic biochar samples, interactions between amide and hydroxyl groups of tetracycline with hydroxyl and carboxylate groups of biochar plays the key role. Highest adsorption has been found on BC-MMT, which was observed at pH 6.5–7.5 with a maximum value of 26 mg/g. Thus, solution pH has a notable influence on the interactions of biochar functional groups and different background ions as well as interactions with tetracycline functional groups. The π - π stacking interaction between the aromatic rings of biochar molecules and tetracycline also plays a key role in the adsorption process.

From the above experimental findings, it can be concluded that the surface property of the adsorbents is driven by the presence of different specific ions, which is an essential factor in the adsorptive removal process. This work imparts a new path for the futuristic study of adsorptive removal of organic pollutant molecules utilizing biochar based composite materials, which is influenced by the surface property of the biochar adsorbent.

Author contribution

Priyakshree Borthakur, Formal analysis, Formal analysis, Writing – original draft. Meysam Aryafard, Formal analysis, Formal analysis, Writing – original draft. Zeenat Zara, Formal analysis, Formal analysis, Writing – original draft. Reha David, Writing-reviewing and editing. Babak Minofar, Conceptualization, Funding acquisition, Writing-reviewing and editing. Manash R. Das, Conceptualization, Funding acquisition, Writing-reviewing and editing. Meththika Vithanage, Conceptualization, Funding acquisition, Writing-reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Meysam Aryafard gratefully acknowledges the support from the Czech Science Foundation grant (ERDF CZ.02.1.01/0.0/0.0/15_003/0000441 and GAJU 017/2019/P) and access to computational resources provided by the CESNET. Authors acknowledge access to computational resources provided by the CESNETLM2015042, the CERIT Scientific Cloud LM2015085, under the program “Projects of Large Research, Development, and Innovations Infrastructures.” The authors would like to thank Director, CSIR–NEIST, Jorhat, for his kind interest in carrying out this work. The authors also acknowledge the financial support from the DST, New Delhi (CSIR-NEIST Project No. GAP-0737) and research grant ASP/01/RE/SCI/2017/83, Research Council, University of Sri Jayewardenepura.

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5.5 Article 5

Journal of Molecular Liquids 344 (2021) 117877



Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq



Novel room temperature ionic liquids and low melting mixtures based on imidazolium: Cheap ionic solvents for chemical and biological applications



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Participation of Meysam Aryafard:

MA had the idea of novel ionic solvents, synthesized the new ionic liquids and deep eutectic solvents based on imidazolium, and wrote the paper.

Aryafard, M.; Minofar, B.; Cséfalvay, E.; Malinova, L.; Řeha, D. Novel Room Temperature Ionic Liquids and Low Melting Mixtures Based on Imidazolium: Cheap Ionic Solvents for Chemical and Biological Applications. *J. Mol. Liq.* **2021**, *344*, 117877.

<https://doi.org/10.1016/j.molliq.2021.117877>



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ARTICLE INFO

Article history:

Received 11 August 2021

Revised 7 October 2021

Accepted 16 October 2021

Available online 27 October 2021

Keywords:

Protic ionic liquids

Designer solvents

New ionic solvents based on imidazolium

Green solvents

Non-aqueous solvents for carbohydrates

deep eutectic solvents

low melting mixtures

ABSTRACT

Novel protic ionic liquids (PILs) and low melting mixtures (LMMs) have been synthesized based on green components, cheap sources, the high purity, and easy way of preparation. PILs include [Im][For], [Im][Ace], [Im][Pro], [Im][But], and [Im][Pen]. LMMs include [ImCl][EG], [ImCl][Gly], [ImCl][PEG], [ImCl][ETA], and [ImCl][carbohydrate] + DMSO. These solvents contain imidazolium/imidazolium chloride as a cation/salt. NMR spectroscopy was used to analyze the structures of solvents. Melting points, and thermal stabilities were measured via thermal analyses. We were looking to synthesize new DESs with imidazolium chloride (ImCl); Due to lack of observation the melting points for mixtures of ImCl + hydrogen bond donors (HBDs), these mixtures were called low melting mixtures (LMMs) in this work. The mixtures of PILs/LMMs with molecular solvents showed good implications for homogenous and heterogenous systems which can be used for separation goals. Solubilities of carbohydrates, and some amino acids were tested in pure and mixed of ILs with molecular liquids. Adding DMSO to ILs/LMMs increased the dissolution of carbohydrates. As well, adding water to ILs had a remarkable effect for increasing the solubility of amino acids.

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1. Introduction

Ionic liquids (ILs) and deep eutectic solvents (DESs) have been emerged in the most of scientific and industrial applications as potential green solvents due to their unique properties [1–6]. Characteristics including ionic conductivity, low vapor pressure, no flammability, wide range of temperature usage, and solubility of organic/inorganic compounds. These properties caused ILs and DESs to be used as green solvents, electrolyte, industrial solvents, for biomass, CO₂ absorption, fuels, solar energy storage, pharmaceutical, and biochemistry [7–14]. Advantages of these usages can be found in the structures of these solvents that make them more favorable compared to organic solvents [5–8]. ILs consist of ions; recent famous DESs consist of an ionic component (e.g., quaternary ammonium salt, choline chloride) + a hydrogen bond donor (HBD) component [1–3]. Therefore, the presence of ions in ILs and DESs causes close properties for them and makes these solvents to

have different inter and intra interactions that result in their superiority in contrast to organic solvents.

Until now, amongst ILs, imidazolium ILs have been more attracted than the other ILs based on ammonium, phosphonium, sulfonium, and pyridinium cations. Despite imidazolium ILs are very practicable in most of applications, the cost of preparation of these ILs limits them in some enforceable areas. The reasons come out of the price of materials and procedures to synthesize ILs with high purity. Deprotonation of imidazole, materials (for instance alkyl halides, silver oxide, etc.) and separations steps lead to increase the costs and impurities of ILs. Hence, the cheap pure ILs need to pass a few steps to be synthesized. Moreover, the simple method makes new solvents to be more accessible. E.g., DESs based on the choline chloride salt reported by Abbott et. al [5,6] have been remarkable interested between DESs because of the simple method to prepare, and the inexpensive low toxic material [1–4].

The economic synthesis, favorite imidazolium structure, green sources, purity, and easy way of preparation were our guidelines to achieve novel solvents. Accordingly, our goal was to offer a new class of solvents that benefit of the mentioned advantages.

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<https://doi.org/10.1016/j.molliq.2021.117877>
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Further, miscibility of ionic solvents with organic solvents for separation, and physicochemical applications were investigated [15,16]. Also, dissolution of carbohydrates in ionic solvents were measured.

2. Experimental

2.1. Materials and methods

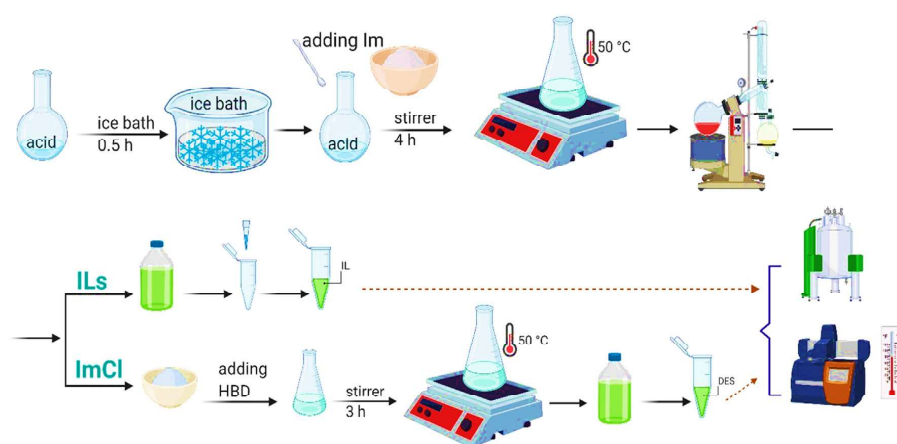
Primary materials were purchased in high qualities and were used without further purification (Table 1). ILs and low melting mixtures (LMMs) were synthesized as it is shown in Scheme 1. The procedure was done by adding each carboxylic acid (formic/acetic/propionic/butanoic/pentanoic acid) in a round-bottom flask, then the flask was placed in an ice bath for 0.5 h. An equimolar of imidazole (solid) was added to each acid and the reaction was stirred for 4 h under slowly increasing the temperature (up to 50 °C) to reach the target ILs (see Supporting Information). Imidazolium chloride (ImCl) was prepared in the same way but an excess equimolar of hydrochloric acid (the molar ratio of HCl to

imidazole was 1.1:1) was used in the first step (Scheme 1). After stirring, the excess of HCl and water were evaporated with a rotary evaporator. At the end, the residue, ImCl, was placed in a vacuum oven (pressure -6 kPa) for 5 h at 80 °C and the amount of water by Karl Fischer titration (0.54%) was measured (See Supporting Information, Fig. S2). Hydrogen bond donors including ethylene glycol, glycerol, polyethylene glycol 400, ethanolamine, urea, imidazole, and maleic acid were added to ImCl and homogeneous liquids were formed to reach the target LMMs (Table 2). The same protocol was used to reach low melting mixtures for liquid and solid HBDs; the only difference in the method was the temperature of stirring after mixing ImCl with HBD. In case of liquid HBDs, the temperature was 50 °C but for solid HBDs the temperature reached up to 140 °C. NMR spectrometer 700 MHz Bruker was used to analyze the structures of samples at 25 °C.

Thermal analyses of samples (melting temperature (T_m), glass transition temperature (T_g) and decomposition temperature, the temperature at which the substance decomposes chemically (T_d)) were measured by DSC250 Auto (TA Instruments, USA) in the range of -90 °C till 100 °C under the nitrogen atmosphere

Table 1
Information of materials used in this work.

Material	Abbreviation	CAS reg. no.	supplier	Mass fraction	Molar mass/g mol ⁻¹
Imidazole	–	288-32-4	Merck	0.99	68.08
Formic acid	–	64-18-6	Merck	0.98	46.02
Acetic acid	–	64-19-7	Penta	0.99	60.05
Propionic acid	–	79-09-4	Sigma-Aldrich	0.99	74.08
Butanoic acid	–	107-92-6	Merck	0.99	88.11
Pentanoic acid	–	109-52-4	Merck	0.98	102.13
Hydrochloric acid	HCl	7647-01-0	Penta	0.35	36.46
Ethylene glycol	EG	107-21-1	Sigma-Aldrich	0.99	62.07
Glycerol	Gly	56-81-5	Merck	0.99	92.09
Ethanolamine	ETA	141-43-5	Sigma-Aldrich	0.99	61.08
Polyethylene Glycol 400	PEG 400	25322-68-3	Fluka	0.99	380–420
Urea	–	57-13-6	Sigma-Aldrich	0.99	60.06
Dimethyl sulfoxide	DMSO	67-68-5	Merck	0.99	78.13
Acetonitrile	–	75-05-8	Sigma-Aldrich	0.99	41.05
Propylamine	–	107-10-8	Fluka	0.99	59.11
n-Hexane	n-H	110-54-3	Sigma-Aldrich	0.97	86.18
Cyclohexane	C-H	110-82-7	Sigma-Aldrich	0.99	84.16
Tetrahydrofuran	THF	109-99-9	Merck	0.98	72.11
D (+) - Glucose	–	50-99-7	Merck	0.99	180.16
Maltose	–	6363-53-7	Merck	0.95	360.31
Cellobiose	–	528-50-7	Merck	0.99	342.30
Sucrose	–	57-50-1	Penta	0.99	342.30



Scheme 1. Procedures for the synthesis of ILs and LMMs.

Table 2
Synthesized ILs and LMMs in this work with thermal properties: melting temperature (T_m), glass transition temperature (T_g) and decomposition temperature (T_d).

ILs	Cation	Anion	Molar ratio	T_g (°C)	T_m (°C)	T_d (°C)
[Im][For]	Imidazolium	Formate	1: 1	– 80.3	14.7	192.0
[Im][Ace]	Imidazolium	Acetate	1: 1	– 69.8	5.0	179.0
[Im][Pro]	Imidazolium	Propionate	1: 1	– 41.8	33.8	175.7
[Im][But]	Imidazolium	Butanoate	1: 1	– 75.2	16.4	173.6
[Im][Pen]	Imidazolium	Pentanoate	1: 1	– 78.2	NO	170.6
[ImCl]					137.3	291.6
LMMs	HBA	HBD	Molar ratio	T_g (°C)	T_m (°C)	T_d (°C)
[ImCl][EG]	ImCl	Ethylene glycol	1: 1.5	NO	NO	258.0
[ImCl][Gly]	ImCl	Glycerol	1: 1	NO	NO	277.7
[ImCl][PEG]	ImCl	PEG 400	1: 1	NO	– 25.8	334.8
[ImCl][Urea]	ImCl	Urea	1: 1	– 53.0	60.6	253.8
[ImCl][ETA]	ImCl	Ethanolamine	1: 1	– 71.1	NO	283.1

NO: the melting temperature or glass transition temperature was not observed (DSC were measured in the range of –90 °C till 100 °C).

(nitrogen flow 50 mL/min), and TGA550 Auto Advanced (TA Instruments, USA) in the range of room temperature till 400 °C under the nitrogen atmosphere (nitrogen flow 60 mL/min). Thermal analyses were measured by using 7–10 mg of each sample with a heating rate of 10 °C min^{–1}. Decomposition temperature was determined as the peak top of the derivative value [15,17].

2.2. Solubility of ILs/LMMs + molecular solvents

Solubility was tested by mixing 2.0 g of IL/LMM with 2.0 mL of each molecular solvent (acetonitrile, acetone, THF, ethyl acetate, ethanol, water, n-hexane, and cyclohexane). Then, three times the mixtures were shaken for 60 s every 4 min at 25 °C [15].

2.3. Solubility of carbohydrates and amino acids in ILs/LMMs

Solubility of carbohydrates (glucose, sucrose, cellobiose, and maltose) and some amino acids (Glycine, L-Alanine, L-Valine, and L-Tryptophan) were tested in ILs and LMMs. As a brief, 20.0 g of ILs/LMMs was put in a flat bottom flask or beaker. It followed by adding carbohydrates/amino acids in the range of 0.1–1.0 g. The solutions were stirred at 25 °C for 0.5 h. Adding water and temperature up to 70 °C for increasing the solubility were noticed.

3. Results and discussion

3.1. NMR results of PILs and LMMs

PILs were synthesized through the neutralization reaction of a carboxylic acid and imidazole as a base (Scheme 1) [18]. The reactions were done under the solvent-free condition. Therefore, they did not have any impurity of solvent and other materials in synthesized ILs which is a good point for every IL. Nuclear magnetic resonance (NMR) spectroscopy was used to analyze the structures of ILs and LMMs; NMR results confirmed that ILs and LMMs did not have any unwanted reaction. (Figs. 1, and 2. See Supporting Information, Figs. S5–S15). Due to very fast proton exchange of imidazole ($>10^9$ s^{–1}) and its possibility to make a cluster system via hydrogen bond interactions, ¹H NMR cannot be useful to distinguish between the structures (imidazole versus imidazolium) at ambient temperature [19,20]. ¹³C NMR spectroscopy was used by Al-badr to analyze the chemical shifts of imidazole, and its derivatives in pharmacy. He reported some measured and calculated ¹³C NMR chemical shifts of imidazole and found the high ability of ¹³C NMR to identify the structures of imidazole derivatives [21].

Therefore, ¹³C NMR was used to identify our ILs based on imidazolium. Presence of two peaks in ¹³C NMR spectra at δ (ppm) – 118.90, 133.31 proved the protonated ring (imidazolium) in the

structures of ILs and LMMs. Also, no evidence of impurity peaks for unreacted carboxylic acids confirmed the high purity of synthesized ILs. Chemical shifts of imidazolium in the structure of ImCl (118.89, 133.32), [Im][For] (118.83, 133.26), [Im][Ace] (118.91, 133.31), [Im][Pro] (118.98, 133.37), [Im][But] (118.99, 133.35), [Im][Pen] (119.03, 133.41) are similar. This is a strong reason for protonation of imidazole in ILs (Figs. 1 and 2. See Supporting Information, Figs. S5–S15). These chemical shifts of imidazolium are different with imidazole (121.60, 135.63). Our measured chemical shifts are in a good accordance with analyses by Al-badr for imidazole (121.96, 135.34) [21].

3.2. Thermal analyses of ILs, ImCl, and LMMs

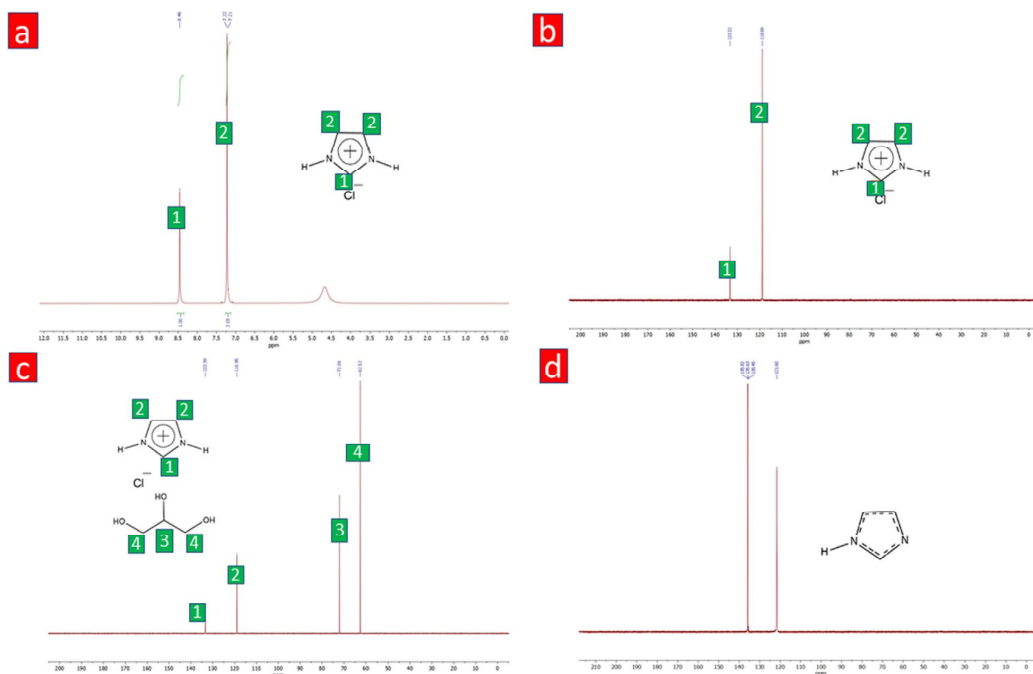
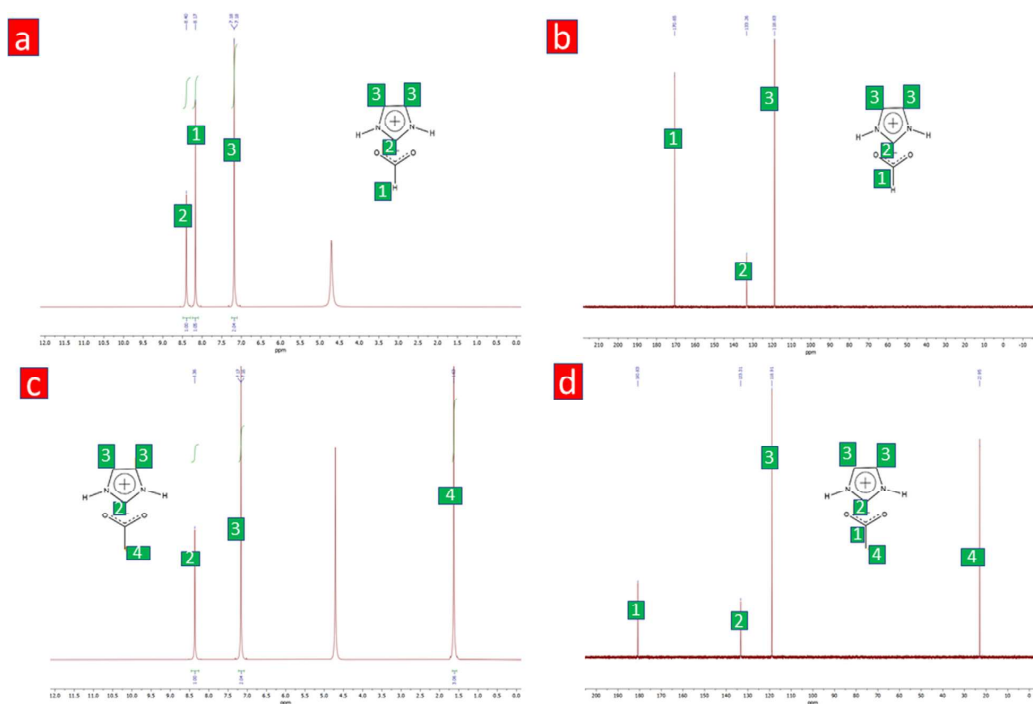
3.2.1. Thermal analyses of ILs

Table 2 presents thermal analyses of solvents. ILs in this work have glass transition temperature around –70 °C, melting point approximately 15 °C and decomposition temperature nearly 175 °C. There was not any meaningful relation between the length of alkyl chain of carboxylate and glass/melting points. The probable reason can be the same cation in all structures and same functional group (carboxylate) in all anions.

It was found out the imidazolium cations have a major effect on melting points of ILs. An increase in the asymmetric structure or the alkyl chain of imidazolium result in change the melting points of ILs [22–25]. In other words, to design a room temperature IL based on imidazolium, alkyl groups are very important. ILs in this study have the symmetric imidazolium cation (Table 2). So far, it has not been reported any room temperature IL based on imidazolium without any alkyl chain. Most of imidazolium ILs have been reported contain alkyl chains on the imidazolium cation [24,25]. ILs in this study have the alkyl chains on anions structures. Besides, utmost of ILs based on imidazolium are aprotic ionic liquids. Although there are several protic ionic liquids (PILs) which have been synthesized based on the other cations (e.g., ammonium) [22–25], we have not seen any room temperature PIL based on imidazolium. From this perspective, this work is the first report of PILs based on imidazolium with two proton donor groups.

3.2.2. Thermal analyses of ImCl and LMMs

Melting point of ImCl was measured 137.3 °C (Table 2) which confirmed that ImCl is a solid salt, and it is not an IL (a salt in the liquid state with melting point lower than 100 °C) like most of alkyl imidazolium halides [24,25]. Melting points of ImCl and PILs in this study (Table 2) display how change the anion of salts can decrease the melting point and turn a salt to a room temperature IL. Melting points of ImCl + HBDs are discussed in 2 parts: ImCl + liquid/solid HBDs.



Mixtures of ImCl + liquid HBDs:

Ethylene glycol, glycerol, polyethylene glycol 400, and ethanolamine were used as a liquid HBD. We were looking to find a eutectic point for mixtures of these HBDs with ImCl over different mole fractions Fig. 3. In general, less than an equimolar of HBDs + ImCl resulted in a liquid + solid phase. More than equimolar of HBDs + ImCl made a homogenous liquid phase Fig. 4. Unfortunately, the melting points of liquids were not seen in the DSC spectra to overcome a eutectic point (Figs. 3, 4 and S27-S33). Hence, the mixtures of ImCl + HBDs were named low melting mixtures. Therefore, it was not possible to plot an accurate phase diagram. The probable phase diagram (Fig. 4) was drawn based on the results of all mixtures of ImCl + HBDs. Table 2 displays glass and melting points of ImCl + HBDs in equal stoichiometric ratios. DSC spectra of [ImCl][EG] and [ImCl][Gly] showed neither melting point nor glass transition point (at temperatures higher than -90°C). Probably, these LMMs have a glass transition temperature lower than -90°C and not visible melting point in negative temperatures. The mixture of ImCl + PEG 400 showed the melting point -25.8°C (Fig. 3). These LMMs were placed in the freezer at -15°C for 10 h and finally all of them were liquids. These are an evidence for non-ideal mixture behavior and a reason for low melting mixtures (-15°C). Based on these results, it seems these types of LMMs can be used in negative temperatures.

Mixtures of ImCl + solid HBDs (urea, maleic acid, and imidazole as HBD) were not liquid at ambient temperature (e.g., the melting point of mixture ImCl + urea with the mole fraction 1:1 was 60.6°C , Fig. 3.). Adding the third component to decrease the melting point of mixtures was examined. We found that by adding an equimolar of DMSO to the mixtures of ImCl + urea/maleic acid/imidazole, the melting points reduced remarkably, and all mixtures became homogenous liquids. Unfortunately, the melting points of these ternary mixtures were not observed in DSC spectra Fig. 3. E.g., the melting point of [ImCl][Urea/Imidazole] + DMSO with the molar ratio 1: 1: 0.5 were not observed (glass transition temperatures were -68.9°C and -73.4°C respectively). These LMMs ([ImCl][Urea/Imidazole/Maleic acid] + DMSO) were put in the free-

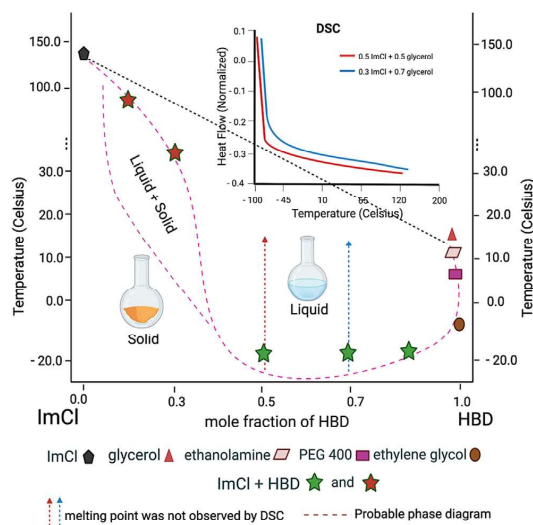


Fig. 4. The probable phase diagram for the low melting mixtures of ImCl + HBDs. All HBDs showed a same trend for measuring the melting points in mixtures with ImCl. Rich HBDs mixtures, mole fractions ≥ 0.5 , were liquids till -15°C (Green stars are the data earned by placing the mixtures in the freezer at -15°C for 10 h).

zer at -15°C for 10 h and no phase change was seen (they were liquids). Therefore, these LMMs can be applied as a solvent made of ternary compounds with the melting point -15°C .

3.3. Solubility of ILs/LMMs + molecular solvents

The solubility of ILs/LMMs with molecular solvents is shown in Fig. 5. All ILs and LMMs exhibited high solubility with water which can be due to polarity and hydrogen bond interactions [26,27],

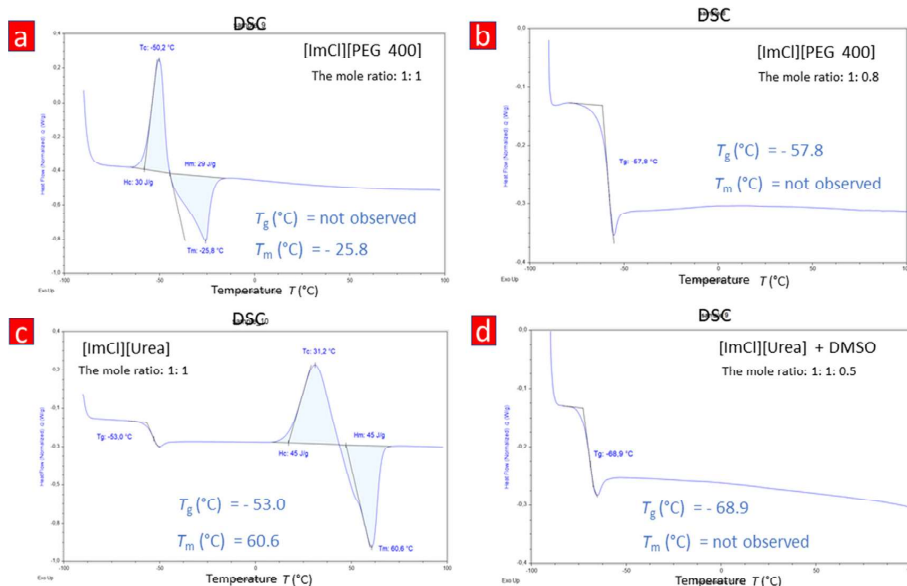


Fig. 3. The DSC spectra of LMMs.

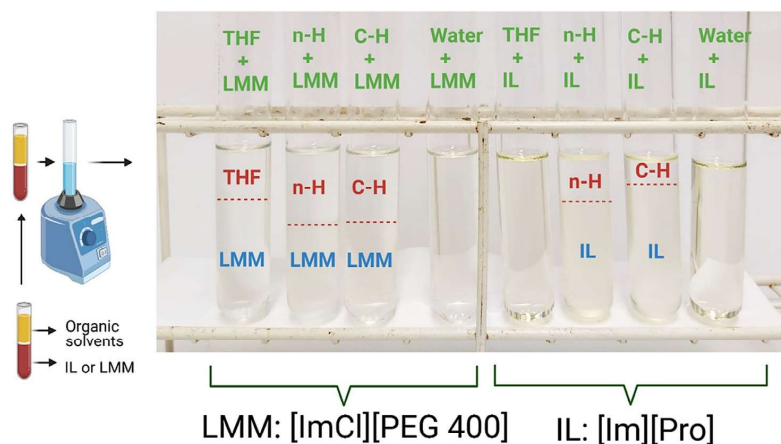


Fig. 5. Miscibility of the LMM/IL with tetrahydrofuran (THF), n-hexane (n-H), cyclohexane (C-H), and water in equal volume mixtures.

ethanol had good miscibility as well. Aprotic and polar solvents including acetonitrile, acetone, and ethyl acetate were soluble but not like water (for water it was miscible immediately after adding without shaking). It can be because of less hydrogen interactions and polarity than water.

Neither ILs nor LMMs were soluble in hydrophobic solvents (n-hexane and cyclohexane) and biphasic layers were seen (Fig. 5). Polarity seems to play the key role for them [26,27]. ILs and LMMs showed different solubility with THF. For instance, [Im][Pro] as an IL was soluble with THF but [ImCl][PEG 400] was not soluble (Fig. 5). It seems the different structures of anions (propionate and chloride) and PEG 400 have more effects than imidazolium cation for solubility with THF.

More than ILs and LMMs, solubility of ImCl was examined in molecular solvents. Except DMSO/DMF, ImCl did not have good solubility in molecular solvents (methanol, ethanol, acetone, acetonitrile, etc.). Carboxylic acids were examined for the solubility of ImCl. It was found out that acidic mixtures of ImCl + carboxylic acids (CA) depend to the alkyl group of CA. Homogenous liquids were achieved at the molar ratio 1:1.2, 1:1.6, 1:1.8 for the mixtures of ImCl with formic acid, acetic acid, and propionic acid, respectively. By increasing the alkyl chain, the more amount of acid is needed. These acidic mixtures can be used in some applications [1,7,8].

Solubility of carbohydrates (glucose, sucrose, cellobiose, and maltose) and possibility to have carbohydrates DESs were examined in a same protocol as ImCl + solid HBDs. Their structures were confirmed by NMR results (Supporting Information, Figs. S16–S20). As a brief, 0.1 mol of imidazolium chloride was placed in a round-bottom flask. Then it followed by adding 0.03 mol of each carbohydrate to ImCl under heating in an oil bath (up to 140 °C) for 3 h. Stirring these two components' mixtures were not successful to have a useable LMMs (they were like a glue). Hence, it was needed to add at least an equimolar of DMSO (adding more amount of DMSO can decrease the viscosity of solvents). Therefore, at the first step, the flask which contained ImCl + DMSO + carbohydrate was put in an oil bath (80 °C) and stirred for 3 h. Instead of DMSO in these ternary solvents, that is possible to have glycerol or water in the structures of solvents (Supporting Information, Fig. S4). These ternary solvents (ImCl + carbohydrate + DMSO/water/glycerol) can be a report of probable imidazolium LMMs with carbohydrates. Mixtures of ImCl + carbohydrate + DMSO/glycerol did not show any phase change till –5 °C by putting in the freezer.

In a good accordance to our findings, some DESs based on choline chloride + carbohydrates + water was reported by Marrucho et al. [28]. They found that without adding water these solvents are not applicable to be used.

Carbohydrates had good solubility in ILs. Glucose had more solubility than the others because it a monosaccharide with a lower molar mass Table 1. Adding the temperature can improve the dissolution of carbohydrates. Increasing the amount of carbohydrates give rise to the higher viscosity of solutions. These solvents can be used for biological applications when it is needed to have non aqueous solvents with presence of carbohydrates. Solubility of some amino acids in [Im][Ace] as an IL was tested. Unfortunately, they were slightly soluble in pure [Im][Ace] (lower than 0.1 g in 20.0 g IL). Increasing the temperature did not disintegrate them. Adding water as a co-solvent to [Im][Ace] enhanced the solubility and made it possible to have more dissolution for amino acids.

In addition to solvent effects of ILs/LMMs, and possibility to be used as a pure or mixed solvents, it has been found out that imidazolium chloride can act as a catalyst for some chemical reactions [29]. Thus, these solvents (ILs, and LMMs) with imidazolium will have catalysis effects in some applications.

4. Conclusions

In summary, for the first time, a series of PILs and LMMs based on imidazolium without any alkyl chain were synthesized. Because of non-observation the melting points for mixtures of ImCl + HBDs, it was not possible to plot the phase diagrams and find the eutectic points. Hence, the mixtures of ImCl + HBDs were named low melting mixtures. These solvents solve the cost, purity, and difficulty of preparation ILs and DESs based on imidazolium, and they can be used in several applications. These solvents have good potential as industrial solvents. It is possible to design a homogenous/heterogenous system of IL/LMMs with water/n-hexane for separation or purification usages. Binary mixtures of PILs/LMMs with molecular solvents have significant implications to tune some physicochemical properties in future studies. The major difference in the structures of ILs and LMMs is the kind of anion in this work. If the presence of chloride anion is annoying or an anion with alkyl chain is desirable, and/or pure ionic solvents are interested, ILs will be suggested. As a hint, choosing an IL or LMM depends to

conditions of reactions. These solvents open up multi tool uses that can be investigated for future applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

CIISB, Instruct-CZ Centre of Instruct-ERIC EU consortium, funded by MEYS CR infrastructure project LM2018127, is gratefully acknowledged for the financial support of the measurements at the CF NMR. Meysam Aryafard acknowledges Otakar Humpa and Radovan Fiala for the processing of NMR. The authors thank BioRender.com for creating graphic figures.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.molliq.2021.117877>.

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CHAPTER 6

Supporting information

Novel Room Temperature Ionic Liquids and Low Melting Mixtures Based on Imidazolium: Cheap Ionic Solvents for Chemical and Biological Applications

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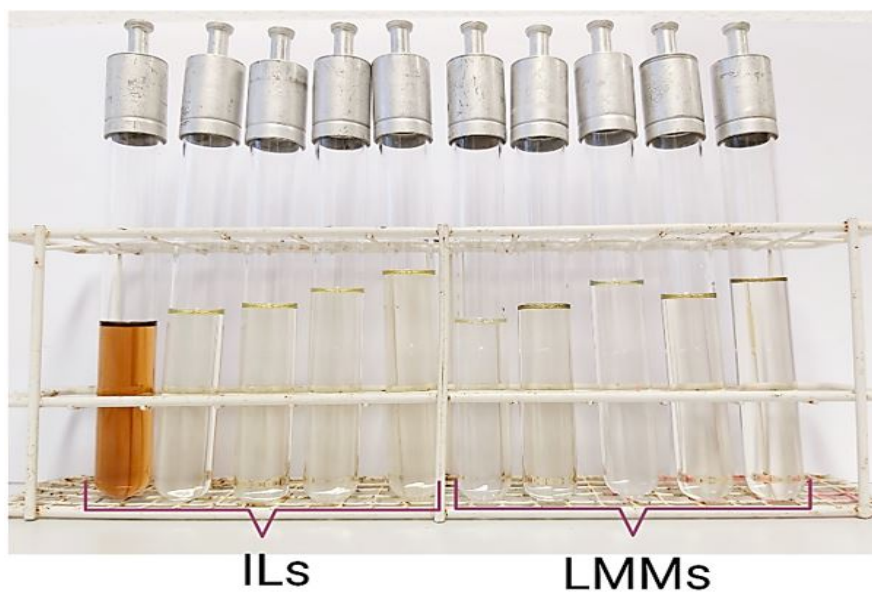


Fig. S1. Synthesized ionic liquids and low melting mixtures based on imidazolium.

ILs (left to right):

Imidazolium formate, Imidazolium acetate, Imidazolium propionate, Imidazolium butanoate, Imidazolium pentanoate.

Low melting mixtures (left to right):

Imidazolium chloride EG, Imidazolium chloride Gly, Imidazolium chloride PEG 400, Imidazolium chloride ethanolamine, Imidazolium chloride glucose DMSO.

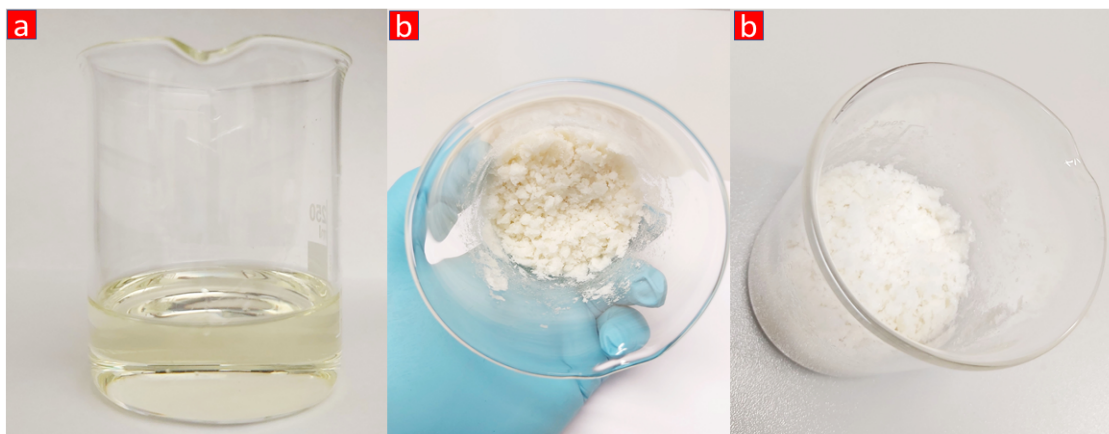


Fig. S2. Imidazole in HCl (35%) after stirring for 4 h (a), and imidazolium chloride after evaporating the water and excess of HCl (b).

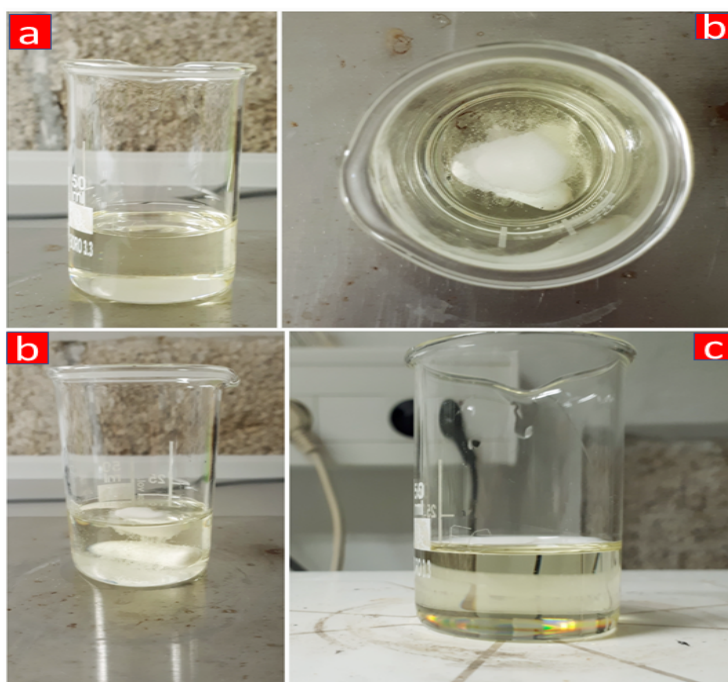


Fig. S3. 20.0 g of pure imidazolium acetate (a), adding 1.0 g of glucose in 20.0 g of imidazolium acetate before stirring (b), and after stirring for 15 min (c).

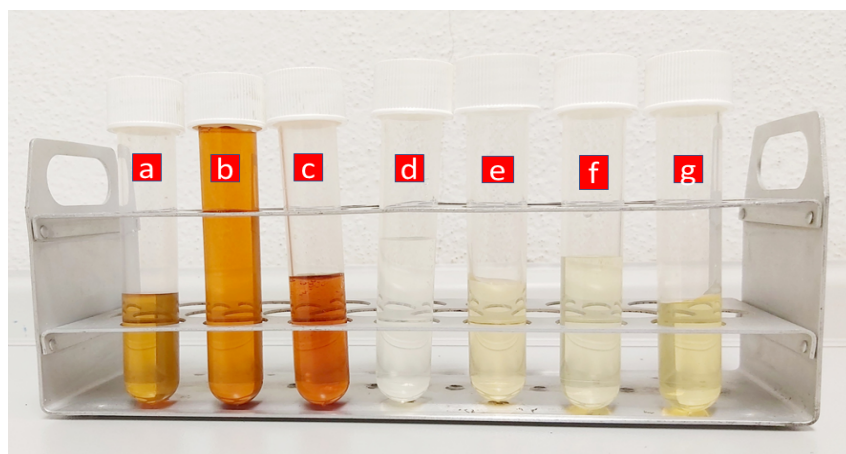


Fig. S4. Carbohydrates in low melting mixtures.

- a) ImCl + glucose (amount of water 4%)
- b) ImCl + sucrose (amount of water 7%)
- c) ImCl + maltose (amount of water 9%)
- d) ImCl + DMSO
- e) ImCl + DMSO + maltose
- f) ImCl + DMSO + sucrose
- g) ImCl + glycerol + glucose

A1, ^{13}C NMR in D_2O

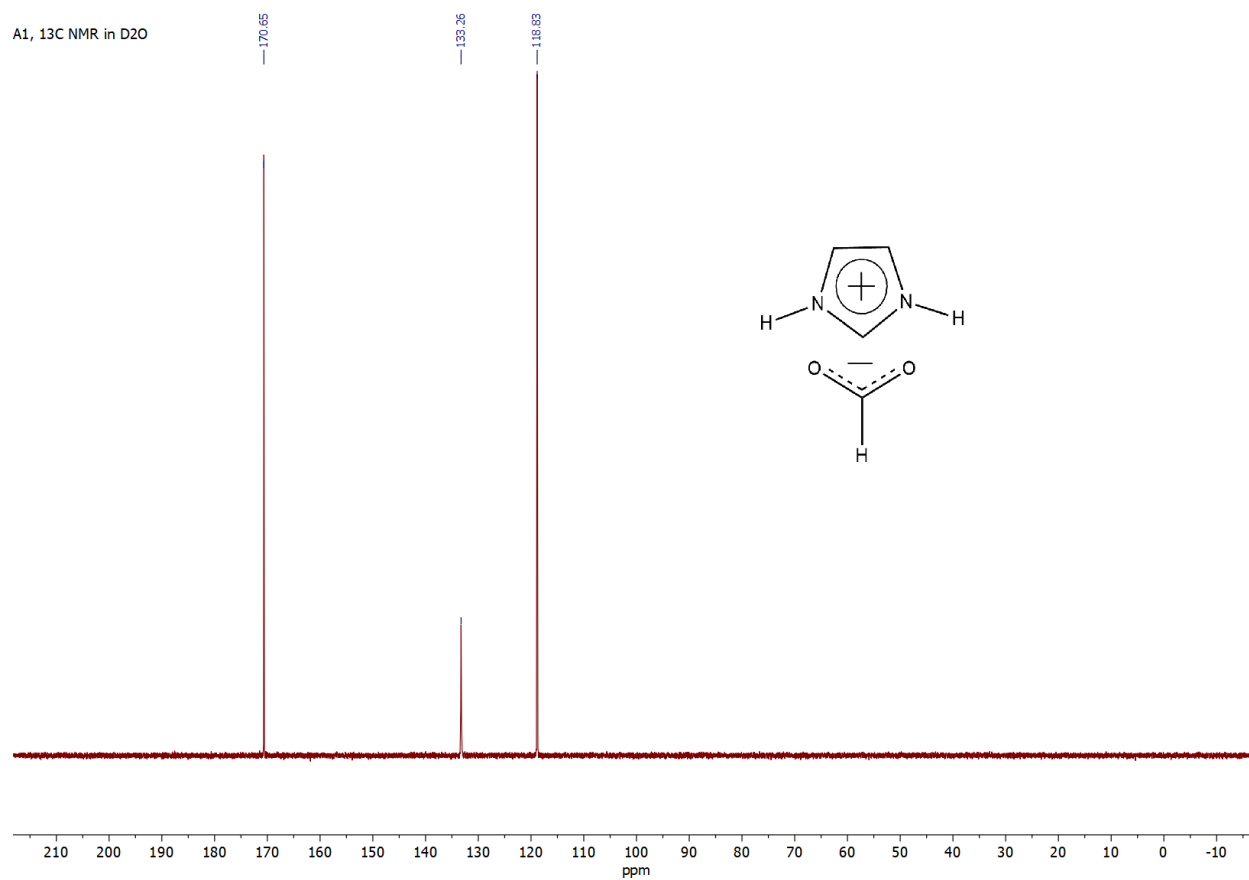


Fig. S5. *Imidazolium Formate* ([Im][For]): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 118.83, 133.26, 170.65.

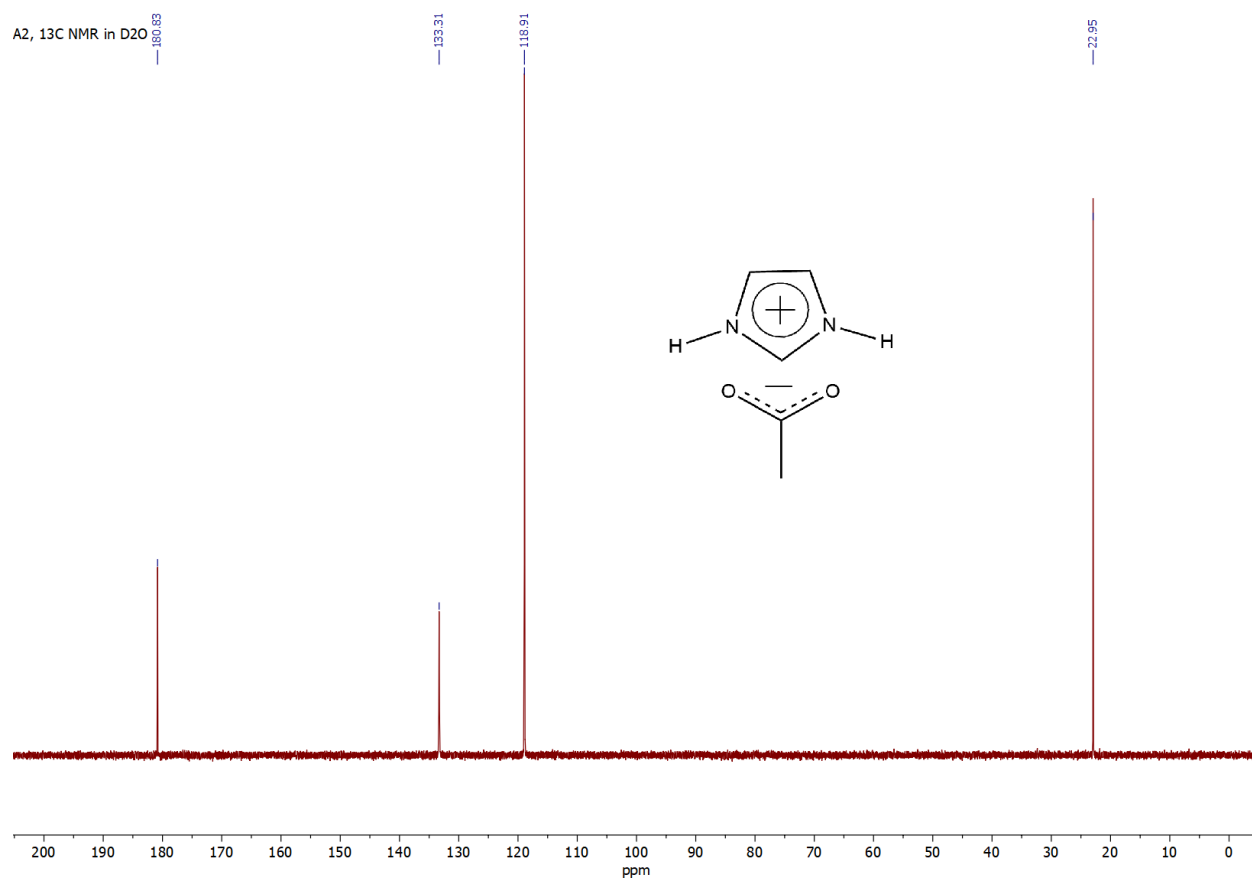


Fig. S6. *Imidazolium Acetate* ($[\text{Im}][\text{Ace}]$): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 22.95, 118.91, 133.31, 180.83.

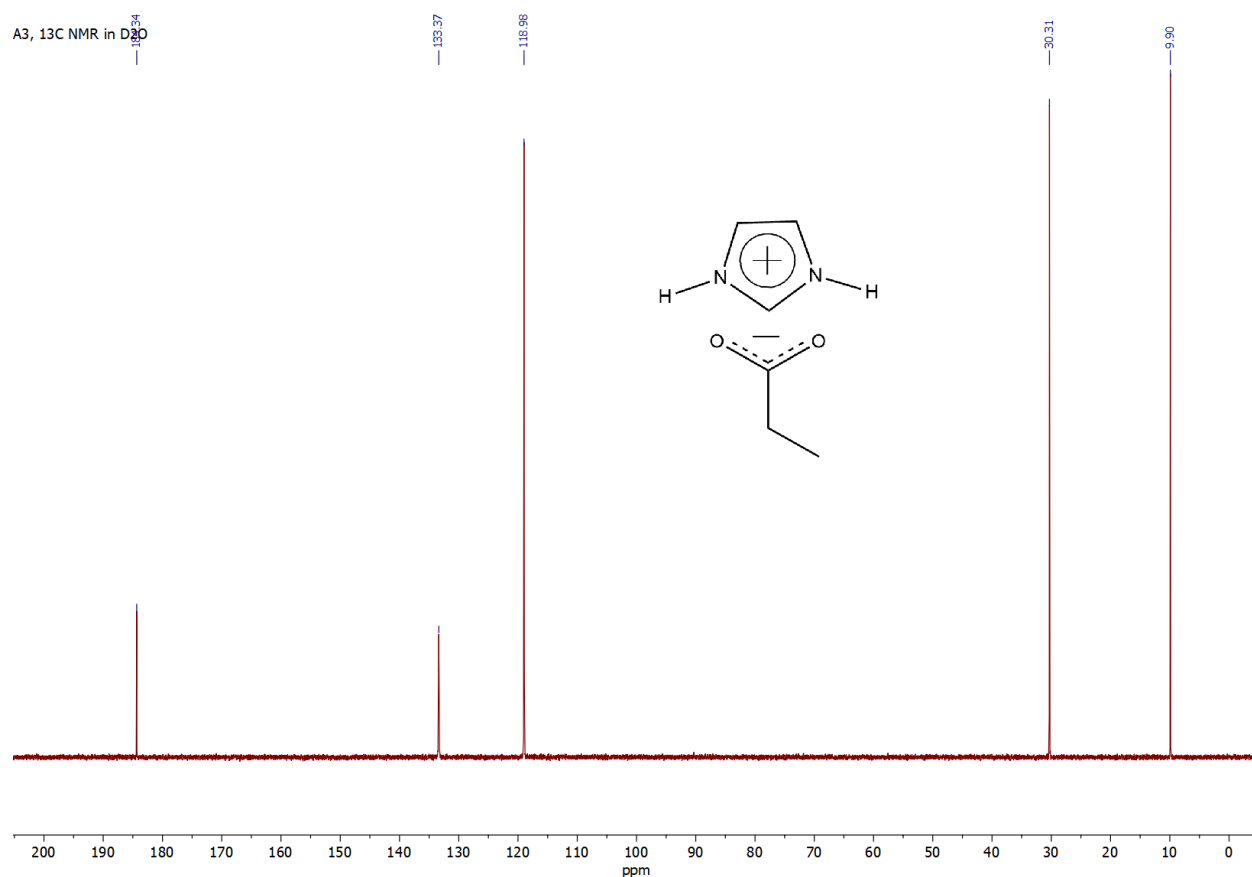


Fig. S7. *Imidazolium Propionate* ([Im][Pro]): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 9.90, 30.13, 118.98, 133.37, 184.34.

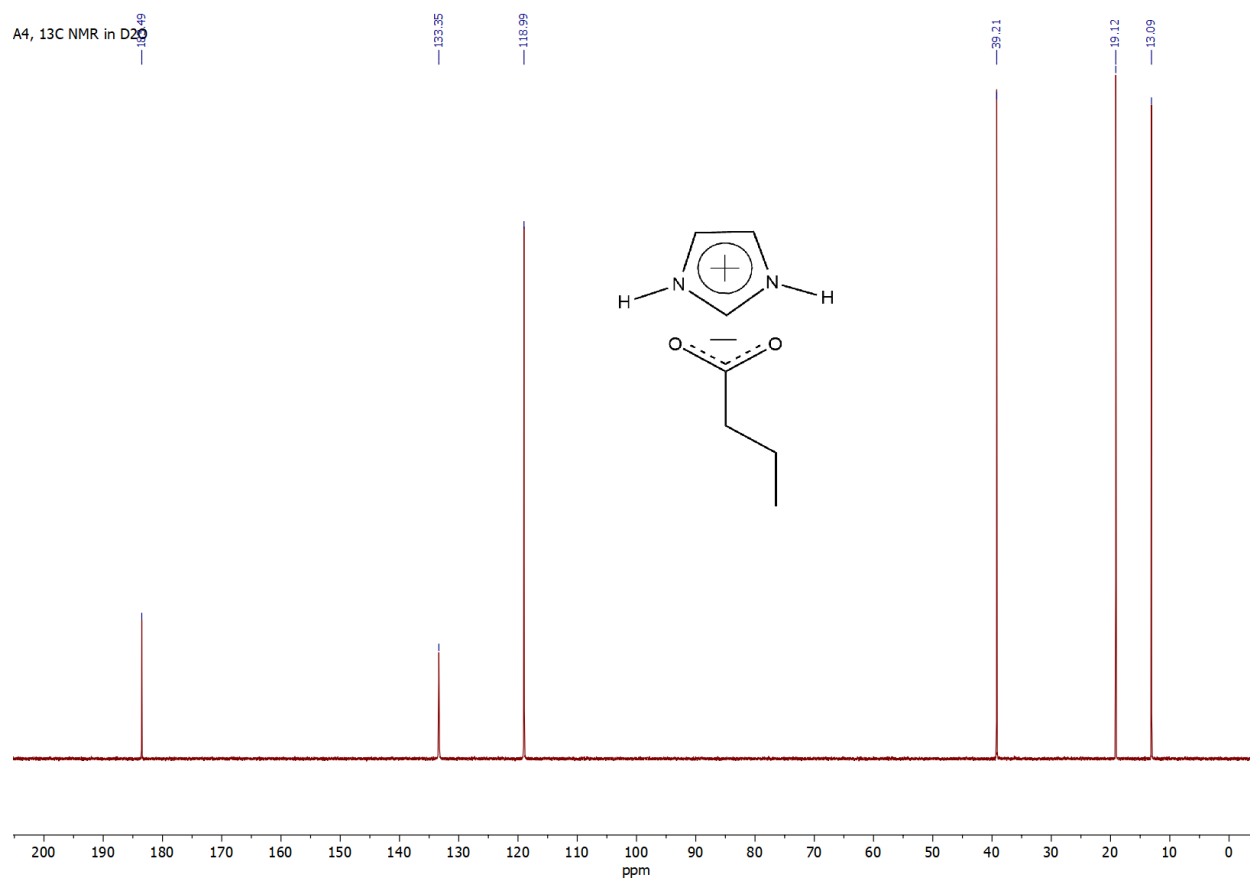


Fig. S8. *Imidazolium Butanoate* ([Im][But]): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 13.09, 19.12, 39.21, 118.99, 133.35, 183.49.

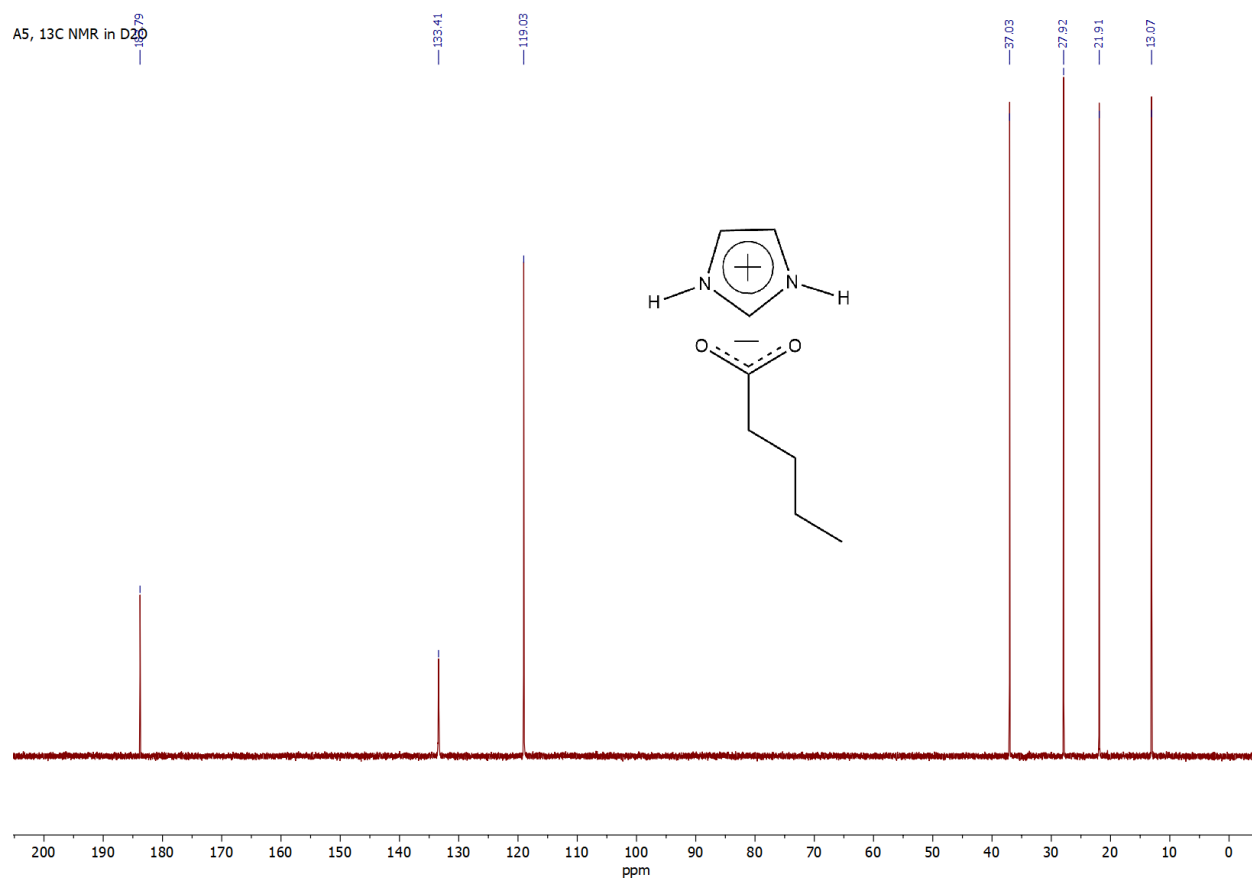


Fig. S9. *Imidazolium Pentanoate* ([Im][Pen]): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 13.07, 21.91, 27.92, 37.03, 119.03, 133.41, 183.79.

A10, ^{13}C NMR in D_2O

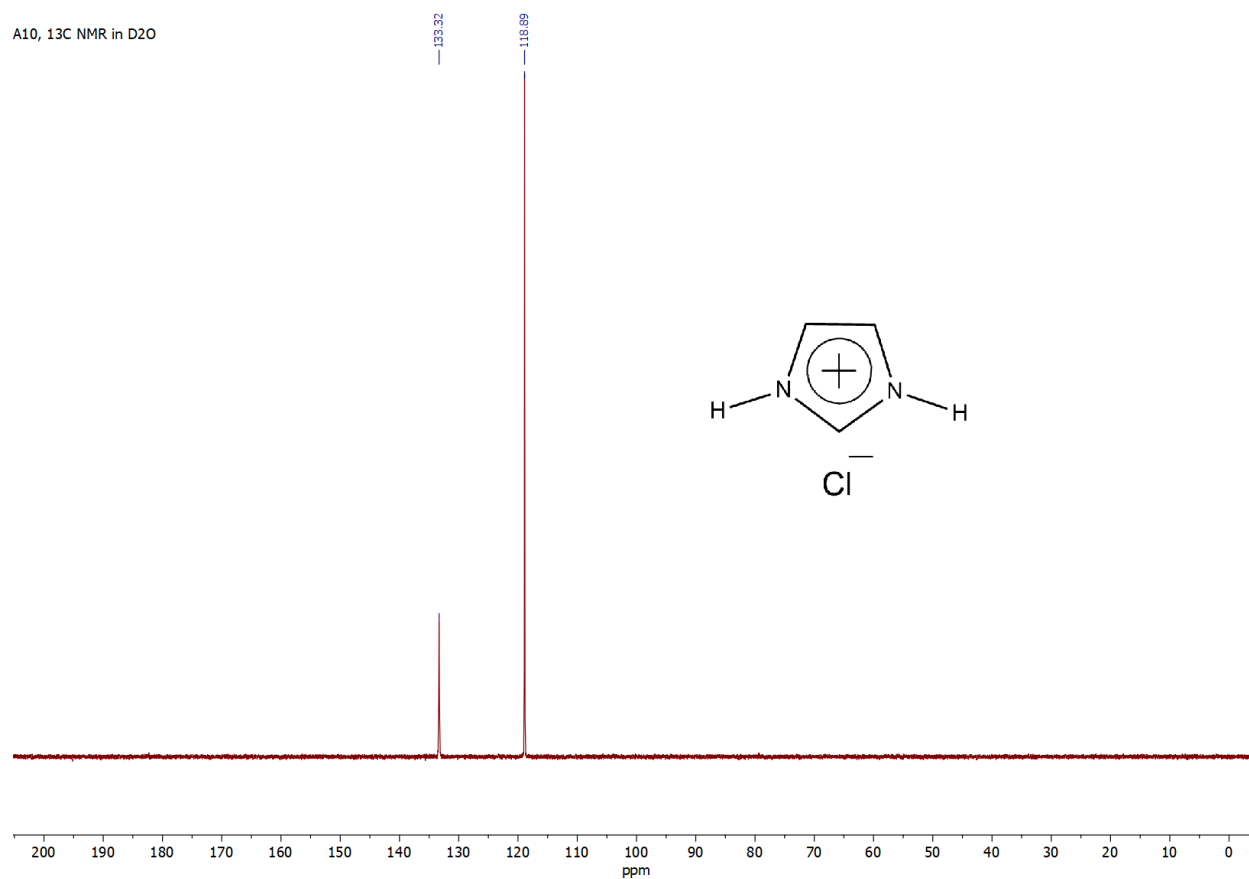


Fig. S10. *Imidazolium Chloride* ($[\text{ImCl}]$): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 118.89, 133.32.

A15, ^{13}C NMR in D_2O

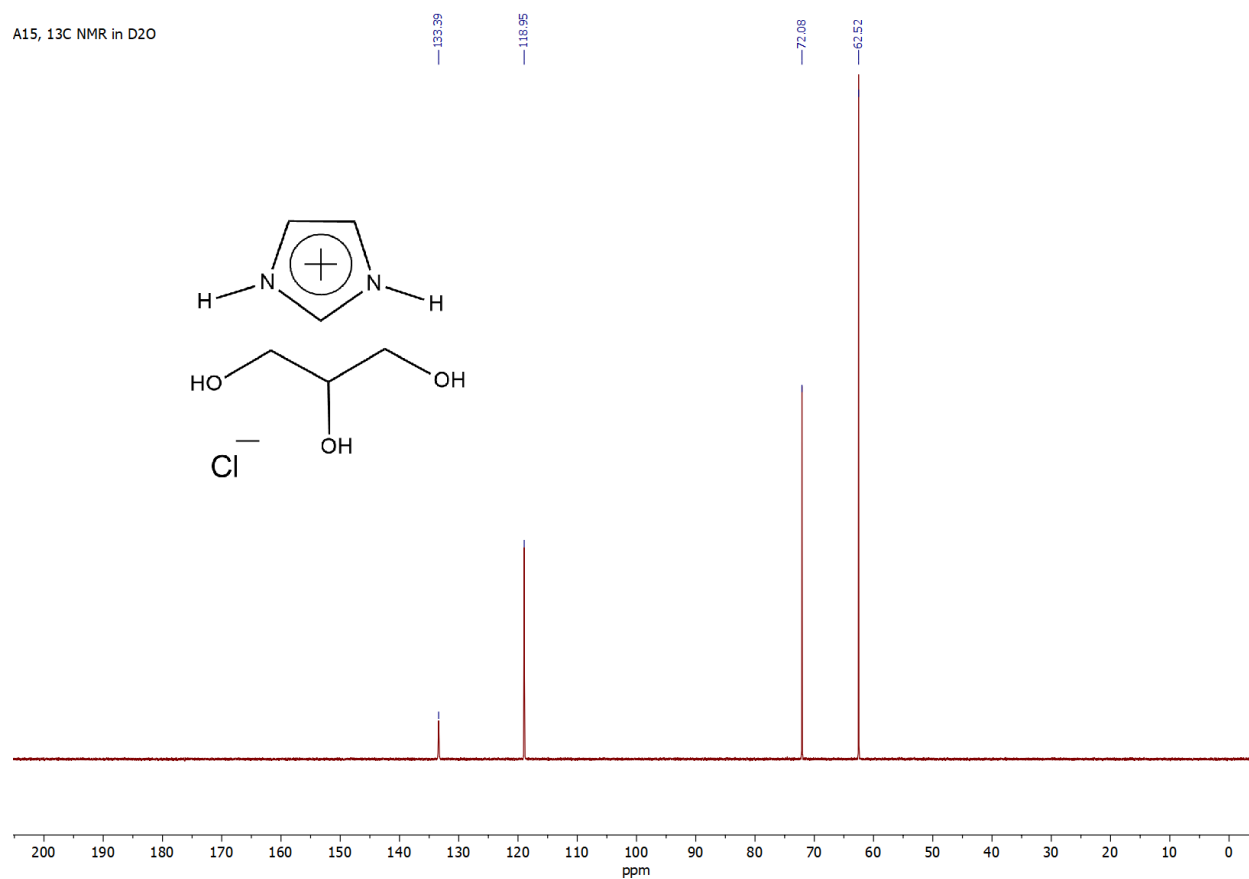


Fig. S11. *Imidazolium Chloride Glycerol* ($[\text{ImCl}][\text{Gly}]$): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 62.52, 72.08, 118.95, 133.39.

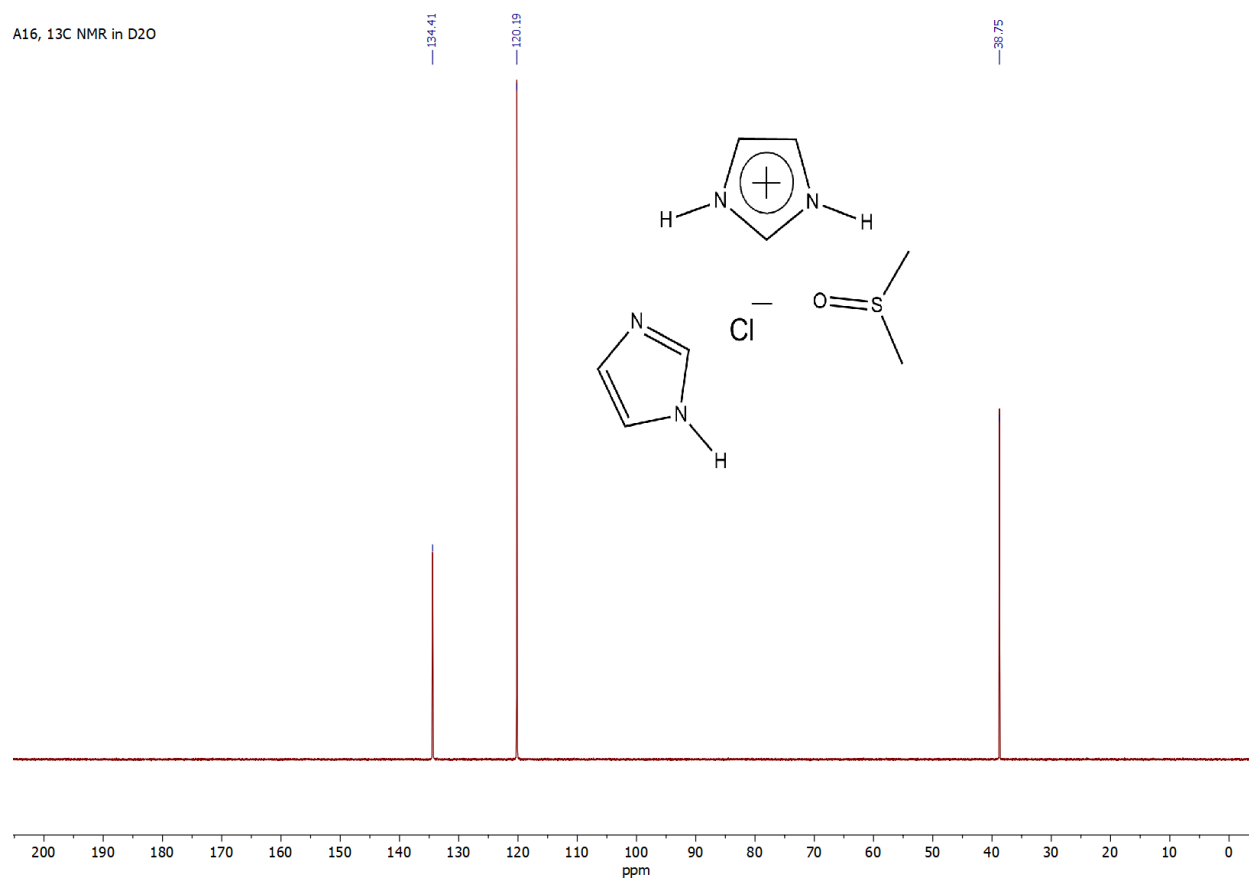


Fig. S12. *Imidazolium Chloride Imidazole DMSO* ($[\text{ImCl}][\text{Imi}] + \text{DMSO}$): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 38.75, 120.19, 134.41.

A19, ^{13}C NMR in D_2O

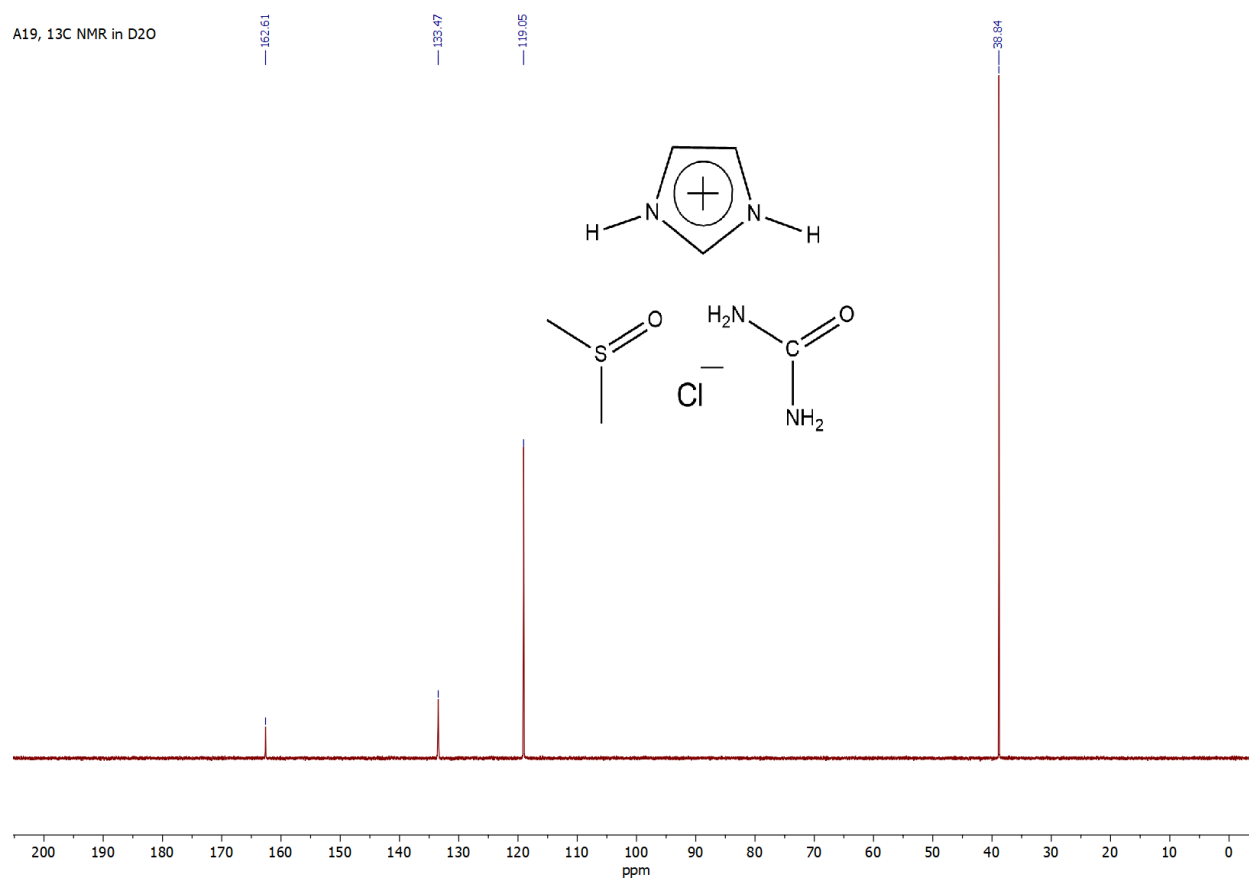


Fig. S13. *Imidazolium Chloride Urea DMSO* ($[\text{ImCl}][\text{Urea}] + \text{DMSO}$): ^{13}C NMR (175 MHz, D_2O): δ (ppm) = 38.84, 119.05, 133.47, 162.61.

A6, ^{13}C NMR in D_2O

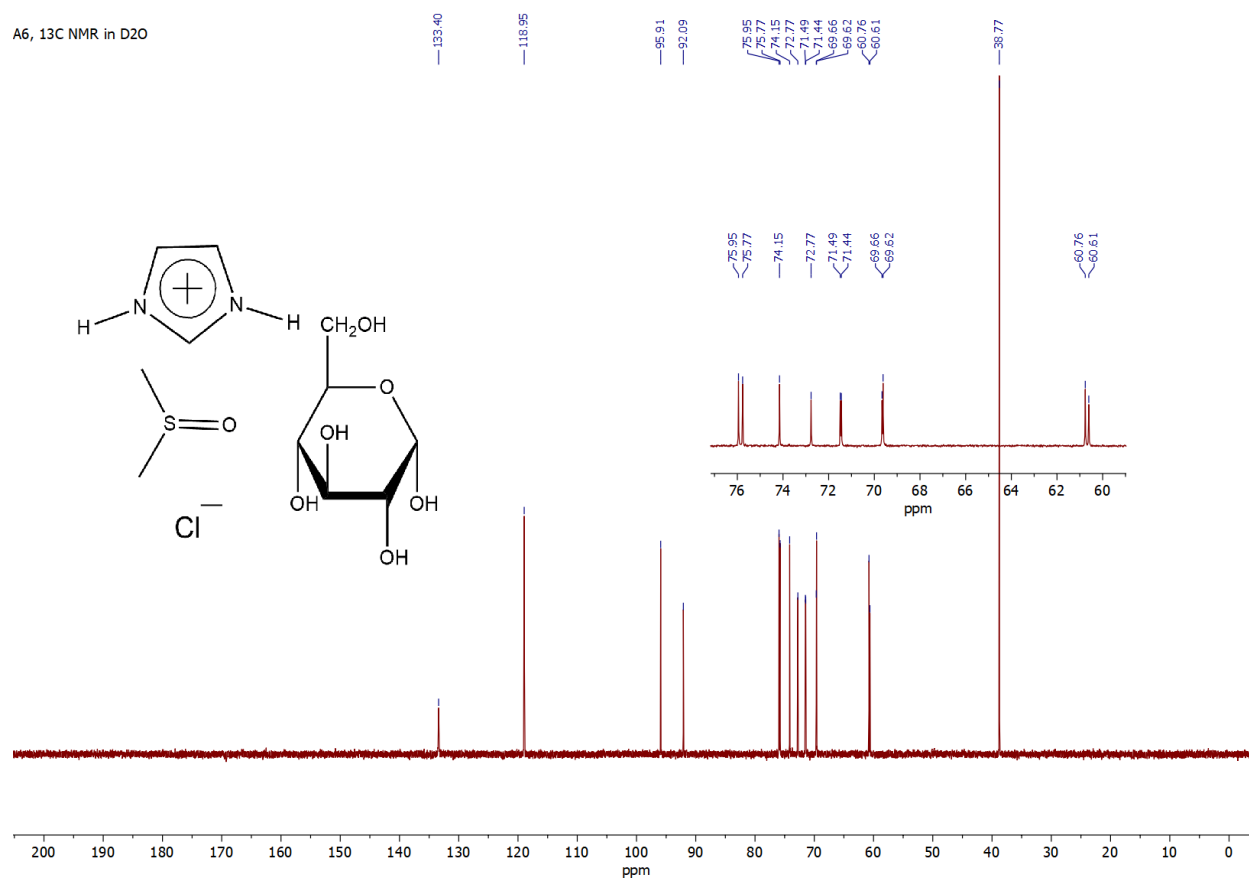


Fig. S14. ^{13}C NMR (175 MHz, D_2O) of [ImCl][glucose] + DMSO.

A7, ^{13}C NMR in D_2O

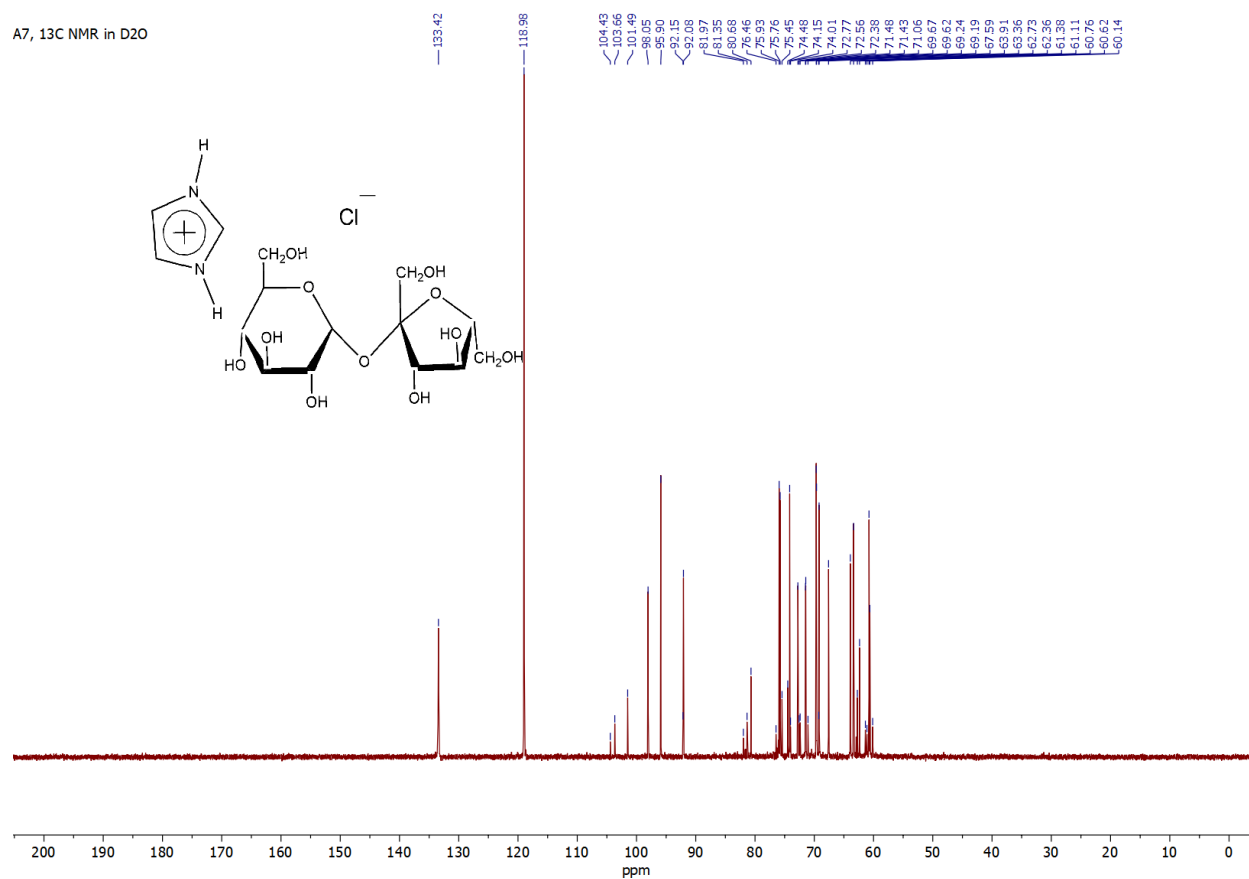


Fig. S15. ^{13}C NMR (175 MHz, D_2O) of [ImCl][sucrose].

A8, ^{13}C NMR in D_2O

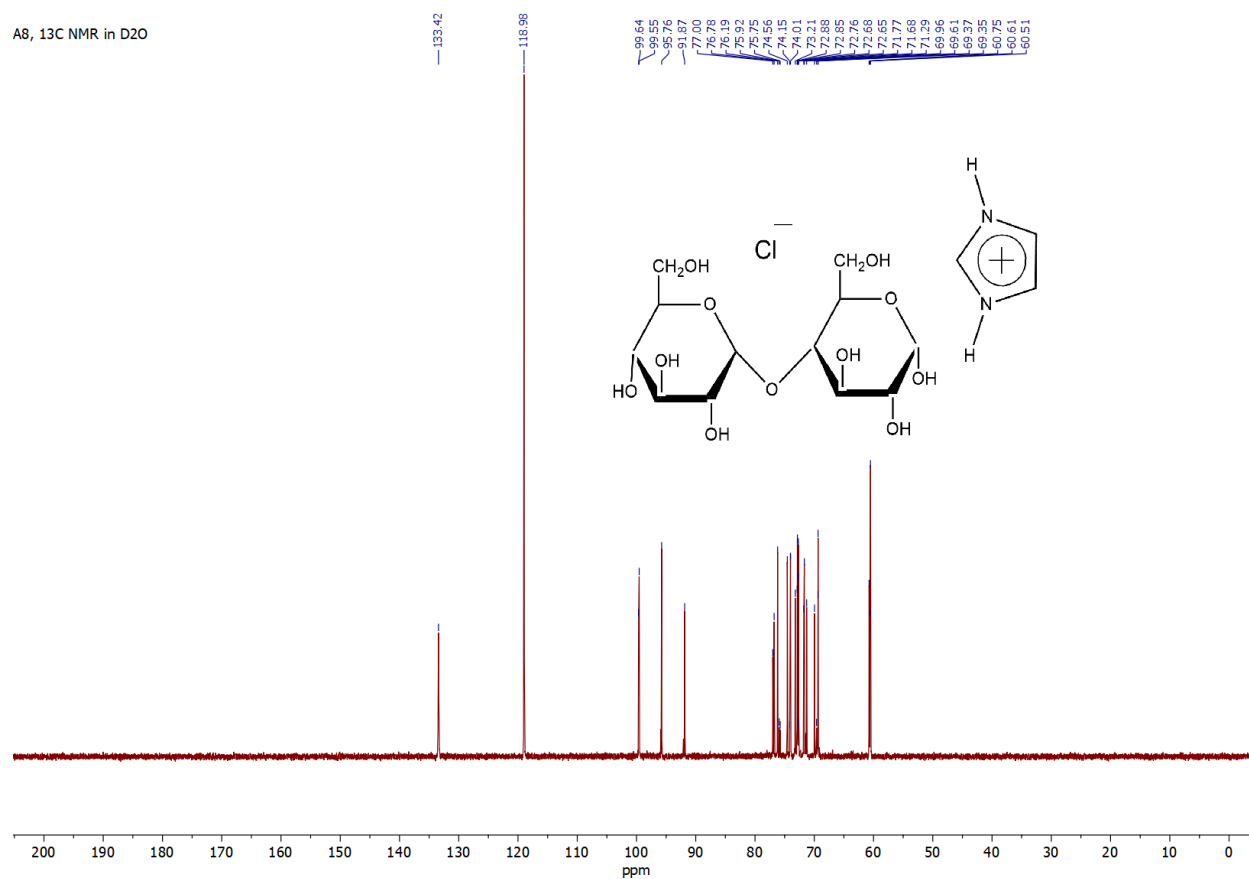


Fig. S16. ^{13}C NMR (175 MHz, D_2O) of $[\text{ImCl}][\text{maltose}]$.

A13, ^{13}C NMR in D_2O

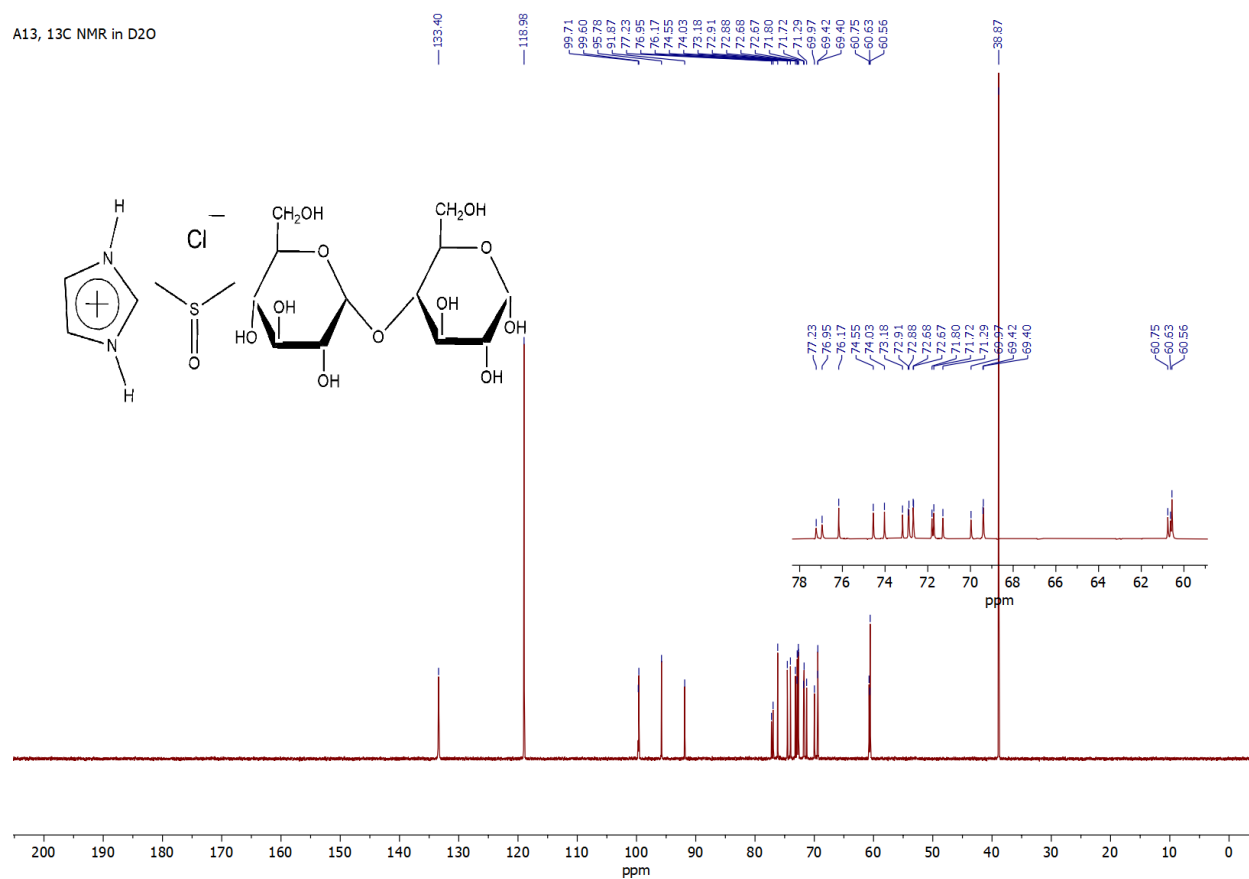


Fig. S17. ^{13}C NMR (175 MHz, D_2O) of $[\text{ImCl}][\text{maltose}] + \text{DMSO}$.

—133.38
—118.94
—103.61
98.01
95.86
92.09
92.03
—81.31
76.46
75.87
75.73
74.14
74.00
72.75
72.54
72.34
72.03
71.46
71.39
69.65
69.60
69.24
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63.90
63.33
62.50
62.37
62.34
61.38
60.75
60.62
60.15

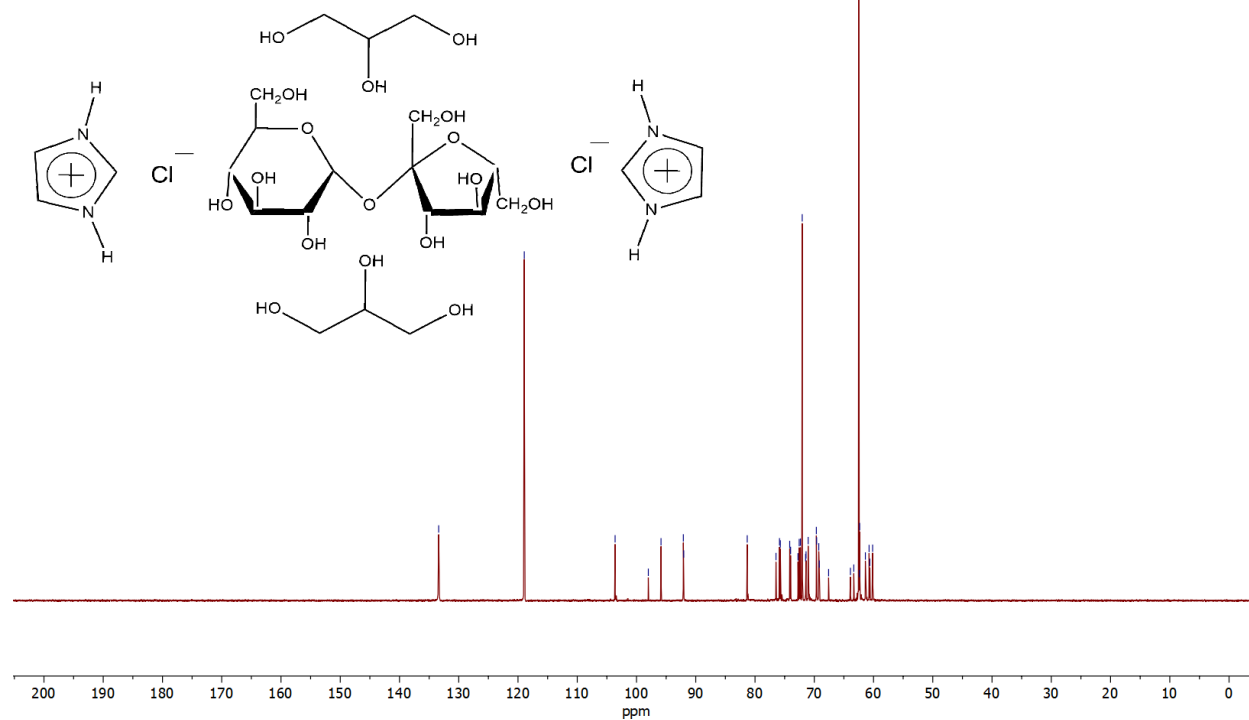


Fig. S18. ^{13}C NMR (175 MHz, D_2O) of $[\text{ImCl}][\text{sucrose}][\text{Gly}]$.

Thermal analyses (melting temperature (T_m), glass transition temperature (T_g) and decomposition temperature (T_d)) were measured by DSC 250, and TGA 550 Auto Advanced (TA Instruments, USA).

Nitrogen flow 60 mL/min

Ramping temperature 10°C/min.

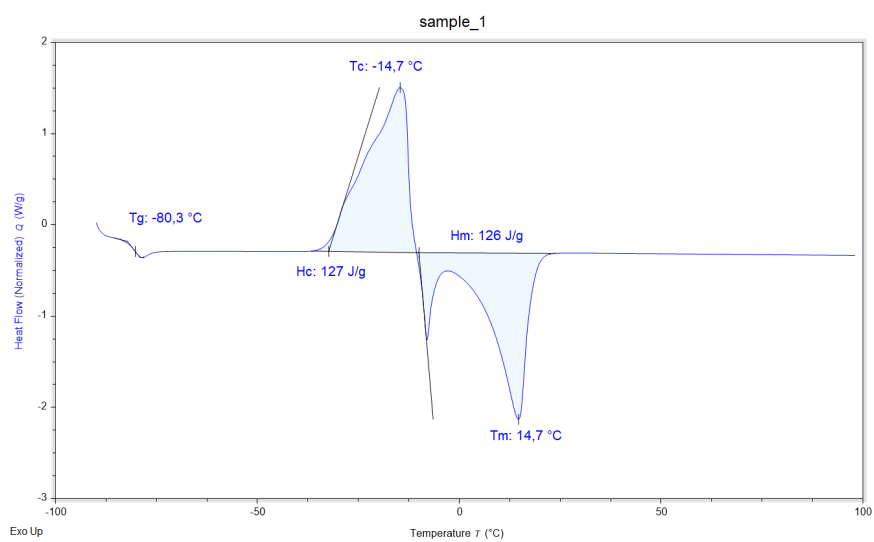


Fig. S19. The DSC spectrum of [Im][For].

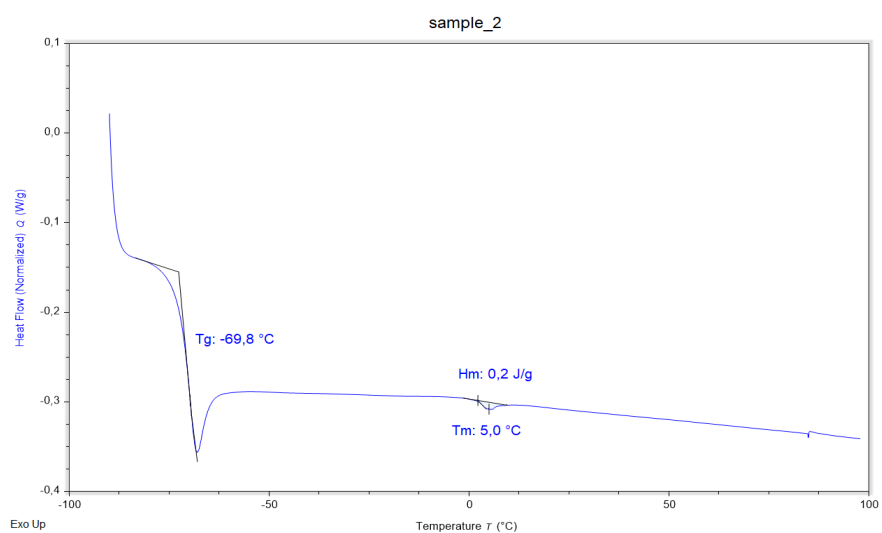


Fig. S20. The DSC spectrum of [Im][Ace].

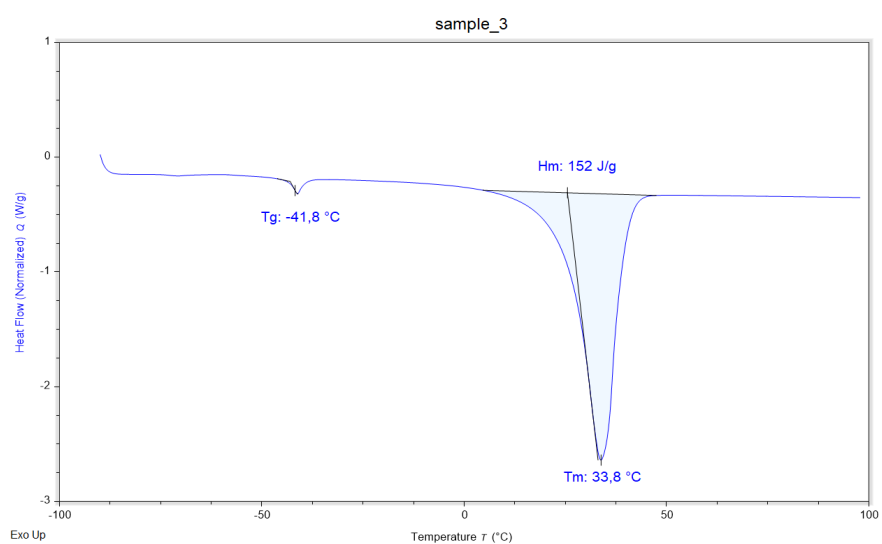


Fig. S21. The DSC spectrum of [Im][Pro].

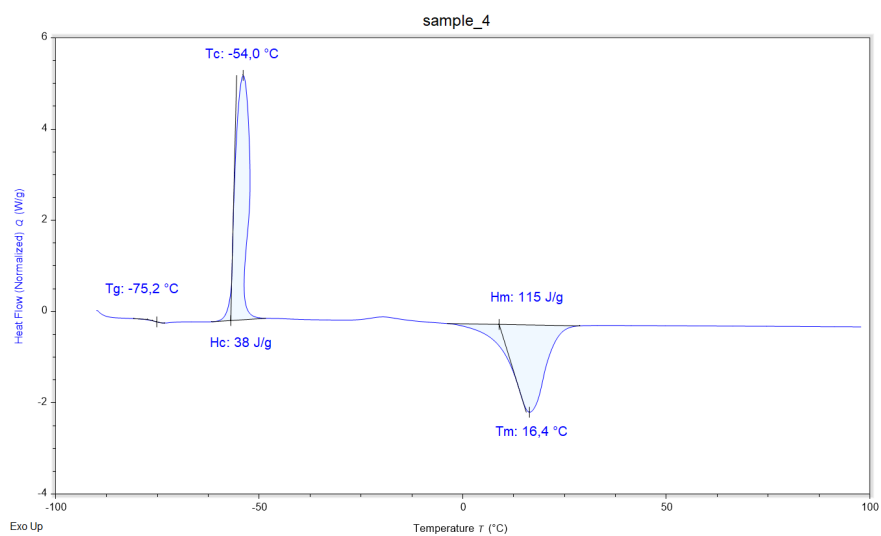


Fig. S22. The DSC spectrum of [Im][But].

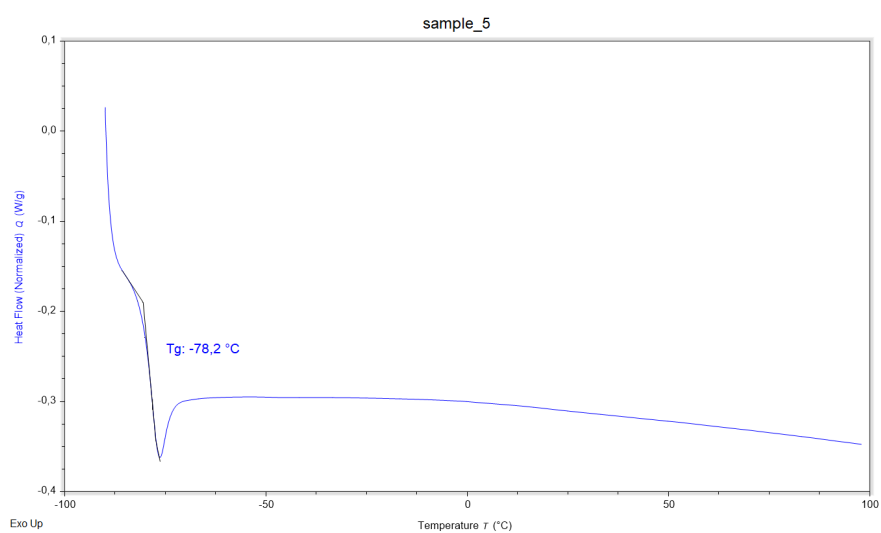


Fig. S23. The DSC spectrum of [Im][Pen].

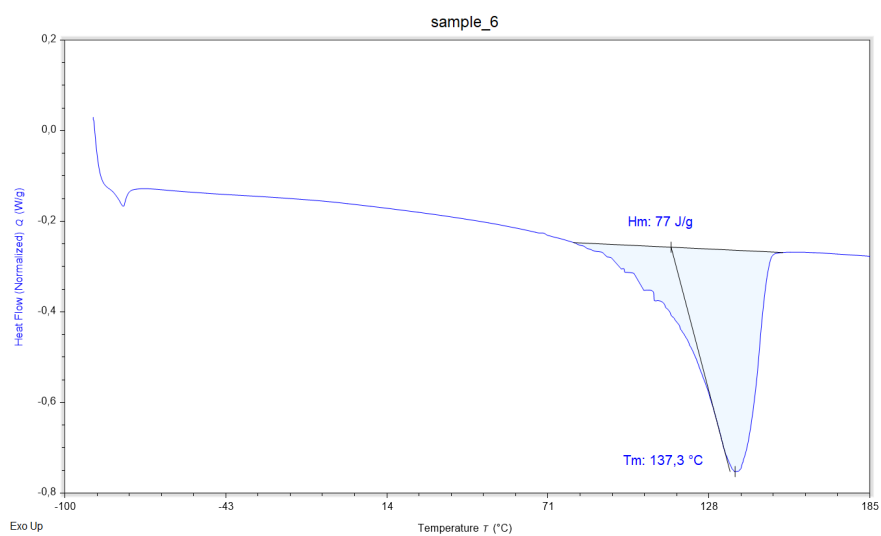


Fig. S24. The DSC spectrum of [ImCl].

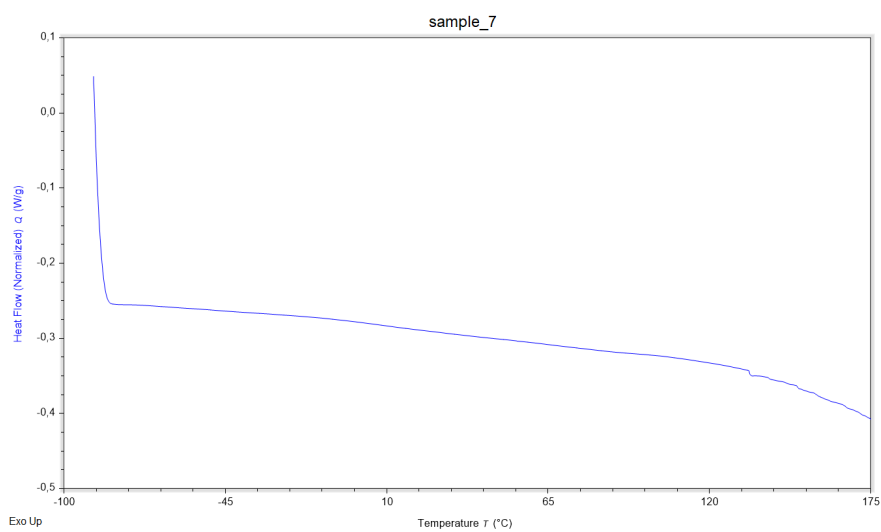


Fig. S25. The DSC spectrum of [ImCl][EG].

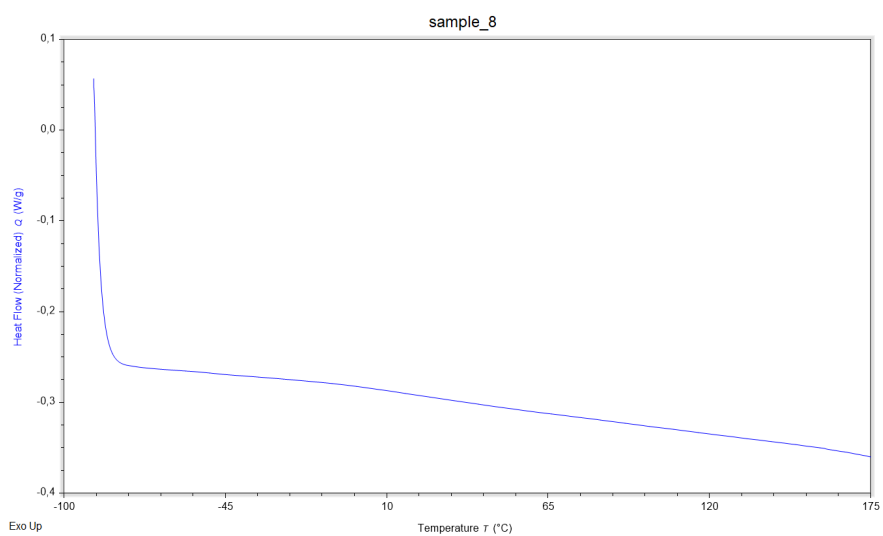


Fig. S26. The DSC spectrum of [ImCl][Gly].

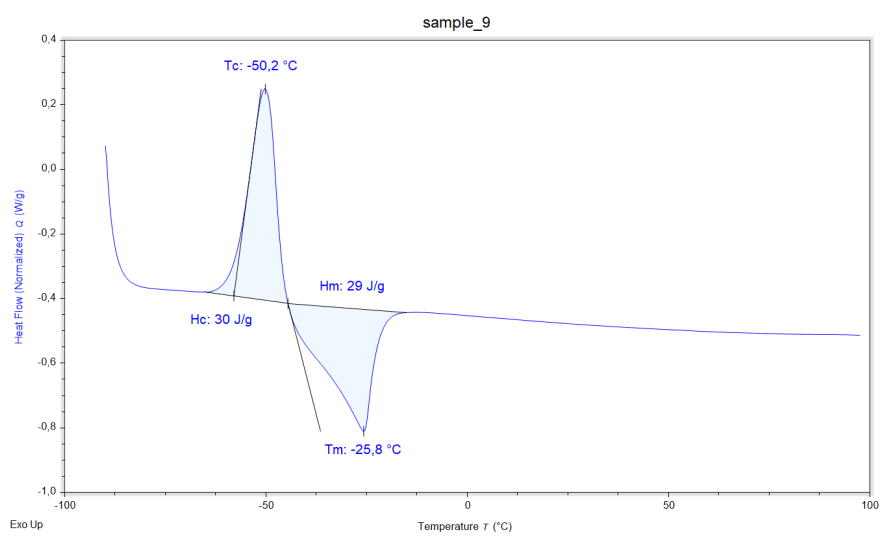


Fig. S27. The DSC spectrum of [ImCl][PEG 400] with the mole ratio 1: 1.

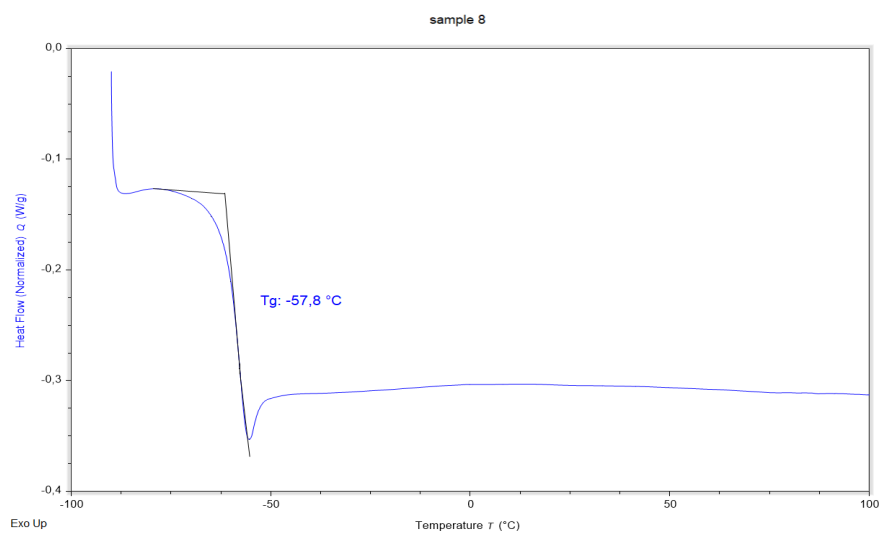


Fig. S28. The DSC spectrum of [ImCl][PEG 400] with the mole ratio 1: 0.8.

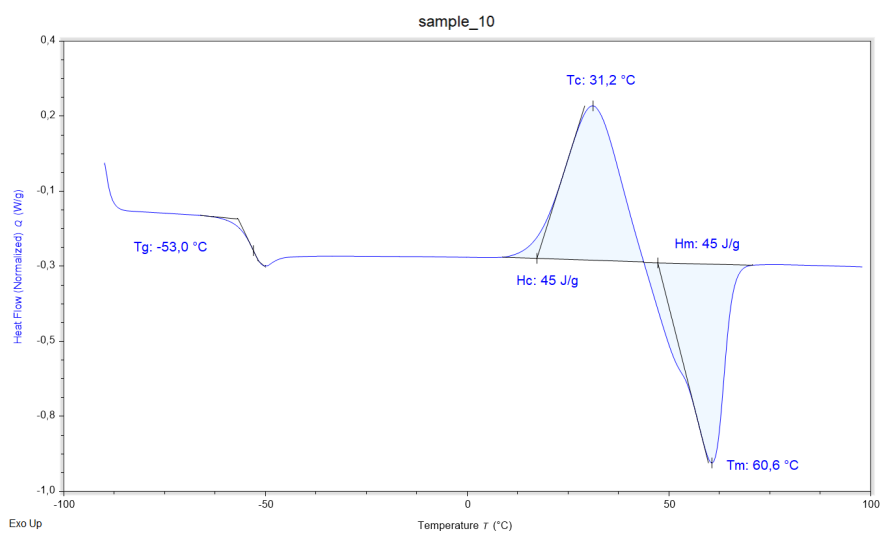


Fig. S29. The DSC spectrum of [ImCl][Urea].

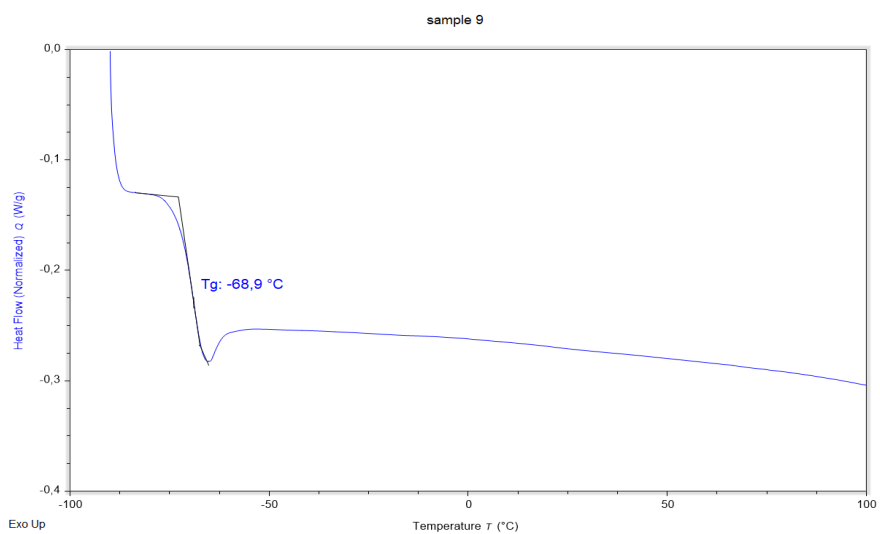


Fig. S30. The DSC spectrum of [ImCl][Urea] + DMSO.

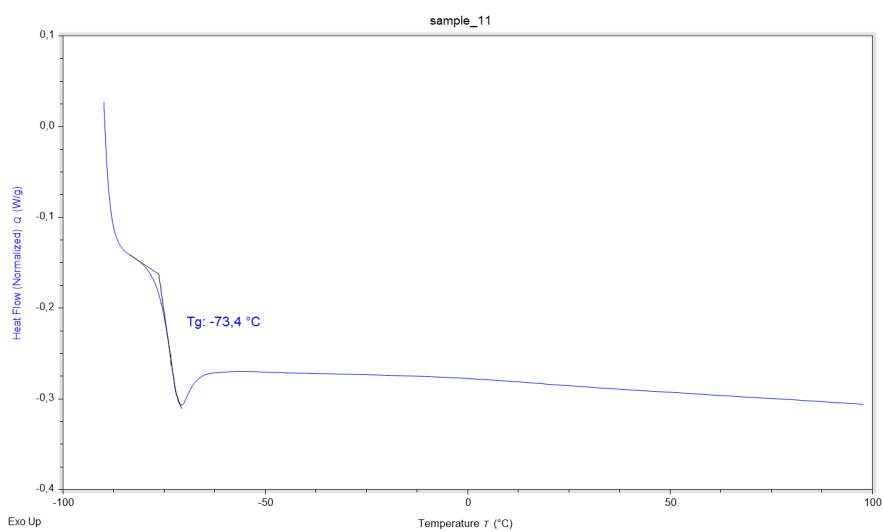


Fig. S31. The DSC spectrum of [ImCl][Imidazole] + DMSO.

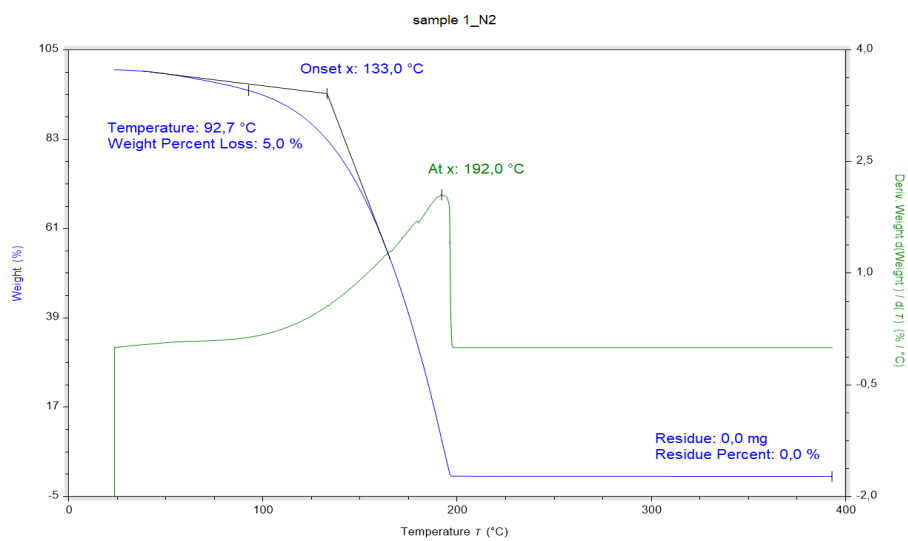


Fig. S32. The TGA spectrum of [Im][For].

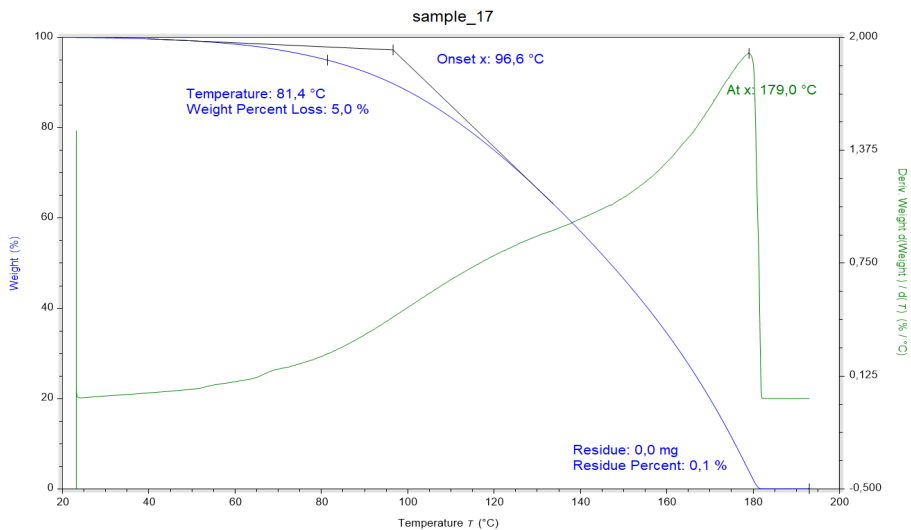


Fig. S33. The TGA spectrum of [Im][Ace].

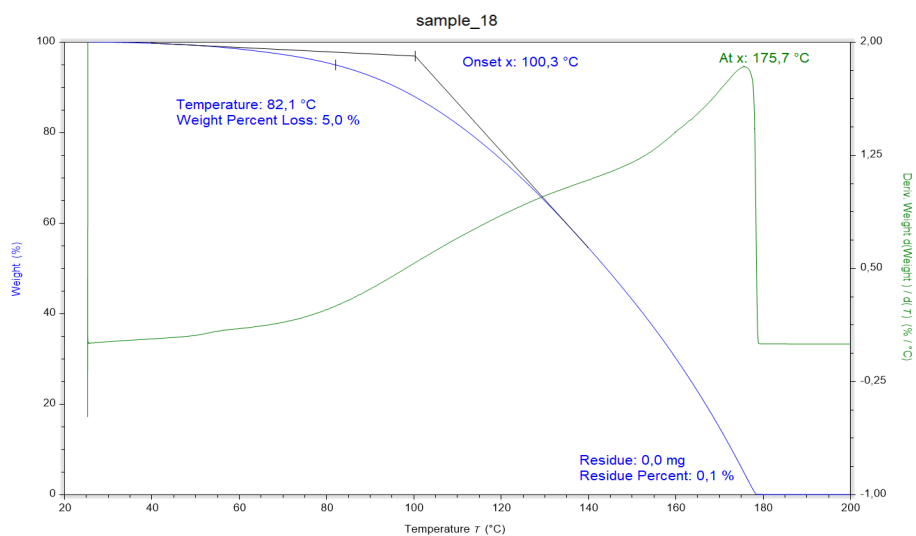


Fig. S34. The TGA spectrum of [Im][Pro].

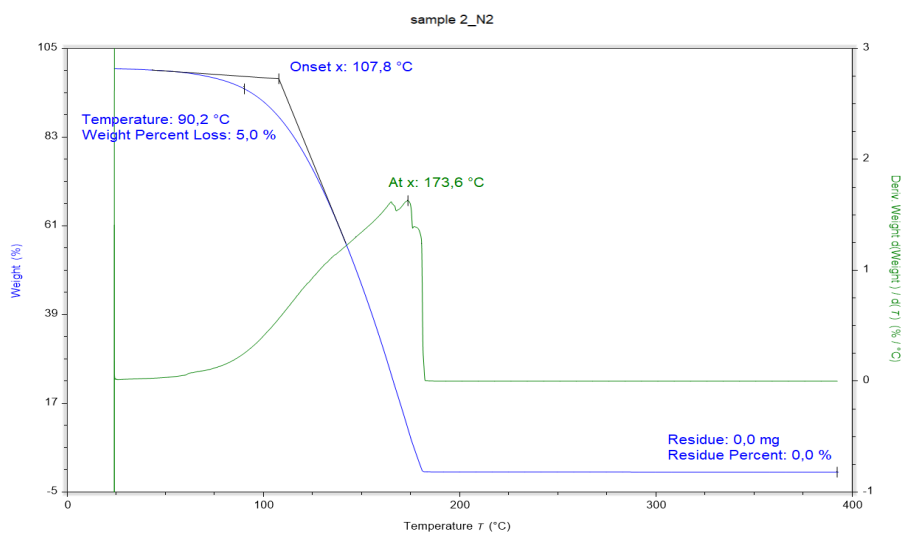


Fig. S35. The TGA spectrum of [Im][But].

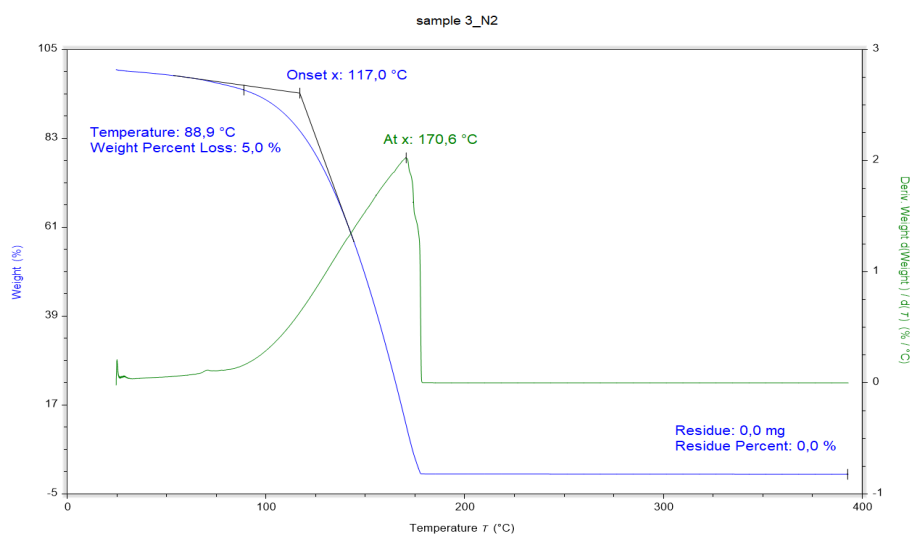


Fig. S36. The TGA spectrum of [Im][Pen].

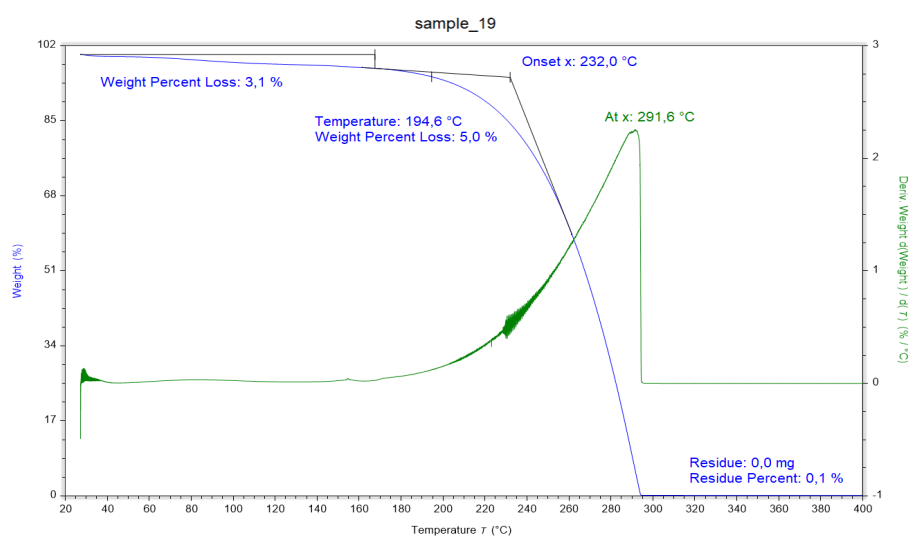


Fig. S37. The TGA spectrum of [ImCl].

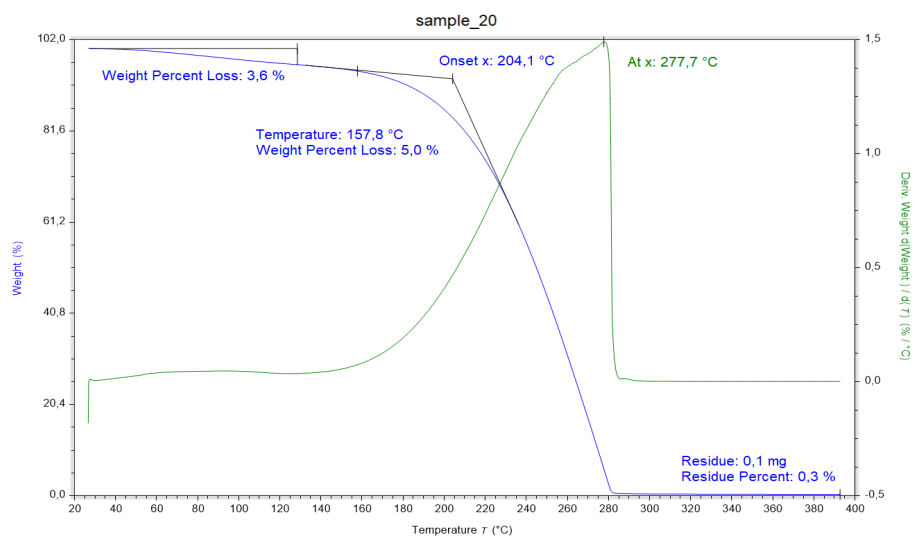


Fig. S38. The TGA spectrum of $[\text{ImCl}][\text{Gly}]$.

6.2 Appendix

We used the GROMACS package 465.

Creating .top files:

```
Pdb2gmx_465 -f filename.pdb -p name.top -o name.gro ignh -ss
```

It will create files: name.top, name.gro, posre.itp

Defining the box for the solute:

```
editconf_465 -f name.gro -o name_box.gro -bt cubic -d 1.0 -c
```

Solvating the box with water:

```
genbox_465 -cp name_box.gro -cs -o name_sol.gro -p name.top
```

Creating tpr files:

```
grompp_465 -f mini_pbc.mdp -c name_sol.gro -p name.top -o name_ion.tpr
```

Neutralization of the system:

```
genion_465 -s name_ion.tpr -nn 1 -o -name_ion.gro -p name.top
```

Creating tpr files for minimization:

```
Grompp_465 -f mini_pbc.mdp -c name_ion.gro -p name.top -o name_min.tpr
```

Run minimization:

```
mdrun_465 -deffnm name_min -v
```

Creating tpr files for NVT simulation:

```
Grompp_465 -f nvt.mdp -c name_min.gro -p name.top -o name_nvt.tpr
```

Run NVT simulation:

```
mdrun_465 -deffnm name_nvt -v
```

Creating tpr files for NPT simulation:

```
Grompp_465 -f npt.mdp -c name_nvt.gro -p name.top -o name_npt.tpr
```

Run NPT simulation:

```
mdrun_465 -deffnm name_npt -v
```

Creating tpr files for n steps simulation:

```
Grompp_465 -f md_cpu.mdp -c name_npt.gro -p name.top -o name_md.tpr
```

Run simulation:

```
mdrun_465 -deffnm name_md -v
```

Here are some commands for analyzing the trajectories.

```
trjconv_465 -f name_md.xtc -s name_md.tpr -pbc whole -o name_md_pbc.xtc
```

for creating groups in index file:

```
make_ndx_465 -f name_md.tpr -o name.ndx
```

Calculating RMS:

```
g_rms_465 -f name_md_pbc.xtc -s name_md.tpr -n name.ndx -o name_rms.xvg
```

Calculating RMSF:

```
g_rmsf_465 -f name_md_pbc.xtc -s name_md.tpr -n name.ndx -o name_rmsf.xvg -res
```

Calculating RDF:

```
g_rdf_465 -f name_md_pbc.xtc -s name_md.tpr -n name.ndx -o name_rdf.xvg
```

CHAPTER 7

Curriculum vitae

7.1 Curriculum vitae

Meysam ARYAFARD

Biophysics, physical chemistry, organic chemistry, green chemistry

 www.linkedin.com/in/meysam-aryafard-b5b0a5112/
 +420 776833250  meysam.aryafard@gmail.com
 798/19, Studentska 20, Ceske Budejovice, Czech Republic
 Researchgate



I am interested in sustainable chemistry to make the reactions in environmental conditions (green chemistry, less toxicity, recyclable, natural and eco-friendly). To achieve these goals, I have been working on solvents which have these potentials. ionic liquids – deep eutectic solvents – supercritical CO₂. Applications of ionic liquids, organic and biochemical reactions in these green solvents, improving the reactions, and separations are my goals.

EDUCATION

- 2018–2023 **PhD student in Biophysics**, University of South Bohemia, Czech Republic
Thesis Projects :
Synthesis of novel ionic liquids and deep eutectic solvents.
Biomolecular interactions in ionic liquids, deep eutectic solvents, and organic solvents.
Investigation of solute-solvents interactions by UV-Vis spectroscopy (probe dyes), MD simulations, DFT calculations.
Cellulose dissolution in ionic liquids.
Supervisors : Dr. Babak Minofar, Dr. David Reha.
- 2010–2012 **M.Sc. physcial organic chemistry**, Kharazmi University, Tehran, Iran.
Total GPA : 17.27 /20
Thesis Title : Synthesis of ionic liquids and determination solvatochromic parameters in mixtures of solvents.
Supervisor : Dr. Alireza Harifi mood.
- 2006–2010 **B.Sc. in Chemistry**, Bamonar University, Kerman, Iran.
Thesis Title : Oxidation of ketones by selenium dioxide.

PROFESSIONAL EXPERIENCE

- from November 2022 **now** **Visiting researcher in the laboratory of organic chemistry, JOHANNES KEPLER UNIVERSITY, Austria**
 > Stereochemistry
 catalysts organocatalytic syntheses Ketoester chiral ammonium salt HPLC NMR
- May 2022 **PhD Internship, MEASURING THE POLARITY OF DEEP EUTECTIC SOLVENTS + SUPERCRITICAL CO₂. USING sCO₂ AS A GREEN SOLVENT FOR REACTIONS, Madrid, Spain**
August 2022 **now** **Supercritical Fluids**
 supercritical CO₂ Polarity UV-Vis spectroscopy DESs sCO₂ as a green solvent hydrophobic solvents
- Present **Research assistant and lab technician , UNIVERSITY OF SOUTH BOHEMIA IN CESKE BUDEJOVICE, Czech Republic**
February 2018
 > Application of ionic liquids for cellulose dissolution
 > Biochar for tetracycline adsorption
 > Designing ionic liquids for drug delivery
 > Synthesis of novel ionic liquids and deep eutectic solvents
 > Measuring the peroperties of solvents
 Ionic liquids Deep eutectic solvents Solvatochromic properties MD simulations DFT calculations
 UV-Vis measurements NMR analysis

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ghanba00@jcu.cz

Title: Biomolecular interactions at the surfaces in aqueous and non-aqueous solutions.
Ph.D. Thesis Series, 2023, No. 8.

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Printed in the Czech Republic by Typodesign
Edition of 10 copies

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