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Article

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Nanoscale Clustering of Alcoholic Solutes in Deep Eutectic Solvents Studied by Nuclear Magnetic Resonance and Dynamic Light Scattering

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Abstract

It was previously shown that water distributes heterogeneously in deep eutectic solvents (DESs). The aim of this study was to see whether this behavior was common to other hydrogen bonding compounds and determine when a solute formed an emulsion or a homogeneous solution. Pulsed field gradient (PFG) and nuclear Overhauser effect (NOE) NMR, and dynamic light scattering (DLS) are employed to probe the phase behavior of glucose, 1-pentanol and phenol in Ethaline (ethylene glycol: choline chloride, 2:1). By comparing the measured values of self-diffusivities to those calculated assuming Stokesian behavior, it was discovered that glucose forms a homogeneous solution, whereas 1-pentanol forms a heterogeneous mixture. A change in aggregates size of 10 wt% phenol in Ethaline is observed at 313 K. Above 313 K aggregation is enhanced and larger aggregates are formed, suggesting a melting of phenol affects the phase behavior. $\{^1\text{H}, ^1\text{H}\}$ -NOESY NMR showed that glucose interacts strongly with Ethaline whilst with 1-pentanol and phenol this interaction is weaker. DLS experiments further indicated the heterogeneity and homogeneity. Results suggest that solid solutes that are capable of strong hydrogen bonding are soluble in DESs whereas liquid solutes form heterogeneous nanophases due to the weaker solute - solvent interactions and density difference.

Key words

Aggregation, nanoemulsion, DES, diffusion, solute, nanophase

Introduction

Deep eutectic solvents (DESs) are mixtures of a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA) mixed together in a suitable ratio. Hydrogen bond formation between the components reduces the melting point of the mixture, and therefore many DESs are liquid at room temperature. The preparation of a DES is simple and atom-efficient, as HBA is just mixed with HBD, and no purification step is needed. By selecting the right combination of a HBD and HBA, the properties of a DES can be easily affected and, hence, tailored for particular applications. Choline chloride (ChCl) is the most commonly used HBA, mainly because it is cheap, non-toxic and biodegradable.¹ Correspondingly, some of the ChCl-based DESs have proven to be non-toxic and readily biodegradable, i.e. Ethaline (ethylene glycol and ChCl, 2:1), Reline (urea and ChCl, 2:1) and Glyceline (glycerol and ChCl, 2:1).¹ Furthermore, DESs offer other benefits such as low volatility, low flammability and high thermal stability.^{2,3} These novel solvents have been used as green alternatives for several organic and aqueous solvents on a large scale in different applications.^{4,5}

While DESs are connected through strong hydrogen bonding, solutes that can hydrogen bond are expected to have good solubility in DESs. Indeed, DESs are reported to be able to dissolve various solutes including lignocellulosic biomass⁶, pharmaceutical chemicals⁷ and metal oxides⁴. The hydrogen bonding ability of DESs has been utilized especially in extraction, which has recently become a topic of significant interest among researchers. Abbott et al.⁸ emphasized the importance of hydrogen bonding in enabling selective extraction by using a variety of alkanes with different functional groups in six DESs. It was shown that the order for partition coefficient at equilibrium was carboxylic acid > alcohol > ester > ketone, the strongest hydrogen bond donor being the easiest to extract. Wazeer et al.⁹, likewise, used three chloride-based DESs for the separation of benzene from alcohols via liquid–liquid extraction. They discovered that an azeotrope formed between benzene and either methanol or ethanol could be separated if the alcohol content was less than 40 wt%. Above that level, the hydrogen bonds within the DES structure were destroyed. Hammond et al.¹⁰ also claimed that the critical amount of water in Reline was ca. 42 wt%. However, all these studies did not quantify the formed aggregate sizes.

The pure DESs are known to form completely homogenous mixtures¹¹, whereas aqueous mixtures of DESs undergo microscopic phase separation despite the hydrophilicity of the salt and HBD¹². D'Agostino et al.¹² used pulsed field gradient nuclear magnetic resonance (PFG NMR) spectroscopy to probe the phase behavior in Ethaline, Reline and Glyceline with different water contents and revealed that these mixtures form heterogeneous microphases when water content exceeds 2.5 wt% (1 : 1 mole equivalent of water : chloride.).

Previously, PFG NMR has showed its usefulness in characterizing the mobility of different species, and examining solvent - solvent and solvent - solute interactions in ionic liquids (ILs) and DESs.^{11–15}

In this study, PFG NMR, 2D nuclear Overhauser effect spectroscopy (NOESY) NMR and dynamic light scattering (DLS) are used to study the solvent - solute interactions and phase behavior of three alcohols, namely glucose, 1-pentanol and phenol, in Ethaline. Previous studies showed that a low surface tension increased extraction efficiency for thiophene and related compounds.⁸ Therefore, Ethaline, with low surface tension, is a promising solvent for further studies. The solutes were selected based on our previous study on glucose solvation¹⁴ and partitioning in DESs⁸. Clustering of solutes to form a microemulsion would negate classical methods of modelling solute solubility.

Experimental section

Choline chloride (ChCl) ($\geq 98\%$), ethylene glycol (EG) ($\geq 99\%$), glucose ($\geq 99.5\%$), 1-pentanol ($\geq 99\%$) and phenol ($\geq 99\%$) were purchased from Sigma Aldrich, and used as received. Ethaline was prepared by mixing ChCl and EG in 1:2 ratio at 333 K until a homogeneous liquid was formed. The water content of the solutions were measured using volumetric Karl-Fischer titrator with a 'Hydranal® Composite 5' solution, and found to be 0.57 ± 0.04 wt%.

The viscosity of the mixtures was measured using an Anton Paar Physica MCR 301 cone/plate rheometer with a CP50-2/TG spindle. The instrument was equipped with a temperature control unit, allowing the investigation at different temperatures from 298 K to 328 K. Four samples per temperature were measured. The viscosity was studied as a function of shear rate from 1 s^{-1} to 400 s^{-1} . The determined viscosities are an average of the measurements and stabilized viscosity values were recorded. The standard deviation for each viscosity value is presented in ESI.

NMR measurements were performed on a Bruker Avance III HD spectrometer operating at a ^1H frequency of 400.13 MHz with a direct-detection (BBO) probe. Equipped with z-Gradient, this probe was capable of producing gradient pulses of up to 50.1 G/cm. 5 mm NMR tubes with 7 inch length were used. ^1H and $\{^1\text{H}, ^1\text{H}\}$ -NOESY were recorded at 298 K and capillary inserts with DMSO- d_6 used for internal reference. ^1H DOSY NMR spectra were measured as bulk liquids from 298 K up to 328 K in 5 K increments. Per temperature controlled measurement the sample was left at set temperature for a minimum of 15 minutes before acquisition to let it reach thermal equilibrium. As the growth of the NOE has a linear dependence on mixing time¹⁶, and should be adjusted for each solution, 2D NOESY spectra were recorded with mixing times of 100 ms, 300 ms, 500 ms and 700 ms each with gradient pulses applied during the mixing time. PFG NMR was used to acquire ^1H DOSY NMR spectra with the

STE pulse sequences. Maximum values of 4 ms pulse duration (δ) and 400 ms observation (Δ) were needed to reach the desired diffusion signal attenuation with the gradient g varied in 16 linearly spaced increments.¹⁷ Regression analysis with the Bruker software TopSpin® 4.0.6 was used to obtain the values of self-diffusion coefficients. The error for self-diffusion coefficients was estimated to be 3-5 %.

The diameters of the solute particles in Ethaline were measured using a Nano-S Zetasizer (Malvern Instruments, UK) at 298 K and 323 K. The samples were filtered through PTFE membrane syringe filters, with a pore size of 0.45 μm . Correlograms, cumulants and distribution fits were used to validate the obtained data.

Results and Discussion

Intermolecular interactions – viscosity

In general, DESs show higher viscosity than most molecular solvents due to the strong interactions holding the DES components together. Abbott et al.¹⁸ rationalized the high viscosity of DESs by using the hole theory. According to this theory, the small void size of DESs restricts the movement of species and therefore results in high viscosity. ¹⁸ Figure 1 shows the viscosity of pure Ethaline¹¹ and 10 wt% solutes (glucose, 1-pentanol and phenol) in Ethaline as a function of temperature from 298 to 328 K. The obtained viscosities are in good agreement with previous viscosity studies in DESs. ^{3,12,19}

Figure 1. Viscosity of 10 wt% solutes (glucose, 1-pentanol and phenol) in Ethaline and pure Ethaline¹¹ as a function of temperature from 298 to 328 K.

The viscosity of 10 wt% glucose in Ethaline was higher than in pure Ethaline below 308 K, but lower at higher temperatures. This indicates that glucose can form favorable interactions with Ethaline, but these interactions

are disturbed at higher temperatures leading to a significant decrease of viscosity. It is commonly known that temperature weakens hydrogen bonding. Therefore, glucose most probably forms hydrogen bonds with Ethaline through its many hydroxyl groups, and these interactions can be significantly affected by temperature. On the other hand, it has been observed that the weakening of hydrogen bonds does not lead to lower viscosity in 1,3-dialkylimidazolium-based ILs.²⁰ As DESs are formed via hydrogen bonding, it might be that not only the hydrogen bonds of the solute-solvent are affected, but also those of the solute-solute and solvent-solvent. Therefore, it is possible that the hydrogen bonds of the solvent-solvent weaken faster than those of the solute-solute, thus facilitating fluidity. The viscosity of 10 wt% 1-pentanol and phenol in Ethaline was less than in pure Ethaline and 10 wt% glucose in Ethaline indicating weaker interactions as these systems have only one hydroxyl group for hydrogen bond formation. In summary, these results on viscosity suggest that glucose forms stronger interactions with Ethaline than 1-pentanol and phenol which suggests a greater degree of structure in the solution.

Diffusion of species in Ethaline

The addition of a solute (glucose, 1-pentanol and phenol) into Ethaline introduces a second HBD and the relative interactions between the anion/cation and both HBDs will affect the diffusion coefficients of each component. To assess the effect of the solute on mobility and intermolecular interactions between the Ch^+ cation and EG, the self-diffusivities of four species, namely aliphatic Ch^+ , OH on Ch^+ , aliphatic EG and OH on EG were examined. The diffusion coefficients measured using the CH_2 in ChCl resonance yield the same value as CH_3 in Ch^+ , as expected, and therefore only that measured using the CH_3 moiety is presented in Figure 2. Likewise, EG OH and EG CH_2 have the same mobility (see ESI, electronic supporting information), meaning that hydroxyl protons remain bound to the rest of the molecule as they diffuse.

Figure 2 shows the self-diffusion coefficients of the Ch^+ aliphatic protons for 10 wt% glucose, phenol and 1-pentanol as a function of fluidity (η^{-1}) achieved by varying the temperature of the solutions from 298 to 328 K. As for the trend of diffusion coefficients, it can be seen that an increase in fluidity (η^{-1}), the latter being an increasing function of temperature, leads to an increase of diffusion coefficients in all cases, which is expected, and an increase in fluidity means a decrease in liquid viscosity. The strong hydrogen bonding interactions between glucose and Ethaline increase viscosity and slow the mobility of all species being reflected in lower self-diffusion values than in other solutes in Ethaline and pure Ethaline¹² (Figure 2).

Figure 2. Self-diffusivities of Ch⁺ aliphatic species in 10 wt% glucose, 1-pentanol and phenol in Ethaline as a function of fluidity achieved by varying the temperature of the solutions from 298 to 328 K. The dashed line shows the Stokesian behavior of Ch⁺.

The use of the Stokes-Einstein model, eq 1, can help to understand diffusion mechanisms with the mixture.²¹

$$D = \frac{kT}{6\pi\eta r} \quad (1)$$

In eq 1 D is diffusivity, k is the Boltzmann constant, T is the temperature, η the viscosity, and r is the radius of the diffusing solute molecule.

Comparing the experimentally measured diffusivity of the Ch⁺ aliphatic species (Figure 2) with that expected from Stokes-Einstein calculations, i.e., theoretical line calculated for Ch⁺ using eq 1 and assuming the hard sphere radius of 3.29 Å for Ch⁺ (calculated using a Hartree–Fock model and used previously)^{12,22} it is possible to see a good correlation between the measured and calculated values for Ch⁺ for the 10 wt% glucose in Ethaline sample. This suggests that aliphatic Ch⁺ diffuses in a Stokesian manner. The validity of the Stokes-Einstein relation in describing the diffusion of Ch⁺ in the glucose-based sample indicates that Ch⁺ species tend to diffuse as isolated species in a continuous medium. This is different to that observed when 10 wt% water was added to Ethaline when a heterogeneous liquid was formed.¹²

For the two Ethaline samples containing phenol and 1-pentanol, also shown in Figure 2, Ch⁺ diffuses slower than predicted from a Stokesian model. This is similar to that experienced by aliphatic Ch⁺ in Ethaline when water was

added as a solute as shown in a previous study.¹² This suggests that the Ch^+ diffuses in a phase which is more viscous than the bulk viscosity indicating heterogeneities in the mixture, which can be ascribed to the formation of larger, slower diffusing clusters of molecules due to self-aggregation. Previously, the tendency for self-aggregation has been observed also in several ILs.^{14,23,24} Analysis of the diffusion data in Figure 2 for phenol shows that unlike the other two samples, there is a change in the slope for the Ch^+ cation diffusion trend, which occurs at about 313 K, with the values of self-diffusivity becoming significantly increasingly lower than those calculated using the Stokesian model above this temperature. This suggests that above 313 K aggregation becomes more significant and aggregates are formed relative to the behavior below 313 K. Such results can be explained by considering solvation effects. Interestingly, the melting point of phenol is 313 K and the above results could suggest that, below 313 K phenol is present in solution as a soluble solid, hence there is an effective solvation by Ch^+ leading to a more homogenous mixture. Above 313 K the phenol-chloride interactions might be weaker leading to an increase in the phenol-phenol interactions and an increase in aggregation. In simple terms, a weakening of solvent - solute interactions with increasing temperature (i.e., fluidity) favors self-aggregation of the solvent (DES) species, which becomes more significant above the melting point of the phenol solute. This also suggest that above 313 K the liquid tends to form distinct nanophases, in particular solvent-rich and solute-rich phases. The behavior of phenol in Ethaline is opposite to that observed in phenol in water mixtures, which show an upper critical solution temperature at 340 K and 33.9 wt% phenol, which is the critical point for the mixture where the two liquids become in one phase and completely miscible.²⁵

Comparing the diffusivity of Ch^+ OH and Ch^+ aliphatic, it can be seen that as fluidity increases the difference between the Ch^+ OH and Ch^+ aliphatic diffusion coefficients increases (see ESI). This behavior was not seen in pure Ethaline, as the $-\text{OH}$ diffusion of Ch^+ and EG remained the same as the aliphatic counterpart¹² indicating that in pure Ethaline there is no significant proton exchange between Ch^+ and EG. Interestingly, Ch^+ OH and EG have the same mobility in the glucose solution up to a fluidity of $0.045 \text{ mPa}\cdot\text{s}^{-1}$ (Figure 3), meaning that Ch^+ OH is apparently attached to EG below that level. However above that, the mobility of the Ch^+ OH proton increases. This indicates that glucose enhances significantly the proton mobility of the Ch^+ OH proton. This could be due to a Grotthuss mechanism, whereby protons jumps across glucose molecule *via* hydrogen-bonding facilitating proton mobility.²⁶ A Grotthuss-like proton hopping has also been observed between the ionic and neutral species in protic and pseudo-protic ILs.^{27,28} These results suggest that glucose is the best facilitator for the exchange between Ch^+ OH and EG, indicating that it tends to homogenize the liquid structuring more than 1-pentanol and phenol. The proton exchange between Ch^+ OH, EG OH and water was also seen in high water amounts in aqueous Ethaline mixtures¹².

The self-diffusivity data above appear to show that solid solutes capable of hydrogen bonding form homogeneous solutions whereas liquid solutes form more heterogeneous mixtures.

Figure 3. Self-diffusivities of different species in 10 wt% glucose in Ethaline as a function of fluidity achieved by varying the temperature of the solutions from 298 to 328 K. The dashed line shows the Stokesian behavior of Ch^+ .

Size distribution –DLS measurements

DLS was used to investigate the aggregation of solutes in Ethaline with 10 wt% solute in Ethaline samples at 298 K and 323 K. The results obtained by PFG NMR measurements suggested that solid solutes form homogeneous solutions whereas liquid solutes cluster to form nanoscale emulsions. DLS will not only confirm this but will provide information about cluster size. Viscosity and refractive index of solutions were measured before the DLS measurements, as these parameters are needed for particle size distribution calculations. The reported size distributions were obtained from the values that gave the best cumulants and distribution fits.

DLS experiments did not show any aggregates for either 10 wt% glucose in Ethaline at both temperatures and 10wt% phenol in Ethaline at 298 K confirming that the solid solutes formed homogeneous solutions. Furthermore, DLS confirmed that aggregates form when 10 wt% 1-pentanol is dissolved in Ethaline at both temperatures, and a phase difference is observed in 10 wt% phenol in Ethaline at 323 K as seen in Figure 4. It is worth mentioning that PFG NMR is more sensitive to smaller aggregates, whereas DLS to larger.²⁹ Therefore, DLS measurement might have reached its limit in the case of phenol at 298 K. In particular, the average aggregate size for 10 wt% 1-pentanol in Ethaline at both temperatures was 3.2 ± 1.0 nm, whereas for 10 wt% phenol at 323 K 1.58 ± 0.5 nm as seen in Figure 4, which is at lower sensitivity of DLS. The obtained values are significantly

smaller than the anionic surfactant sodium dioctyl sulfosuccinate aggregate sizes (38 - 45 nm) in Ethaline and its mixtures with water.³⁰ It is impossible to describe these dispersed phases to pure components but it is helpful to realize that these phases are approximately 5 to 10 molecular dimensions in diameter. These results confirmed that nanoemulsions were formed in 10 wt% 1-pentanol at both temperatures and 10 wt% phenol at 323 K. As no aggregate formation was observed in 10 wt% glucose in Ethaline solution at both temperatures, this supports the fact that glucose forms a homogenous system in Ethaline. Previous studies have shown that the solution nanostructures, solvent composition, and temperature influence on molecular self-assembly in ILs and DESs, which could be beneficial for i.e. drug-delivery, colloidal systems and biosensing.³¹⁻³³

Figure 4. Size distribution by intensity of (green) 10 wt% 1-pentanol in Ethaline at 298 K, size 3.20 ± 1.0 nm, (blue) 10 wt% 1-pentanol in Ethaline at 323 K, 3.24 ± 1.0 nm, and (red) 10 wt% phenol in Ethaline at 323 K, 1.59 ± 0.5 nm.

An illustrative scheme of the systems is presented in Figure 5. The intermolecular forces between solute and solvent particles must be strong enough to compete with those between solute particles and those between solvent particles in order to be completely soluble and miscible. It is clear that solute - solvent interactions dominate in 10 wt% glucose in Ethaline as the particles are homogeneously distributed to the liquid, and solvated by Ethaline. This is not surprising taking into account that glucose has many hydroxyl groups to form strong hydrogen bonds with Ethaline. In contrast, solute - solute interactions dominate in 10 wt% 1-pentanol in Ethaline at both temperatures as the particles are heterogeneously distributed to the liquid, and 1-pentanol cannot form as strong interaction with Ethaline as glucose. In 10 wt% phenol in Ethaline on the other hand, solute - solute, solute - solvent and solvent - solvent interactions are equally represented at 298 K, but at 323 K greater solute - solute interactions and weakened solute - solvent interactions cause larger aggregate formation.

Figure 5. Phase behavior of 10 wt% glucose, 1-pentanol, and phenol in Ethaline at 298 K and 323 K.

NOESY –solute-solvent interactions

$\{^1\text{H}, ^1\text{H}\}$ -NOESY NMR spectra were measured of all 10 wt% solutes in Ethaline and pure Ethaline to investigate the intermolecular behavior and in some extent the phase behavior.

Solute-solvent interactions in pure Ethaline

In pure Ethaline, cross-peaks showing intramolecular connectivity are observed as expected (Figure 6 b). Furthermore, it is shown that the methylene units of EG are in proximity to the aliphatic protons of ChCl and both hydroxyl protons show exchange. The individual components, ChCl and EG, show intramolecular NOE signals. Positive intermolecular NOE signals are also observed between $\text{Ch}^+ \text{OH}$ and EG CH_2 , and EG OH and $\text{Ch}^+ \text{C1 CH}_2$ proving the strong interaction of both components that form the building block of this DES.

Looking at the spectrum obtained for 10 wt% glucose in Ethaline (Figure 6 d), some similarities can be seen. EG and ChCl show intramolecular and intermolecular connectivity, meaning that the DES structure is not destroyed. In addition, a strong interaction of the glucose protons with both EG and ChCl protons is observed and are more

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3 prominent for the resonances that are further downfield shifted. The hydroxyl protons of glucose show exchange
4 with the other hydroxyl protons in the DES. Even for the aliphatic protons cross-peaks can be seen with the DES
5 hydroxyl protons, caused by the proximity of both molecules. The most evident difference is that the amount of
6 intense positive NOEs, especially intermolecular connectivity between EG and ChCl, has significantly decreased.
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8 This emphasizes the fact that 10 wt% glucose weakens the interaction between ChCl and EG, and shows a
9 homogeneous distribution between both components.
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16 10 wt% 1-pentanol in Ethaline (Figure 6 f) shows a different behavior. The dominant part of the spectrum shows
17 the inter- and intra-molecular connections between EG and ChCl as seen for pure Ethaline. Moreover, positive
18 NOE cross-peaks between ChCl and EG are observed, indicating that the strong DES-DES interactions are
19 maintained. However, this NOESY spectrum only features further cross-peaks indicating weak interactions of the
20 aliphatic chain of 1-pentanol with the methyl protons of ChCl. Exchange between all hydroxyl protons in the
21 solution can be seen as expected. Altogether this gives rise to the assumption that 1-pentanol is merely sparsely
22 interacting with the DES and shows a more heterogeneous behavior.
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Figure 6. a) NOE-interactions of EG and ChCl observed in pure Ethaline. **b)** The 2D $\{^1\text{H}, ^1\text{H}\}$ - NOESY spectrum of pure Ethaline at 298 K. The spectrum was recorded with a 500 ms mixing time and a recovery delay of 1.21 s. **c)** NOE-interactions between EG, ChCl and glucose in 10 wt% glucose in Ethaline. **d)** The 2D $\{^1\text{H}, ^1\text{H}\}$ - NOESY spectrum of 10 wt% glucose in Ethaline at 298 K. The spectrum was recorded with a 100 ms mixing time and a recovery delay of 1.13 s. **e)** NOE-interactions between EG, ChCl and 1-pentanol in 10 wt% 1-pentanol in Ethaline. **f)** The 2D $\{^1\text{H}, ^1\text{H}\}$ - NOESY spectrum of 10 wt% 1-pentanol in Ethaline at 298 K. The spectrum was recorded with a 300 ms mixing time and a recovery delay of 0.74 s. **g)** NOE-interactions between EG, ChCl and phenol in 10 wt% phenol in Ethaline. **h)** The 2D $\{^1\text{H}, ^1\text{H}\}$ -NOESY spectrum of 10 wt% phenol in Ethaline at 298 K. The spectrum was recorded with a 500 ms mixing time and a recovery delay of 1.35 s. The red and blue arrows show intermolecular connections, and no intramolecular interactions are presented here. The dashed arrows indicate the signals that cannot be determined because of overlay of signals. The ChCl-ChCl and EG-EG intramolecular NOE cross-peaks are marked with a black circle, the ChCl-EG intermolecular interactions with red, the solute-DES interactions with blue, the intramolecular solute-solute interactions with green, and intra- and intermolecular connectivity with dashed black circles.

The NOESY spectrum of 10 wt% phenol in Ethaline (Figure 6 h) shows the same basic behavior of Ethaline as already seen for the other two systems. The largest cross-peaks and thus interactions are seen between the Ethaline protons of the aliphatic chains and the exchange between the hydroxyl protons, respectively. However, in this case, a variety of other interactions with phenol can be observed. As expected, the hydroxyl proton of phenol is in exchange with the other three hydroxyl protons of the DES as indicated by the cross-peaks with the negative phase. Interestingly, the aromatic protons all show a cross-peak with the methyl groups of ChCl indicating proximity in solution. Interaction between EG and phenol on the other hand is only seen through the cross-peaks between the EG methylene and phenol OH as well as the EG OH and phenol CH in α -position. This indicates a closer relation between EG and phenol than ChCl and phenol. Regardless, all these solvent-solute signals are comparably low in intensity irrespective of the mixing time, meaning that the DES itself still dominates in its inter-molecular connectivity and phenol can be regarded as a heterogeneously dispersed solute.

Conclusions

We demonstrated that three alcoholic solutes (glucose, 1-pentanol and phenol) behave differently in Ethaline. PFG NMR measurements revealed that introduction of solute molecules to Ethaline affects the $-\text{OH}$ proton dissociation in Ch^+ , which is ascribed to glucose being the best facilitator, suggesting that it tends to homogenize the liquid structuring more than 1-pentanol and phenol. This is further supported by Stokesian behavior of the glucose sample, and with $\{^1\text{H}, ^1\text{H}\}$ -NOESY and DLS data. Larger aggregates are formed above 313 K in 10 wt% phenol in Ethaline, suggesting a melting of phenol affects the phase behavior. As glucose forms a homogenous mixture, but 1-pentanol heterogeneous phases at nanoscopic level, and phenol larger aggregates above its

melting point these findings suggest that solid solutes favor to form a homogenous mixture whereas liquid solutes heterogeneous. Most probably, the phase behavior is driven by hydrogen bonding strength between the solute and the solvent (DES), as DESs are hold together by strong hydrogen bonding. This data provides more understanding on these complex systems and aid the development of DESs as greener alternatives for non-aqueous and hazardous media. Furthermore, nanoscale clustering might be useful in designing self-assembly applications.

Supporting information

Supporting Information is available free of charge on the ACS Publications website at DOI:

Viscosity values, ^1H NMR spectra with peak assignments, PFG NMR attenuation plots, self-diffusion values and ratios.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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Abbreviations

Ch⁺, choline cation; ChCl, choline chloride; DES, deep eutectic solvent; DLS, dynamic light scattering; EG, ethylene glycol; IL, ionic liquid; PFG NMR, pulsed field gradient nuclear magnetic resonance

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Synopsis

Liquid solutes cluster in deep eutectic solvents, which are considered as green alternatives for petrol-based solvents, whereas solid solutes form homogeneous solutions.

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