Hydrotropy and Cosolvency in Lignin Solubilization with Deep Eutectic Solvents

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Supporting Information

ABSTRACT: The mechanisms responsible for the good solubility of lignin in aqueous solutions of deep eutectic solvents are here investigated using both monomer model compounds and technical lignins (kraft and organosolv). The results show the ability of deep eutectic solvents to act either as hydrotropes or cosolvents, enhancing the solubility of poorly soluble solutes (technical lignins or their monomers). Hydrotropy was shown to lead to a remarkable enhancement of organosolv lignin solubility of 474.7 ± 2.7 times using an aqueous solution of propionic acid:urea (2:1), while for the systems where the solubilization mechanism was cosolvency, the best solubility enhancement was 194.2 ± 4.1 times using ethylene glycol:tetrabutylphosphonium chloride (2:1). The solubility of kraft lignin was also enhanced using an aqueous solution of propionic acid:urea (2:1) (228.3 ± 8.2 times) and ethylene glycol:tetraethylammonium chloride (2:1) (163.0 ± 16.1 times) by the same mechanisms.

KEYWORDS: Deep eutectic solvents, Solubility, Hydrotropy, Cosolvency, Lignin monomer model compounds, Technical lignins, Biorefinery

INTRODUCTION

Lignocellulosic biomass is the most important feedstock in the biorefinery framework. However, its complexity and structural heterogeneity represent a major challenge to the development of efficient fractionation processes. A pulp and paper mill is an example of a primary lignocellulosic biorefinery, which targets cellulose fibers. Lignin is the main byproduct, which is mainly used for energy valorization. For a more sustainable and competitive pulp and paper industry, the valorization of lignin is fundamental. High-value products from isolated lignin include low-cost carbon fibers, engineering plastics and thermoplastic elastomers, polymeric foams and membranes, and a variety of fuels and chemicals.

Kraft and sulfite pulping processes are performed at high temperatures in strong alkaline and acidic media, respectively. These harsh processing conditions induce the lignin depolymerization. These technical lignins are characterized by the incorporation of sulfur into its chemical structure, which further complicates its downstream valorization. Organosolv uses a mixture of water and organic solvents in the presence or absence of catalyst and has a smaller environmental footprint and simpler solvent recovery and operates at milder conditions, producing a high-quality, sulfur-free lignin fraction. Recently, novel solvents such as ionic liquids attracted great attention. IonoSolv is a process using low-cost ionic liquids in aqueous solution to dissolve lignin and hemicelluloses, preserving the cellulose properties. Its main advantages over organosolv are higher lignin removal yield, lower solvent cost, and lower process pressure. However, this process induces significant structural changes in the lignin that may compromise its valorization.

The development of fractionation processes able to selectively extract high-purity lignin under mild conditions and to induce minimal structural degradation while achieving high lignin yield and preserving cellulose properties is imperative to achieve a complete and sustainable valorization of lignocellulosic biomass.

Recently, deep eutectic solvents (DESs) have emerged as promising alternatives for biomass fractionation. DESs are mixtures of hydrogen-bond donors (HBDs) and acceptors (HBAs) with low melting points. Francisco et al. were the first to study the solubility of alkali lignin, cellulose, and starch, in DESs combining carboxylic acids with choline chloride ([Ch][Cl]) and amino acids. They concluded that most of the selected combinations show high lignin solubility and very poor or negligible cellulose solubility. However, the best DES to solubilize lignin reported was lactic acid: [Ch][Cl] (9:1).

Other DESs were also investigated for wood fractionation [of
urea. Their signature characteristic is a sigmoidal solubilization profile; in some cases where the entire concentration range can be explored, they even display a maximum of the solubility, suggestive of cooperative intermolecular interactions involved in the solubilization process. Recent studies showed the coaggregation of the solute with the hydrotropes, above a minimum hydrotrope concentration (MHC), to be the main mechanism behind the enhanced solubilization. The MHC of a hydrotrope is considered as a measure of the stability of its aggregation form relative to its monomeric form. Thus, the lower the MHC, the greater the hydrotrope’s stability. The main advantage of hydrotropes is the quick recovery of the solute from hydro tropic solutions by simple dilution with water, followed by filtration.

Cosolvents are water-soluble compounds that can enhance the solubility of poorly aqueous, soluble hydrophobic compounds. This solubilization process, unlike that for hydrotropes, is not based on the formation of aggregates but on the solvation of the solute by a mixed solvent (water + cosolvent) with physical properties and a solvation ability that are intermediate to those of pure water and cosolvent. Depending on the nature of the solute, many different compounds may be used as cosolvents in aqueous solutions, but for poorly soluble hydrophobic compounds, ethanol, propylene glycol, glycerol, and polyethylene glycols are widely used. Most cosolvents have HBD and/or HBA groups as well as important functional groups ensuring water miscibility, while their nonpolar regions may create dispersive interactions with the solute and interfere with the water hydrogen-bonding network, reducing the overall intermolecular attraction of water. By disrupting water self-association, cosolvents reduce the ability of water to squeeze out nonpolar, hydrophobic compounds, thus increasing their solubility. The solubilization effected by cosolvent is a linear or monotonic function of its concentration. Contrary to a hydrotropic system, the solute recovery is achieved by cosolvent evaporation.

Hydrotropes and cosolvents have been used for a long time in several drug formulations, cleaning agents, and personal care products. However, in biomass processing, studies on the application of hydrotropes have been scarce when compared with the extensive use of cosolvents. Yet, DESs with hydrotropic or cosolvent behavior in aqueous media seem to hold a lot of potential to be applied in this field, where novel, greener, and more performant solvents are in great demand.

In our previous study, hydrotropy was identified as the mechanism responsible for the good performance of DES...
aqueous solutions, in the solubilization of technical (kraft and organosolv) lignins and their monomers (syringaldehyde and syringic, vanillic, and ferulic acids). This study clearly established that the solubilization of these solutes was driven by the formation of hydrotope−solute nanoaggregates. These results were in good agreement with those previously reported by Claudio et al.22 using ionic liquids as hydrotropes to enhance the solubility of phenolic compounds in aqueous solutions.

Encouraged by this previous work, the current study attempts to further expand the solubility studies of technical lignin and their monomers in DESs, in order to assess the solubilization mechanisms responsible for the high solubility of lignin in DES aqueous solutions. To achieve this purpose, the solubilities of lignin monomer model compounds (LMMCs) and technical lignins in DES aqueous solutions were investigated, and the effects of the DES components and their concentrations were studied. It is expected that the results here reported will open new perspectives for the development of biomass fractionation and lignin conversion processes, as well as processes for the fractionation/purification of aromatic compounds present in black liquor.

**EXPERIMENTAL SECTION**

**Chemicals.** Several HBDs (polyols, carboxylic acids, and ureas) and HBAs (choline chloride, ammoniums, phosphoniums, and urea) were combined to prepare DESs and were used in this work to study the effects of the HBD and HBA chemical structures on the solubilization of technical lignins. The key information about the HBDs and HBAs used is summarized in Table 1, and their structures are shown in Figure 1.

![Chemical structures of investigated HBDs and HBAs.](image)

Figure 1. Chemical structures of investigated HBDs and HBAs.

On the basis of our previous work,21 the LMMCs (syringaldehyde, as well as syringic, ferulic and vanillic acids), were used in this work to better understand the mechanisms behind the lignin solubilization in DES.

Two technical lignins were selected to study the solubilization mechanism in aqueous solutions of DESs, given the considerable influence of the isolation process on the structure of this biopolymer23,24 and consequently on their solubility: a *Eucalyptus globulus* wood ethanol organosolv lignin (kindly supplied by Lignol Innovations) and a *E. globulus* industrial kraft lignin (kindly supplied by The Navigator Co., isolated from the kraft liquor following the procedure described by Pinto et al.25).

The key information about the LMMCs is summarized in Table 2, and their chemical structures are shown in Figure 2. All technical lignins and LMMCs were used as received.

**Table 2. Lignin Monomer Model Compounds Information: Name, CAS Number, Molecular Weight, Mass Fraction Purity, and Supplier**

<table>
<thead>
<tr>
<th>LMMC</th>
<th>CAS number</th>
<th>MW/g mol−1</th>
<th>purity/wt %</th>
<th>supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>syringaldehyde</td>
<td>134-96-3</td>
<td>182.17</td>
<td>98</td>
<td>Acros Organics</td>
</tr>
<tr>
<td>vanillic acid</td>
<td>121-34-6</td>
<td>168.15</td>
<td>97</td>
<td>Acros Organics</td>
</tr>
<tr>
<td>syringic acid</td>
<td>530-57-4</td>
<td>198.117</td>
<td>&gt;98</td>
<td>Acros Organics</td>
</tr>
<tr>
<td>ferulic acid</td>
<td>1135-24-6</td>
<td>194.18</td>
<td>&gt;99</td>
<td>Acros Organics</td>
</tr>
</tbody>
</table>

**DES Preparation.** The DES families investigated in this study (Table 3) were prepared following the procedure described by Soares et al.21

**Solubility of LMMCs in DESs.** The solubility assays of LMMCs in DESs (neat or in aqueous solutions) was carried out following the methodology previously described by Soares et al.21 The amount of LMMC (syringaldehyde and ferulic, syringic, and vanillic acids) was quantified by UV−vis spectroscopy using a T60UV−Visible spectrometer (PG Instruments Ltd), at a wavelength of 306, 313, 265, and 252 nm, respectively, using calibration curves [see Figure S5 and Table S3 of the Supporting Information (SI)].

When pure water was used, due to its low solubility, the amount of dissolved lignin in samples was quantified by UV−vis spectroscopy, following a previously reported methodology,21 at a wavelength of 280 nm using the calibration curve of alkali lignin (supplied by Sigma-Aldrich) (see Figure S5 and Table S3, SI).
RESULTS AND DISCUSSION

To investigate the solubilization mechanisms responsible for the good performance of DES aqueous solutions in lignin solubilization, the solubilities of LMMCs and technical lignins were evaluated, and the effect of the DES components and their concentration was studied.

Effect of DES Components and Concentrations on the Solubilization of LMMCs. Several families of DESs were prepared by combining HBDs (carboxylic acids, polyols, and U) with HBAs ([Cl]Ch, [P4444]Cl, and U) at a molar ratio that results in a liquid DES at room temperature, aiming to study the effects of HBDs and HBAs on the solubilization mechanism of LMMCs. Due to the good performance of LA:[Ch]Cl (10:1) to solubilize lignin, as reported by some authors, this mixture was also studied for comparative purposes instead of the LA:[Ch]Cl (2:1) reported in our previous work. The HBA [P4444]Cl was here selected due to the recognized capacity of phosphonium-based ionic liquids to dissolve lignin. The effect of DES concentration in aqueous solution was studied in the entire concentration range, from pure water to neat DES, at 323.15 K. The influence of DES components and concentrations on the LMMC solubility is illustrated in Figures 3 and 4. The detailed solubility values and the respective standard deviations are reported in Table S4 (SI). In Figures 3 and 4, the S and S0 represent the solubility (mg g⁻¹) of LMMCs in the aqueous solutions of DESs and in pure water, respectively. Therefore, the S/S0 ratio represents the solubility enhancement due to the use of a DES. The

Table 3. List of DES Families Investigated and the Respective Molar Ratio

<table>
<thead>
<tr>
<th>DES families</th>
<th>molar ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carboxylic Acids</td>
<td></td>
</tr>
<tr>
<td>FA:[Ch]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>LA:[Ch]Cl</td>
<td>10:1</td>
</tr>
<tr>
<td>PA:[Ch]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>PA:U</td>
<td>2:1</td>
</tr>
<tr>
<td>BA:U</td>
<td>2:1</td>
</tr>
<tr>
<td>PTSA:[Ch]Cl</td>
<td>1:1</td>
</tr>
<tr>
<td>Polyols</td>
<td></td>
</tr>
<tr>
<td>G:[Ch]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>EG:[Ch]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>EG:[N1111]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>EG:[N2222]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>EG:[N3333]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>EG:[N4444]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>EG:[P4444]Cl</td>
<td>2:1</td>
</tr>
<tr>
<td>Reference</td>
<td>2:1</td>
</tr>
</tbody>
</table>

Figure 3. Hydrotropic behavior of DESs in aqueous solutions for the solubilization of LMMCs at 323.15 K. See the secondary axis for EG:[P4444]Cl (2:1) in ferulic acid and U:[Ch]Cl (2:1) in syringaldehyde and syringic and vanillic acids.
Two different solubility behaviors of the LMMCs can be observed in these figures. While the results grouped in Figure 3 for the DESs PA:[Ch]Cl (2:1), U:[Ch]Cl (2:1), PTSA:[Ch]Cl (1:1), and EG:[P4444]Cl (2:1) present a nonmonotonic solubility enhancement with the DES concentration, with a maximum at intermediate DES concentrations, those in Figure 4 present a monotonic increase of solubility from the water to the neat DES.

Figure 3 shows that aqueous solutions of PA:[Ch]Cl (2:1), U:[Ch]Cl (2:1), PTSA:[Ch]Cl (2:1), and EG:[P4444]Cl (2:1), at concentrations of 50 and 75 wt %, seem to allow the best solubility enhancement of the LMMCs. The shape of these curves, with maxima at intermediate DES percentages, suggest that the solubility of these monomer model compounds is being driven by a hydrotropic mechanism. A similar behavior was previously reported by us for the solubility of these compounds in aqueous solutions of PA:U (2:1) as well as for the solubility of phenolic compounds in aqueous solutions of ionic liquids, reported by Claudio et al. Furthermore, the sigmoidal profile of hydrotropy observed in Figure 3 for vanillic acid solubility in aqueous solutions of EG:[P4444]Cl (2:1) and for ferulic acid in aqueous solutions of PTSA:[Ch]Cl (1:1) is suggestive of a cooperative intermolecular interaction being involved in the solubilization process, as reported by Balasubramanian et al. This group of DESs demonstrated to have a higher ability to enhance the solubility of the most hydrophobic compounds, i.e., ferulic acid, considering the chemical structures of these LMMCs and their poor solubility in water. The hydrophobicity of the phenolic acids follows the sequence ferulic acid (increase the alkyl chain length) > syringic acid (presence of two methoxy groups) > vanillic acid (one methoxy group). Regarding the DES components, it is possible to observe that EG:[P4444]Cl (2:1) has the highest ability to increase the solubility of LMMC, followed by PA:[Ch]Cl (2:1), PTSA:[Ch]Cl (1:1), and U:[Ch]Cl (2:1). The aqueous solution of EG:[P4444]Cl (2:1) at 50 or 75 wt % enhanced the solubilities of ferulic, syringic, and vanillic acids and syringaldehyde by (202.5 ± 16.9), (116.6 ± 1.6), (59.3 ± 2.5), and (34.9 ± 6.7)-fold, respectively. This pattern reflects the effects of the HBDs and HBAs chemical structures in the DESs through their ability to act as hydrotropes. These results suggest that the dispersive interactions between the nonpolar moiety of the HBDs and the lignin monomer structure are the main reason for the good performance of PA, instead of the hydrogen bond interactions and π···π interactions from the aromatic moiety in PTSA and the polar character of polyols, as previously reported. As for the HBA, the higher ability of [P4444]Cl to act as a hydrotrope when compared with [Ch]Cl was previously demonstrated by Claudio et al. Bauduin et al. suggested that the volume fraction of the nonpolar moiety of the hydrotrope in water positively correlates with the ability to enhance the solubility of poorly water-soluble compounds. This seems to be in accordance with the results observed in this work.

The EG:[P4444]Cl (2:1) aqueous solutions demonstrated an impressive ability to solubilize LMMCs. However, the ability of U:[Ch]Cl (2:1) to solubilize syringaldehyde and syringic and vanillic acids seems to be weaker. Finally, PA:[Ch]Cl (2:1) and PTSA:[Ch]Cl (1:1) only showed hydrotrropic capability to solubilize syringaldehyde and ferulic acid, respectively. This suggests that DESs can be chosen to selectively dissolve target groups of compounds from complex mixtures.

A different solubility behavior is observed for the DES systems reported in Figure 4. Again, the solubility of syringaldehyde and syringic, ferulic, and vanillic acids is shown to depend not only on the DES components but also on their concentration. The most important point that emerges from Figure 4 is that the solubilization induced by these DESs {LA:[Ch]Cl (10:1), FA:[Ch]Cl (2:1), PA:[Ch]Cl (2:1), PTSA:[Ch]Cl (1:1) and EG:[Ch]Cl (2:1)} is a monotonic function of their concentration, being maximal for the neat
DES, as typically observed in the cosolvency mechanism.30 The solubilization of LMMCs by these five DESs with cosolvent behavior could be ranked in the following order: PA:[Ch]Cl (2:1) > EG:[Ch]Cl (2:1) > PTSA:[Ch]Cl (1:1) > FA:[Ch]Cl (2:1) > LA:[Ch]Cl (10:1). This pattern reflects the effects of the HBDs chemical structure on their ability to act as cosolvents and the interactions with the LMMCs. The neat PA:[Ch]Cl (2:1) and EG:[Ch]Cl (2:1) enhanced the ferulic solubility by (85.4 ± 0.8)- and (82.0 ± 2.1)-fold, respectively. The studied DESs demonstrated a much lower ability to solubilize syringaldehyde, even if PA:[Ch]Cl (2:1) could enhance its solubility by more than 20 times by hydrotropy, as discussed above. The same behavior was observed for PTSA:[Ch]Cl (1:1), where hydrotropy seems to be the favored mechanism in the solubilization of ferulic acid.

The results hitherto reported reveal that two different solubilization behaviors, here interpreted as hydrotropy or cosolvency, are responsible for the good solubility of LMMCs in DESs. The solubility behaviors observed are independent of temperature, as shown in Figures S6 and S7 and Tables S5 and S6 (SI), in agreement with our previous studies.21

Additionally, it is important to highlight the excellent performance of DES aqueous solutions in the solubilization of LMMCs by a hydrotropy mechanism that may improve the solubility of these model compounds by 2 orders of magnitude when compared with water. On the other hand, given the selective character of DESs to solubilize aromatic aldehydes and acids (by hydrotropy or cosolvency solubilization mechanisms) and the possibility to recover these compounds by using water as antisolvent, these results open new promising pathways for the fractionation of phenolic compounds from pulp industry black liquors, where the selective recovery and separation of these compounds is an important challenge in the biorefinery framework.31

### Effect of DES Components and Concentration on Solubilization of Technical Lignins.

On the basis of the results of LMMC solubility in DES aqueous solutions reported above, the solubility of kraft and organosolv lignins in DES aqueous solutions was investigated at 353.15 K. Several DESs were prepared combining HBDs (carboxylic acids, polyols, and U) with HBAs ([Ch]Cl, [N3333]Cl, [P4444]Cl, and U) at a molar ratio that results in a liquid DES at room temperature, aiming to study the effects of HBDs and HBAs on the solubilization of technical lignins. In this study, it was decided to include also an ammonium-based DES to compare with phosphonium- and choline-based DESs. On the basis of our preliminary study of technical lignin solubility in neat DES at 353.15 K, we selected the [N3333]Cl to assess the solubilization mechanism induced by this HBA combined with EG to enhance the solubility of technical lignins (see Figure S8 and Table 4).
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acssuschemeng.9b02109.

The method to quantify the technical lignin solubility in DES (calibration curve and statistical analysis); the calibration curves of lignin monomer model compounds and alkali lignin in water at 298.15 K; the experimental solubilities of lignin monomer model compounds in different DES aqueous solutions at 323.15 K; the experimental solubilities of lignin monomer model compounds in FA:[Ch]:Cl (2:1) and EG:[Ch]:Cl (2:1) at different concentrations in aqueous solution and three temperatures; the experimental solubilities of kraft and organosolv lignins in polyols-based DES at 353.15 K; the experimental solubilities of kraft and organosolv lignins in different neat DES at 353.15 K; the experimental solubility of kraft and organosolv lignins by different solubility mechanisms. Furthermore, FA:[Ch]:Cl (2:1) and EG:[Ch]:Cl (2:1) also present good performances, enhancing the solubility of organosolv lignin by (190.8 ± 23.0)- and (172.9 ± 22.4)-fold, respectively. Finally, we again observe that the profiles of the hydrotrropy and cosolvency mechanisms are independent of temperature [see Figures S9 and S10 and Tables S9 and S10 (SI) and the results reported in our previous work\textsuperscript{14}].

**CONCLUSIONS**

This work attempts to know the solubilization mechanisms responsible for the good performance of DES aqueous solutions in lignin solubilization using LMMCs and technical lignins. Considering the complex chemical structure of lignin, it seems to be possible, through the evaluation of LMMCs, not only to predict the performance of DESs (neat or in aqueous solution) in the lignin solubilization but also to demonstrate the mechanisms that rule their solubilization.

Regarding the lignin monomer model compounds (syringaldehyde and syringic, vanillic, and ferulic acids), a maximum solubilization was achieved using EG:[P\textsubscript{4444}]:Cl (2:1) aqueous solution at 50 or 75 wt % of concentration and 323.15 K \(([34.9 ± 6.7]-, [116.6 ± 1.6]-, [86.8 ± 0.4]-, \text{and} [202.5 ± 16.9]-)\)-fold, respectively driven by the hydrotrropy mechanism. Furthermore, the impressive ability of PA:U (2:1) aqueous solution at 50 wt % and neat EG:[N\textsubscript{3333}]:Cl (2:1) to solubilize kraft lignin at 353.15 K, driven by different solubilization mechanisms, hydrotrropy and cosolvency, respectively (\((228.3 ± 8.2)-\) and (163.0 ± 16.1)-fold, respectively), were here identified. Additionally, remarkable improvement of organosolv lignin solubility was achieved by PA:U (2:1) aqueous solutions at 75 wt % of \((474.7 ± 2.7)-\)fold, by hydrotrropy, and of \((194.2 ± 4.1)-\)fold using the pure EG:[P\textsubscript{4444}]:Cl (2:1), by cosolvency. In summary, these results show the capability of DESs to act as hydrotrops or cosolvent, selectively enhancing the solubility of poorly soluble solute depending on the DES components and solute hydrophobicity. These studies provide a new understanding of lignin solubilization mechanisms in DES aqueous solutions and demonstrate that DESs are promising solvents to apply in biomass processing, as well as novel solvents for the selective extraction of aromatic compounds present in black liquor, aiming at their future valorization.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acssuschemeng.9b02109.
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