Assessing Solute Partitioning in Deep Eutectic Solvent-Based Biphasic Systems Using COSMO-RS

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Deep Eutectic Solvents (DES)

Choline chloride

302 °C

Tm(A)

T °C

A

x_B /-

B

I

monophase: liquid

II

biphasic: solid-liquid

III

biphasic: solid-liquid

below -60 °C

IV

biphasic: solid A – solid B

Levulinic acid

33 °C

Tm(B)

Hydrogen bond acceptor (HBA)

Hydrogen bond donor (HBD)

Possible HBA and HBD:

alcohols, polyols, carboxylic acids, sugars, amides, ammonium salts

Choline chloride-levulinic acid (CLA)

HBA:HBD = 1:2 mol:mol

Image: Ullah et al., 2015
Why Use Deep Eutectic Solvents?

- Inexpensive starting material
- High solvation capacity
- Low vapor pressure
- Non-flammable, non-toxic
- Tunable physical properties
- Easy preparation

Application in separation technology
- Selection of suitable DES difficult
- Large number of possible combinations

Objective
- Screening procedure for DES
- Example: centrifugal partition chromatography
Centrifugal Partition Chromatography

Liquid-liquid equilibrium

\[ x_i^1 \gamma_i^1 = x_i^{II} \gamma_i^{II} \]

- \( \gamma_i \): activity coefficient of compound \( i \)
- \( x_i \): mole fraction of component \( i \)

Partition coefficient

\[ P_i = \frac{c_{i,SP}^{MP}}{c_{i,MP}} = \frac{x_i^{SP}}{x_i^{MP}} \frac{\nu^{MP}}{\nu^{SP}} = \frac{\gamma_i^{\infty,SP}}{\gamma_i^\infty} \frac{\nu^{MP}}{\nu^{SP}} \]

- \( \gamma_i^{\infty} \): limiting activity coefficient of solute \( i \)
- \( \nu \): molar volume of the phase
Centrifugal Partition Chromatography

Liquid-liquid equilibrium

\[ x_i^I \gamma_i^I = x_i^{II} \gamma_i^{II} \]

\( \gamma_i \) activity coefficient of compound \( i \)

\( x_i \) mole fraction of component \( i \)
Selection of a DES-Based Biphasic System

Selection of suitable DES:
- HBA
- HBD
- Molar ratio

Selection of biphasic system:
- Alkanes
- Alcohols
- Nitriles
- ...

Biphasic system composition:
- Log $P_i$ between -0.4 and 0.4
- Separation factor

Best candidates from screening:
- Measurement of $P_i$

Selection of process parameters

DES with low phase transition temperature
Model-based solvent screening
DES-based biphasic solvent systems
Exp. validation of best candidate
CPC-separation
Representation of DES Molecules

Electroneutral mixture

Ion pair

\[ \nu_{HBA^+} = \nu_{HBA^-} \]
\[ \nu_{HBA^+} \cdot \nu_{HBA^-} = \nu_{HBD} \]

Equimolar mixture of fully dissociated ions
\( \rightarrow \) ions of HBA are calculated separately

Geometry optimization of
the ion pair (HBA)

Parametrization

- TZVP \( \rightarrow \) triple-zeta valence polarized basis set
- TZVPD-FINE \( \rightarrow \) new h-bond term and fine grid for the construction of cavities
Limiting Activity Coefficients

Choline chloride - glycerol 1:2 mol:mol; Elec. – electroneutral; Ps. C. – DES scaled to pseudo compound definition

- Reliable prediction of limiting activity coefficients with TZVPD-FINE
- Scaling depends on experimental definition

Experimental data taken from Verevkin et al., Industrial & Engineering Chemistry Research, 2015, 54(13):3498-504
Selection of Solvent Combinations

Example DES: L-menthol - levulinic acid 1:1 mol:mol

- DES + solvent = 2 liquid phases
- DES + solvent = miscible
Prediction of Liquid-Liquid Equilibria

n-Heptane/ ethanol/ choline chloride – levulinic acid 1:2 mol:mol (CLA)

- Prediction of 12 LLE
- 2 Parameterizations
- 2 Approaches for molecular representation

→ Good agreement of experiment and predicted values


Bezold et al., 2017, Fluid Phase Equilib. 437; 23–33.
Partition Coefficients of Natural Compounds

N-Heptane/ethanol/CLA, 30/40/30 wt/wt/wt

- Model validation with G.U.E.S.S.-mix components
- Trend of solute distribution could be reproduced
- Highest deviations for very polar or non-polar compounds
- Good agreement for partition coefficients within the „sweet spot“ (-0.4 < \( \log P_i \) < 0.4)

\[ \text{Arbutin, Caffeine, Vanillin, Coumarin, R-carvone, Naringenin, } \beta\text{-ionone, Retinol, } \alpha\text{-tocopherol} \]

\[ \text{Experimental, Ion pair TZVPD-FINE, Electroneutral TZVPD-FINE, Ion pair TZVP, Electroneutral TZVP} \]

Separation of Tocopherols - Screening

 Selected biphasic system

30/40/30 wt/wt/wt

37.5/25/37.5 wt/wt/wt

α-tocopherol
β-tocopherol
γ-tocopherol
δ-tocopherol

"sweet spot"
Separation of Tocopherols - Experiment

- Tocopherols are separated due to their different H-bond interaction with the DES
- High solubility in the solvent system

n-Heptane/ethanol/CBD (30/40/30 wt/wt/wt)

- Descending mode
- flow rate 20 ml min$^{-1}$
- $c_{\alpha\text{-toc}} = c_{\gamma\text{-toc}} = 36$ g l$^{-1}$
- $V_{\text{injection}} = 2$ ml
Conclusion

✓ DES have high potential for application in separation technology and were successfully applied in CPC
✓ Prediction quality of COSMO-RS for studied systems sufficient for solvent screening
✓ Screening method successfully applied to tocopherol separation

Outlook

• Prediction of solid-liquid equilibria (poster Ahmad Alhadid)
• DES mainly located in one phase of biphasic system (extraction), for CPC systems with DES in both phases are possible
• Modelling as quaternary systems with variable HBA:HBD ratio
Thank you for your attention!

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