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### **Review Article**

## **Deep Eutectic Solvents and Their Applications as Green Solvents**

### Suhail Shaikh\*

St. Xaviers College, Ahmedabad.

ARTICLE INFO	ABSTRACT
Published: 27 Mar. 2025 Keywords: DES biomass, cross coupling reactions, biocatalyst. DOI: 10.5281/zenodo.15097697	Several examples demonstrate the effectiveness of Deep Eutectic Solvents (DESs) as eco-friendly alternatives to traditional volatile organic compounds (VOCs) in polar organometallic chemistry, as well as in metal- and bio-catalyzed processes. Beyond their environmental benefits, the use of DESs in these areas has revealed new reactivity features with practical significance that merit detailed mechanistic exploration. Specifically: (a) metal-mediated organic transformations can be carried out in DESs, often at room temperature and in air, without being hindered by protonolysis; (b) metal- catalyzed reactions are more efficient and occur under milder conditions in DESs compared to VOCs, with both the catalyst and DES being easily recycled; and (c) biocatalysts tend to show improved stability, selectivity, and performance in DES mixtures compared to aqueous solutions, with a notable and intriguing effect on

stereoselectivity.

### **INTRODUCTION**

From a thermodynamic perspective, the term "deep" in deep eutectic solvents (DESs) should technically apply only to mixtures with an eutectic point significantly lower than that of an ideal liquid mixture. DESs are typically binary or ternary systems consisting of a hydrogen bond donor and a hydrogen bond acceptor, which form strong hydrogen bonds that reduce the lattice energy and lower the melting point. Some DESs don't have a distinct melting point, showing glass transitions instead, and are referred to as lowtransition-temperature mixtures (LTTMs). DESs are often compared to ionic liquids (ILs) due to similar properties, like low vapor pressure, high thermal stability, non-flammability, and However, conductivity. DESs are more environmentally friendly, as their componentssuch as choline chloride, urea, and glycerol-are renewable, biodegradable, and low in toxicity. From a thermodynamic perspective, the term "deep" in deep eutectic solvents (DESs) should technically apply only to mixtures with an eutectic point significantly lower than that of an ideal

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\*Corresponding Author: Suhail Shaikh Address: St. Xaviers College, Ahmedabad. liquid mixture. DESs are typically binary or ternary systems consisting of a hydrogen bond donor and a hydrogen bond acceptor, which form strong hydrogen bonds that reduce the lattice energy and lower the melting point. Some DESs don't have a distinct melting point, showing glass transitions instead, and are referred to as lowtransition-temperature mixtures (LTTMs). DESs include eutectic mixtures of Lewis or Brønsted acids and bases, which can contain various ionic species. DESs are often compared to ionic liquids (ILs) due to similar properties, like low vapor pressure, high thermal stability, non-flammability, and conductivity. However, DESs are more environmentally friendly, as their componentssuch as choline chloride, urea, and glycerol-are

renewable, biodegradable, and low in toxicity. DESs are increasingly replacing volatile organic compounds (VOCs) due to their low ecological cost-effectiveness. customizable impact, properties, and ease of preparation. However, the exact structure of DESs in their liquid state is still not well understood. Hydrophilic DESs, in particular, are notable for their strong hydrogenbonding networks and the role water plays in modifying their structure and interactions with biological macromolecules like proteins and nucleic acids. Initially studied for metal electrodeposition and extraction processes, DESs have gained attention in areas such as solar energy, photosynthesis, and electrochemistry.



**Figure 1.** Structure of some hydrogen-bond acceptors and hydrogen-bond donors commonly used for DESs preparation.

### 2. Properties of Des

Choline chloride (CHCL), commonly used as a hydrogen bond acceptor (HBA), forms deep eutectic solvents (DESs) when combined with various hydrogen bond donors (HBDs). For example, ChCl (melting point 303°C) and urea (134°C) form a DES at a mole ratio of 1:2, with a eutectic point of 12°C. Other combinations, such as ChCl with fluoride, nitrate, and tetrafluoroborate, also form DESs with urea at the same ratio, yielding eutectic points of 1°C, 4°C, 12°C, and 67°C, respectively. The trend in these eutectic temperatures ( $F^- > NO_3^- > Cl^- > BF_4^-$ )



indicates a correlation with the strength of hydrogen bonds. DESs formed by ChCl and different dicarboxylic acids. For instance, ChCl combined with oxalic acid (melting point 190°C), malonic acid (135°C), and succinic acid (185°C) at a 1:1 mole ratio resulted in eutectic points of 34°C, 10°C, and 71°C, respectively. Interestingly, the findings show that the eutectic point is not necessarily related to the alkyl chain length of the dicarboxylic acid, suggesting that the DES formation may involve complex interactions, such as a 1:1 complex between the acid and chloride ion or bridging between adjacent chloride ions. Choline chloride (ChCl) can form deep eutectic solvents (DESs) with phenolic compounds such as phenol, o-cresol, and 2,3-xylenol. At a ChCl to HBD mole ratio of 1:3, the eutectic point (EP) temperatures for these combinations are -20°C, -23°C, and 17°C, respectively. These phenolic compounds act as hydrogen bond donors (HBDs) by interacting with the chloride ions in ChCl. However, the varying lattice energies of the resulting DESs lead to different freezing points for each mixture.



Fig. Two-component T-x phase diagram with a eutectic point and DES (liquid)

# **3.** Applications of DESs in polar organometallic chemistry

Polar organometallic compounds, particularly those from the s-block (like Grignard and organolithium reagents), are frequently employed in both academic and industrial chemical synthesis. However, their strong basicity, high kinetic reactivity, and extreme sensitivity to air and moisture require the use of strict conditions. Traditional processes involve anhydrous, aprotic volatile organic compounds (VOCs), inert atmospheres, and very low temperatures (often -78°C or lower), leading to higher production costs and environmental concerns. The nucleophilic addition of organolithium compounds to nonactivated imines and nitriles has been shown to be highly effective and chemoselective, occurring at room temperature with vigorous stirring, without the need for an inert atmosphere. This reaction can take place in water or bio-based solvents like 1ChCl/2Gly (a mixture of choline chloride and glycerol), leading to high yields (up to over 99%) of amines, tertiary carbinamines, and ketones.





Additionally, organolithium-initiated anionic polymerization of olefins such as styrene and vinylpyridines has been successfully carried out in DESs like 1ChCl/2Gly under aerobic conditions, producing polyolefins with yields as high as 90% and low polydispersities. The combination of cyclopentyl methyl ether (CPME) with DES was crucial for achieving regioselective reactions like THF-directed ortho-lithiation and lateral lithiation of aryl- and o-tolyltetrahydrofuran derivatives, yielding functionalized diaryltetrahydrofurans and primary alcohols. Moreover, the same solvent system was used to program fast directed ortho metalation (DoM) or nucleophilic acyl substitution (SNAc) reactions on aromatic carboxylic acid amides, leading to the formation of functionalized amides and ketones.

Deep eutectic solvents (DESs) have garnered significant attention as reaction media for transition metal-catalyzed cross-coupling reactions due to their ability to facilitate these reactions under milder conditions while allowing for the recycling of both the catalyst and solvent, enhancing the process's sustainability.

• For example, in the Suzuki–Miyaura (SM) coupling reaction, phenyl boronic acid reacts efficiently with aryl bromides and iodides in ChCl-based DESs when combined with specially designed phosphine ligands and PdCl<sub>2</sub>. This same PdCl<sub>2</sub>-phosphine ligand combination has also proven effective in promoting Heck and Sonogashira coupling reactions in DESs.0

## 4. Applications of DESs in metal-catalysed reactions





• The 1ChCl/2Gly mixture has proven to be an effective reaction medium for chemoselective, ligand-free Suzuki-Miyaura (SM) couplings involving various (hetero)aryl halides (Cl, Br,

I). In this process, mono- and bifunctional aryltrifluoroborates serve as nucleophiles instead of boronic acids. The reactions are conducted in air under mild conditions.



 Hiyama-type cross-coupling reactions involving aryl halides and various organosilanes have been successfully conducted in either a biomass-derived eutectic mixture like 1ChCl/2Gly or in Gly, using an engineered NCN-pincer-Pd complex as the catalyst. This catalytic system can be effectively recycled up to three times in a deep eutectic solvent (DES), and the reactions have also been scaled up to gram quantities. Experimental findings suggest that the mechanism operates through a Pd(II)/Pd(IV) catalytic cycle.



5. Absorption of acidic gases

• SO<sub>2</sub> Apsorbtion

ChCl and glycerol can form a series of deep eutectic solvents (DESs) that effectively absorb SO2, with the absorbed SO2 easily desorbing afterward. The DES with a ChCl to glycerol mole ratio of 1:1 demonstrates the highest SO2 absorption capacity of 0.678 g·g<sup>-1</sup> at 20 °C and 0.1 MPa of SO2. The absorbed SO2 can be recovered at 50 °C under an N2 flow, allowing for the regeneration of the DES. However, NMR analysis shows that the interaction between SO2 and the DES is physical, indicating that it may not be suitable for removing SO2 at low concentrations. Four ChCl-based DESs and found that the ChCl+thiourea DES had the highest absorption capacity of 2.96 mol·mol<sup>-1</sup> at 20 °C and 0.1 MPa of SO2. Deep eutectic solvents (DESs) formed 1-ethyl-3-methylimidazolium from chloride (EMIMCl) and ethylene glycol (EG) in various mole ratios have been tested for SO2 capture. The results showed that the SO2 absorption capacity increased with higher EMIMCl content, with a DES having an EMIMCl to EG mole ratio of 2:1 capturing 1.15  $g \cdot g^{-1}$  at 20 °C and 0.1 MPa of SO2. These DESs can effectively absorb high concentrations of SO2 due to physical interactions. However, since SO2 concentrations in flue gas are much lower (around 0.2% by volume), there is a need to develop functional DESs that can chemically interact with SO2 for effective capture in low-concentration scenarios.



Fig. 2 The proposed mechanism of SO<sub>2</sub> absorption by L-car+EG DES.

### CO<sub>2</sub> Absorption

The solubility of CO2 in deep eutectic solvents (DESs) composed of ChCl and urea was studied at temperatures between 40 °C and 60 °C and CO2 pressures up to 13 MPa. The DES with a ChCl to urea mole ratio of 1:2 demonstrated the highest absorption capacity, with minor enthalpy changes indicating that the absorption process is exothermic. In 2013 ChCl-based DESs with glycerol at a mole ratio of 1:2, measuring CO2 solubility at temperatures from 30 °C to 70 °C and pressures up to 6.3 MPa, finding a CO2 solubility of 4.0% (mass fraction) at 30 °C and 1.22 MPa. CO2 solubility in DESs formed with ChCl and various hydrogen bond donors (HBDs) like ethylene glycol, glycerol, and malonic acid ChCl

and lactic acid at a 1:2 mole ratio, achieving a CO2 absorption of 0.71% (w) at 30 °C and 1.655 MPa, significantly lower than that of the ChCl+urea DESs, though the ChCl+lactic acid DESs exhibited greater stability. CO2 solubility in ChCl with levulinic acid and furfuryl alcohol, calculating the Gibbs free energy, enthalpy, and entropy of dissolution. Three types of guaiacolbased DESs, measuring CO2 solubility at temperatures from 20 °C to 50 °C and pressures up to 600 kPa. The CO2 absorption in these DESs is primarily physical and follows Henry's law. Deep eutectic solvents (DESs) composed of ChCl, glycerol, and 1,5-diazabicyclo[4.3.0]-non-5-ene (DBN) in a mole ratio of approximately 1:2:6 were studied for CO2 solubility, achieving about 10  $g \cdot g^{-1}$  at 0.1 MPa of CO2. Additionally, due to the



volatility of monoethanolamine (MEA), researchers created ChCl+MEA DESs, finding that a DES with a ChCl to MEA mole ratio of 1:6 could absorb  $0.075 \text{ g} \cdot \text{g}^{-1}$  at 25 °C and 1.0 MPa of CO2.

### **6.** Extraction of sulfur-contained compounds

Organic sulfides in fuels are a major source of pollution, leading to the implementation of strict environmental regulations to limit sulfur content. As a result, desulfurization of fuels has emerged as a critical scientific challenge requiring urgent attention. Efficient removal of sulfur compounds from fuel oils is essential. Deep eutectic solvents (DESs) have gained significant interest for this purpose due to their inexpensive and readily available raw materials, higher extraction efficiencies, and straightforward, eco-friendly synthesis processes. ChCl, tetramethylammonium chloride (TMAC), and tetrabutylammonium chloride (TBAC) were used as hydrogen bond acceptors (HBAs), while various compounds such malonic (MA), glycerol as acid (Gly), tetraethylene glycol (TEG), ethylene glycol (EG), polyethylene glycol (PEG), and propionate (Pr) served as hydrogen bond donors (HBDs). Under optimal conditions, the extraction efficiency of the TBAC+PEG deep eutectic solvent can reach up to 82.8%, significantly surpassing that of traditional and functionalized ionic liquids. After five extraction cycles, the efficiency can rise to 99.5%. Furthermore, the sulfur content in fuels can be reduced to less than 8.5  $\mu g \cdot g^{-1}$ , achieving deep desulfurization. Deep eutectic solvents (DESs) offer a promising approach for deep extraction desulfurization of fuels due to their low-cost and readily available materials, raw high desulfurization efficiencies, eco-friendly characteristics, and insolubility in fuels. The formation of hydrogen bonds between DESs and sulfur-containing compounds contributes significantly to their high desulfurization effectiveness.

# 7. Extraction of nitrogen compounds from fuel oils

The removal of nitrogen compounds (Ncompounds) from fuels has garnered significant interest due to the need to reduce nitrogen oxide emissions and enhance sulfur removal. The denitrogenation of fuels using deep eutectic solvents (DESs) as extractants, such as ChCl+urea, ChCl+malonic acid, and ChCl+phenylacetic acid, has shown promise. The ChCl+phenylacetic acid DES in a 1:2 mole ratio exhibited the best denitrogenation performance, effectively removing both basic and non-basic nitrogen compounds simultaneously. Without involving chemical reactions, the extraction efficiencies for pyridine and carbazole at 35 °C with a 1:1 DES to oil mass ratio were 99.2% and 98.2%, respectively, outperforming conventional solvents. The extraction efficiency was stable, showing little sensitivity to variations in the DES to oil mass ratio and temperature, and it remained consistent even after four regeneration cycles. The TBAB+EG and tetrabutylphosphonium bromide deep eutectic (TBPB)+EG solvents were synthesized in a molar ratio of 1:2 and utilized to extract pyrrole, pyridine, indoline, and quinoline from a model diesel compound, n-hexadecane. Besides their "green solvent" properties, these findings collectively highlight the significant potential of deep eutectic solvents (DESs) as effective materials for the denitrogenation of fuels.

# 8. Separation of aromatics and aliphatics mixtures

Aromatic compounds, commonly used in the chemical industry, are primarily derived from petroleum and coal processes and are often mixed with aliphatic compounds. Separating aromatics

from alkanes presents a significant challenge due to their similar boiling points and the formation of azeotropes. Current commercial methods for this separation typically involve liquid-liquid extraction using organic solvents like sulfolane, dimethyl sulfoxide, N-methylpyrrolidone, and Nformylmorpholine. However, these solvents are toxic, flammable, and can dissolve in the raffinate phase (the aliphatic-rich layer) during extraction. Thus, there is a pressing need for new extraction solvents to address these issues. Deep eutectic solvents (DESs) have garnered significant interest for their tunable properties, making them promising candidates for separating aromatics aromatics/aliphatics from mixtures. The TBPB+EG deep eutectic solvent can effectively separate various mixtures of benzene and hexane, with the hydrogen bond donor (HBD) EG playing a primary role and the hydrogen bond acceptor (HBA) TBPB serving a secondary role. However, achieving both high extraction rates and selectivity remains challenging. The same research group measured liquid-liquid equilibrium data for ternary systems involving toluene and heptane using TBPB+EG and TBPB+sulfolane DESs at temperatures of 40, 50, and 60 °C. This study demonstrates the potential of these DESs as solvents for separating aromatic and aliphatic mixtures. The separation of BTEX aromatics from n-octane was carried out using a TBAB+sulfolane deep eutectic solvent, with phase equilibrium data for the ternary system reported at 25 °C. Notably, there was no sulfolane detected in the oil phase, indicating a strong interaction between TBAB and sulfolane.

### CONCLUSION

This review highlights the properties of deep eutectic solvents (DESs) and their applications over the past decade. DESs share similar physical characteristics with ionic liquids (ILs), placing them in a distinct category of liquids that differs from molecular liquids. While DESs are biodegradable and easy to prepare, ILs tend to have lower biodegradation rates and more complex synthesis processes. The differences in chemical properties between DESs and ILs indicate that DESs are suited for different application areas. Their favorable properties make them ideal for efficient separations. Over the last decade, DESs have been used in various applications, including the absorption of acidic gases, extraction of bioactive compounds, removal of sulfur and nitrogen compounds from fuel oils, separation of phenolic compounds from oils, separation of aromatic and aliphatic mixtures, separation of alcohols from water, and the removal of glycerol from biodiesel. These diverse applications suggest a promising future for DESs. Despite the extensive development of various deep eutectic solvents (DESs) for separation processes, further research is still needed to advance their use. First, there is a lack of reported data in the literature regarding the physical chemistry properties of DESs, such as their behavior when extracting or absorbing acidic gases, specific heat capacity, and the heat associated with extraction or absorption. Second, the compositional flexibility of DESs enables the creation of new formulations, which can lead to enhanced properties for innovative applications, particularly in the development of functional DESs.

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