Deep Eutectic Solvents in Organic and Inorganic Transformations: Physicochemical Properties and Potential Pharmaceutical Applications

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Abstract
Background: Deep Eutectic Solvents (DESs) are emerging as alternative, environmentally friendly solvents to conventional organic solvents due to their low toxicity, biodegradability, and ease of preparation. The physicochemical properties and transformation efficiency of a choline chloride–urea deep eutectic solvent solution were evaluated in this study.
Method: The technique of DES synthesis was to blend choline chloride and urea in a 1:2 molar ratio with heat and constant stirring. Physicochemical properties measured were pH, density, viscosity, conductivity, stability and homogeneity. The esterification of ethanol and acetic acid was examined for the organic transformation, and the inorganic application was examined by solubility experiments of copper sulphate.
Result: The prepared DES formed a clear, stable, and homogeneous liquid with a pH of 6.4 ± 0.2, density of 1.18 ± 0.03 g/cm³, viscosity of 42.5 ± 2.1 cP, and conductivity of 3.8 ± 0.4 mS/cm. The viscosity decreased with increasing temperature, indicating enhanced molecular mobility. Compared with the conventional aqueous medium, the prepared DES reduced the esterification reaction time from 70 ± 5 min to 35 ± 3 min. In the inorganic application, the DES exhibited improved copper sulphate solubility (96.2 ± 2.1%) and better solution homogeneity than distilled water.
Conclusion: Choline chloride–urea DES is a stable, effective and sustainable green solvent with potential uses in organic synthesis, inorganic transformations, and green chemical procedures, according to the study.
Keywords: *Deep Eutectic Solvent; Green Chemistry; Choline Chloride; Esterification; Copper Sulphate.*
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1. Introduction

Deep eutectic solvents (DESs) have gained popularity recently as green solvents because of their ease of synthesis, structural designability, and environmental friendliness [1]. DESs have been used for mixture separation and absorption. A deep eutectic is a eutectic mixture made up of compounds (typically one or both solids) in which the eutectic temperature is much lower than what would be expected based on perfect solution theory and the known enthalpies of fusion of the pure compounds [2]. Hirpara et al., (2026), like this literature, Deep eutectic solvents (DESs) have emerged as a sustainable alternative to the traditional solvents used in extraction and separation processes due to their low volatility, solubility controllability, ease of production, cheapness, and environmental friendliness. Deep eutectic solvents (DESs) are used in extraction by using a preformed DES to selectively dissolve or absorb certain chemicals or by generating a DES in situ by incorporating a hydrogen bond acceptor (HBA) into a mixture containing hydrogen bond donors (HBDs) [3].

There are three main types of Deep Eutectic Solvents (DESs) based on the properties of their components and their interactions [4]. Type I DESs are formed by the combination via coordination interactions of a quaternary ammonium salt such as choline chloride with a metal chloride (e.g. zinc chloride) [5]. Type II DESs are similar to Type I in that incorporate hydrated metal salts, which also influence other properties such as viscosity and conductivity since include water molecules [6]. The most widely studied category of (DESs) includes a hydrogen bond acceptor (HBA) like choline chloride and a hydrogen bond donor (HBD) such as urea, glycerol or organic acids [7]: these are particularly sought after in green chemistry applications due to their low toxicity, biodegradability and easy preparation. Instead of using quaternary ammonium salts [8], which are the usual components of type IV deep eutectic solvents (DESs), metal salts in conjunction with hydrogen bond donors are used to form type IV (DESs) [9].

1.1. Structure-property relationship of Deep Eutectic Solvent (DESs)

The composition of DESs, especially the selection of hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD), is crucial in determining their properties [10]. Any changes in the molar ratios have direct effects on the strength of hydrogen bonding and the size of the supramolecular network [11]. Greater amounts of HBD often reduce the melting point and the viscosity, although optimization of the ratio is known to increase the solvation capacity of the system, its polarity and overall stability [12]. Abbasi et al., (2022) reported that DESs that are based on Choline chloride are extensively used in organic synthesis, catalysis, electrochemistry, and separation science. Past studies have found that the extraction efficiency is significantly modified when the molar ratio of HBD in chloride systems of DES is varied, but none of the studies has been able to relate it to their solvation characteristics. Hydrogen bond basicity levelled off in both DESs at larger molar ratios of HBD, but hydrogen bond acidity was maximized at HBA/HBD ratios of 1:10. The solvation characteristics of DESs are significantly different from those of their materials; the ratio of HBA/HBD varies their solvation interactions, which can affect such critical factors as extraction yield [13].

One of the most significant properties of deep eutectic solvents (DESs) is viscosity, which is normally greater than that of conventional solvents because of strong hydrogen bonding interactions [14]. Stronger interactions raise viscosity and may slow down mass transfer, but this can be decreased by changing composition or raising temperature [15]. DESs are usually moderately to highly dense, depending on their components, with systems that contain metal salts or heavier donors of hydrogen bonds having higher density, which affects the phase behaviour and the solubility of solutes [16]. Polarity in DESs is highly variable and depends on the type of the hydrogen bond donor; polar DESs (e.g., containing organic acids or sugars) are best suited to dissolve polar molecules, but less polar systems can dissolve hydrophobic molecules, making them more versatile [17]. The conductivity of DESs is mainly governed by the ion mobility and is usually lower than that of ionic liquids due to the presence of strong hydrogen bonding interactions; however, conductivity increases with temperature and decreases with more intense hydrogen bonding interactions [18]. Lemaoui et al., (2020) reported that the effect of Molecular descriptor-based QSPR modelling is a cost-effective method of predicting the physicochemical properties of deep eutectic solvents (DESs). Density, viscosity, and others were modelled using both experimental data and COSMO-RS. The models were highly accurate, and the validation tests showed that the predicted and experimental values were in fine agreement [19].

Temperature and water content have a considerable impact on the characteristics of DES. Higher temperatures cause a decrease in viscosity and an increase in ionic mobility, leading to increased conductivity and reaction rates [20]. The presence of small amounts of water may weaken hydrogen bonds, leading to reduced viscosity and enhanced mass transfer [21]. Nevertheless, the DES structure can be readily disturbed by a lot of water, which has an impact on the stability and efficacy of the structure [22]. Kivela et al., (2022) provide that (DESs), which are hydrogen bond donors and acceptors, represent a promising new type of solvent. Both hydrophilic and hydrophobic binary deep eutectic solvents readily take up water, resulting in ternary mixes, and low levels of water are always present under ambient conditions. The changes in physical properties caused by water are beneficial to a variety of potential applications; however, water leads to the formation of an acidic aqueous nanophase with a high concentration of halide ions, which can have chemically detrimental effects [23]

1.2. DESs in organic transformation

Deep Eutectic Solvents (DESs) have garnered considerable interest as eco-friendly substitutes for traditional organic solvents [24]. Their minimal vapour pressure, low toxicity, and biodegradability render them suitable substitutes for volatile organic compounds (VOCs) in organic synthesis [25]. DESs offer a steady reaction environment and frequently obviate the necessity for extra deleterious solvents, thus promoting sustainable chemical processes [26].

Deep eutectic solvents (DESs) are widely used in the process of esterification to enhance the transfer of protons and maximizing the efficiency of the reaction under mild conditions [2]. The strong hydrogen bonding in DESs enhances the interaction between alcohols and acids, which results in higher yields and reduced reaction time as compared to traditional methods [28]. The aldol and Knoevenagel types of condensation are both successfully carried out in the deep eutectic solvent (DES) media [29]. The solvation capacity and polarity of DESs improve the reaction of reactants, leading to improved product formation and reaction profiles that are more efficient [30]. Beiruty et al., (2024) reported that the chemoselectivity of cyclic and acyclic ketones in aldol reactions with aldehydes was strongly affected by a variety of nucleophilic Knoevenagel competitors. The method is not restricted to prolinebased catalyst templates anymore; an example of this is commercially available O-t-Bu-L-threonine, which can be used with acyclic ketones. Both traditional (in-water) and non-traditional (deep eutectic solvents) conditions use water as the medium. High aldol-to-Knoevenagel chemo-selectivity (>10:1) and good product profiles (yield, and ee) were observed with few exceptions. [31]

1.3. Green chemistry perspective of deep eutectic solvent (DESs)

The global chemical industry is facing increasing pressure to lessen its environmental impact. The key objective of green chemistry is to minimize waste and the utilization of risky substances [32]. In this regard, the emphasis is placed on replacing traditional organic solvents, which often exhibit a high degree of volatility, intrinsic toxicity and lead to the release of volatile organic compounds into the atmosphere [33].

The advancement of green processes and strategies in green chemistry is particularly essential towards reducing the impact of these agents and processes on the environment without compromising their ability to regulate the reaction of these agents to the environment, and their cost-effectiveness [34]. Green chemistry is an area that is gradually gaining ground with the aim of solving such questions as human health issues and environmental hazards [35]. Green chemistry, broadly speaking, tries to embrace sustainability and is now gaining momentum in the science community as well as many of the international agencies [36]. Green chemistry focuses on reducing the number of solvents used, limiting the amount of waste, and the use of safe green solvents [37]. Chen et al., (2024) found that green solvents, such as water and ionic liquids (ILs), serve as the foundation of green chemistry and processing. Deep eutectic solvents (DESs), which were first proposed as a new class of ILs, have advanced rapidly during the last two decades. This work critically reviews DESs and extends the notion to low-melting mixture solvents (LoMMSs), which include a wide range of components such as ionic chemicals, molecular compounds, and metals. Six classes of LoMMSs are proposed as the new classification scheme, with examples provided. Finally, numerous thermodynamic concerns regarding LoMMSs are addressed [38].

Although choline chloride-urea deep eutectic solvent (often referred to as Reline) has been extensively researched, many studies have focused on the solvent's chemical characteristics and/or its individual uses. While a thorough assessment of the transformation efficacy of both organic and inorganic processes has been conducted on a laboratory scale under comparable experimental settings, it remains rather constrained. This research aimed to formulate choline chloride and urea-based CES through physical mixing, characterize its physicochemical properties, and evaluate their potential as an eco-friendly reaction medium for various organic and inorganic transformations. The findings aim to facilitate the implementation of this prevalent DES system for sustainable chemical processes at the laboratory scale.

2. Material and Methodology

2.1. Study design

An analytical and experimental study was planned to assess the physicochemical characteristics and practical use of Deep Eutectic Solvents (DESs) in organic and inorganic transformations. This research highlights green chemistry practices by utilizing biodegradable, low-toxicity materials and using moderate reaction conditions.

2.2. Study setting and duration

All the experiments were conducted with the use of a typical chemical lab equipped with all the required glassware and equipment. The total duration of the study, including time spent planning, performing experiments, and analyzing the results, was approximately two or three months.

2.3. Material and Reagent

The chemicals used were all analytical grade and were not further purified. Choline chloride (hydrogen bond acceptor) and urea or glycerol (hydrogen bond donors) were used when developing Deep Eutectic Solvents (DESs). Distilled water was used as a reference solvent. Organic reactions were done using acetic acid and ethanol, and an inorganic metal salt was used in the study of solubility using copper sulphate. During the research, standard laboratory glassware and standard laboratory instruments, including a magnetic stirring device with a heating capability, thermometer, pH meter and density bottle, were used.

2.4. Preparation of deep eutectic solvent (DESs)

Deep eutectic solvents (DESs) were prepared via the hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD) methodology.

➢ **Procedure**

- Choline chloride and urea were mixed in a 1:2 molar ratio.
- The mixture was heated at 70- 80 °C under continuous stirring using a magnetic stirrer.
- Heating continued until a clear, homogeneous, and colorless liquid was formed.
- The resulting DES was cooled to room temperature and stored in an airtight container for further use.

2.5. Experimental procedures

➢ **Physicochemical characterization**

- The prepared DES were analyzed for basic physicochemical properties.
- Viscosity.
- Density measurement using a pycnometer.
- pH determination using a calibrated pH meter.
- Visual inspection for color and stability over time.

2.6. Organic transformation: Esterification reaction

To evaluate the applicability of DES in organic synthesis, an esterification reaction was performed.

- **Procedure**
- A mixture of acetic acid and ethanol was prepared.
- The prepared DES was used as the reaction medium during the esterification reaction.
- The reaction mixture was heated under conditions (50- 70 °C)
- Reaction progress was monitored based on time, OD change (ester formation) and qualitative yield)

2.7. Inorganic application: Metal salt solubility

The ability of DES to dissolve inorganic salts was studied.

- **Procedure**
- A known quantity of copper sulfate was added to the DES.
- The mixture was stirred at room temperature.
- Solubility was evaluated based on dissolution rate and visual clarity.
- **Inclusion criteria**

The study covered (DES) systems, which were easy to synthesize using readily available, low-toxicity, and biodegradable components. Only the reactions that could be run under the conditions of a simple laboratory set-up, using simple equipment and following the principles of green chemistry, were chosen. Those experiments that could be reproduced easily and fitted into a traditional laboratory setting were given preference.

- **Exclusion criteria**

The research has eliminated tests that involved dangerous or highly toxic materials and reactions that required extreme conditions like high temperature or high pressure. Procedures that require complex analytical tools (e.g., NMR, GC-MS) or complex configurations were eliminated to achieve safety, simplicity, and feasibility.

2.8. Data collection and analysis

Data were collected through direct observation and laboratory measurements. Reaction performance was evaluated based on esterification time under identical conditions. Solubility efficiency referred to the percentage of dissolved copper sulphate; solution homogeneity was assessed by the absence of visible precipitation, and ionic stabilization indicated the stability of the dissolved salt during storage. The following parameters were recorded:

• Physical appearance (colour, clarity and homogeneity)
• pH
• Density
• Viscosity
• Conductivity
• Esterification reaction time
• Copper sulphate solubility and solution stability

3. Result

3.1. Physical characteristics of prepared Deep eutectic solvent (DES)

Deep Eutectic Solvent (DES) was prepared in a 1:2 molar ratio of chloride choline to urea, and a clear, homogeneous colourless liquid was obtained on heating the synthesised DES at 70-80 °C with stirring. Excellent physical stability with no precipitation or phase separation was found when stored at room temperature for 14 days. The DES is more viscous than distilled water and has high hydrogen-bonding interactions between hydrogen-bond acceptor and donor components.

Table 1: Physical appearance and stability of prepared DES

Parameter	Observation
Composition	Choline chloride: Urea (1:2)
Appearance	Clear and colorless liquid
Homogeneity	Completely homogeneous
Odor	Mild characteristic odor
Phase separation	Not observed
Crystallization during storage	Absent
Stability at room temperature	Stable for 14 days
Relative viscosity	Higher than distilled water

Interpretation: In the present study, the Deep Eutectic Solvent's (DES) viscosity is affected by temperature. When the viscosity of the DES was measured at various temperatures, it decreased as the temperature increased, as shown in the following figure. The viscosity of DES is inversely proportional to the temperature. As the temperature increases, the intermolecular hydrogen bonding interactions between the urea and choline chloride molecules are reduced, and the internal resistance in the solvent system decreases. Moreover, at high temperatures, molecular mobility and fluidity are increased, which eases the flow of DES. At high temperatures, the viscosity is lower, which can increase the efficiency of chemical transformations, mass transfer, and the rate of diffusion and solubility.

3.2. Physicochemical properties of DES

The prepared DES was evaluated and compared to distilled water (deionized water), which was used as a reference solvent. The pH of the DES would range from mild acidity to neutrality, and the density and viscosity of the DES would be higher than the density and viscosity of water. The increased viscosity and density were attributed to strong intermolecular hydrogen bonding interactions present in the DES framework.

Table 2: Comparative physicochemical properties of DES and distilled water

Parameter	Prepared DES	Distilled Water
Color	Colorless	Colorless
pH	6.4 ± 0.2	7.0 ± 0.1
Density (g/cm³)	1.18 ± 0.03	1.00 ± 0.01
Viscosity (cP)	42.5 ± 2.1	1.0 ± 0.1
Conductivity (mS/cm)	3.8 ± 0.4	0.05 ± 0.01
Stability	Stable	Stable
Homogeneity	Excellent	Excellent

Interpretation: In this table, it is reported that the formulation of the Deep Eutectic Solvent (DES) was successful, and the product had no color, no precipitation and was highly homogeneous like distilled water. However, it showed some special physicochemical properties, such as a slightly acidic pH (6.4 ± 0.2), high density (1.18 ± 0.03 g/cm³), significantly higher viscosity (42.5 ± 2.1 cP) and high conductivity (3.8 ± 0.4 mS/cm) than distilled water. The variations indicate greater intermolecular hydrogen bonding, greater ionic character and increased organization of the liquid system in DES, which could improve solubilization and extraction efficiency and make DES a suitable green solvent for pharmaceutical applications.

3.3. Effect of temperature on the viscosity of DES

Viscosity measurements were performed over a range of temperatures to understand how temperature changes affect the DES. The viscosity of the mixtures decreased with increasing temperature, indicating decreased hydrogen bonding interactions and increased molecular mobility at higher temperatures.

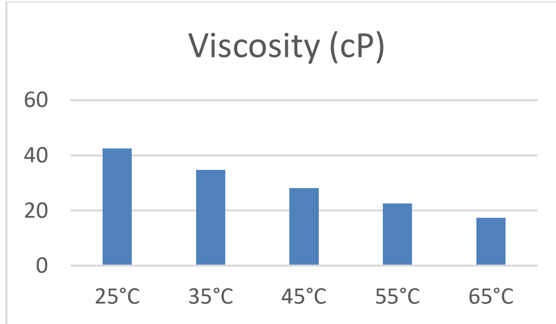

Figure 1: Effect of temperature on viscosity of DES

Interpretation: In the present study, the impact of temperature on the Deep Eutectic Solvent's (DES) viscosity. The DES's viscosity gradually dropped from 42.5 ± 2.1 cP at 25°C to 17.4 ± 1.0 cP at 65°C, indicating that temperature and viscosity have an inverse relationship. The intermolecular hydrogen bonding connections between urea and choline chloride molecules are weakened by rising temperatures, which lowers internal resistance in the solvent system. Additionally, molecular mobility and fluidity are improved at higher temperatures, making DES flow easier. During chemical transformations, mass transfer, diffusion rate, solubility, and qualitative reaction performance can all be enhanced by the lower viscosity at higher temperatures.

3.4. Esterification reaction in DES medium

An esterification reaction between ethanol and acetic acid was used to assess DES's suitability for chemical synthesis. At 60°C, the reaction was carried out in the DES medium. The development of a pleasant fruity odor and a qualitative yield assessment were used to identify ester production. The DES system showed better product production and quicker reaction completion than a traditional aqueous medium.

Table 3: Esterification reaction performance in DES and Conventional medium

Parameter	DES Medium	Conventional Medium
Reaction temperature	60°C	60°C
Reaction time	35 ± 3 min	70 ± 5 min
Ester odor intensity	Strong	Moderate
Qualitative yield	High	Moderate
Reaction efficiency	Enhanced	Lower
Visual observation	Clear reaction mixture	Slight turbidity

Interpretation: The table indicates that the conventional medium was used with the same reaction temperature (60°C), and the efficacy of esterification in the DES medium was found to be significantly higher than that of the conventional medium. The reaction time has decreased approximately 50 % (35 ± 3 min versus 70 ± 5 min), and indicates that the reaction in the DES system is faster. The intensity of the ester smell and the higher qualitative yield indicate that the reaction proceeded more efficiently to prepare the ester; the higher qualitative reaction performance also validates the improved catalytic and/or solvent properties of DES. The transparency of the reaction mixture suggests a higher solubility and/or homogeneity of the reactant in the DES medium; the small turbidity for the conventional medium may indicate lower miscibility of the reactant and/or may imply that the reaction was not completed.

3.5. Solubility behaviour of copper sulphate in DES

Dissolving tests with copper sulphate were carried out to investigate the inorganic application of the deep eutectics. Solubility characteristics of the DES were improved compared to water, with improved dissolution and optical clarity.

Table 4: Solubility analysis of copper sulphate in DES and water

Parameter	DES	Distilled Water
Amount of $CuSO_4$ added (g)	1.0	1.0 mL
Dissolution time (min)	3.5 ± 0.5	9.0 ± 1.0
Final solution appearance	Clear blue solution	Slightly turbid
Solubility efficiency (%)	96.2 ± 2.1	68.5 ± 3.8
Precipitation after 24 h	Absent	Present
Ionic stabilization	Excellent	Moderate
Solution homogeneity (%)	94.1 ± 2.5	70.4 ± 3.9

Interpretation: In this table, the prepared Deep Eutectic Solvent (DES) had superior copper sulphate solubility compared to distilled water. DES dissolved 1.0 g of $CuSO_4$ much faster (3.5 min ± 0.5) than distilled water (9.0 min ± 1.0) and produced a clear, homogeneous blue solution; water produced a solution that became clear and had some turbidity, but was not homogenous, and after 24 hours, there was some precipitation. The DES showed higher solubility efficiency (96.2 ± 2.1%) as well as better ionic stabilization (94.1 ± 2.5%) and homogeneity of solution when compared with distilled water. The results indicated that strong hydrogen-bonding and ionic interactions between the metal salt and the DES system could increase the dissolution and stability of the metal salt in the DES system.

3.6. Conductivity behavior during inorganic transformation

The conductivity of the deep eutectic solvent (DES) was enhanced following the dissolution of copper sulphate, signifying augmented ionic mobility within the solvent system.

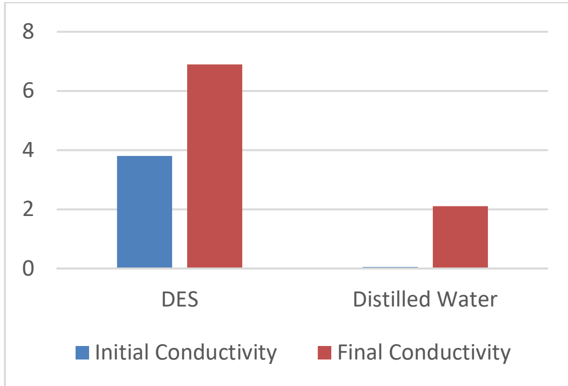

Figure 2: Conductivity analysis before and after CuSO4 dissolution

Interpretation: In the present study, the conductivity of DES and distilled water both increased after the CuSO4 was broken down, indicating an increase in mobility of ions in the solutions. The conductivity of DES increased from 3.8 ± 0.4 mS/cm to 6.9 ± 0.5 mS/cm, suggesting that the conductivity of the DES solution has increased due to the stabilization of ions and the movement of charges in the DES solution. Even though a distilled water sample had a much higher percentage increase (4100%) due to its starting conductivity being relatively low, the end conductivity of distilled water was still lower than that of DES. The higher final conductivity of DES confirms its improved ionic environment, mobility, and suitability for inorganic transformations and electrochemical applications.

3.7. Stability of inorganic salt solution

The dissolved copper sulphate solution remained stable in DES throughout extended storage without any evident precipitation.

Table 5: Stability study of copper sulphate solution

Observation Period	DES Solution	Water Solution
1 hour	Stable and clear	Slight turbidity
6 hours	Stable homogeneous solution	Mild precipitation

12 hours	No precipitation	Visible precipitation
24 hours	Fully stable	Increased precipitation

Interpretation: The table shows that the Deep Eutectic Solvent (DES) exhibited enhanced stability for the dissolved copper sulphate solution in comparison to water over the whole observation period. After 24 hours, the DES solution had no turbidity or visible precipitation, while the aqueous solution gradually became turbid and had visible precipitation. The results have shown that DES shows better ionic stabilization, better dispersion of the solutes and better efficacy of the solvent in inorganic applications.

3.8. Reproducibility of experimental observation

Each experiment was repeated three times to ensure repeatability and consistency of results. A small amount of change was observed between the repeated measurements, indicating the reliability of the developed DES system and the related experimental procedures.

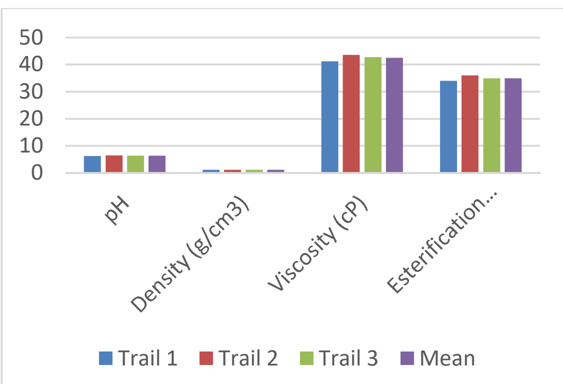

Figure 3: Reproducibility assessment of DES properties

Interpretation: In the present study, three experiments were conducted, with all of the prepared Deep Eutectic Solvent (DES) being consistent and repeatable. The pH values (6.3, 6.5 and 6.4) were rather similar, so the mean value was 6.4 ± 0.2, which showed a stable acidity and consistent composition of the solvent. The density measurement was also quite consistent at 1.18 ± 0.03 g/cm³, which means that the DES system was ready to use consistently. The viscosity values were also quite similar, with an average of 42.5 ± 2.1 cP, suggesting strong and consistent intermolecular hydrogen bonding between the molecules in the solvent. Moreover, the reaction time for esterification was found to be almost constant at 34-36 minutes, with an average of 35 ± 3 minutes.

4. Discussion

The study also confirms that the stable and uniform CCS system is produced via strong hydrogen bonding interactions, with high physical stability and viscosity compared to water, making it a suitable, efficient and green solvent for organic and inorganic transformations. Jurić et al., (2021) reported that the deep eutectic solvents (NADES) are called hydrogen bond donors-acceptors and are environmentally friendly. The research showed that the physicochemical properties and thermal stability depend on the hydrogen bond donor used, and FT-IR confirmed the role of hydrogen bonding in eutectic formation. The outcomes have shown that NADES are flexible, eco-friendly solvents that can be used in a variety of applications [39].

The study proved that the Deep Eutectic Solvent prepared also had desirable physicochemical properties, including good stability, high homogeneity, suitable pH, high viscosity, high density and high conductivity. These features exhibited good hydrogen-bonding interactions and confirmed the effectiveness of DES as a stable and effective green solvent in chemical and inorganic transformations. Fuad et al., (2022) reported that the research validated that the Prepared DES had good physicochemical properties, including good stability, high homogeneity, good pH, high viscosity, high density and high conductivity. These characteristics were found to show good hydrogen bonding interactions and confirm the effectiveness of DES as a stable and efficient green solvent for chemical and inorganic transformations [40].

The Study confirms that Deep Eutectic Solvent (DES) has a higher efficiency of inorganic transformation compared to the use of distilled water. It took 1.0 ± 0.5 minutes to dissolve 1.0 g of $CuSO_4$ in DES, and 9.0 ± 1.0 minutes in distilled water. The solubility efficiency of DES was significantly greater (96.2 ± 2.1%) than that of distilled water (68.5 ± 3.8%) and showed greater solution homogeneity (94.1 ± 2.5% vs 70.4 ± 3.9%). In addition, after 24 hr the solution obtained from DES was blue with no precipitation, indicating a higher level of ionic stabilization and metal salt solubilization ability. Topçu et al., (2025) reported that deep eutectic solvents (DESs) are efficient, environmentally friendly solvents for fast extraction of copper at ambient temperature. The isolated atacamite displayed an orthorhombic crystalline structure, an average particle size of 85.59 µm and an optical band gap value of 2.72 eV [41].

The study confirms that the prepared Deep Eutectic Solvent (DES) had extremely reproducible and consistent physicochemical properties in all the experimental trials. The pH value was consistently maintained at 6.4 ± 0.2, the density at 1.18 ± 0.03 g/cm³, the viscosity at 42.5 ± 2.1 cP and the duration of the esterification reaction at 35 ± 3 minutes, indicating consistent solvent stability, reaction homogeneity and good experimental repeatability for application in organic transformation reactions. Alcalde et al., (2019) reported that the physicochemical properties of choline chloride–lactic acid NADES (viscosity and conductivity) were dependent on temperature and water content. Water reduced the clustering effect, but maintained hydrogen bonding, making the solvent more suitable for industrial applications [42].

4.1 Limitations

The present investigation focused on laboratory-scale evaluation of the physicochemical properties and practical performance of the prepared choline chloride–urea deep eutectic solvent. Advanced structural characterization techniques including FTIR, NMR, DSC, TGA, GC–MS and HPLC were beyond the scope of the present study. Future investigations should incorporate these techniques together with mechanistic studies and quantitative product analyses to further validate the observed behaviour.

5. Conclusion

The prepared Deep Eutectic Solvent (DES) made of urea and choline chloride was presented in this work as an eco-friendly reaction medium for a few chosen organic and inorganic reactions. It was discovered to have favourable physicochemical properties like stability, homogeneity, appropriate pH, high viscosity, density, and conductivity. The practical performance of the DES under the examined experimental settings and mass transfer was enhanced by the reduction in viscosity as the temperature rose, which showed an increase in molecular mobility. In addition to demonstrating a shorter esterification reaction time than the traditional aqueous medium, the produced DES also demonstrated good copper sulphate solubility, stability, and homogeneity, making it a promising medium for application in both organic and inorganic laboratory-scale processes.

The overall results of the study indicate that the prepared choline chloride–urea DES could be a more environmentally friendly alternative to the traditional reaction media, especially in selected laboratory applications. The study gives informative experimental data on its physicochemical behaviour and practical performance, but did not include advanced structural characterization, quantitative analysis of products, and mechanistic studies. Further research that utilizes other analytical methods, such as FTIR, NMR, DSC, TGA and chromatography, and the assessment of other DES compositions and reaction systems could allow for a deeper understanding of their behaviour and expanded applications in sustainable chemical processes.

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