

Physicochemical Properties of Potassium Carbonate-Ethylene Glycol Mixtures at Different Molar Ratios and Temperatures

Syarifah Nursyimi Azlina Syed Ismail^{1a*}, Mohd Azlan Mohd Ishak^{2a}, Nur Nasulhah Kasim^{3a}, Azil Bahari Alias^{4b} and Razi Ahmad^{5c}, Khudzir Ismail^{6a}

Abstract: Deep Eutectic Solvents (DESs) are highly effective and environmentally benign for various industrial applications, including extraction, catalysis, and synthesis. The success of DESs relies on the types of hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD), as well as the molar ratios and temperatures used during the process. The study investigated the solubility of PC-EG mixture at various molar ratios to determine suitable molar ratios for achieving a eutectic mixture. Then, the physicochemical properties of the PC-EG mixtures, such as phase behavior, H-bonding, density, viscosity, conductivity and thermal stability across different molar ratios and temperatures, were analyzed. Differential Scanning Calorimetry (DSC) analysis confirmed that all mixtures were DESs, as their freezing points were lower than those of their individual components. The solid-liquid phase diagram showed that DES-8, DES-12, DES-16, and DES-19 remained in the liquid phase at temperatures of 470°C, 350°C, 220°C and 180°C, respectively. Meanwhile, FTIR analyses verified the presence of H-bonding within the DESs, but DES-19 showed minimal interaction between PC and EG. The results indicated that adding more EG content raised the molar ratio but weakened H-bonding. Similarly, increasing the molar ratio and temperature decreased the pH, density, and viscosity of the DESs, while ionic conductivity increased. Thermal analysis indicated the thermal instability of the mixtures at very high temperatures, suggesting their suitability for use at moderate temperatures. The result found that DES-12 and DES-16 had low viscosity, with strong H-bonding and excellent ionic conductivity within 30°C–40°C and 50°C–70°C. The findings of this study provide significant guidance on the effective use of PC-EG at appropriate molar ratios and temperatures to enhance desulfurization, carbon capture, and various industrial applications to achieve optimal results.

Keywords: Deep Eutectic Solvent, Intermolecular H-bonding, Ionic conductivity, Physicochemical properties, Potassium carbonate-ethylene glycol.

1. Introduction

Industrial organic solvents present significant hazards due to their high flammability, volatility, and persistence. The emission of volatile organic compounds (VOCs) contributes to atmospheric pollution, global warming, and ozone depletion. DESs are safe and environmentally benign alternatives to traditional solvents. They are formed by mixing an HBA and an HBD that result in a eutectic mixture stabilized by strong hydrogen bonding interactions. These interactions significantly lower the melting point of the mixture compared to its individual components, enabling DESs to remain liquid under ambient conditions. Compared with conventional organic solvents, they exhibit advantageous properties such as low flammability, low volatility, thermal stability, biodegradability, low toxicity, cost-effectiveness, and ease of preparation, making them a preferable choice (Ali et al., 2026).

Authors information:

^aFaculty of Applied Sciences, Universiti Teknologi Mara, Arau Campus, 02600 Perlis, MALAYSIA. Email:

syarifah_nursyimi@uitm.edu.my¹; azlanishak@uitm.edu.my²; nurnasulhah@uitm.edu.my³; khudzir@uitm.edu.my⁶

^bFaculty of Chemical Engineering, Universiti Teknologi Mara, Shah Alam Campus, 40450 Selangor, MALAYSIA. Email: azilbahari@uitm.edu.my⁴

^cFaculty of Civil Engineering Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, MALAYSIA. Email: razi@unimap.edu.my⁵

*Corresponding Author: syarifah_nursyimi@uitm.edu.my

The concept of DESs has been extended to low-transition-temperature mixtures (LTTMs), which are eutectic solvents with low transition temperatures (Wang & Baker, 2018). Their preparation is similar to DESs, but the choice of components and molar ratios determines whether the result is a DES or an LTTM (Francisco et al., 2013). Both possess low transition temperatures, wide liquid ranges, low vapor pressures, and excellent thermal stability. However, DESs show a freezing temperature peak in DSC, while LTTMs only display a glass transition temperature without a crystallization peak. Glass transitions behavior can occur even at low cooling rates, making it significant for characterizing DESs (Ghaedi et al., 2019).

DESs are effective for removing carbon dioxide (CO₂) and sulfur dioxide (SO₂). Their gas absorption depends on the types of HBAs and HBDs, their molar ratios, and temperature (Manafpour et al., 2024). Therefore, selecting suitable HBAs and HBDs with proper molar ratios is important for optimal performance at specific temperatures.

Matjie et al. (2018) showed that potassium carbonate (PC) effectively reduces SO₂ emissions during coal pyrolysis due to its high thermal stability, maintaining performance at temperatures of up to 950°C. The carbonate ion (CO₃²⁻), with its two negatively charged oxygen atoms, exhibits strong basicity and high electron density (Zhou et al., 2024), allowing it to accept H-bonds from

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HBDs like ethylene glycol (EG) and promote stable DES formation. EG has two OH groups at both ends, which promote strong hydrogen bonding, making it an effective HBD and an innovative eutectic solvent. Rogošić and Kučan (2019) found that increasing the percentage of EG improved thermal conductivity and temperature diffusivity while lowering heat capacity.

The choice of PC–EG DES for this study is supported by previous reports on its effectiveness in CO₂ absorption at molar ratios of 1:6 and 1:10 (Ghaedi et al., 2022; Saeed et al., 2022). The liquid solvent aids in selective component extraction, while a solid salt increases separation through enhanced volatility differences (Naser J. et al., 2013). The PC–EG eutectic mixture has a basic pH, indicating strong alkalinity, which makes alkaline DESs effective in absorbing acidic gases (Mjalli et al., 2014). For example, the choline chloride (ChCl)–urea mixture's moderate alkalinity enables it to capture small amounts of CO₂ (Zhang et al., 2021). In comparison, the higher alkalinity of the PC–EG is expected to further enhance its interaction with CO₂ and improve its removal efficiency (Ghaedi et al., 2022). Available data on PC–EG behavior near the eutectic composition remain limited, highlighting the need for a more comprehensive analysis across different molar ratios. The HBA-to-HBD molar ratio significantly affects the physicochemical properties and extraction performance of DESs. Increasing the HBD molar ratio can enhance SO₂ solubility by providing more active hydrogen sites, thereby facilitating stronger interactions with sulfur-containing species (Zou et al., 2026).

The molar ratio of DES components significantly affects its viscosity, thereby influencing practical applications through mass transfer rates. High-viscosity DESs decrease extraction efficiency by hindering molecular diffusion. Low-viscosity DESs, while exhibiting poor solubility, can enhance extraction efficiency due to crucial hydrogen bonding interactions with target compounds (Şahin et al., 2026). Thus, a balanced optimization of solvent properties is essential. Experimental studies show that ChCl–EG with higher HBD ratios (1:2, 1:3, and 1:3.5) enhances desulfurization efficiency. The ChCl–EG systems achieved a 70.9% extraction efficiency at a 1:3.5 molar ratio in one cycle and reached 99% efficiency after four cycles (Rogošić & Kučan, 2019). These findings highlight the importance of optimizing molar ratios in designing effective DES systems, as they significantly influence physicochemical properties like phase behavior, hydrogen-bonding interactions, and thermal stability (Mamtani et al., 2023).

Thermal stability is another critical parameter that ensures DES and the target compound maintain their structural integrity and perform reliably during the extraction process. Studies show that optimal extraction occurs between 30°C and 60°C. If the temperature exceeds this range, the extraction efficiency may decrease due to changes in the solvent's structure (Lakhmir et al., 2022).

Our previous study (Ismail et al., 2025) showed that a PC–EG mixture at a 1:16 molar ratio and 30°C optimally extracted sulfur from coal. This research builds on those findings by examining the physicochemical properties of the DESs for broader applications. The solubility of the DESs was evaluated at various molar ratios

(1:2, 1:4, 1:6, 1:8, 1:10, 1:12, 1:14, and 1:16) to identify the eutectic composition. Additionally, Response Surface Methodology-Centered Composite Design (RSM-CCD) produced ratios of 1:8, 1:12, 1:16, and 1:19 to analyze their respective properties, including phase behavior, H-bonding, density, viscosity, conductivity, and thermal stability, across different molar ratios and temperatures. Understanding the eutectic mixture and the physicochemical properties of DESs clarifies the interactions between PC and EG, allowing for performance prediction in desulfurization and extraction at optimal molar ratios and temperatures. This research also supports safety and environmental goals of the 2030 Agenda for Sustainable Development by addressing existing gaps in the limited studies on PC–EG mixtures.

2. Materials and Methods

Preparation of PC–EG Mixtures

Potassium carbonate (PC) (R&M Chemicals) and 98% ethylene glycol (EG) (Merck) were mixed at 30°C in the following molar ratios (mol/mol): 1:2, 1:4, 1:6, 1:8, 1:10, 1:12, 1:14, and 1:16 until a clear solution was obtained. Then, the solutions were stored in sealed Schott bottles and kept in a desiccator for 24 hours to reach the eutectic phase (Albayati et al., 2021). The molar ratios of DESs without precipitation were analyzed using Response Surface Methodology-Central Composite Design (RSM-CCD), generating ratios of 1:8, 1:12, 1:16, and 1:19. A significant variance of at least 2 g was observed between the 1:8 and 1:12 ratios. This difference is significant, whereas the variance between the 1:8 and 1:10 ratios was smaller and likely less impactful on physicochemical properties. The 1:19 ratio represents the upper limit set by RSM-CCD.

Differential Scanning Calorimetry (DSC) for Freezing Points Determination

The melting or freezing point of DES was measured using a Netzsch DSC 200 F3 DSC. About 10 mg of the sample was first cooled to –196°C at a rate of 20°C/min, then cooled from 25°C to –60°C and reheated to 25°C at 10°C/min (Majid et al., 2020).

Construction of Solid-Liquid Phase Diagram

A phase diagram was constructed to identify the eutectic point (Majid et al., 2020). The diagram is based on the mole fraction of PC, as defined in Eq. 1. For instance, a molar ratio of 1:8 means 1 mol of PC for every 8 mol of EG.

$$\text{Mole fraction of PC} = \frac{\text{Mole number of PC}}{\text{Total mole number of PC and EG}} \quad (1)$$

Determination of pH, Density, Viscosity, and Ionic Conductivity

The pH, density, viscosity, and ionic conductivity of DESs were measured using a Hanna pH meter, an Attension digital density meter, a Brookfield rotational viscometer, and a Mettler Toledo Seven Compact S230 conductivity meter with a 2-platinum-pole conductivity cell, respectively. Measurements were taken at temperatures of 30°C, 40°C, 50°C, 60°C, and 70°C. Due to the instability of the mixtures, two measurements were recorded to calculate an average.

Fourier Transform Infrared (FTIR) Spectroscopy for Functional Group Characterization

Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy was used to analyze liquid samples of DES. A small amount of DES was placed on the pad, and spectral data were recorded from 4000 to 400 cm⁻¹ at a resolution of 2 cm⁻¹, with a total of 64 scans to enhance accuracy (Biernacki et al., 2020).

Thermogravimetric Analysis (TGA) for Assessing Thermal Stability of DESs

A TG analyzer from NETZSCH was used to study the mass loss of DESs. Approximately 10–12 mg of sample was placed in an alumina crucible and heated from room temperature to 400°C at a rate of 20°C/min under nitrogen (Khan & Srivastava, 2022).

3. Results and Discussion

Solubility of PC-EG Mixtures as a DES

After 4 hours of mixing at 30°C–35°C, it was observed that DES-2 and DES-4 remained insoluble, while DES-6, DES-8, DES-10, DES-12, DES-14, and DES-16 were soluble. However, after 24 hours, DES-6 showed white precipitation, indicating poor mixing and instability. This phase transition led to the formation of crystals and precipitates in some DES formulations. It is essential to keep the solvent as a clear liquid at room temperature without solid recrystallization after 24 hours. Although the solubility of the 1:19 ratio was not tested, it is likely soluble, as reported by Zeng et al. (2024). Figure 1 illustrates the various molar ratios of DESs, and Table 1 displays the composition of the studied DESs.



Figure 1. PC-EG mixture at various molar ratios.

Table 1. Composition of DESs

Molar ratio	Abbreviations	Appearance at room temperature
1:2	DES-2	Turbid white liquid
1:4	DES-4	Turbid white liquid
1:6	DES-6	A colorless liquid, but a residue appeared after 24 hours
1:8	DES-8	Colorless liquid
1:10	DES-10	Colorless liquid
1:12	DES-12	Colorless liquid
1:14	DES-14	Colorless liquid
1:16	DES-16	Colorless liquid
1:19	DES-19	Colorless liquid

Phase Behavior

Figure 2 shows the phase transitions of DESs at different molar ratios, highlighting three thermal transitions identified by DSC.

The freezing point (T_f) is the highest exothermic peak during cooling (Pinho et al., 2024), observed between -36°C and -38°C for all DESs. The second exothermic peak near -58°C corresponds to the cold crystallization temperature (T_{c-c}), occurring during reheating after rapid cooling. While both T_f and T_{c-c} involve crystallization, T_f occurs during cooling and T_{c-c} during heating (Pinho et al., 2024). The endothermic peak around 17°C indicates the glass transition temperature (T_g). Heating causes the DESs to transition from a rigid state to a fluid state, leading to reduced viscosity and increased molecular mobility (Zeng et al., 2024). These results confirm that the PC–EG mixtures function as DESs due to their significantly lower freezing points compared to pure PC (891°C) and EG (-12.9°C), highlighting strong H-bonding and eutectic behavior (Zeng et al., 2024). Table 2 compares the T_{c-c} , T_f , and T_g temperatures for all DESs.

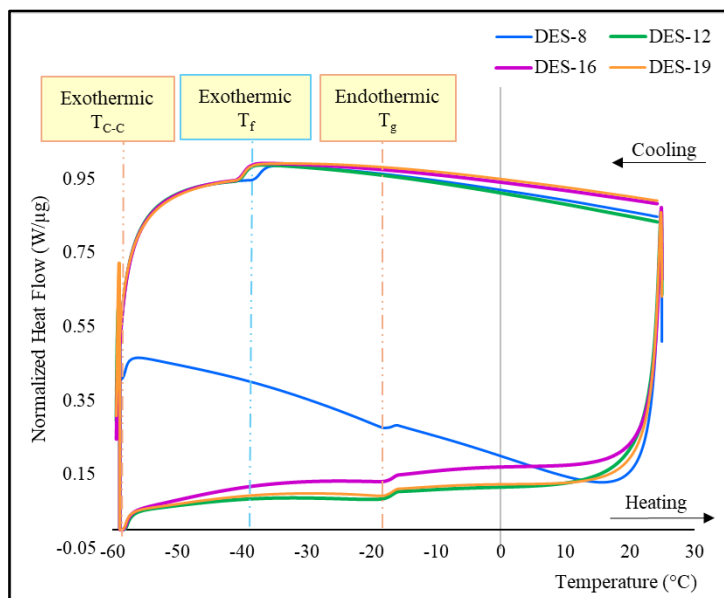


Figure 2. Phase transitions of DESs at molar ratios 1:8, 1:12, 1:16 and 1:19.

Table 2. Cold-Crystallization, Glass-Transition and Freezing Temperatures of PC-EG eutectic mixtures at different molar ratios.

Phase behavior	Thermic type	DES-8	DES-12	DES-16	DES-19
T _{C-C}	Exo	-58.84 ±0.47	-58.26 ±0.11	-58.26 ±0.06	-58.47 ±0.10
T _f	Exo	-35.88 ±1.95	-38.51 ±0.18	-38.26 ±0.30	-38.18 ±0.19
T _g	Endo	-7.52 ±0.37	-8.42 ±0.95	-8.25 ±0.94	-8.14 ±0.67

Construction of Solid-Liquid Phase Diagram

The construction of the solid-liquid phase diagram (Majid et al., 2020) highlights the importance of understanding DES behavior to avoid solid-phase formation during applications. The diagram

was created using Eq. (1), and Table 3 displays the molar fractions and mole numbers of PC-EG DESs at different molar ratios.

Table 3. Molar fraction and mole number of PC-EG DESs at various molar ratios.

DES	Mole number of PC	Mole number of EG	The molar fraction of PC
DES-8	1	8	1/ (1 + 8) = 0.11
DES-12	1	12	1/ (1 + 12) = 0.08
DES-16	1	16	1/ (1 + 16) = 0.06
DES-19	1	19	1/ (1 + 19) = 0.05

The red asterisk (*) in the phase diagram indicates the mole fraction of PC at 1:8, 1:12, 1:16, and 1:19 molar ratios. The pure freezing points of PC (891°C) and EG (-12.9°C) are marked with blue asterisks (*). Initial eutectic point is detected at a PC molar fraction of 0.11 (molar ratio 1:8) with a freezing point of around -35°C, similar to Figure 2. DES-12, DES-16, and DES-19 show slight freezing point reductions, likely due to decreased intermolecular H-bonding (Şahin et al., 2026). However, no visible precipitation was observed, and the DESs remained liquid (Figure 1). Freezing point depression (ΔT_f) occurs when the PC-EG mixture's freezing point is lower than its components (Majid et al., 2020).

The EG + liquid mixture region exists below EG's freezing point

(-12.9°C), where solid EG coexists with liquid EG. The PC + liquid region appears below PC's freezing point (891°C), with solid PC coexisting with liquid. In this area, solid PC forms first due to its higher mole fraction, but some of the mixture remains liquid because of EG's presence. The green line in the phase diagram indicates the temperature range for the desulfurization study, confirming the mixture stayed liquid between 30°C and 80°C. The solid EG and solid PC regions below the dashed blue line represent a binary solid phase (Majid et al., 2020). The solid-liquid phase diagram verifies that the DES mixtures remained liquid at 30°C–78°C.

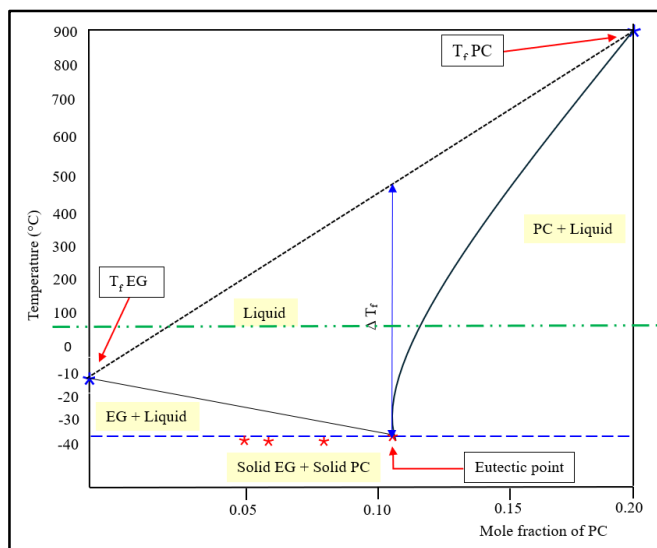


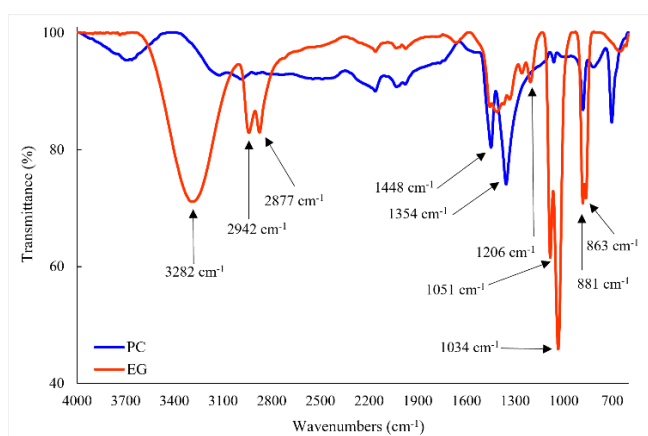
Figure 3. Phase diagram of PC-EG eutectic mixtures at various molar ratios and temperatures.

Intermolecular Interaction (H-Bonding) of PC-EG Eutectic Mixtures

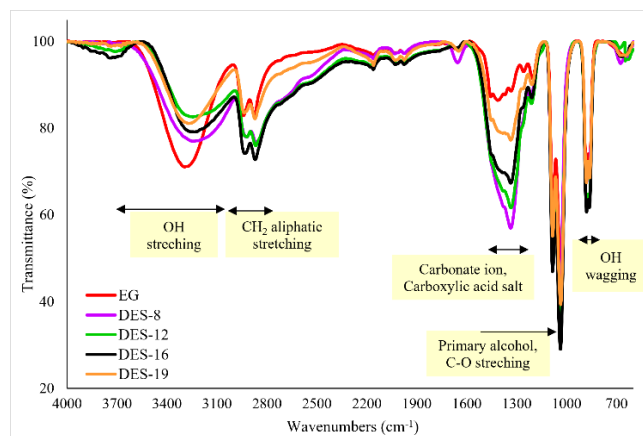
Figures 4(a) and 4(b) show the FTIR spectroscopy of PC, EG, and PC-EG mixtures at various molar ratios. The O-H stretching vibrations are observed around 3800–3100 cm⁻¹ in all DES samples, including EG, which contains a diol group, consistent with prior studies (Ghaedi et al., 2022). As the EG concentration increased, significant changes in the OH peaks of the DESs were observed, with shifts to lower wavenumbers for DES-8 (3229 cm⁻¹), DES-12 (3234 cm⁻¹), DES-16 (3238 cm⁻¹), and DES-19 (3249 cm⁻¹). The peaks broadened, indicating stronger H-bonding interactions between PC and EG. However, DES-19 showed a slight shift due to the high EG presence, limiting interactions and reducing H-bonding at 19 mol EG. This observation aligns with previous research (Zeng et al., 2024; Saeed et al., 2022). The peaks at 2942–2877 cm⁻¹, 1051–1034 cm⁻¹, and 881–863 cm⁻¹ represent C-H stretching of aliphatic hydrocarbons, C-O stretching

of primary alcohols, and OH wagging vibrations, respectively. These peaks, found in EG, are present in all DES components. When mixed with PC, the wavenumbers shifted to higher values, indicating increased bond strength between the compounds (Zeng et al., 2024).

In the PC sample, the peak at 1448–1354 cm⁻¹ indicates C=O stretching vibrations linked to carboxyl groups (carbonate ions). In the DES mixtures, peaks for carbonate ions and carboxylic acid salts appear at 1434–1336 cm⁻¹ (Sultana et al., 2022). The peak shift to higher wavenumbers suggests stronger bonding between the carbonate ion and the OH group of EG (Zeng et al., 2024). Overall, FTIR analysis confirmed the interaction between PC and EG, revealing eutectic mixtures formed through hydrogen bonding, which strengthened with higher PC-EG molar ratios but decreased at an EG ratio of 19 mol.



(a)



(b)

Figure 4. FTIR Spectroscopy of (a) PC and EG components; (b) PC-EG eutectic mixtures at molar ratios 1:8, 1:12, 1:16 and 1:19.

pH of PC-EG Eutectic Mixtures

Figure 5 shows the pH values of EG and various DESs at different molar ratios and temperatures. All DESs had a very alkaline pH between 12.5 and 13, while the pH of EG was between 7.5 and 8.0. At room temperature, DES-8 had the highest pH, and DES-19 had the lowest. As the molar ratio of EG increased from 8 to 19 mol, pH values decreased, consistent with Mjalli et al. (2014), who noted that increasing HBDs such as glycerol and EG reduces basicity. EG can donate protons (H^+) via its OH groups, forming bicarbonate ions (HCO_3^-), which are less basic than carbonate ions. This interaction further decreases basicity, particularly in higher molar-ratio DESs like DES-16 and DES-19. Zhang et al. (2021) found that alkaline DESs are highly effective at separating and purifying acidic gases, with moderate alkalinity in the ChCl-urea mixture enabling the absorption of CO_2 .

The pH of the DESs is also affected by temperature. As the temperature increases from 50°C to 70°C, the pH of all DESs and EG decreases slightly. Overall, pH levels across all DESs remain stable at different temperatures, consistent with a study showing that alcohol-based DESs also exhibit a gradual pH decrease with increasing temperature (Hansen et al., 2021).

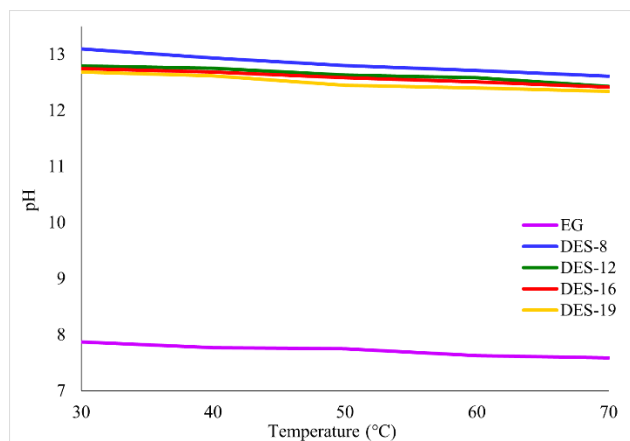


Figure 5. pH of PC-EG eutectic mixtures at various molar ratios and temperatures.

Density of PC-EG Eutectic Mixtures

Figure 6 shows the density of EG and DESs at different molar ratios and temperatures. At ambient temperature, DES-19 has the lowest density, while DES-8 has the highest. The strong interaction between EG molecules and PC in DES-8 leads to the strongest H-bonding among the analyzed solvents, consistent with Ghaedi et al. (2019), who noted that higher-density DESs exhibit stronger H-bonding. FTIR analysis also confirmed strong H-bonding in DES-8. While Hansen et al. (2021) suggested that DES density increases with increasing hydroxyl (OH) content, our findings suggest otherwise. At a molar ratio of 1:8, OH groups in EG form new H-bonds with PC, restricting molecular movement. As the EG molar ratio increases, density decreases due to excess unbound OH groups, allowing more free movement within the DES.

The density of DESs is also affected by temperature. The density of DESs decreases from DES-8 to DES-19 as temperature rises

from 30°C to 70°C. Increased thermal energy allows molecules to move more freely, leading to larger intermolecular distances and lower density (Şahin et al., 2026). Lower temperatures can reduce pore size and change molecular packing, resulting in increased density (Zhang et al., 2021).

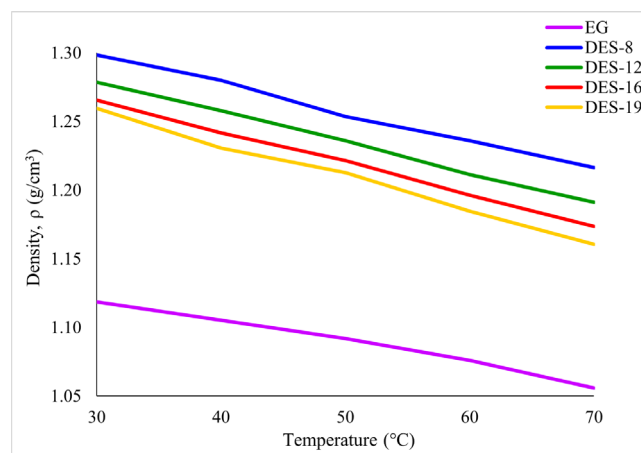


Figure 6. Density of PC-EG eutectic mixtures at various molar ratios and temperatures.

Viscosity of PC-EG Eutectic Mixtures

Figure 7 illustrates the viscosities of EG and DESs at different molar ratios and temperatures. Viscosity measures a fluid's resistance to flow (Şahin et al., 2026). DES-8 has the highest viscosity, while DES-12, DES-16, and DES-19 demonstrate a decrease in viscosity as the molar ratio of EG increases. The increase in viscosity indicates the formation of a strong H-bond network between HBA and HBD, resulting in reduced DES mobility (Şahin et al., 2026). Thus, the decrease in DES-19 viscosity indicates reduced PC-EG interactions. This occurs because unbound molecules near the PC-EG groups actively enhance the movement of unbound molecules in the solvent. The finding is also supported by several studies (Şahin et al., 2026; Ijardar et al., 2022).

The viscosity of DESs also decreases as temperature increases. At 70°C, the viscosities of all DESs become comparable to EG. The findings suggest that the thermal energy is sufficient to weaken or break the H-bonds between the PC-EG components, leading to a significant reduction in viscosity and flow resistance (Ghaedi et al., 2022; Yan et al., 2022), as observed in DES-16 and DES-19. DESs with low viscosities have greater potential for green technology because their properties can be tailored by varying the sizes of the HBD and cation components (Şahin et al., 2026). Furthermore, the low viscosity DES increases the rate of SO_2 absorption (Yan et al., 2022). The low viscosity of DES-16 and DES-19 provides an advantage in desulfurization. The high viscosity of the liquid impedes chemical reactions due to poor mass transfer. For example, extracting substances from solids becomes challenging because reactions occur at the interface between the solid and liquid phases. Diffusion affects these reactions, adding another layer of difficulty to the process. Once stirring stops, separating solid particles from highly viscous liquids becomes challenging. The particles settle slowly, and the liquids adhere to

their surfaces, increasing the risk of fluid loss (Binnemans & Jones, 2023). Additionally, there is a positive correlation between conductivity and viscosity. The higher viscosity of DESs can lead to poor conductivity. Thus, the molar ratio of DES components significantly affects both viscosity and conductivity (Xiaoyu et al., 2023).

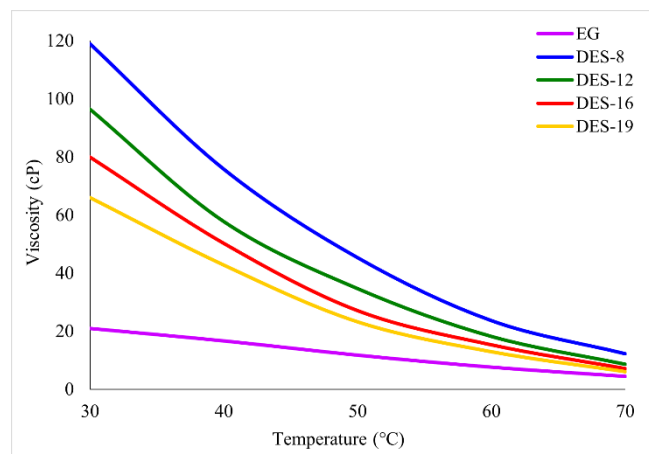


Figure 7. Viscosity of PC-EG Eutectic Mixtures at Various Molar Ratios and Temperatures.

Ionic Conductivity of PC-EG Eutectic Mixtures

Figure 8 illustrates the ionic conductivities of EG and PC-EG at various molar ratios and temperatures. At lower temperatures, the ionic conductivity is stable and consistent across all DESs, despite varying viscosities. High viscosity restricts ionic mobility, directly affecting ionic conductivity (Xiaoyu et al., 2023). At 30°C, DES-16 has the highest ionic conductivity, followed by DES-19, DES-12, and DES-8. The results indicate that increasing the EG molar ratio enhances conductivity, aligning with Xiaoyu et al. (2023), who observed that reducing the ChCl (HBA) ratio from 1:2 to 1:10 improves ionic conductivity.

The graph shows a positive correlation between higher temperatures and increased conductivity. As the temperature increased from 30°C to 40°C, the conductivity of the DESs rose, with DES-12 showing the biggest rise, followed by DES-16 and DES-19. The result suggests that a higher molar ratio of EG may enhance ionic conductivity. DES-8 exhibited the lowest conductivity, likely due to its viscosity hindering ion diffusion (Talip et al., 2021). While increasing the temperature from 40°C to 50°C did not enhance conductivity, significant increases were noted between 60°C and 70°C. The results indicate that higher temperatures disrupt the H-bond network in DES-8, thereby enhancing ionic mobility and conductivity. At 50°C, the ionic conductivity of DES-12 slightly decreases, while DES-16 and DES-19 maintain stable conductivity between 40°C–50°C. At 70°C, DES-12 outperformed DES-16, making it the best-performing DES. The findings also suggest that increased EG concentration results in less consistent thermal conductivity, and DES-19, despite having the highest EG concentration, does not show the highest conductivity. Additional EG in DES-19 increases the number of conductive ions but limits conductivity at high temperatures.

The thermal conductivity of DESs can be enhanced by OH groups and potassium ions (K^+). However, higher temperatures can increase electron motion and lower ionic conductivity (Albayati et al., 2021). EG shows almost zero conductivity between 30°C and 70°C, indicating that it is a poor conductor. Zeng et al. (2024) found that the ionic conductivity of PC-EG correlates with its viscosity at a 1:20 molar ratio, which yields the highest conductivity before it declines. In summary, DES conductivity depends on PC-EG interaction, viscosity, and temperature, with a higher EG ratio improving ionic conductivity.

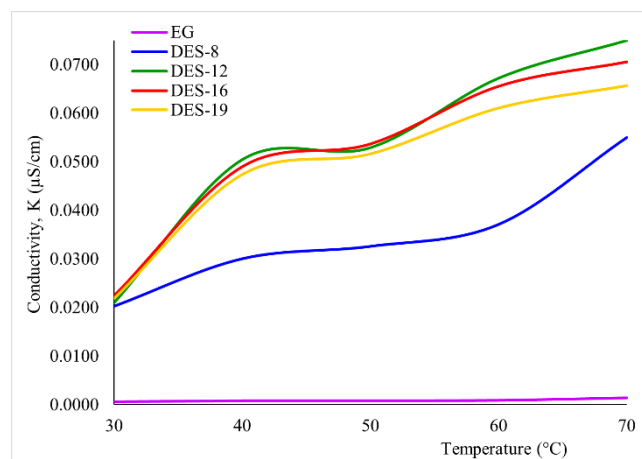


Figure 8. Ionic conductivity of PC-EG eutectic mixtures at various molar ratios and temperatures.

Thermal Analysis of PC-EG Eutectic Mixtures

The thermal stability of DESs at various molar ratios was assessed using thermogravimetric analysis. The goal was to determine the temperature range in which structural integrity is preserved and thermal degradation is prevented. Figure 9 illustrates the TGA results, showing that PC remained stable at up to 300°C, while EG began to degrade at around 98°C. The result indicates a notable difference in thermal stability, with PC being more stable than EG. According to Figure 9, DES-12 and DES-16 were thermally stable up to 130°C, while DES-8 remained stable until 160°C before degrading due to the EG volatilization. DES-19 started to lose weight at 110°C, which highlights the influence of EG. Zeng et al. (2024) noted that PC decomposes at higher temperatures than EG, and increasing HBD content leads to greater weight loss during initial decomposition. All DESs were fully degraded at around 350°C, with final weights of 21.52% for DES-8, 12.64% for DES-12, 16.90% for DES-16, and 2.56% for DES-19. The findings suggest interactions between PC and EG, with H-bond strength decreasing at higher temperatures (Saeed et al., 2022). Overall, PC-EG mixtures are effective at moderate temperatures but lose structural integrity at 130°C. Although the 1:8 molar ratio is stable at temperatures of up to 180°C, its high viscosity limits ionic conductivity and efficiency.

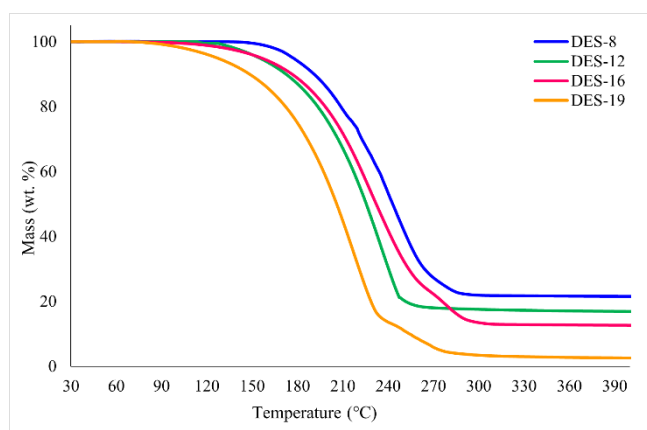


Figure 9. TGA analysis of PC-EG eutectic mixtures at different molar ratios.

4. Conclusions

The PC-EG mixture formed a eutectic at a 1:8 molar ratio, remaining a clear liquid at room temperature even after 24 hours. DSC analysis revealed lower freezing points, confirming they are DESs. The solid-liquid phase diagram indicated that DES-8, DES-12, DES-16, and DES-19 remained liquid at 470°C, 350°C, 220°C, and 180°C, respectively, but degraded at around 350°C. This analysis suggests that DESs are suitable for moderate temperatures but unstable at high temperatures. FTIR analysis revealed H-bonding in the mixtures, with bond strength increasing at higher PC-EG ratios before decreasing at an EG molar ratio of 19. The molar ratio and temperature also influenced the pH, density, viscosity, and conductivity of the DESs. DES-8 had the highest pH, density, and viscosity, while DES-19 had the lowest. Higher molar ratios and temperatures decreased viscosity but enhanced ionic conductivity. DES-12 and DES-16 exhibited low viscosity, strong H-bonding, and excellent conductivity at 30°C–40°C and 50°C–70°C, suggesting potential for extraction and industrial use.

5. Acknowledgements

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6. References

Albayati, N., Kadhom, M., Abdullah, G., & Salih, S. (2021). Thermal Conductivity of Room Temperature Deep Eutectic Solvents. *Thermal Science*, 30(6), 1960-1972.

Ali, A., Li, R., Zhu, R., Mahmood, S., Chen, Q., & Yao, S. (2026). Deep eutectic solvents for green extraction and separation of bioactive compounds from traditional Chinese medicines. *Chinese Medicine*, 21(1), 38.

Biernacki, K., Souza, H. K. S., Almeida, C. M. R., Magalhães, A. L., & Gonçalves, M. P. (2020). Physicochemical properties of choline chloride-based deep eutectic solvents with polyols: An experimental and theoretical investigation. *ACS Sustainable Chemistry & Engineering*, 8(50), 18712-18728.

Binnemans, K., & Jones, P. T. (2023). Ionic liquids and deep-eutectic solvents in extractive metallurgy: mismatch between academic research and industrial applicability. *Sustainable Metallurgy*, 9(2), 423-438.

Francisco, M., Van Den Bruinhorst, A., & Kroon, M. C. (2013). Low-transition-temperature mixtures (LTTMs): A new generation of designer solvents. *Angewandte Chemie International edition*, 52(11), 3074-3085.

Ghaedi, H., Kalhor, P., Zhao, M., Clough, P. T., Anthony, E. J., & Fennell, P. S. (2022). Potassium carbonate-based ternary transition temperature mixture (deep eutectic analogues) for CO₂ absorption: Characterizations and DFT analysis. *Frontiers of Environmental Science & Engineering*, 16(7), 92.

Ghaedi, H., Zhao, M., Ayoub, M., Zahraa, D., Shariff, A. M., & Inayat, A. (2019). Preparation and characterization of amine (N-methyl diethanolamine)-based transition temperature mixtures (deep eutectic analogues solvents). *Chemical Thermodynamics*, 137, 108-118.

Hansen, B. B., Spittle, S., Chen, B., Poe, D., Zhang, Y., Klein, J. M., Horton, A., Adhikari, L. I., Zelovich, T., Doherty, B. W., Gurkan, B., Maginn, E., Ragauskas, A., Dadmun, M., Zawodzinski, T. A., Baker, G. A., Tuckerman, M. E., Savinell, R. F., & Sangoro, J. R. (2021). Deep eutectic solvents: A review of fundamentals and applications. *Chemical reviews*, 121(3), 1232-1285.

- Ijardar, S. P., Singh, V., & Gardas, R. L. (2022). Revisiting the physicochemical properties and applications of deep eutectic solvents. *Molecules*, 27(4), 1368.
- Ismail, S. N. A. S., Ishak, M. A. M., Ahmad, R., & Ismail, K. (2025). Impact of optimized molar ratio, temperature and time on organic sulfur transformation and thermophysical properties of high-sulfur coal. *Technology*, 16(2), 395-410.
- Khan, N., & Srivastava, V. C. (2022). Extractive desulfurization using ethylene glycol and glycerol-based deep eutectic solvents: engineering aspects and intensification using ultrasound. *Chemical Engineering and Processing-Process Intensification*, 180, 108973.
- Lakhmira, M. A., Soomro, S. A., Unara, I. N., & Akhterb, F. (2022). A review of chemical demineralization and desulphurization of high ash & high sulphur lignite coal. *Jurnal Kejuruteraan*, 34(3), 353-364.
- Majid, M. F., Mohd Zaid, H. F., Fai Kait, C., Jumbri, K., Lim, J. W., Masri, A. N., & Yulianto, B. (2020). Liquid polymer eutectic mixture for integrated extractive-oxidative desulfurization of fuel oil: An optimization study via response surface methodology. *Processes*, 8(7), 848.
- Mamtani, K., Stevenson, S. J., Galvosas, P., Weber, C. C., Farid, M. M., & Shahbaz, K. (2023). Synthesis and characterization of acidic deep eutectic solvents based on p-Toluenesulfonic acid. *Molecular Structure*, 1294, 136378.
- Manafpour, A. A., Feyzi, F., & Rezaee, M. (2024). An environmentally friendly deep eutectic solvent for CO₂ capture. *Scientific Reports*, 14(1), 19744.
- Matjie, R. H., Lesufi, J. M., Bunt, J. R., Strydom, C. A., Schobert, H. H., & Uwaoma, R. (2018). In situ capturing and absorption of sulfur gases formed during thermal treatment of South African coals. *ACS Omega*, 3(10), 14201-14212.
- Mjalli, F. S., Naser, J., Jibril, B., Al-Hatmi, S. S., & Gano, Z. S. (2014). Ionic liquids analogues based on potassium carbonate. *Thermochimica Acta*, 575, 135-143.
- Naser, J., Mjalli, F., Jibril, B., Al-Hatmi, S., & Gano, Z. (2013). Potassium carbonate as a salt for deep eutectic solvents. *Chemical Engineering and Applications*, 4(3), 114.
- Pinho, M. R., Lima, A. S., de Almeida Ribeiro Oliveira, G., Liao, L. M., Franceschi, E., Silva, R. D., & Cardozo-Filho, L. (2024). Choline chloride-and organic acids-based deep eutectic solvents: Exploring chemical and thermophysical properties. *Chemical & Engineering Data*, 69(10), 3403-3414.
- Rogošić, M., & Kučan, K. Z. (2019). Deep eutectic solvents based on choline chloride and ethylene glycol as media for extractive denitrification/desulfurization/dearomatization of motor fuels. *Industrial and engineering chemistry*, 72, 87-99.
- Saeed, U., Khan, A. U., Khan, A. L., Gilani, M. A., & Bilad, M. R. (2022). Separation of Carbon Dioxide by Potassium Carbonate Based Supported Deep Eutectic Liquid Membranes: Influence of Hydrogen Bond Donor. *Membrane Science and Research*, 8(1), e244300.
- Şahin, S., Kurtulbaş, E., Toprakçı, İ., Anwar, F., Khan, R., Çiğeroğlu, Z., & Falsafi, S. R. (2026). Deep Eutectic Solvents for Sustainable Extraction of Bioactive Compounds from Biomass: Mechanistic Insights and Scale-Up Challenges. *Molecules*, 31(5), 880.
- Sultana, K., Rahman, M. T., Habib, K., & Das, L. (2022). Recent advances in deep eutectic solvents as shale swelling inhibitors: A comprehensive review. *ACS Omega*, 7(33), 28723-28755.
- Talip, R. A. A., Yahya, W. Z. N., & Bustam, M. A. (2021). Viscosity and ionic conductivity of imidazolium based ionic liquids bearing triiodide anion. *In E3S Web of Conferences* (Vol. 287, p. 02015). EDP Sciences.

- Wang, X., Wang, Y., Dong, M., Fang, Z., Hu, Y., Xue, K., & Peng, X. (2023). A two-dimensional nanochannel facilitates ionic conductivity of a deep eutectic solvent for an efficient supercapacitor. *Materials Today Energy*, 34, 101285.
- Wang, J., & Baker, S. N. (2018). Pyrrolidinium salt based binary and ternary deep eutectic solvents: green preparations and physicochemical property characterizations. *Green Processing and Synthesis*, 7(4), 353-359.
- Xiaoyu, W. Yuqi, D., M., F., Z., H., Y., X., K., Y., Z., & P., X. (2023). A two-dimensional nanochannel facilitates ionic conductivity of a deep eutectic solvent for an efficient supercapacitor. *Materials Today Energy*, 34, 101285.
- Yan, Z., Lai, S. Y., Ngan, C. L., Li, H., & Mohamed, A. R. (2022). Recent advances in energy-efficient and regenerative SO₂ absorption over deep eutectic solvents. *Environmental Chemical Engineering*, 10(6), 108967.
- Zeng, P., Wu, D., Wang, T., Liu, P., & Jia, D. (2024). Redefine the existence form and function of water in potassium carbonate-based deep eutectic electrolyte. *Fuel*, 357, 129738.
- Zhang, M., Zhang, X., Liu, Y., Wu, K., Zhu, Y., Lu, H., & Liang, B. (2021). Insights into the relationships between physicochemical properties, solvent performance, and applications of deep eutectic solvents. *Environmental Science and Pollution Research*, 28(27), 35537-35563.
- Zhou, Y., Chen, M., Dong, X., & Yang, D. (2024). The reaction between K₂CO₃ and ethylene glycol in deep eutectic solvents. *Molecules*, 29(17), 4113.
- Zou, Y., Xing, X., Wang, C., Tao, D., Ji, H., Wu, P., & Zhu, W. (2026). Investigating the SO₂ absorption behavior of pyrimidine-based deep eutectic solvents via a dual-site thermodynamic model. *Industrial Chemistry & Materials*.