Diyala Journal of Engineering Sciences Vol (17) No 3, 2024: 115-129

Diyala Journal of Engineering Sciences

Journal homepage: https://djes.info/index.php/djes

ISSN: 1999-8716 (Print); 2616-6909 (Online)

Absorption-Desorption Characteristics of the Synthesized Deep Eutectic Solvents for Carbon Dioxide Capture

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ARTICLE INFO

Article history:
Received May 7, 2024
Revised August 16, 2024
Accepted August 23, 2024
Available online September 1, 2024

Keywords:
CO_2 capture
Chemical absorption
Deep eutectic solvents
Choline chloride
Tetrabutylammoniumbromide

ABSTRACT

The development of an environmentally friendly CO_2 absorbent with significant energy utilization which can be an alternative to CO_2 capture by an ethanolamine solution is presently an obligatory issue. In this work, binary and ternary deep eutectic solvents (DESs) were prepared according to their CO_2 absorption/desorption performances. A series of DESs comprise different hydrogen bonding donor (HBD)- acceptor (HBA) pairs as CO_2 capturing solvents; HBAs include choline chloride (ChCl) and tetrabutylammonium bromide (TBAB), and selected amines are represented as HBDs and include monoethanolamine (MEA), diethanolamine (DEA), and triethanolamine (TEA). Binary DESs synthesized of ChCl/MEA, ChCl/DEA, ChCl/TEA, TBAB/MEA, TBAB/DEA, and TBAB/TEA in a CO_2 absorption cell at a mole ratio of 1:4. While selected amidines were represented as super-based (SB) and included 1,5-Diazabicyclo [4.3.0] non-5-ene (DBN) and 1,8-Diazabicyclo [5.4.0] undec-7-ene (DBU). The ternary DESs were prepared by adding DBN or DBU to the binary DESs system in a 1:4:3 molar ratio. CO_2 absorption experiments were attained at atmospheric pressure and a temperature of 30 °C using 15 vol.% CO_2 with 85 vol.% N_2. On the other hand, the regeneration process for DESs was conducted at 90 ºC. Binary DES synthesized from ChCl/MEA gives a higher absorption rate of CO_2 of 0.0177 mole/kg. min, CO_2 absorption loading of 2.9092 mole CO_2/kg solvent, cyclic loading of 2.0001 mole CO_2/kg solvent, and a regeneration efficiency of 68.75%. The synthesis DESs showed a better performance compare with a common Ionic liquid.

1. Introduction

Rapid global economic growth has resulted in a significant increase in the use of fossil fuels and natural gas in industries and transportation, leading to a notable surge in CO_2 emissions [1]. CO_2 is a well-known greenhouse gas, and reports have shown a worrying pattern of emissions rising continuously since the 1960s, with a net yearly rise of 2.11% and reaching 1200 ppm in the ensuing 53 years [2]. The process of carbon capture and storage (CCS) entails removing CO_2 from emission sources and transporting to a pre-designated storage site where it may be safely kept apart from the atmosphere for a long time [3]. There are several separation processes that can be successfully applied to separate CO_2 from gas streams, including permeation through organic and inorganic membranes [4-7], adsorption processes [8], cryogenic [9], and physical and chemical absorption [10].

Chemical absorption has evolved into a well-established carbon capture technology,

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DOI: 10.24237/djes.2024.17308

characterized by its substantial processing capacity, promising capture efficiency, and versatile applicability. In this context, alkanol amines have gained widespread recognition as suitable solvents renowned for their remarkable acid gas absorption capacity [11, 12]. The main alkanolamines applied for this approach are MEA, DEA, and TEA [13]. These solvents have shown a number of drawbacks despite their many benefits, such as corrosiveness, instability, deterioration, high energy requirements for solvent regeneration, and the production of amine salts. These difficulties have led scholars to look at different approaches [11]. Thus, different types of solvents are required in order to capture CO_2 and avoid the disadvantages of using, alkanolamines. Many researchers are interested in using DESs and Ionic liquids (ILs) as possible alternatives to aqueous amine solutions due to their low vapor pressure, ability to select the right ions, excellent thermal and chemical stability. When there's low vapor pressure, the amount of energy needed to regenerate and remove CO_2 is lower, resulting in lower operating costs [14].

It has been suggested to use ILs for CO_2 capturing [15]. However, a number of chemical processes and purification stages must occur in order to obtain ILs, which drives up the solvent's cost. It's important to take into account some ILs' potential for toxicity and biodegradability. Moreover, compared to regular solvents, their high viscosities restrict their large-scale applicability [16]. Due to these drawbacks, DESs have gained widespread acceptance as innovative CO_2 capture solvents. However, these drawbacks may occasionally worsen, depending on the IL precursor components utilized in their production. [17]. As a result, DESs have been developed as new IL counterparts. Hence, DESs are the novel analogs of ILs that have been created. HBAs, such as organic halide salts, and HBDs, such as amines, amides, carboxylic acids, and alcohols, often form hydrogen bonds that result in the creation of DESs [11]. When compared to ILs, DESs have some notable advantages, like being novel CO_2 capture absorbents in order to address the drawbacks of ILs, being almost non-volatile, non-flammable, non-poisonous, less expensive, and frequently biodegradable [18], having high CO_2 solubilities [19], and having nontoxic components that can be used for their components [20], making them superior solvents for absorbing carbon dioxide [18]. The present research is aimed at synthesizing binary and ternary DESs using different types of HBAs, HBDs, and SBs at a fixed molar ratio for CO_2 capture and studying the performance of absorption and desorption of CO_2.

2. Methodology

2.1 Chemicals

Choline chloride (ChCl, 98%), tetrabutylammonium bromide (TBAB, 99%), 1,5-Diazabicyclo [4.3.0] non-5-ene (DBN, 98%), and 1,8-Diazabicyclo [5.4.0] undec-7-ene (DBU, 99%) were acquired from Macklin China. While monoethanolamine (MEA, 99%) and diethanolamine (DEA, 99%) were acquired by Loba India, triethanolamine (TEA, 99%) was acquired by Central Drug House India. The N_2 gas (99.99%) and the cylinders of CO_2 gas (99.99%) needed to create flue gas were acquired from the Biladi plant for gases in Iraq.

2.2 Synthesis of DES Systems

In this work, ChCl and TBAB were used as HBAs, while MEA, DEA, and TEA were used as HBDs in the synthesis of DESs. The binary DESs solvent was prepared by drying ChCl for 48 hours at 65 °C and TBAB at 50 °C to get rid of any possible moisture, then heating first (HBD) up to 80 °C on a hotplate with magnetic stirring at 500 rpm. After that, gradually add HBA with a molar ratio of 1 mole HBA to 4 mole HBD, then leave the mixture stirred for 4 hours. Translucent and homogenous liquids were produced. The moisture from DES was removed by drying at 80 °C overnight. The prepared DES is ready for absorption and desorption experiments [21]. On the other hand, ternary DES was prepared with a mole ratio of 1 mole HBA:4 mole HBD:3 mole SB through heating the DES-dried binary up to 50 °C on a hotplate with magnetic stirring at 500 rpm, after which a suitable amount of the intended SB is added. An additional half-hour was spent magnetically agitating the ternary DES final mixture. Afterwards, it was permitted to cool to 30 °C. At this stage, the DES was operational in the absorption and desorption experiments [22].

2.3 Experimental procedure for CO_2 absorption

Apply 40 ml of the prepared DESs in the water bath, which was acquired by Memmert from Germany, and allow the gas mixture (15 vol.% carbon dioxide and 85 vol.% nitrogen) to contact the solvent for absorption of CO_2. The flow rates of gas were controlled by mass flow controllers acquired from Beijing Ifan Peng Instrument Co., Ltd., China. The operating conditions of the absorption process were controlled at 30 °C and atmospheric pressure with a gas mixture flow rate of 100 ml/min, i.e., 15 ml/min for carbon dioxide and 85 ml/min for nitrogen. An analysis of CO_2 was performed on the absorption cell's outlet gas (AtmoCheck Double from the USA) every five minutes for the purpose of knowing the saturation of the solvent, where no more CO_2 was absorbed by the solvent. Figure 1 shows the process of absorption's schematic diagram.

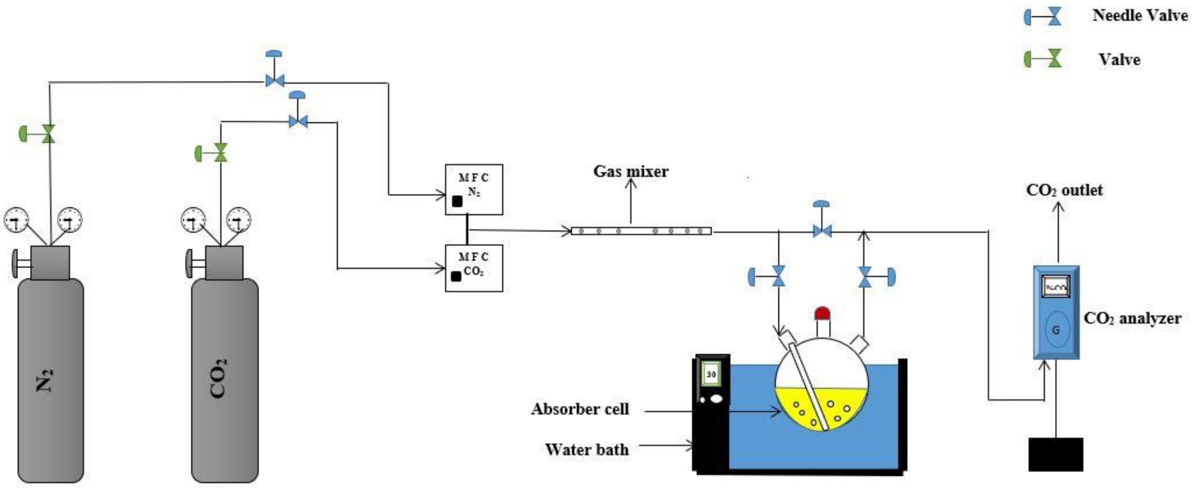

Figure 1. The schematic of the absorption experimental

2.4 Desorption process for CO_2

Following the absorption procedure, 40 ml of CO_2-rich DES was added to a 50 ml desorption cell, which was then submerged in a water bath set at 90 °C. To minimize heat losses, the water bath's level is set at the same height as the desorption cell's neck. The condenser is filled with room-temperature water to minimize solvent losses. The desorption temperature of 90 °C was verified by inserting a thermometer into the desorption cell. The CO_2-rich solvent was vigorously agitated at 90 °C for ninety minutes. Every experimental desorption process operational parameter, including: DES volume and regeneration temperature, were maintained during this study. After regeneration, the solvent was repeated to absorb CO_2 [13, 23]. Figure 2 illustrates the schematic diagram of the desorption process.

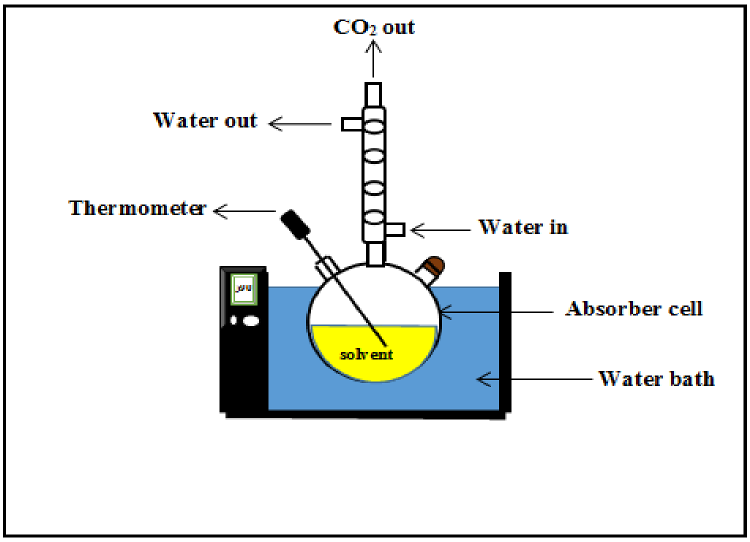

Figure 2. The schematic of the desorption process

2.5 CO₂ analysis

The CO_2 analyzer is used to analyze the vol.% of CO_2 gas from the input and output of the cell of absorption, through which the solvent's saturation can be determined as a guide to the end of the carbon dioxide absorption experiment. The rate of absorption of CO_2 by the DESs is the difference in carbon dioxide gas rate between the input and output of the absorber from the gas phase. While the carbon dioxide absorption loading of the absorbents was obtained by computing the integral characteristic value of rate of absorption to time of absorption [24]. As in the following equations:

$$r = \frac{Q_{in} - Q_{out}}{m \times 22.4 \times 1000} \qquad (1)$$

Where: r: is the rate of absorption of solvents (mole/kg*min); Q_{in} and Q_{out} are the input and output gas flow rate (ml/min); m is the weight of solvents (kg).

$$C_T = \int_0^t r\,dt \qquad (2)$$

Where: **C_T:** is the absorption loading of absorbents (mole/kg); t is the time of absorption (min). The regeneration efficiency of the solvent can be obtained as follows [24]:

$$\text{Regeneration efficiency} = \frac{C_n}{C_o} \times 100\% \qquad (3)$$

Where: C_n and C_0 are the loading absorption loading of absorbents after n^{th} regeneration and initial absorbents (mole/kg).

2.6 FTIR Spectroscopy

Fourier transform infrared spectroscopy, which studies changes in covalent chemical bonding in molecules, is used to determine the chemical structure of the produced DESs. FTIR spectra for the samples were acquired with a Shimadzu spectroscope (FT/IR Affinity-1, Shimadzu Corporation). spectrometer, SN: A21375003264 CZ/PIN 206-73500-38, Japan) at the College of Science/ Department of chemistry /University of Diyala, Iraq. The potassium bromide (KBr) pellet technique was used to record the infrared spectra within the wavenumber range of 4000-400 cm^{-1}. Before analysis, the sample and KBr were dried for two hours at 105 °C. They were then ground together in a mass ratio of 1:20 (KBr: sample) to produce a clear pellet. Using a uniaxial press, the fine powder combination was compressed at 75 MPa to create a thin pellet that measured around 1 mm. The FT-IR unit's IR radiation was applied perpendicularly to the pellet while it was in a sample holder.

3. Results and discussion

3.1 (FTIR) analysis

The IR spectra of pure ChCl, pure MEA, and synthesized DES at a molar ratio of 1:4 before absorption of CO_2 is shown in Figure 3. The pristine ChCl material displays IR vibrational bands assigned at 948 cm^{-1} indicate C-C symmetry [25]. Whereas the vibrational bands at 1134 cm^{-1} indicate CN+ symmetry stretching [26]. Meanwhile, vibrational bands at 1470 cm^{-1} indicate CH_2 bending. The vibrational bands at 1650 cm^{-1} indicate N-H bending [27]. On the other hand, FT-IR spectra of the pure MEA observed that the vibrational bands at 950 cm^{-1} refer to C-C symmetry [25]. The vibrational bands at 1134 cm^{-1} indicate C-N [26]. While the vibrational bands at 1597 cm^{-1} indicate the NH bending of primary amine bending [28], The vibrational bands at 1470 cm-1 indicate CH_2 [27]. IR for the synthesized DES before the absorption of CO_2 As all of the functional groups of both elements were recognized from the published spectra, the results validate the production of DES. 950 cm^{-1} refers to C-C [25]. While observed, the band less obvious at 1224 cm^{-1} indicates C-N stretching [27], which indicates the creation of hydrogen bonds within the ChCl-MEA.

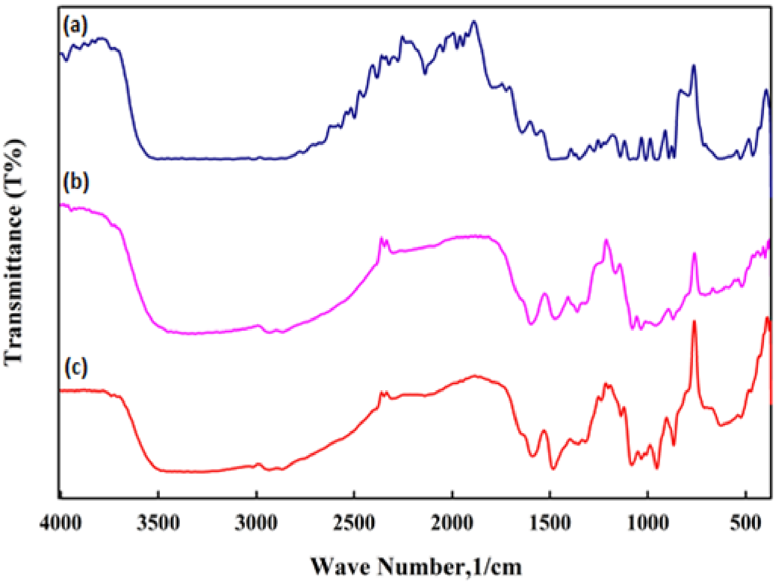

Figure 3. FTIR spectra for (a) Pure ChCl; (b) Pure MEA; and (c) Synthesized DES with a mole ratio of 1:4 before absorption of CO_2

Figure 4 illustrates the FT-IR spectra of synthesized DES with a molar ratio of 1:4 after absorption of CO_2 at 30ºC and after regeneration at a temperature of 90 ºC. The IR bands of synthesized DES after the absorption of carbon dioxide show that the structure of DES changed due to the reaction of CO_2 with DES. It can be observed in small bands at 950 cm^{-1} that are less obvious or weakened. While the bands at 1224 cm^{-1}, 1470 cm^{-1} and 1650 cm^{-1} disappeared compared to the DES after regeneration, this indicates this indicates the formation of carbamate [26]. The results of the FT-IR spectra demonstrated that even after CO_2 is absorbed, the amine group present in the DES is still present. This suggests that even when the solvent is completely saturated with carbon dioxide, some amines have not yet reacted. This implies that, in addition to the process's chemical absorption, there may also be physical absorption. The development of a carbamate indicates that there has been chemical absorption between 2241 cm^{-1} and 2023 cm^{-1} [29]. Similarly, after regeneration at a temperature of 90 ºC, the structure of ChCl-MEA resumes before the absorption of carbon dioxide. It might be noted that the bands more obvious at 948 cm^{-1} indicate C-C stretching [25]. While appearing small and less obvious at 1224 cm^{-1} it indicates C-N stretching. Whereas, the vibrational bands more obvious at 1470 and 1650 cm^{-1} present the -CH_2 group, respectively, and NH bending of primary amine, and the bands in the range between 2850 and 2900 cm^{-1} refer to CH stretching [27], which demonstrates that the two of them have formed hydrogen bonds in the ChCl-MEA 1:4 molar ratio after regeneration at a temperature of 90 ºC.

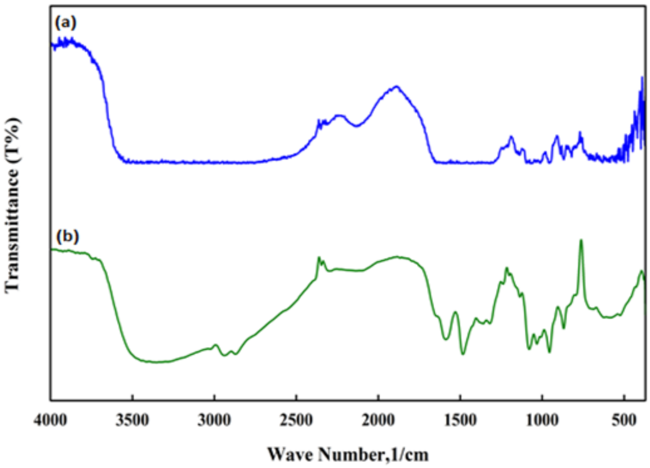

Figure 4. IR spectra for synthesized DES in a molar ratio of 1:4 for (a) DES after absorption of CO_2 at 30 ºC and **(b)** DES after regeneration at a temperature of 90 ºC

IR spectra of pure TBAB, pure MEA, and synthesized DESs at a molar ratio of 1:4 before absorption of CO_2 is shown in Figure 5. It might be observed that the IR bands for the pure TBAB appearing at 1100 cm^{-1} and 1480 cm^{-1} indicate CN and –CH_2 functional groups. While, the vibrational bands at 2850 cm^{-1} to 2800 cm^{-1} exhibit the -CH [27], Whereas, the bands of the MEA spectrum were earlier attributed in considerable detail, as shown in Figure 5. Similarly, the IR spectrum of the DES before absorption of CO_2 was observed that disappeared from the band in the range of 2850 cm^{-1} to 2800 cm^{-1}. While appearing, the vibrational bands at 3100 cm^{-1} to 3000 cm^{-1} indicate an O-H stretch [27]. The vibrational bands at 3600 cm^{-1}to 3200 cm^{-1} indicate the N-H stretch [30]. This is because of the hydrogen bond, which indicates the formation of hydrogen bonds for the synthesized DES. The exothermal reaction caused carbamate production to decrease as the temperature rose [31].

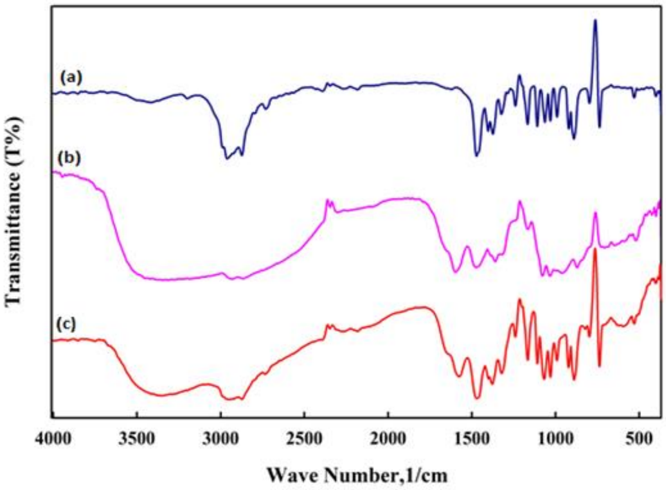

Figure 5. FTIR spectra for (a) pure TBAB; (b) pure MEA and (c) Synthesized DES with a mole ratio of 1:4 before absorption of CO_2

Figure 6 displays the IR spectra for synthesized DES from TBAB and MEA with a mole ratio of 1:4 after absorption of CO_2 at 30 ºC and after regeneration at a temperature of 90 ºC. It might be noted the FTIR spectrum of DES confirms the present of DES after absorption. Small bands compared to DES after regeneration at 1480, 1500 cm^{-1} and 1100 refer to the $-CH_2$, $C-N^+$, and NH bending groups, respectively. The reason for this is that the absorption of CO_2 weakens hydrogen bonds. [26, 27]. In addition, the new band at 2166 cm^{-1}can be linked to the carbamate's formation [29]. The band at 2850 cm^{-1} is disappeared; this is explained by the hydrogen bonds becoming weaker as a result of absorbing CO_2. The IR spectrum results of TBAB-MEA after the regeneration show the bands appearing more obvious at 1470 cm^{-1} and 1500 cm^{-1} present the $-CH_2$ and NH bending. The resonant bands at 1100 cm^{-1} indicate the CN^+ symmetric stretching group, respectively. The band in the range of 2850 cm^{-1} refers to the CH, and this is linked to the hydrogen bond regeneration as a result of CO_2 removal from DES. The exothermal reaction resulted in a decrease in carbamate production as temp rose [27, 31].

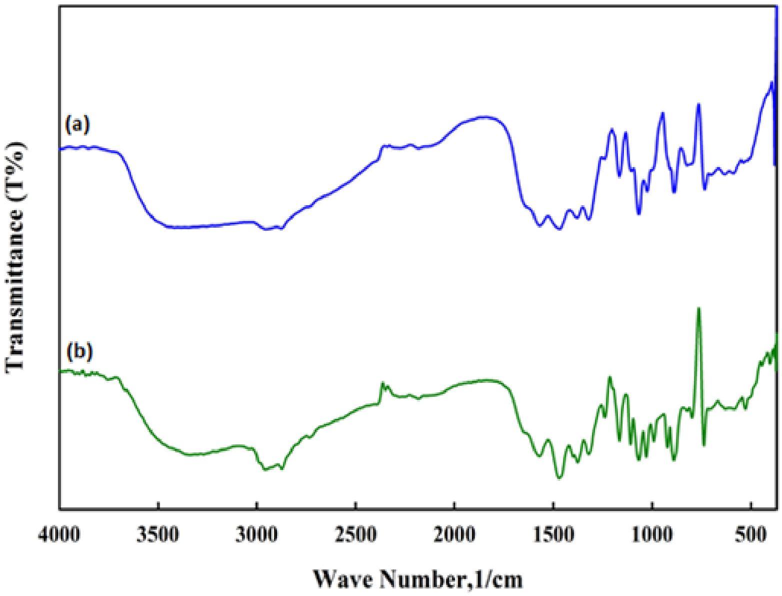

Figure 6. FT-IR spectra of DES with a mole ratio of 1:4 for (a) DES after absorption of CO_2 at a temperature of 30 ºC and (b) after regeneration DES at a temperature of 90 ºC

3.2 Binary deep eutectic solvents

3.2.1 Absorption rate of CO_2

Figure 7 illustrates the impact of absorption time on the absorption rates of CO_2 for different synthesized DESs (ChCl/MEA, ChCl/DEA, ChCl/TEA, TBAB/MEA, and TBAB/DEA) with a 1:4 molar ratio, an absorption temperature of 30 ºC, 1 atm, and 15 vol% CO_2. It can be observed that the absorption rate of CO_2 for all synthesized DESs decreased gradually with an increase in absorption time. Binary DESs synthesized from ChCl/MEA and TBAB/MEA have a higher CO_2 absorption rate of 0.0177 moles/kg/min (1.359 mmol/min) than the other DESs. Whereas, the absorption of CO_2 for ChCl/MEA solvent continues for a long time (530 min) compared to that for TBAB/MEA solvent (450 min). These results can be interpreted as indicating that even after the CO_2 is absorbed and the solvents are completely saturated with carbon dioxide, there is still some amine group present in the DES. This suggests that in addition to the process's chemical absorption, there may also be physical absorption. The development of a carbamate indicates that there has been chemical absorption, as appears in the FTIR results [29, 32]. However, this might be the result of an extended carbon chain, which lowers the alkanolamine's initial absorption rate. Less carbamate and a greater influence from the bicarbonate reaction during production could be the source of the absorption rate drop [33]. In order to control the rate at which carbon dioxide (an acid gas) is absorbed, basicity is crucial. Therefore, in contrast to DEA and MEA, which have higher basicity, the poor basicity of TEA lowers the absorption rate as a result [34]. In order to generate carbamate with tertiary amines during the chemical process via which CO_2 is absorbed, there is only one reaction step, and that reaction step needs water [29]. The CO_2 absorption rate of ChCl/MEA and TBAB/MEA in this work was found higher than that of the MEA solution with absorption rate of 0.5270 mmol/min at 25ºC [32].

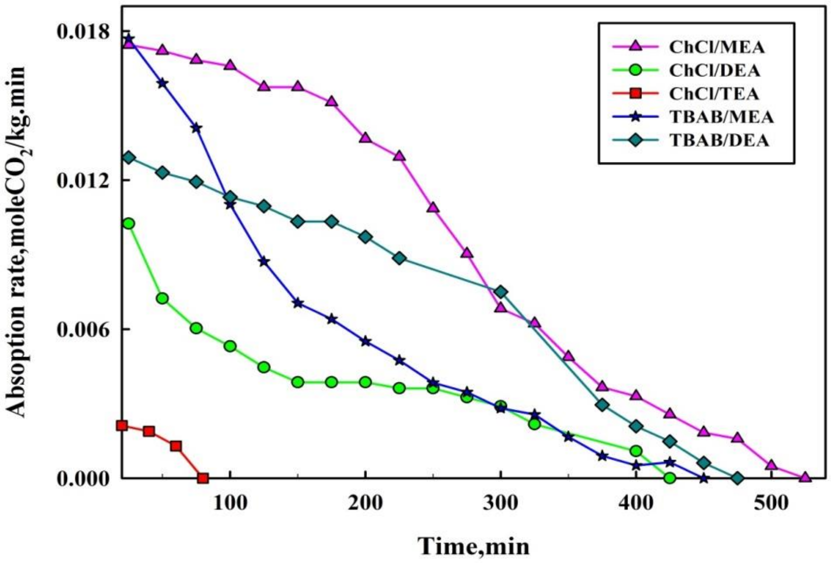

Figure 7. Absorption rate of CO_2 for several binary DESs a molar ratio of 1mole acceptor:4 mole donor, 30ºC, 1 atm and 15 vol.% CO_2

3.2.2 Absorption Loading of CO_2

The impact of absorption time on the absorption loading of CO_2 for different synthesized DESs (ChCl/MEA, ChCl/DEA, ChCl/TEA, TBAB/MEA, and TBAB/DEA) with a 1:4 molar ratio, an absorption temperature of 30 ºC, 1 atm, and 15 vol% CO_2 is illustrated in Figure 8. It is noted that the carbon dioxide absorption loading for all synthesized DES increased gradually with an increase in absorption time. DES synthesized from ChCl/MEA has a higher CO_2 absorption loading (2.9092 mol CO_2/kg) compared to the other DESs and to the reported absorbents listed in Table 1. It indicates that in addition to the chemical absorption occurring during the expression, there is also physical absorption.

The FTIR results show that the creation of a carbamate confirms the chemical absorption [29]. However, the reduction in absorption loading may be due to a rise in bicarbonate generation and a decrease in carbamate construction [33]. Also, low absorption loading may be possibly due to the physical absorption of CO_2 by DES. On the other hand, DES synthesized from ChCl/TEA has a lower CO_2 absorption loading (0.1 mol CO_2/kg) than the other DESs. This may be due to the absence of H on the TEA N_2 atoms, which resulted in delayed absorption because they do not directly interact with carbon dioxide [35].

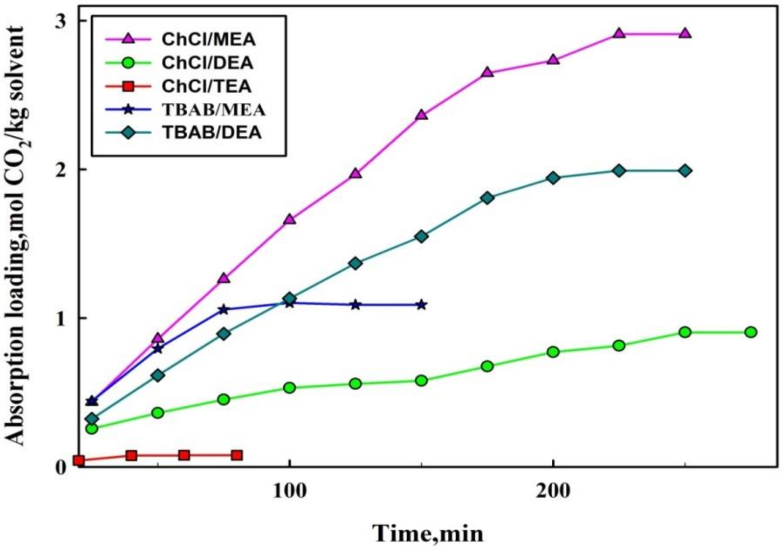

Figure 8. Absorption loading of CO_2 for several binary DESs at a molar at a molar ratio of 1mole acceptor:4 mole donor, 30 ºC, 1 atm. and 15 vol.% CO_2

Table 1: Comparisons of CO_2 absorption loading

Absorbents	T, ºC	Absorption loading, mole CO_2 kg^{-1}	Ref.
ChCl/MEA	30	2.91	This work
DBU/glycerol	25	1.74	[36]
MEA/water	40	2.36	[37]
AMP/MEA/water	40	2.50	[38]
[C_3OHmim] Cl + MEA	60	1.25	[39]
[P_{66614}][Ala]	25	1.15	[40]
[P_{66614}][Im]	23	1.82	[41]

3.2.3 Cyclic loading absorption of CO_2

Figure 9 demonstrates the impact of using different synthesized DESs in the absorption process (ChCl/MEA, ChCl/DEA, ChCl/TEA, TBAB/MEA, and TBAB/DEA) on the cyclic absorption and regeneration at a 1:4 molar ratio, an absorption temperature of 30 ºC, 1 atm, and 15 vol% CO_2. It can be seen that ChCl/MEA showed the highest cycling loading of 2.91 and 2.0 mole/kg in the first cycle and original cycle, respectively, compared to the other DESs. The decrease in cyclic absorption loading of CO_2 in the first cycle compared to the original cycle may be due to a decrease in carbamate production as temperature rose and the exothermal reaction [31]. When the regeneration first started (with a high carbon dioxide loading), some of the HCO_3^{-}/CO_3^{-2} desorbed CO_2 via thermal breakdown, and some of them combined with $MEAH^{+}$ to create carbamate. Despite the entire desorbed state of $HCO_3^{-}/CO3^{-2}$, the desorption reaction proceeded to a second stage (low carbon dioxide loading), where carbamate reacted with H+ to produce monoethanolamine and desorbed CO_2 during regeneration [42].

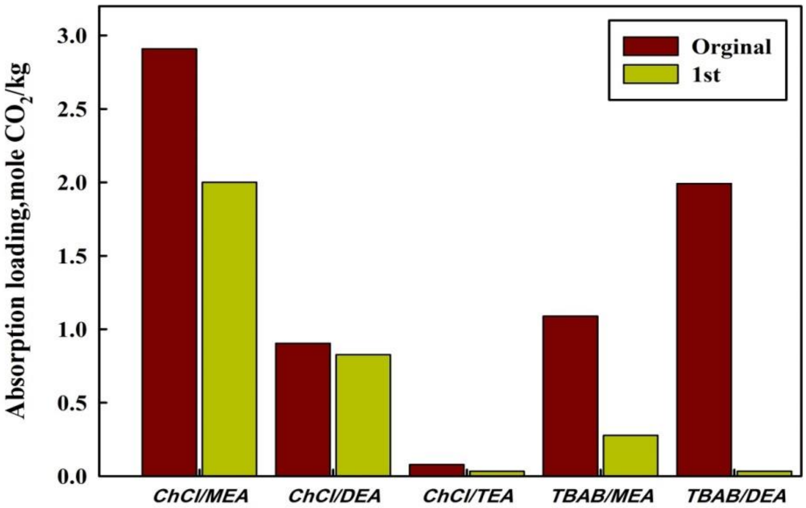

Figure 9. Cycling absorption/desorption loading of CO_2 for several binary DESs at a molar ratio of 1mole acceptor: 4 mole donor, absorption temperature of 30 ºC ,1 atm., 15 vol.% CO_2 and a desorption temperature of 90 ºC

3.2.4 Regeneration efficiency

Figure 10 presents the regeneration efficiency for several binary DESs at a molar ratio of 1 mole acceptor: 4 mole donors, an absorption temperature of 30 ºC, 1 atm., 15 vol.% CO_2, and a desorption temperature of 90 ºC. That is observable. Figure 10 revealed the highest regeneration efficiency of 91.45%, 68.75%, 42.11%, 25.51%, and 2% for ChCl/DEA, ChCl/MEA, ChCl/TEA, TBAB/MEA, and TBAB/DEA, respectively. This is due to the decreased formation of carbamate in ChCl/DEA as the desorption temperature increases. As the carbamate formation reaction is exothermic, the increased stability of carbamate in the other binary DESs at the given temperature leads to lower regeneration efficiency [12, 43]. The regeneration efficiency of synthesized DESs in this work was found higher than that of the MEA (30%), PZ/DETA (15/15), PZ/DETA/NaADS (15/15/10), and PZ/NaADS (15/25) at 35.6, 30.8, 25.9, and 21.8%, respectively, using a rotating packed bed (RPB) [12].

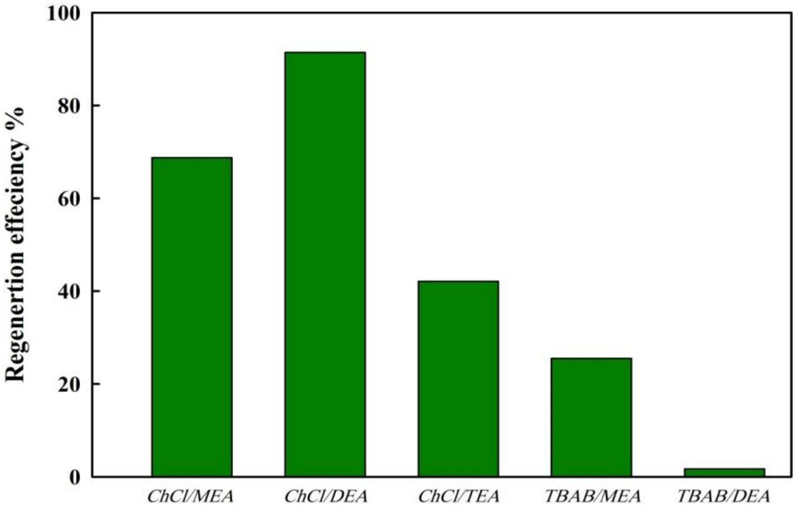

Figure 10. Regeneration efficiency for several binary DESs at a molar ratio of 1mole acceptor: 4 mole donor, absorption temperature of 30 ºC, 1 atm., 15 vol.% CO_2 and a desorption temperature of 90 ºC

3.3 Ternary deep eutectic solvents

3.3.1 Absorption rate of CO_2

The impact of absorption time on the absorption rates of CO_2 for different synthesized DESs (ChCl/MEA/DBN, TBAB/MEA/DBN, ChCl/MEA/DBU, and TBAB/MEA/DBU) at 1 mole acceptor: 4 mole donors: 3 mole super base molar ratio, at an absorption temperature of 30 ºC, 1 atm., and 15 vol.% CO_2 is revealed in Figure 11. It might be seen that the CO_2 absorption rate of all synthesized ternary DESs reduces progressively with a rise in absorption time. Ternary DES synthesized from ChCl/MEA/DBU has a higher CO_2 absorption rate (0.0194 mole/kg. min) than the other DESs. Whereas, the absorption of CO_2 in the ChCl/MEA/DBN solvent continues for a long time (450 min) compared to the other DESs. Although the absorption rate of CO_2 for the ternary DESs prepared from ChCl/MEA/DBU and ChCl/MEA/DBN is a little higher than that of the binary DES, the absorption saturation time for the prepared binary DES is slightly longer [35], in addition to the high viscosity that is formed during absorption for ternary DESs, which makes this solvent difficult to handle during the absorption experiments. On the other hand, even when combined with the rival CO_2 collection accomplishment the viscosity of these DESs with particular tasks is one to two orders of magnitude greater, and the viscosities whose shear rate depends exhibit non-Newtonian conduct. This implies that for these dynamically and structurally complicated fluids, the Stokes-Einstein-Debye relation might not be a reliable performance indicator [22].

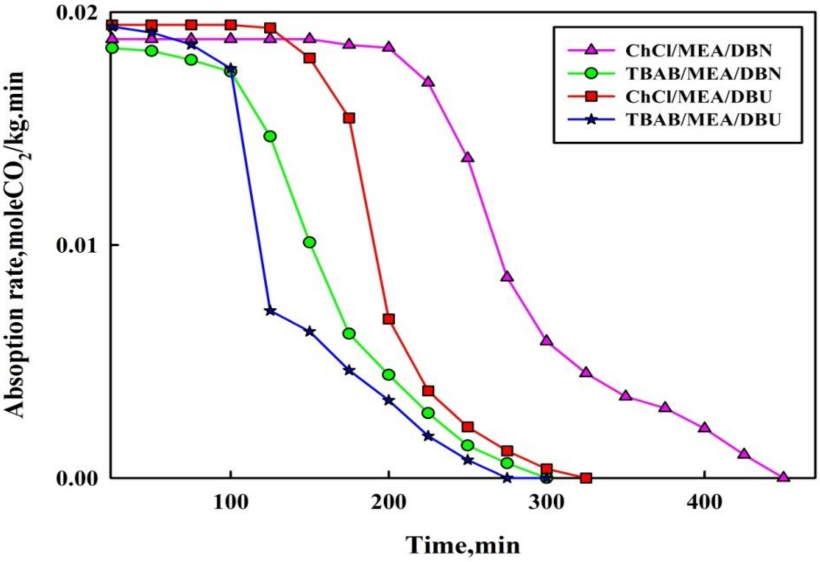

Figure 11. Absorption rate of CO_2 for several ternary DESs at a molar ratio of 1mole acceptor:4 mole donor: 3 mole super base, 30 ºC, 1 atm. and 15 vol.% CO_2

3.3. 2 Absorption Loading of CO_2

Figure 12 presents the impact of absorption time on the absorption loading of carbon dioxide for different synthesized DESs (ChCl/MEA/DBN, TBAB/MEA/DBN, ChCl/MEA/DBU, and TBAB/MEA/DBU) at 1 mole acceptor, 4 mole donor, 3 mole super base molar ratio, and an absorption temperature of 30 ºC, 1 atm., and 15 vol.% CO_2. It might be observed that the absorption loading of CO_2 for all synthesized ternary DESs improved progressively with an increase in absorption time. DESs synthesized from ChCl/MEA/DBN have a higher CO_2 absorption loading (3.8173 mol CO_2/kg) than the other DESs.

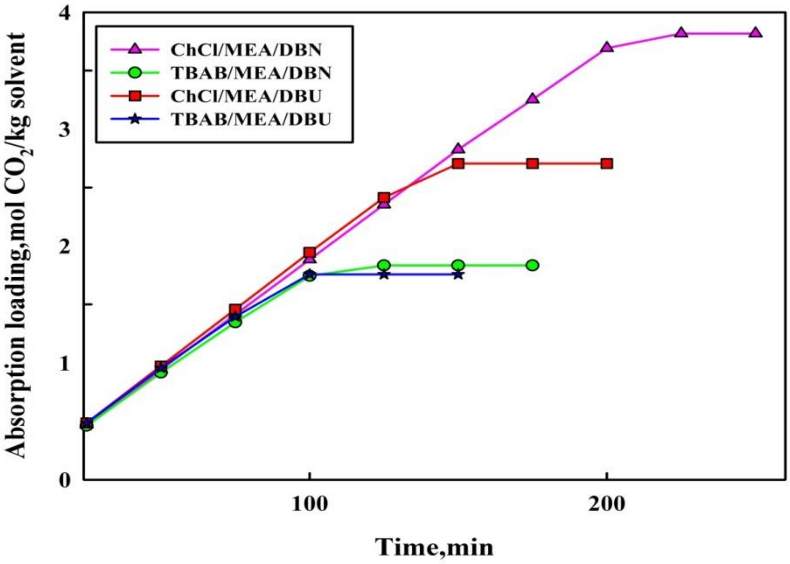

Figure 12. Absorption loading of CO_2 for several ternary DESs at a molar ratio of 1mole acceptor:4 mole donor: 3 mole super base, 30 ºC, 1 atm. and 15 vol.% CO_2

3.3.3 Cyclic loading absorption of CO_2

Figure 13 illustrates the effect of using different synthesized DESs in the absorption process (ChCl/MEA/DBN, TBAB/MEA/DBN, ChCl/MEA/DBU, and TBAB/MEA/DBU) on the cyclic absorption and regeneration at 1 mole acceptor: 4 mole donors: 3 mole super base molar ratio, an absorption temperature of 30 ºC, 1 atm, and 15 vol.% CO_2. It can be realized that ChCl/MEA/DBN exhibited the highest cycling loading of CO_2 in the first cycle and original cycle (3.8173 and 1.9779 mole CO_2/kg), respectively, compared to the other ternary DESs.

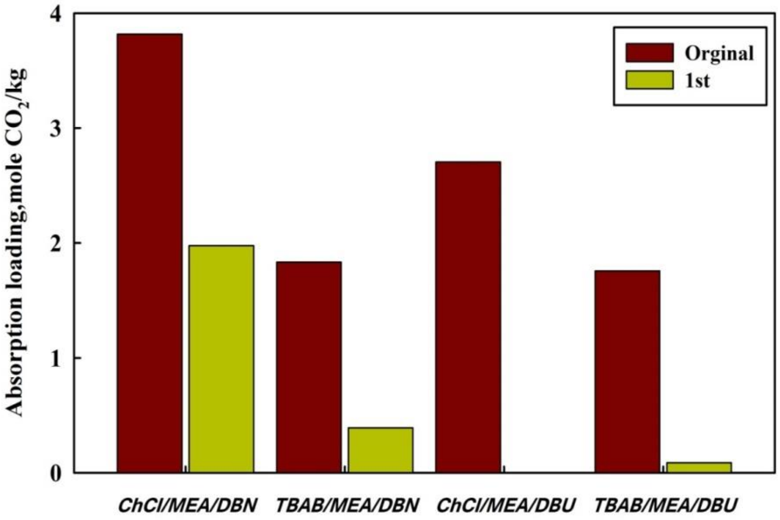

Figure 13. Cycling absorption/desorption loading of CO_2 for several ternary DESs at a molar ratio of 1mole acceptor: 4 mole donors: 3 mole super base, absorption temperature of 30 ºC ,1 atm., 15 vol.% CO_2 and a desorption temperature of 90 ºC

3.3.4 Regeneration efficiency

Figure 14 shows the regeneration efficiency for several ternary DESs at a molar ratio of 1 mole acceptor: 4 mole donors: 3 mole super base, an absorption temperature of 30 ºC, 1 atm., 15 vol.% CO_2, and a desorption temperature of 90 ºC. It can be detected that it revealed the highest regeneration efficiency of 51.81% for ChCl/MEA/DBN compared to the other ternary DESs. The regeneration efficiency for ternary DESs is lower than that for binary DESs.

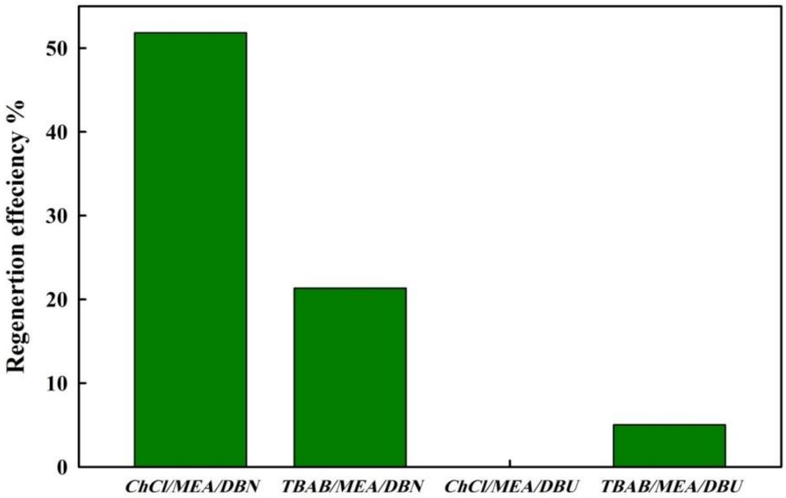

Figure 14. Regeneration efficiency for several ternary DESs at a molar ratio of 1mole acceptor: 4 mole donor: 3 mole super base, absorption temperature of 30 ºC, 1 atm., 15 vol.% CO_2 and a desorption temperature of 90 ºC

4. Conclusions

Binary and ternary DESs were successfully synthesized from different types of acceptors (ChCl and TBAB), donors (MEA, DEA and TEA) and a super based (DBN and DBU) with a molar ratio of 1:4 for a binary DESs and 1:4:3 for a ternary DESs for enhancement the absorptionof CO_2. The FTIR analysis confirmed the chemical interactions of the donor with acceptor to form DES. The absorption rate for all binary and ternary DESs decreases with an increase in absorption time, with a higher absorption rate of 0.0177 mole CO_2/kg. min for a binary DESs synthesized from ChCl/MEA with (1:4) molar ratio. Whereas, the CO_2 absorption loading increases with an increase in absorption time, with a higher value of 2.9092 mole CO_2/kg. The cyclic loading exhibits that the synthesized DESs can be used many times after the regeneration, with a drop in CO_2 loading of less than 30% for ChCl/MEA solvent. The regeneration efficiency for ChCl/MEA was higher than the other prepared solvents at 68.75%. It has been established that among the five binary DESs solvents, the absorption and desorption characteristics of ChCl/MEA are higher than those of other solvents. The synthesized ternary DESs exhibit good absorption characteristics with lower desorption characteristics than the binary DESs.

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