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Review Article

Deep Eutectic Solvents for Industrial Gas Absorption: Recent Advances and Perspectives

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ABSTRACT: Deep eutectic solvents (DESs) have emerged as promising environmentally benign alternatives to conventional solvents, exhibiting physicochemical properties akin to ionic liquids while offering distinct advantages such as low toxicity, high biodegradability, straightforward synthesis, and low cost of raw materials. Consequently, DESs have witnessed rapid development and found diverse applications across numerous scientific and industrial fields in recent years. This review comprehensively summarizes the fundamental aspects of DESs, including their definition, key properties, and classification systems. The primary focus, however, lies in critically reviewing recent advancements in the application of DESs for gas absorption. The performance and mechanisms of DESs in capturing major target gases, specifically carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S), are discussed in detail, along with their potential for absorbing other relevant gases. Based on the extensive literature surveyed, the review draws pertinent conclusions regarding the current state of DES-based gas capture technology and provides insightful perspectives on future research directions and challenges for enhancing the efficacy and applicability of DESs in this crucial environmental domain.

Keywords: Deep eutectic solvents; Gas absorption; Carbon dioxide capture; Sulfur dioxide removal; Hydrogen sulfide removal; Green solvents.

1. INTRODUCTION

The rapid accumulation of greenhouse gases and toxic pollutants such as SO_2, and H_2S in the atmosphere has raised serious concerns about climate change, environmental degradation, and human health. Among the available mitigation strategies, gas absorption and separation using liquid solvents is recognized as one of the most mature and effective approaches for industrial emission control. Conventional solvents, such as aqueous amine solutions (e.g., monoethanolamine, MEA), have long been employed for CO_2 capture due to their high reactivity and absorption efficiency. However, these solvents face significant drawbacks, including high volatility, corrosiveness, energy-intensive regeneration, and rapid degradation, which limit their economic and environmental viability [1-3]. As a result, the development of advanced solvents with enhanced performance, lower environmental impact, and improved sustainability has become an urgent research priority. Against this backdrop, ionic liquids (ILs) have attracted tremendous interest as next-generation solvents. ILs are salts composed of bulky organic cations and organic or inorganic anions that remain liquid at or near room temperature. Their unique physicochemical properties-including negligible vapor pressure, wide liquid temperature range, high thermal and chemical stability, and structural tunability through functional group modification-make them attractive in a variety of fields. They have been applied in solvent

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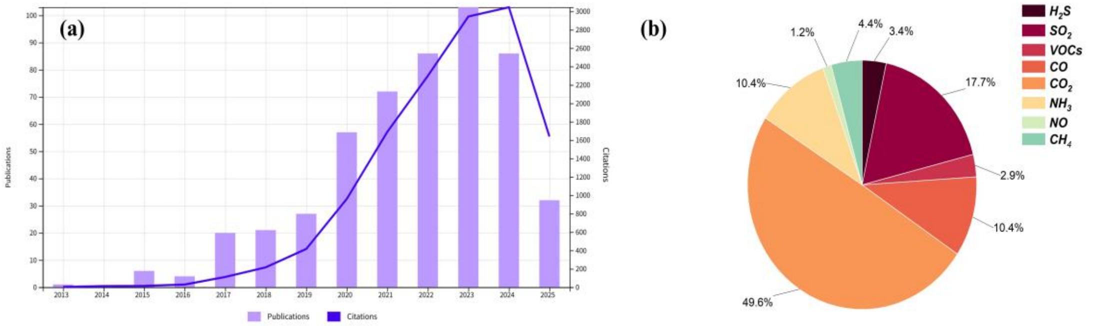

Figure 1: (a) Number of publications and citations from 2013 to 2025 related to deep eutectic solvents (DESs) in the context of gas absorption or capture. The data were obtained from the Web of Science database. (b) Percentage breakdown of publications from 2013 to 2025 that report the removal of specific gas-phase impurities using DESs. (Data accessed on July 21, 2025.)

engineering, catalysis, electrochemistry, separation processes, and environmental remediation, and have demonstrated excellent performance in capturing acidic gases such as CO_2, SO_2, and H_2S [4-7]. Despite these promising features, the large-scale deployment of ILs remains restricted by critical challenges. The synthesis of ILs often involves complex multi-step reactions and demanding purification procedures, leading to high costs. Furthermore, uncertainties regarding their toxicity, biodegradability, and environmental fate raise concerns over potential ecological risks [8,9]. To address these limitations, deep eutectic solvents (DESs) have recently emerged as a new generation of green solvents and are increasingly considered sustainable alternatives to ILs. First introduced by Abbott and co-workers in 2003, DESs are typically formed through hydrogen-bond interactions between a hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD) in a specific molar ratio, resulting in a eutectic mixture with a melting point far lower than that of the individual components. Unlike ILs, which are stabilized by strong electrostatic interactions, DESs form a “liquid hydrogen-bond network,” which confers many of the beneficial characteristics of ILs-such as low vapor pressure, low volatility, high polarity, and good thermal stability-while substantially reducing toxicity and improving biodegradability. In addition to their favorable physicochemical properties, DESs offer distinct environmental and economic advantages. They can be synthesized simply by mixing inexpensive, renewable, and often bio-based raw materials such as choline chloride, urea, glycerol, amino acids, and organic acids under mild conditions, without producing byproducts. This near-100% atom economy is fully aligned with the principles of green chemistry. The structural diversity of HBAs and HBDs provides DESs with a broad design space, enabling precise modulation of viscosity, polarity, hydrophilicity, acidity/alkalinity, and conductivity through composition and functionalization [10-13]. This tunability has established DESs as versatile solvents with strong potential in applications such as biomass conversion, catalysis, electrochemistry, drug delivery, and particularly in gas adsorption and separation [14-17].

In recent years, DESs have shown great promise in gas adsorption and separation, particularly for the efficient capture of acidic gases such as CO_2 and SO_2. As shown in Figure **1**, the number of publications related to gas adsorption by DESs has grown rapidly since 2020, reaching a peak in 2023 (Figure **1a**). Among these, studies on CO_2 and SO_2 adsorption dominate (Figure **1b**), reflecting the substantial potential of DESs in greenhouse gas control and flue gas treatment. Among the various types of DESs, Type III DESs, which are formed by mixing quaternary ammonium salts (e.g., choline chloride) with molecular HBDs (e.g., alcohols, acids, amines), have garnered particular attention due to their mild preparation conditions and strong functionalization potential. By incorporating various functional HBA or HBD molecules, Type III DESs can achieve enhanced selective adsorption toward target gases. They have shown excellent performance in CO_2 capture, SO_2 separation, and process optimization, and are increasingly viewed as a promising direction for green solvent design and environmental technology.

Although it is receiving increasing attention, unfortunately, there are still very few critical reviews based on the characteristics and applications of DES. Contrary to the earlier comments that mainly focused on general characteristics or certain specific fields (such as a single pollutant for DESs), this study particularly emphasized their role in gas absorption and separation. We summarize recent progress with a focus on how structural design influences solvent performance, especially in the capture of CO_2, SO_2, and other acid gases. Beyond presenting application examples, this

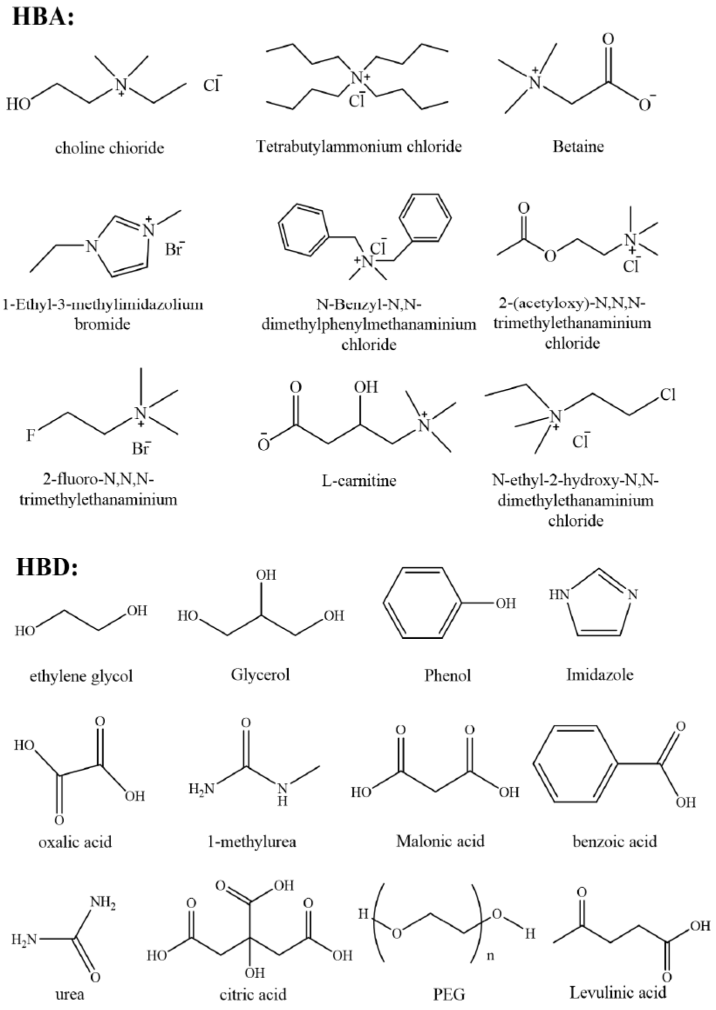

Figure 2: Common HBA (Hydrogen bond acceptors) and HBD (Hydrogen bond donor) structures.

review highlights the key challenges-such as selectivity, mass transfer limitations, recyclability, and scalability-that must be addressed for practical deployment. By doing so, we aim to provide a more targeted perspective on DES-based gas separation, clarifying the current status of research while outlining directions that could guide future development.

2. DEFINITION, NATURE OF DEEP EUTECTIC SOLVENTS

2.1. Definition and Classification of Deep Eutectic Solvents

The concept of deep eutectic solvents (DESs) was first systematically proposed by Abbott *et al*. in 2003, when they reported a transparent liquid formed by mixing a quaternary ammonium salt (e.g., choline chloride) with an amide (e.g., urea) in a specific molar ratio [11]. This eutectic mixture remained liquid at room temperature and exhibited properties similar to those of ionic liquids (ILs), such as extremely low vapor pressure, high thermal stability, and excellent solvation ability. Because of these similarities, DESs were initially described as “pseudo-ionic liquids” or “novel ionic liquids,” and were quickly recognized as a solvent system aligned with the principles of green chemistry. The essential feature of DESs lies in their strong hydrogen-bond interactions between the components, which lower the melting point of the mixture significantly compared to the individual components, leading to the characteristic “deep eutectic” behavior. Traditionally, DESs were defined as binary or ternary systems consisting of a hydrogen bond acceptor (HBA)-typically a quaternary ammonium salt-and a hydrogen bond donor (HBD) such as carboxylic acids, polyols, or amides, in specific molar ratios. The gas absorption performance of deep eutectic solvents (DESs) can be rationalized by their distinct interaction mechanisms with gas molecules, which differ according to their component types. Based on Abbott’s classification [51], four major categories of DESs can be associated with different dominant absorption pathways:

Type I DESs (metal halides+quaternary ammonium salts): Gas absorption is primarily governed by Lewis acid-base interactions and coordination effects. The halide anions (e.g., Cl^-, Br^-) act as basic sites to interact with protonic species in H_2S, while metal halides provide coordination centers that strongly bind SO_2. These properties make Type I DESs particularly suitable for capturing acidic gases (SO_2, H_2S) through chemical affinity.

Type II DESs (hydrated metal halides + quaternary ammonium salts) : In addition to the Lewis acid-base and coordination mechanisms observed in Type I, the presence of hydrated metal salts introduces strong ion-dipole interactions, which enhance the solvation of polarizable molecules such as SO_2. The hydrated structure also facilitates multiple interaction pathways, improving the overall absorption efficiency for polar acidic gases.

Type III DESs (quaternary ammonium salts + molecular HBDs, e.g., alcohols, acids, amines): These are the most versatile and widely studied DESs, where hydrogen bonding and dipole-quadrupole interactions dominate the absorption process. Hydroxyl, amino, and carboxyl groups in the HBD components interact strongly with CO_2, stabilizing it via hydrogen bonding to the carbonyl oxygen or through acid-base interactions with the amine groups. As a result, Type III DESs are particularly effective for CO_2 capture, and their tunability through functionalized HBDs enables selective gas absorption.

Type IV DESs (metal halides + molecular HBDs, without quaternary ammonium salts): These systems combine features of both Type I/II and Type III. Gas absorption involves coordination from metal halides together with hydrogen bonding from molecular HBDs. Consequently, Type IV DESs are capable of interacting with both acidic gases (SO_2, H_2S) and greenhouse gases (CO_2), although they remain less investigated compared to Type III.

In summary, the gas absorption mechanisms of DESs encompass hydrogen bonding, Lewis acid-base interactions, coordination binding, ion-dipole interactions, and physical dissolution. The relative contribution of each pathway depends strongly on the DES type and its composition, underscoring the importance of tailoring DES design to target specific gases.

2.2. The Nature of deep Eutectic Solvents Physicochemical Properties and Green Advantages of DESs

Deep eutectic solvents (DESs) are IL-like liquids whose macroscopic properties arise from a microscopic network of hydrogen bonding and, in some systems, coordination/ion-dipole interactions between a hydrogen-bond acceptor (HBA) and a hydrogen-bond donor (HBD). These specific interactions disrupt the lattice energies of

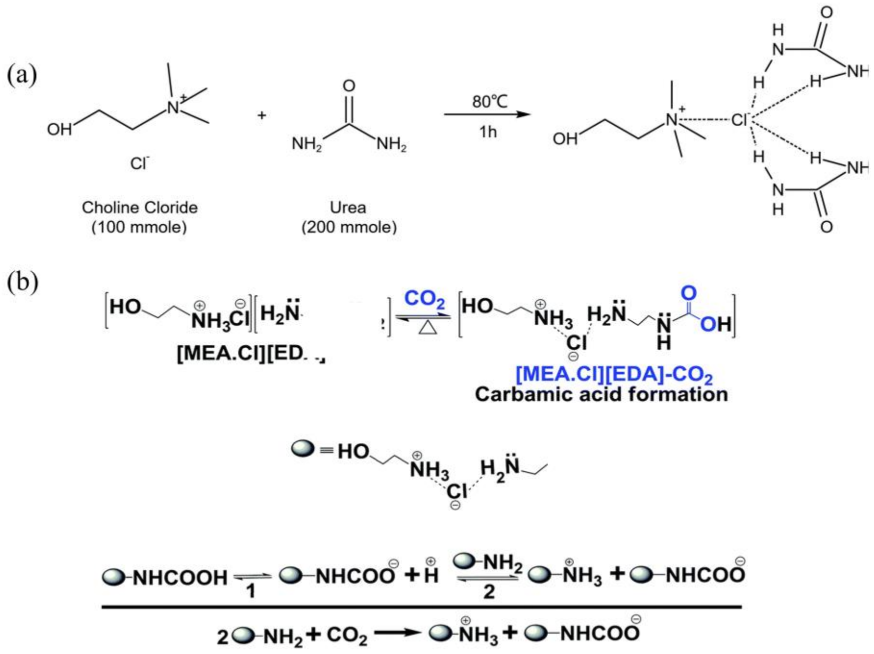

Figure 3: (a) Synthesis of ChCl/urea Deep eutectic solvent (b) Proposed mechanism of DES network formation via electrostatic interactions between ammonium and carbamate Reprinted with permission from *Ref. 29. Copyright 2016, Royal society of chemistry.*

the pure components and delocalize charge, producing a pronounced eutectic depression so that the mixture forms a stable liquid at or near room temperature with negligible vapor pressure and very low volatility. The same interaction network that lowers the melting point also governs bulk behavior: stronger hydrogen-bonding generally increases viscosity and polarity while suppressing volatility, whereas composition (choice and ratio of HBA/HBD) allows orthogonal tuning of hydrophilicity/hydrophobicity, conductivity, acidity/basicity, and gas solubility-hence DESs are “molecularly programmable” media rather than single-property solvents. In terms of synthesis, most DESs can be prepared by a simple heating and stirring method. Typically, the HBA and HBD are mixed at a predetermined molar ratio and stirred at approximately 80 °C until a clear and homogeneous liquid forms-thus yielding the target DES solvent [13]. This process does not require harsh reaction conditions or complex purification, offering advantages such as simplicity, high yield, and low energy consumption. As shown in Figure **3a**, a classic example is the formation of a DES by mixing choline chloride and urea, in which multiple hydrogen bonds between the two components stabilize the liquid structure. The resulting system has a well-defined composition, no side reactions, and nearly 100% atom efficiency, representing a model of green synthesis. No solvent, catalyst, or post-purification is required, which translates to near-quantitative atom economy, low energy input, and straightforward scale-up using inexpensive, often bio-based feedstocks (e.g., choline salts, urea, glycerol, organic acids). Compared with many conventional ILs, representative DESs frequently show lower cytotoxicity and ecotoxicity profiles and improved environmental compatibility, although toxicity remains composition-dependent and should be verified case by case. Thermally, DESs are usually stable over moderate operating windows and exhibit a characteristic multistage degradation: initial disruption of the supramolecular Hydrogen-bond network (reversible dissociation into HBA/HBD), followed by preferential decomposition/volatilization of the less stable donor (e.g., urea) and, at higher temperatures, breakdown of the acceptor; this sequence informs solvent recovery, regeneration, and process design. In addition, DESs exhibit unique thermal decomposition behavior. Studies have shown that DESs typically undergo multistage mass loss during thermal degradation [14-15]. In the first stage, intermolecular hydrogen bonds are disrupted by thermal agitation, leading to dissociation of the DES into its original HBA and HBD components. In the second stage, the HBD-often less thermally stable (e.g., urea)-undergoes preferential decomposition or volatilization. In the third stage, the HBA begins to thermally decompose or evaporate, ultimately resulting in the complete breakdown of the system. This decomposition pattern helps elucidate the thermal stability mechanisms of DESs and provides a technical basis for their thermal processing, recovery, and reuse[16-22].Altogether, the coupling between supramolecular structure and tunable physicochemical properties gives DESs a coherent advantage set-low volatility, low melting point, designable polarity, viscosity, affinity, and simple, economical synthesis-positioning them as practical green alternatives to conventional organic solvents and as promising absorbents for targeted gas capture in sustainable chemical engineering.

3. DEEP EUTECTIC SOLVENT USED IN GAS ABSORPTION FIELD

3.1. CO_2 Absorption by Deep Eutectic Solvents

Carbon dioxide (CO_2), primarily emitted from fossil fuel combustion and industrial activities, is one of the major greenhouse gases responsible for global climate change. Although traditional CO_2 capture technologies-such as amine-based absorption-have been widely applied, they often suffer from significant drawbacks including high energy consumption, solvent corrosiveness, poor thermal stability, and low regeneration efficiency [23-25]. These limitations underscore the urgent need for greener, more efficient absorbents. In recent years, deep eutectic solvents (DESs) have emerged as promising candidates for CO_2 absorption due to their environmental friendliness, low toxicity, structural tunability, and excellent thermal stability. Among them, DESs composed of choline chloride (ChCl) as the hydrogen bond acceptor (HBA) are the most extensively studied systems.

Leron *et al*. [26] systematically investigated the CO_2 solubility in a ChCl/urea DES (molar ratio 1:2) under conditions of 303.15-343.15 K and 0-6.0 MPa. The results showed that the solubility increased with gas pressure and decreased with temperature, exhibiting typical gas-liquid equilibrium behavior. Building on this, Li *et al*. [27] further explored the influence of temperature, pressure, and the HBA/HBD molar ratio on CO_2 solubility. Their findings indicated that external thermodynamic conditions significantly affect the stability of the hydrogen-bonding network within DESs, thereby modulating gas solubility. This structure-property relationship highlights the importance of controlling hydrogen bond strength and molecular geometry to optimize CO_2 absorption capacity. Beyond urea-based systems, researchers have

Table1: Comparative CO_2 uptakes (mol and wt%) and molecular weights of various DESs and ILs.

IL/DESs	MW (g.mol^{-1})	CO_2 Uptake[a] (mol)	CO_2 Uptake (wt%)	T[b] (℃)	References
[MEA.Cl][EDA] [g]	69.46	0.54	33.7	30	[29]
[TEA.Cl][EDA] [g]	91.49	0.45	24.2	30	[29]
[UE.Cl][EDA] [g]	69.2	0.26	17.8	30	[29]
[TAE.Cl][EDA][g]	72.97	0.25	14.6	30	[29]
[P$_{66614}$][3-OMe$_3$-2-Op [c]	607.97	1.65	12	20	[57]
[P$_{66614}$][Pyr][c]	455.15	1.02	8	23	[60]
[P$_{66614}$][Pro]	597.98	0.9	7.7	22	[59]
[aP$_{4443}$][Gly]	334.48	1	13	RT	[62]
[DAIL]	249.15	1.05	18.5	30	[61]
[MTPP.Br][EA][f]	103.38	0.14	7.1	25	[58]
[TBA.Br][EA] [f]	98.41	0.12	5.91	25	[63]

Note : [a]Mole CO_2 per mole solvent. [b]Absorption temperature. [c]Based on pure ILs or DESs. [d]Obtained in aqueous ILs. [e]ILs supported on porous SiO_2. [f]DESs with HBA:HBD = 1:6 (molar). [g]DESs with HBA:HBD = 1:3 (molar). [h]Uptakes measured after 24 h. RT = Room temperature.

incorporated amides and amines into DESs to enhance CO_2 affinity. For example, Adeyemi *et al*. [28] developed a DES from ChCl and monoethanolamine (MEA), which exhibited notable CO_2 absorption performance, suggesting possible chemical interactions between the amine groups and CO_2.

Trivedi *et al*. [29] reported a novel DES composed of MEA hydrochloride and ethylenediamine (EDA). By adjusting the acid–base ratio, they found that the optimal CO_2 uptake occurred at [MEA·Cl]:[EDA] = 1:3. This system not only displayed favorable thermal stability, low corrosiveness, and excellent recyclability, but also revealed a distinctive absorption mechanism. As illustrated in Figure **3b**, CO_2 first reacts with amine groups to form carbamate species, which subsequently undergo deprotonation (reaction 1). In this process, adjacent amine groups in [MEA·Cl][EDA] become protonated (reaction 2), ultimately leading to the experimentally observed 1:2 molar ratio between [MEA·Cl][EDA] and CO_2.The comparative CO_2 uptake performance of representative ILs and DESs is summarized in Table **1**. Among the ILs, [N$_{66614}$][Lys] exhibits the highest uptake on a molar basis (2.10 mol CO_2 per mol IL), but its large molecular weight (612.07 g.mol^{-1}) significantly reduces the capacity when expressed on a weight basis (13.1 wt%). In contrast, [MEA·Cl][EDA] (1:3) achieves a moderate molar uptake of 0.54 mol CO_2 per mol DES, yet due to its much smaller molecular weight, it reaches 33.7 wt%-demonstrating superior practical potential. Neat EDA shows a similar initial absorption behavior but quickly plateaus after ≈ 30 minutes, whereas the DES system maintains continued uptake over longer timescales. This enhanced performance can be attributed to the stabilizing hydrogen-bonding network and proton-transfer processes inherent to the DES structure. Considering the known drawbacks of pure amines, such as oxidative degradation and corrosion under high-temperature conditions, DESs clearly offer more balanced and sustainable advantages over both single-component amines and conventional ILs.

In addition to intrinsic solvent design, external factors also affect CO_2 absorption. The presence of water, for example, may disrupt the hydrogen-bond network, leading to reduced solubility [30]. Conversely, incorporation of long-chain alkyl groups can increase hydrophobicity or free volume, thereby promoting physical dissolution of CO_2 [31]. Overall, the absorption performance of DESs is governed by a combination of molecular composition, hydrogen-bonding interactions, functional group chemistry, and environmental conditions. Future research that integrates rational molecular design with mechanistic understanding will be crucial for optimizing DESs and accelerating their application in carbon capture and utilization (CCU) technologies.

3.2. SO_2 Absorption by Deep Eutectic Solvents

Sulfur dioxide (SO_2), one of the major pollutants emitted during coal combustion, is a key precursor to acid rain and contributes significantly to the formation of fine particulate matter (PM$_{2.5}$) and atmospheric smog. Its environmental and health hazards have prompted a strong demand for the development of efficient, green, and recyclable SO_2 absorbents, making it a crucial

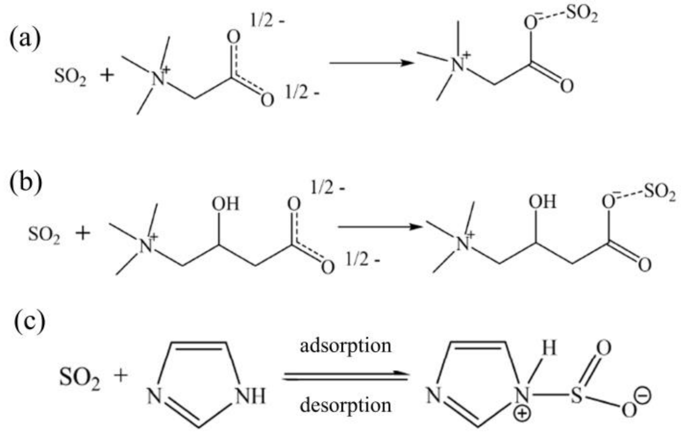

Figure 4: (a) Reaction mechanism of hydrogen bond donor with sulfur dioxide sulfur dioxide+betaine (B) sulfur dioxide+L-carnitine. (c) Mechanism of a chemical reaction between ACC/Im (1:2) and SO_2.

research focus in pollution control [32]. In recent years, deep eutectic solvents (DESs) have been widely investigated for both physical and chemical absorption of SO_2, owing to their compositional tunability, structural flexibility, and favorable thermodynamic properties. Among them, systems employing choline chloride (ChCl) as the hydrogen bond acceptor (HBA) are among the most extensively studied.

Yang *et al*. [33] systematically examined the effect of temperature, pressure, and molar ratio on SO_2 absorption in a ChCl/glycerol DES (molar ratio 1:1). The results showed that the system exhibited excellent physical absorption capabilities, with SO_2 uptake increasing at lower temperatures and higher partial pressures. At 20 °C and 1 atm, 1 gram of DES could absorb 0.678 g of SO_2. Moreover, the solvent could be effectively regenerated and reused via nitrogen gas purging, demonstrating promising reusability and application potential. Deng *et al*. [34] synthesized a series of DESs by mixing levulinic acid (LA) with six different quaternary ammonium salts (e.g., ChCl, TEAC, TBAB) at a 3:1 molar ratio. The absorption capacities followed the order: LA-TBAB (Tetrabutylammonium bromide) > LA-TEAB (tetraethylammonium bromide) > LA-TBAC (Tetrabutylammonium chloride) > LA-TEAC (Tetraethylammonium chloride) > LA-CAC(2-Ethoxyethyl acetate) > LA-ChCl. These results suggest that the structure of the cation plays a significant role in SO_2 absorption: replacing chloride with bromide and using longer alkyl chains enhanced the absorption performance. Although elevated temperatures led to reduced SO_2 uptake, the DES systems maintained good cyclic stability, retaining high absorption capacity after five regeneration cycles. In another study, Yang *et al*. [35] synthesized a DES composed of 1-ethyl-3-methylimidazolium chloride ([EMIM]Cl) and ethylene glycol (EG) and evaluated its SO_2 absorption performance. They found that increasing the concentration of the imidazolium salt enhanced SO_2 affinity. At 20 °C and 1 atm, the [EMIM]Cl/EG system (molar ratio 2:1) could absorb 1.15 g of SO_2-outperforming many previously reported systems and demonstrating excellent capacity. On the other hand, to address the limited absorption efficiency of conventional DESs under low SO_2 partial pressures, researchers have begun developing functionalized DESs with basic or reactive groups. Zhang *et al*. [37] constructed two biodegradable DESs using betaine (Bet) and L-carnitine (L-car) as HBAs, and ethylene glycol as the HBD. Both systems showed good SO_2 absorption capacity under low-pressure conditions. FT-IR and NMR analyses revealed that, in addition to physical dissolution, SO_2 also undergoes acid-base reactions with the carboxylic groups in the HBAs, thereby enhancing absorption efficiency (see Figure **4**). Deng *et al*. [38] further developed four DESs based on acetylcholine chloride (ACC) and imidazole derivatives (Im, Tri). Among them, ACC-Im (molar ratio 1:2) demonstrated excellent low-pressure absorption, with a capacity of 0.381 g SO_2 at 303.15 K and 0.1 bar. Mechanistic studies revealed that SO_2 chemically interacts with the nitrogen atom in the imidazole ring, forming reversible bonds. The proposed reaction pathway is illustrated in Figure **4c**.

In summary, the SO_2 absorption mechanisms of DESs involve both physical dissolution and chemical interaction. By tailoring the structure, charge distribution, and functional groups of the HBA and HBD components, it is possible to precisely control absorption behavior [36]. These strategies hold significant promise for the development of efficient, environmentally friendly, and regenerable flue gas desulfurization technologies based on DES platforms.

3.3. H_2S Absorption by Deep Eutectic Solvents

Hydrogen sulfide (H_2S) is a highly corrosive and toxic acidic gas commonly found in natural gas, biogas, refinery off-gases, and chemical process emissions. Its presence poses serious threats to worker safety in industrial environments, while also leading to equipment corrosion and catalyst deactivation [39,40]. At present, industrial-scale H_2S removal relies primarily on dry desulfurization and wet desulfurization techniques. Dry methods include metal oxide adsorption [41-43], the Claus process [43], and activated carbon-based approaches [44], whereas wet processes mainly encompass absorption techniques [45,46] and wet oxidation processes [47,48]. In recent years, with the rapid development of green solvents, deep eutectic solvents (DESs) have emerged as a promising alternative for H_2S capture due to their tunable structure, high solubility, and environmental adaptability. Moreover, DESs can be functionally modified to enhance their capture and conversion performance, offering excellent regeneration and reusability potential.

Guo *et al*. [49] developed a series of DESs composed of tetrabutylammonium bromide (TBAB) and caprolactam (CPL) at molar ratios ranging from 1:1 to 1:7, and evaluated their H_2S absorption performance at 303.15 K. The system with a TBAB:CPL ratio of 1:1 exhibited the best physical absorption performance, with an absorption mass fraction of up to 5.40%. After absorption, air bubbling led to the formation of a yellow solid, which was identified as elemental sulfur via X-ray diffraction (XRD). Notably, after six absorption-regeneration cycles, the solvent maintained consistent performance, demonstrating excellent stability and reusability. Wang *et al*. [50] further introduced polyethyleneimine (PEI) to functionally modify DESs, constructing four DES systems using ChCl(choline chloride) as the HBA and ethylene glycol, urea, glycerol, and propylene glycol as HBDs. Among these, the ethylene glycol/ChCl system with 25 wt% PEI exhibited the highest H_2S absorption capacity. The absorption process was found to be highly sensitive to both temperature and H_2S concentration, with lower temperatures and lower gas concentrations favoring more effective uptake. Additionally, water molecules played a significant synergistic role, likely through stabilizing the hydrogen bond network or participating in proton transfer mechanisms, further enhancing the absorption capacity. The functionalized DES system maintained excellent absorption performance over multiple cycles, indicating strong industrial potential.

Although research on DES-based H_2S absorption is still in its early stages and limited in scope, these preliminary studies have demonstrated the feasibility and exploratory value of DESs in this field. Overall, DESs offer a sustainable and green pathway for H_2S removal. By introducing oxidants, amine functional groups, or tuning solvent viscosity and polarity, the absorption capacity and selectivity for H_2S can be significantly improved. It is important to note, however, that compared with the more extensively studied CO_2 and SO_2 systems, systematic investigations into the H_2S absorption mechanisms remain limited. The micro-level processes, reaction pathways, and long-term stability under real-world conditions are not yet well understood. Future research should focus on the molecular design of functionalized DESs, combined with high-throughput screening and theoretical modeling, to accelerate their deployment in natural gas purification, biogas upgrading, and industrial flue gas treatment.

3.4. Exploratory Applications of DESs for Multicomponent Gas Absorption

To date, research on deep eutectic solvents (DESs) in the field of gas absorption has primarily focused on three representative acidic gases: carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S). These gases are characterized by high polarity and strong reactivity, making them prone to physical adsorption or chemical bonding interactions with hydrogen bond donors, acceptors or reactive groups within DES matrices. However, to further expand the potential of DESs in multicomponent gas separation and complex pollution control, researchers have begun investigating their absorption performance toward other industrially relevant gases, such as nitric oxide (NO), methane (CH_4), hydrogen (H_2), carbon monoxide (CO), nitrogen (N), and various volatile organic compounds (VOCs) [51]. Although current studies remain in the early stages and the number of published reports is limited, initial findings suggest that DESs exhibit selective adsorption capability for certain gases, laying a promising foundation for future theoretical and engineering exploration.

For instance, Sun *et al*. [52] designed and synthesized four DES systems based on 1,3-dimethylthiourea (1,3-DMTU) and various tetrabutyl cationic salts (including $P_{4444}Br$, $P_{4444}Cl$, $N_{4444}Br$, and $N_{4444}Cl$), and systematically evaluated their NO absorption capacities. All DESs showed effective NO uptake, with the 1,3-DMTU/$P_{4444}Cl$ system (molar ratio 3:1) demonstrating the highest performance, achieving an NO absorption capacity of

4.25 mol/mol. Mechanistic analysis revealed that 1,3-DMTU exhibited enhanced deprotonation tendencies within the DES matrix, which facilitated NO coordination and significantly improved absorption efficiency. To gain further insight into the absorption mechanism, the researchers employed quantum chemical calculations, Fourier-transform infrared spectroscopy (FT-IR), and ^1H nuclear magnetic resonance (NMR). The results indicated that NO formed stable adducts with deprotonated 1,3-DMTU via hydrogen bond-induced electron redistribution and coordination interactions. This study provides a theoretical basis for the design of highly selective NO capture systems.

In another study, Xie *et al*. [53] determined the solubilities of five gases (CO_2, CH_4, H_2, CO, and N_2) in a choline chloride/urea (ChCl/Urea, molar ratio 1:2) DES system. The solubility of each gas increased with increasing pressure and decreased with rising temperature, in accordance with Henry's law. Notably, CO_2 showed significantly higher solubility than the other gases, indicating that the ChCl/Urea DES possesses strong selectivity for CO_2, making it highly suitable for preferential CO_2 capture in multicomponent gas separation processes [54,55]. It is particularly noteworthy that the introduction of a moderate amount of water into this DES system did not impair gas solubility; instead, it improved the fluidity and mass transfer properties of the solvent, thereby reducing energy consumption and operational costs during the absorption process. This finding suggests a promising optimization strategy for the practical, large-scale deployment of DESs, especially in the treatment of moist industrial flue gases.

3. CONCLUSION AND PROSPECT

In summary, deep eutectic solvents (DESs) represent a structurally versatile and environmentally benign platform with considerable promise for multicomponent gas absorption and separation. Their supramolecular hydrogen-bonding networks endow them with tunable polarity, viscosity, and interaction sites, which has proven advantageous for acidic gases and is now being explored for unconventional targets such as NO, CH_4, and H_2. Nevertheless, several urgent challenges must be addressed before DESs can move toward practical deployment. Chief among these is the difficulty of achieving high gas selectivity in complex mixtures without incurring excessive heats of absorption or slow desorption, particularly under humid conditions where water co-absorption can strongly alter speciation and stability. Equally critical are viscosity-related mass-transfer limitations, since many DESs thicken upon CO_2 or NO loading, leading to slower uptake at industrially relevant timescales. Long-term stability and material compatibility also remain uncertain, as oxidative degradation, reactions with NO_x/SO_x, corrosion of metallic components, and solvent losses by entrainment could limit durability. Finally, most regeneration strategies still rely on energy-intensive thermal desorption, and reliable techno-economic or life-cycle data under real process conditions are scarce, making it difficult to benchmark DESs against established solvents.

Looking forward, progress requires a clear prioritization of research directions. At the molecular scale, rational design of HBA-HBD combinations and functional motifs is essential to enhance gas selectivity while minimizing co-absorption of water, thereby laying the foundation for DES families tailored to specific targets such as NO, CH_4, or H_2. In parallel, understanding interfacial behavior and transport dynamics must become a central task, where in situ spectroscopy combined with molecular simulation can resolve diffusion pathways and binding mechanisms that dictate uptake rates. Equally important is the evaluation of environmental adaptability, since fluctuations in humidity, temperature, and feed composition are inevitable in practice; systematic thermodynamic and kinetic modeling can provide predictive power under such conditions. In the longer term, the development of green, low-energy regeneration routes-such as vacuum or hybrid electroswing methods-and the integration of DESs with intensified process units including membranes or rotating packed beds will be decisive for bridging laboratory performance with engineering viability. With advances along these directions, DESs can evolve from laboratory curiosities into credible media for multi-pollutant control, industrial gas purification, and clean-energy processing.

AUTHOR CONTRIBUTIONS STATEMENT

Zhihao Liu: Conceptualization, Methodology, Writing - Original draft, Validation. **Tongyu Zhang**: Methodology

CONFLICT OF INTEREST

The authors declare that there is no competing financial or non-financial interest that could have appeared to influence the work reported here.

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