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Enhancing Potassium Carbonate for CO₂-Capture with Novel Green Promoters: Mechanisms and Challenges

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ABSTRACT

Potassium carbonate solvent (K_2CO_3) is an established solvent for CO_2-capture due to thermal stability and lower energy requirements for regeneration compared to conventional amines. However, it's limited intrinsically by notoriously slow absorption kinetics. This review presents three new promoters including task-specific ionic liquids (TSILs), task-specific deep eutectic solvents (TASK-DESs), and amine-amino-acid salts (AAAS) to overcome this kinetic limitation. The current proposition for these promoters is mainly based on their high performance as individual, standalone solvents which shows enhanced capacities and reversible chemisorption pathways. Each class has a different compromise between kinetic enhancement, viscosity, cost and stability. TSILs offer excellent tunability and low-volatility at a high cost and viscosity. TASK-DESs provide a greener and simpler synthesis route but have a high viscosity issue due to hydrogen bond networks. AAAS are especially promising because of their fast kinetics their ionic character (reducing volatility) as well as precipitation resistance and lower regeneration energy. This review concludes by identifying key research gaps and future opportunities focused on the rational molecular design of promoters, understanding synergistic effects in carbonate matrices, and conducting an integrated process validation to achieve the full potential of promoter-enhanced K_2CO_3 technology for scalable carbon capture.

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1. Introduction

The increase in atmospheric carbon dioxide (CO_2) concentration is, without doubt, linked to global climate change and underscores the need for effective carbon capture, utilization, and storage (CCUS) technologies. As can be seen from figure 1, CO_2 makes up 65% of man-made greenhouse gases contribution, thus playing a dominant role. Among the various capture strategies, liquid solvent absorption is among the most mature and economically viable, particularly for processing high-volume gas streams. Capture technologies are broadly classified by combustion process: pre-combustion, oxy-fuel combustion, and post-combustion capture. Each approach operates under different pressure, temperature, and flue gas composition, which directly informs the choice of an adequate capture solvent[1-3].Within the range of available chemical absorbents, aqueous amine solutions, like monoethanolamine (MEA), have been widely used due to their high reactivity with CO_2. However, these systems are noted to have several shortcomings, including high energy consumption for solvent regeneration, solvent degradation through oxidation and thermal decomposition, corrosion problems, and evaporative losses [4, 5]. These limitations have led to the search for alternative solvents having more favorable energy and environmental profiles. Potassium carbonate (K_2CO_3) is an interesting alternative with a long history in industrial acid gas elimination, with more than 700 acid gas plants worldwide treating streams from the ammonia synthesis process, natural gas, and other sources [6]. The appeal of K_2CO_3 is the combination of low solvent costs, very low toxicity, high thermal and oxidative stability, and lowered corrosion tendency, and is relatively low volatile compared with amine systems [8, 10]. Crucially, regeneration of K_2CO_3 solution is less energy intensive as the low heat of absorption (~600 kJ/kg CO_2) and the ability to desorb CO_2 at relatively low temperatures (50-70 °C) under vacuum allows for low-grade waste heat utilization, i.e., thereby reducing energy penalties [7, 8]. Despite these huge benefits, the commercial use of simple K_2CO_3 solutions, particularly for post-combustion capture, is critically hindered by inherently slow reaction kinetics. The absorption of CO_2 into K_2CO_3 is carried out via the carbonate-bicarbonate reaction, whose rate is limited by the slow hydration of dissolved CO_2 at the low partial pressures in flue gas [9-11]. This kinetic limitation translates into low rates of mass transfer in the liquid phase, requiring prohibitively large absorber columns to achieve acceptable capture efficiency, which, in turn, undermines the economic advantage of the solvent's low cost by forcing an increase in capital expenditure [11, 12]. While increasing the operating temperature can moderately improve the kinetics, it is not sufficient to overcome the fundamental constraints on mass transfer without significant energy penalties [12]. Furthermore, there are operational issues such as solvent precipitation, fouling, and corrosion, which are less severe than amine systems, but remain [13-16]. To overcome this central kinetic deficiency, much research has focused on the use of chemical promoters or activators, blended with K_2CO_3 solutions. These compounds work by allowing alternative, faster pathways for reactions to occur, which in turn act as catalysts for the entire absorption process. Early work had focused on inorganic types of promoters such as arsenite, selenite, and vanadate, which are Lewis bases but were ultimately found to be impractical because of their poor efficiency, toxicity, and instability [17-21]. Consequently, organic activators have attracted attention. The ideal promoter should balance a range of parameters: high catalytic activity for CO_2 absorption, economical for industrial applications, low volatility to minimize losses, and high resistance to heat, oxygen, and gas impurities such as SOx and NOx [22]. Three classes of solvents were identified and proposed as novel promoters based on their unique performance as single solvents: task-specific ionic liquids (TSILs), task-specific deep eutectic solvents (TASK-DESs), and amine amino acid salts (AAAS). Each class provides a different way to change the reaction environment. TSILs are salts with reactive amino functional groups, which provide high structural tunability, very low vapor pressure, and the ability to undergo stoichiometric chemical absorption, thereby converting them from a physical to a chemical solvent [23-25]. TASK-DESs, which are generally composed of mixtures such as choline chloride and urea or amines, exploit hydrogen-bond networks to develop low-cost, biodegradable solvents with tunable chemistry for reversible CO_2 binding [26-28]. AAAS, derived from neutralizing amino acids with organic amines, combines the high kinetics of the amine functional group with the useful ionic character to suppress volatility and increase stability, without the precipitation problems of their inorganic amino acid salt counterparts [29, 30]. A critical observation underlying this review is that the promising data and subsequent recommendations for these promoters are largely extrapolated from their performance as individual, standalone solvents. Studies on amine-functionalized TSILs, for example, report CO_2 capacities of around 1.0 mol CO_2/mol IL under idealized conditions [31, 32]. Similarly, evaluations of AAAS, such as piperazine-lysine or SARMAPA, show higher cyclic capacities and regeneration energies than the benchmark MEA [33, 34]. However, their behavior as minor additives in a complex and buffered K_2CO_3 solution, where all the interactions with carbonate/bicarbonate ions, the speciation variations, and the changes in the physical properties, such as viscosity, are involved, can be quite different from their performance when used separately [35, 36]. This disparity between individual solvent performance and effective promotion in a hybrid system is a central challenge for technology development. To address these research gaps, we present a detailed and critical analysis of TSIL, TASK-DES, and AAAS solvents and predict their performance as promoters of K_2CO_3 solvent based on their performance as individual solvents. Specifically, it will: (1) understand the basic promotion mechanisms common to and unique within each class; (2) compare their performance based on published standalone data with emphasis on the issues in extrapolating to promoted systems; (3) analyze the key factors (pressure, temperature, concentration) controlling the performance of promoter enhanced K_2CO_3; (4) identify the persistent technical and economic problems as well as future research opportunities into the development of viable hybrid solvent systems. By collating the state of the art, this review aims to provide a direction for future studies to rationally design and implement the next generation of promoted carbonate solvents for efficient post-combustion carbon dioxide capture.

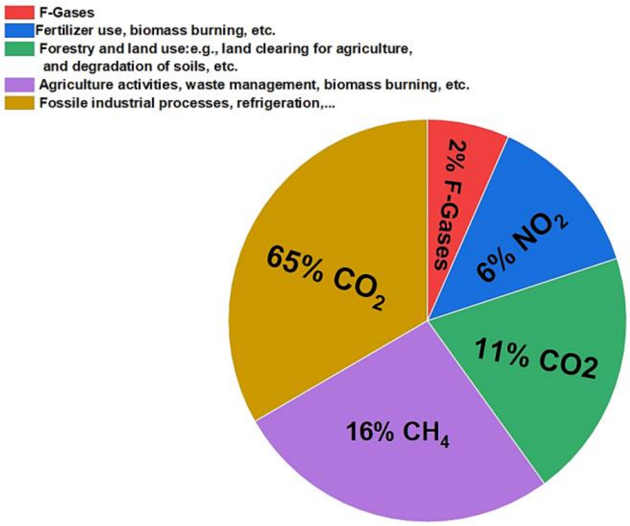

Figure 1. Breakdown of Human-Manmade Emissions of Greenhouse Gases by Gas and Source.

2. CO_2 capture technology

The selection of a specific capture technology depends on several factors, such as the CO_2 concentration in the gas stream, the target CO_2 purity and recovery, the allowable energy requirements, and additional constraints specific to the industrial process [1]. Carbon capture from power plants in industries can be classified as (i) pre-combustion capture, (ii) oxy-fuel combustion, and (iii) post-combustion capture depending on the combustion method and composition of the gas stream. Working conditions, such as pressure and temperature, vary across techniques [2]. Details of various carbon-capturing approaches are shown in table1 and figure 2.

- Pre-combustion, fossil fuel is reacted with air/oxygen and partially oxidized to form syngas (CO and H_2). The syngas reacts with steam, i.e., water–gas shift reaction, to yield CO_2 and H_2. The CO_2 is then separated while H_2 is used for power generation and other applications. However, the fuel conversion process before combustion is complex [37]. The CO_2 concentration in the flue gas is around 15–40%. NO_x and water vapor (steam) are common impurities in various capture processes [3].
- The oxy-fuel process is similar to the post-combustion process but utilizes high-purity (> 95%) O2 (instead of air) and recycled flue gas to generate a mixture of CO_2 and water vapor. However, considerable energy is required to separate O2 from air to initiate combustion [37]. The CO_2 concentration in the exhaust gas ranges from 75% to 80% [3].
- Post-combustion capture, also known as post-conversion capture, involves separating CO_2 from waste gas streams after converting the carbon source to CO_2. In the post-combustion process, fuel combustion occurs in the air, and the CO_2 concentration range in the exhaust gas is about 3-25% [3]. Post-combustion capture is considered the most promising near-term potential strategy [2] for CO_2 emission reduction, as it can be applied to both existing and newly designed power stations, petrochemical and gas industries, biogas sweetening plants, ethylene oxide production plants, cement industries, as well as the fuel, iron, and steel industries [38, 39]. Interestingly, Sask Power (Canada), which captures 1,000,000 MT of CO_2/year, and TMC Mongstad (Norway), which captures 300,000 MT of CO_2/year, are examples of post-combustion capture technology applications [2].

Table 1 Major sources of CO_2 emissions and capturing approaches [3].

Description	Post-Combustion Capture	Oxy-Fuel Combustion Capture	Pre-Combustion Capture
Process Description	CO_2 is separated from flue gas after conventional combustion in air	Fuel is burned in nearly pure O_2, producing a CO_2-rich flue gas	Fuel is converted to syngas; CO_2 is removed before combustion
Operating Pressure	~1 bar	~1 bar	15–40 bar
Operating Temperature	50–75 °C	40–75 °C	40–450 °C

CO_2 Mole Fraction	3–25 %	75–80 %	15–40 %
Major Impurities	N_2, O_2, H_2O	O_2, H_2O	CH_4, CO, H_2
Other Impurities	NO_x, SO_x, H_2O	NO_x, SO_x	NO_x, SO_2, SO_x, H_2O
Typical CO_2 Source Stream	Flue gas	Flue gas after O_2 combustion	Shifted syngas (H_2 + CO_2)
Main Industries	• Coal-thermal power plants • Oil refineries • Cement plants	• Iron and steel plant • Glass fabrication plant • Metallurgical failed	• Gasification plants • Natural gas fields • Fertilizers
Key Advantage	Easily retrofitted to existing plants	High CO_2 concentration simplifies separation	High pressure and CO_2 partial pressure
Key Challenge	Dilute CO_2, high energy demand	Costly air separation unit	Complex upstream processing

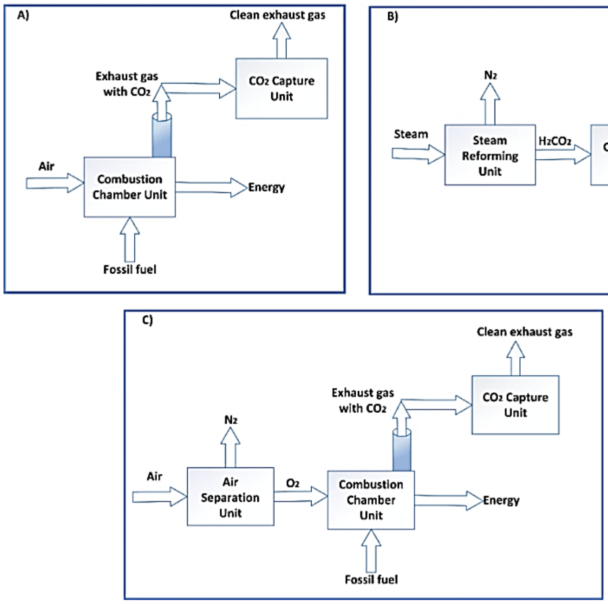

Figure 2. Process Block Diagram for A) Post-Combustion Capture, B) Pre-Combustion Capture, and C) Oxy-Fuel Combustion Capture.

3. K_2CO_3-based CO_2 Capture

Potassium carbonate-based absorption systems are a distinct class of solvent technologies for CO_2 capture, based on carbonate-bicarbonate chemistry and with a long history of industrial applications. Their behavior, performance, and modification through chemical promotion are the basis of the discussion provided in this section. These features are determined by well-defined gas-liquid reaction pathways and by solvent composition and operating conditions, which collectively govern absorption and regeneration behavior.

3.1 Conventional K_2CO_3 Solvent

Potassium carbonate solvent (K_2CO_3)-based systems are among the most proven technologies for acid gas removal, with over 700 plants worldwide using carbonate solutions for the separation of CO_2 and H2S from ammonia synthesis gas, crude hydrogen, natural gas, and town gas streams [6]. The widespread use of carbonate solvents has been largely attributed to their good physicochemical properties, such as low cost, low toxicity, high thermal and oxidative stability, and relatively low solvent losses compared with conventional amine systems [4, 5]. In addition, carbonate solutions are benign to the environment and exhibit reduced volatility and corrosion tendencies, making them attractive for long-term industrial operations [4, 10].

The absorption of CO_2 into potassium carbonate occurs through an exothermic reaction driven by the carbonate-bicarbonate equilibrium and is very effective for gas streams with a high partial pressure of CO_2. One of the most important benefits of K_2CO_3-based systems is their regeneration characteristics. Due to the low affinity between CO_2 and carbonate ions, CO_2 can be desorbed at relatively low temperatures (50-70 °C) and under vacuum conditions (2-8 psia), thus enabling the use of low-grade or waste steam from the power plant cycles and, as a result, greatly reducing parasitic energy losses [7]. The heat of absorption of K_2CO_3 solution (~600 kJ/kg) is significantly less than that of conventional amines such as MEA (1900 kJ/kg) and MDEA (1200 kJ/kg), indicating the intrinsic energy efficiency of carbonate-based capture processes [8]. Despite these advantages, the main drawback of potassium carbonate solvents is their extremely sluggish CO_2 absorption kinetics, especially at low temperatures and low CO_2 partial pressures, which are common in post-combustion flue gas [9-11]. The low alkalinity of K_2CO_3 results in low liquid-phase mass transfer rates, leading to lower capture efficiencies and requiring taller absorber columns to achieve removal levels similar to those of amine-based systems [11, 12]. This requirement directly translates into increased capital expenditure and increased operational complexity, partially counteracting the economic benefits of low solvent cost.The low reaction rate of pure K_2CO_3 solutions has therefore been widely acknowledged as the main limitation to their wider use for CO_2 capture [9]. Although higher operating temperatures of the absorbers, above 318 K, can partially increase reaction kinetics, this strategy is not sufficient to overcome mass transfer limitations without additional equipment or an energy penalty [12]. Furthermore, carbonate systems are prone to operational issues such as solvent precipitation [13, 14], fouling and crystal formation in reboilers and pipelines [15], and corrosion of carbon steel equipment, although to a lesser extent than with amine solvents [16]. To overcome such limitations, many studies have focused on blending promoters or activators into potassium carbonate solutions. The addition of compounds with stronger CO_2 affinity, particularly those containing active N-H functional groups, has been shown to greatly enhance absorption kinetics, increase mass transfer from the liquid phase, and reduce the size requirements of the absorber [14, 40, 41]. However, this approach presents new trade-offs, as enhanced chemical interactions often result in increased heat of absorption and altered phase equilibria, which, in turn, lead to higher regeneration temperatures or vacuum requirements during CO_2 stripping [7]. Reported regeneration energies for promoted K_2CO_3 systems vary from 87.1 to 143 kJ mol-1 because of the competition between kinetic enhancement and thermodynamic penalties [42]. All in all, traditional potassium carbonate solvents inhabit a peculiar place in the space of CO_2 capture. Their combination of low cost, environmental compatibility, thermal stability, and favorable regeneration characteristics is a good basis for industrial deployment. Nevertheless, their intrinsically slow reaction kinetics are the prevailing challenge, requiring ongoing development of efficient promoters and an optimized process configuration. Addressing these kinetic and operational limitations is critical to realizing the full potential of K_2CO_3-based systems in post-combustion CO_2 capture applications.

3.2 Promoted K_2CO_3-Based amine group

The inherently slow reaction kinetics of CO_2 with aqueous potassium carbonate (K_2CO_3) remain a major drawback of carbonate-based capture systems and require the use of chemical activators to achieve higher absorption rates. In a broad sense, promoters studied for K2CO solutions can be divided into inorganic and organic activators, each with unique mechanistic roles and performance limitations. Early research focused on inorganic promoters, such as phosphates, silicates, hypochlorite, and oxyanions such as selenite and tellurate [17, 18]. These species are usually thermally stable and are resistant to oxidation, but are limited by poor efficiency, instability, corrosiveness, and toxicity. [19, 20] concluded that all species that feature O- or OH groups, or those that act as Lewis bases with CO_2 as a Lewis acid, or those with pyramidal or tetrahedral structure to facilitate the CO_2molecule to approach the base site, could potentially act as a catalyst. This is a similar conclusion to that of Dennard and Williams [21], who stated that oxyanion promoters should have a lone pair of electrons and be able to act as acceptors to facilitate CO_2 absorption. However, their performance changes with concentration, temperature, or pH so that species such as boric acid and vanadate are not consistent across conditions. Consequently, inorganic activators are now considered more of a secondary or mechanistic tool than a practical option [43]. In contrast, organic promoters have become the focus of most research efforts due to their better enhancement for kinetics and tunability of chemical functionality. Extensive investigations have shown that organic amines, amino acid salts, imidazoles, and amides can significantly enhance the CO2 absorption rate in K_2CO_3 solutions [9, 44-46]. Designing and screening effective promoters is a balancing act among kinetic, economic, and environmental factors. An ideal promoter should provide a high CO2 absorption rate, be cost-effective for large-scale production, have a low vapor pressure to minimize evaporative losses, and be resistant to degradation at high temperatures, in oxygen, and to flue gas impurities (SOx and NOx). Moreover, promoters should be moderate-strength Lewis bases to achieve efficient CO2 activation without significantly increasing the heat required for absorption or regeneration [22]. These criteria serve as the basis for current research efforts to optimize promoted K_2CO_3 systems for post-combustion CO_2 capture applications. So, we will focus on modern amine-based solvent promoters and predict their efficiency as promoters based on their performance as a single solvent in CO_2 absorption.

3.2.1 Promoted K_2CO_3-Based TSILs

Ionic liquids (ILs) are salts with a melting point lower than the boiling point of water and consist totally of ions, usually a mixture of organic cations and inorganic or organic anions [23]. Its exceptional structural modifiability, arising from the independent variation of positive and negative ions and substituents, means there is a virtually limitless design space, with an estimated 1018 possible IL structures at room temperature [47, 48]. Based on cation, ILs are commonly classified as imidazolium, pyridinium, pyrrolidinium, phosphonium, and ammonium-based systems, while anion classifications include halides, tetrafluoroborate, hexafluorophosphate, amino acid, and hydroxypyridinium species [49]. However, overlapping ion functionalities, such as pyridinium species behaving as a cation or an anion, depending on their chemical modification, makes rigid classification schemes difficult [50, 51]. Consequently, functional classification has been very prominent, especially for CO_2 capture, differentiating conventional ILs from amine-functionalized ILs [52] figure 3. Conventional ILs are mainly physical solvents with pressure-dependent CO_2 solubility and low absorption capacity under flue gas-relevant pressure [52-56]. Extensive experimental studies have demonstrated high CO_2 solubility in fluorinated imidazolium-based ILs, like [BMIM][BF6] [57], [Bmim][PF6], and [Bmim][Tf2N] [58-61], with absorption governed by van der Waals interactions and quadrupole-induced free-volume occupation [56]. Although some conventional ILs surpass the performance of monoethanolamine (MEA) under high pressure [42], under low-pressure post-combustion conditions, IL performance remains poor compared to chemically reactive solvents [24].

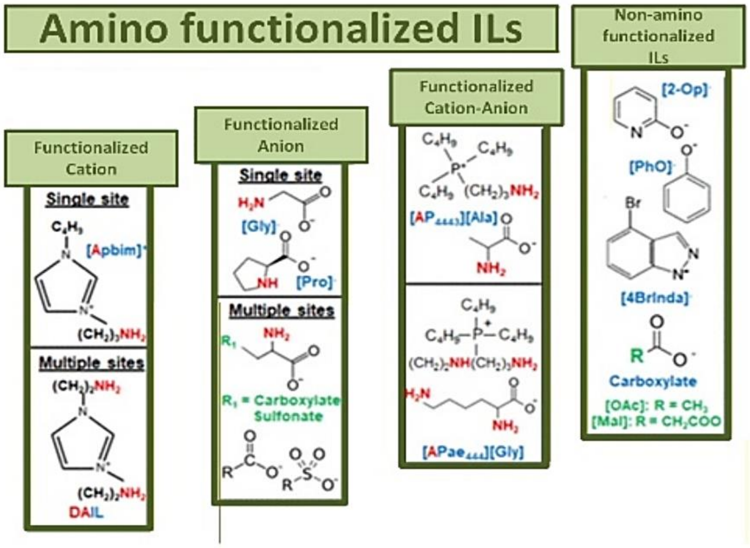

Figure 3. Example of various ILs stractures [62].

The limitations of ILs' physical absorption have led to the development of task-specific ionic liquids (TSILs), also known as functionalized ILs [24]. TSILs introduce reactive functional groups, most often amines, directly into the cation, anion, or both to permit chemical absorption of CO_2 [330]. This functionalization transforms ILs from passive physical solvents into chemically active absorbents, thereby enhancing low-pressure CO_2 capture capacity [25]. The synthesis and performance of TSILs for the chemical capture of CO2 with amine functionality were first reported by the Davis group [24]. Early work by the Davis group determined the feasibility of amine-functionalized TSILs for reversible CO_2 chemisorption [24]. Amine-functionalized TSILs have similar absorption mechanisms as alkanolamines, and form carbamate species with stoichiometries of either 1:2 or, for some advanced systems, 1:1 (CO_2:IL) [63, 64]. For example, Bates et al. [63] reported near-theoretical CO_2 absorption capacities (0.5 mol CO_2/mol IL) in [pabim][BF4], with excellent reversibility and stability across multiple cycles. Amino acid-based TSILs, such as phosphonium-amino acid systems, were the next advance in this concept, enabling the stabilization of carbamic acid intermediates and the formation of a unique 1:1 reaction pathway [56, 64-66]. Imidazolium-based ILs with neutralized amino acid anion were reported for the first time by Ohno and co-workers, without any investigation of their applicability for CO_2 capture solvents [67, 68]. More recently, ILs based on trihexyltetradecyl phosphonium ([P6,6,6,14]) cations with several neutralized amino acid anions have been shown to exhibit a 1:1 mechanism for CO_2 capture, as the anion can exist as a stabilized carbamic acid [64, 65].

Subsequent studies showed that the CO_2 uptake capacity of TSILs with amine groups on both ionic moieties, i.e., dual-functionalized TSILs, can reach nearly 1.0 mol CO_2/mol of IL without capacity loss [31]. Mu et al. [32] synthesized a novel dual amino IL [aemmim][Tau] using amino-functionalized imidazolium cation, and taurine anion. The CO_2 absorption capacity of this IL is as large as 0.9 mol CO_2/mol IL at 303.15 K and 0.1 MPa. The dissolved CO_2 can be easily desorbed at higher temperatures or under vacuum, thus [aemmim][Tau] can be reused, and no significant loss of capability was observed after 6 recycles [69]. Despite these performance enhancements, TSILs remain limited by their high viscosity and often higher (fivefold) production costs compared with conventional ILs [70, 71]. Hydrogen-bonding networks between amine groups and counterions make the viscosity even higher and the absorption equilibrium times long, on the order of 24 h in some systems [72, 73]. Although mixing with water or amines has been suggested to mitigate these drawbacks [24], viscosity and mass-transfer limitations still limit the standalone TSIL deployment at an industrial scale [73]. From a process integration point of view, TSILs show their greatest promise not as stand-alone solvents but as promoters of aqueous potassium carbonate (K_2CO_3) systems. Conventional K_2CO_3 absorption is hampered by slow CO_2 hydration kinetics and moderate equilibrium loading. Incorporating TSILs into K_2CO_3 solutions offers a mechanistically complementary approach: the TSILs provide fast, reversible chemisorption pathways, while the K_2CO_3 retains low-cost bulk absorption capacity. Amine-functionalized TSILs can serve as molecular promoters, accelerating CO2 capture by forming transient carbamate or carbamic acid species, thereby avoiding the rate-limiting hydration step inherent in carbonate systems. Unlike the traditional amine promoters, TSILs have very low vapor pressure and less oxidative degradation, so less solvent is lost and emitted [48, 74]. In addition, amino acid-based TSILs are chemically compatible with carbonate systems, providing superior thermal stability and resistance to irreversible degradation [31, 73]. However, the promoter role of TSILs needs to be critically evaluated. Their inherently high viscosity, especially when increasing amine density, may counteract the benefits of increased kinetic gain by impairing gas-liquid mass transfer [72, 73]. In environments rich in K_2CO_3, ion-ion and hydrogen-bond interactions may further increase viscosity and decrease effective diffusivity. As a result, TSIL loading needs to be carefully optimized to balance the kinetic enhancement with the hydrodynamic penalties. Cost considerations also make low-concentration deployment of TSILs necessary, further supporting their use as additives rather than as primary absorptive materials. In this context, TSILs act similarly to catalytic promoters, i.e., small amounts can have a significant effect on the kinetics of absorption and regeneration efficiency without fundamentally affecting process economics. The demonstrated reversibility, structural tunability, and chemical robustness of TSILs [64, 75, 76] support their strategic integration into K_2CO_3-based systems, provided that viscosity and compatibility-related constraints are rigorously managed. In general, TSIL-enhanced K_2CO_3 systems can be a rational hybrid of clear interaction and independent economy, leveraging the advantages of both solvent classes while eliminating their disadvantages. This positioning does not go so far as to place TSILs as replacements for carbon-disabling agents, but rather as additives that can unlock the full kinetic potential of K_2CO_3 to capture next-generation CO_2.

3.2.2 Promoted K_2CO_3-Based Task DEEPs

The discovery of deep eutectic solvents (DESs) represents a major step forward in the design of green solvents. The term deep eutectic solvent has been introduced by Abbott and his colleagues [26, 27] and refers to eutectic mixtures formed by strong hydrogen-bond interactions between two or more components, usually a hydrogen-bond acceptor (HBA) and a hydrogen-bond donor (HBD) [28]. Over the last 20 years, chemically DESs have emerged as promising, environmentally benign alternatives for post-combustion CO2 capture using conventional solvents [75].DESs are typically synthesized by the combination of quaternary ammonium salts (most notably choline chloride, ChCl) with HBDs such as urea, ethylene glycol, glycerol, carboxylic acids or amines[76-84]. Choline chloride is especially appealing because of its low-cost, biodegradable, non-toxic and widely available nature coupled with compatibility of various HBDs [76-78]. Structurally, DESs are made up of large and asymmetric species with lowered lattice energies, thus melting points are much lower than in their individual components. This depression in melting point is related to the delocalization of charges in the networks of hydrogen bonds [28]. DESs have a number of favorable properties that are also shared with ionic liquids such as virtually zero vapour pressure, lack of flammability, broad liquid state temperature ranges, and tunability [85]. However, unlike ionic liquids, DESs can be produced by simple mixing of inexpensive, often renewable ingredients, and are therefore much cheaper and in some cases biodegradable [77, 78]. These features have sparked much interest in studying the use of DESs as physical and chemical solvents for CO_2 capture. Early studies on CO_2 absorption in DESs focused primarily on physical solubility. CO_2 dissolution in these systems is strongly dependent on pressure, temperature, HBA/HBD identity, alkyl chain length, and molar ratio. Numerous experimental investigations have shown that CO_2 solubility typically increases with pressure and decreases with temperature, in accordance with the behavior of physisorption [86-97]. ChCl-based DESs are the most widely reported in the literature owing to their good physicochemical properties and ease of synthesis. Li et al. [88, 94] reported the solubility of CO_2 in ChCl/urea DESs with different compositions and conditions, and found that a 1:2 ChCl:U ratio had the best CO_2 absorption capacity. Ullah et al. investigated the use of ChCl/levulinic acid (1:2), which showed a CO_2 capacity of 2.3 mmol g-1 at 293.15 K and 5 MPa, with negligible chemical absorption, while a reduction in corrosion (0.027 vs. 0.54 mm y-1) was observed compared to MEA [98]. Despite these benefits, conventional DESs commonly have lower CO_2 solubility than fluorinated ILs and aqueous amine solutions [99-101]. Moreover, experimental results show no general trend between HBA/HBD molar ratio and CO_2 solubility. For example, the addition of glycerol content in ChCl-glycerol DESs reduced CO2 solubility by about 33%, while the addition of ethylene glycol content in ChCl-EG DESs increased solubility by about 13% [102]. This inconsistency reflects the complex interplay among hydrogen bonding, free volume, and solvent polarity [77].In order to surpass the low-pressure performance of traditional DESs, research has therefore tended toward task-specific DESs (TASK-DESs) that may interact chemically with CO_2 [103]. TASK-DESs feature the introduction of reactive functional groups, most often amines or superbases, into the DES structure, enabling reversible chemisorption rather than physical dissolution. Sze et al. [103] reported the first TASK-DES capable of chemically binding CO_2, consisting of choline chloride, glycerol, and a superbase. The superbase deprotonated hydroxyl groups to form alkoxide anions, which reacted irreversibly with CO_2 to form alkyl carbonates, as verified by FTIR and 13C NMR spectroscopy. This study demonstrated a clear pathway for DES-based chemical absorption under mild conditions. Amine-based TASK-DESs have since been widely studied. Adeyemi et al. [104] synthesized ethanolamine-based DESs with different molar ratios and reported CO_2 absorption capacities exceeding 30 wt%, which are higher than those of conventional DESs and aqueous amine solutions. Pishro et al. [105] showed that the polyamine content of ethanolamine hydrochloride (TEPA) DESs enhanced CO_2 uptake in a significant manner with increasing polyamine content. Mukesh et al. [106] designed low-viscosity polyamine-based DESs with CO_2 capacities of 17-22 wt% with fast desorption and low solvent loss, which are superior to monoethanolamine during regeneration. However, high regeneration energy and solvent instability are still the challenges with some TASK-DESs. For example, DESs based on hydrochloride salts and ethylenediamine showed very good initial CO_2 uptake (up to 33.7 wt%) but required substantial energy for regeneration and produced toxic mist when exposed to moisture, which restricts their industrial application [107]. Similarly, DESs such as [MEAHCl][MEA] suffered from solvent loss during regeneration, due to increased stability after CO_2 absorption [108]. One limitation of both conventional and task-specific DESs is consistent and high viscosity, often above 100 cP, from extensive hydrogen bond networks and strong electrostatic interactions [28]. High viscosity has a detrimental effect on gas-liquid mass transfer and increases pumping energy, thereby increasing overall process costs. Although dilution with water, PEG200, or secondary HBDs can have a huge effect on viscosity [52, 109, 110], such modifications can dilute reactive sites or even change absorption mechanisms. When considered promoters rather than sole solvents, TASK-DESs play an important role in potassium carbonate (K_2CO_3)-based CO_2 capture systems. Aqueous K_2CO_3 is attractive economically and thermally stable, but kinetically is limited due to the slow hydration of CO_2 and formation of bicarbonate. TASK-DESs can overcome this limitation by introducing rapid, reversible chemisorption pathways within the carbonate matrix. Amine-based TASK-DESs, in particular, can act as molecular reaction accelerators, forming transient carbamate or carbonate intermediates that overcome the natural kinetic limitations of K_2CO_3 absorption. Unlike traditional amine promoters, TASK-DESs have negligible vapor pressure and reduced corrosivity, thereby reducing solvent loss and equipment degradation [52]. Their hydrogen-bonded networks may also stabilize reaction intermediates, allowing for greater absorption efficiency at low CO_2 partial pressures relevant for the post-combustion capture. However, their promoter efficacy is limited by viscosity in principle. In environments rich in K_2CO_3, strong hydrogen bonding between the DES constituents and carbonate species could further increase viscosity, counteracting the gains in kinetics by decreasing diffusivity. Therefore, TASK-DESs are unlikely to be viable as bulk additives at high concentrations. Instead, their best use is in low-dose promotion, where small quantities provide a disproportionate amount of kinetic enhancement without compromising hydrodynamics or regeneration energy. From a process-design perspective, TASK-DES-promoted K_2CO_3 systems are a hybrid absorption concept that combines the low cost, thermal robustness, and scalability of carbonate solvents with the chemical reactivity of task-specific eutectic mixtures. In summary, TASK-DESs should not be considered as substitutes for K_2CO_3, but as enabling promoters that facilitate much faster kinetics and improved cyclic performance without sacrificing the economic and operational benefits of carbonate-based CO_2 capture systems.

3.2.3 Promoter-based amine amino acid salt

Solvents based on amino acids have interest in CO_2 capture, as amino acids are benign, biodegradable, and structurally related to traditional alkanolamines [112 ،111]. Although amino acids and amino acid salts (AAS) already resolve several of the drawbacks of amine-based solvents, including volatility, oxidative degradation, and corrosion [115-118], neutralization by organic bases can further improve the performance of amino acid salts (AAAS) [30, 34, 113, 114].

AAAS has a reactive amine functional group that enables faster CO_2 uptake and confers an ionic nature that reduces vapor pressure and enhances thermal and oxidative stability [115-118]. In contrast to inorganic amino acid salts, which are produced with KOH or NaOH, AAAS exhibit better absorption-desorption properties and increased operational stability, especially at high CO_2 loadings [29, 30]. The absorption of CO_2 by AAAS follows processes similar to those of amine-based solvents and includes the formation of zwitterions and carbamate/bicarbonate complexes [115]. The presence of the amino and carboxylate functionalities, along with the exchange of protons between amino acids and organic bases, however, does alter the reaction pathways and speciation behavior [35, 36]. Quantitative and qualitative NMR methods have shown that AAAS systems exhibit distinct carbamate and carbonate/bicarbonate formation balances, which directly affect cyclic capacity and regeneration energy [36]. Aronu et al. [29] demonstrated that AAAS solvents exhibit CO_2 absorption behavior at equal concentration as MEA and even better in terms of stability in the cycle operation. Notably, AAAS based on organic bases are superior to inorganic ones because of the increased temperature sensitivity of the equilibrium and more preferable desorption behavior [29]. A number of the AAAS systems have exhibited higher CO_2 cyclic capacities and lower regeneration energy requirements than MEA. According to Kwanghwi Kim et al. [33], a piperazinelysine AAAS system had the highest cyclic capacity of 0.792 mol CO_2/mol absorbent, with minimum regeneration heat among the tested solvents. Equally, Aronu et al. [34] demonstrated that the 3-(methylamino) propylamine salt of sarcosine (SARMAPA) needed much less reboiler heat compared to MEA, even though the absorption rates were lower. These findings are also supported by pilot-scale studies. AAS systems have been demonstrated to have almost zero fugitive emissions, low corrosion, and low oxygen degradation under industrially relevant conditions [119-121]. Remarkably, Siemens Energy also announced a minimum energy consumption of 2.7 MJ/kg CO_2 per amino acid salt-based system, highlighting the promising future of these solvents for energy-saving capture procedures [121].

A major weakness of AAS systems in the traditional system is their precipitation with salt at high CO_2 loadings, making them difficult to operate, especially in membrane contactors [122, 123]. AAAS counters this shortcoming: As shown by Aronu et al. [120], AAAS do not appear as precipitates even at high CO_2 loadings, unlike potassium-based amino acid salts. NMR studies by Hartono et al. [35] and Ciftja et al. [36] showed that full neutralization of amino acids with organic bases does not necessarily take place because of competition between carbamate formation on the organic amine. Although this reduces the degree of amino acid activation, it is also known to increase the bicarbonate production and stabilization of reactive species, which leads to increased cyclic performance and reduced regeneration energy.

AAAS has a number of decisive advantages over conventional amine promoters:

1. Less volatile and emitting because of ionic character, specifically at stripper uncondition [115-119].
2. Increased oxidative and thermal stability, minimizing solvent degradation and makeup requirements [116-118].
3. Less risk of precipitation compared to inorganic AAS, and can operate with higher CO_2 loadings [114].
4. Reduced regeneration energy, i.e., due to altered speciation and lower carbamate stability [33, 115].

Mechanistically, AAAS facilitates CO_2 uptake in K_2CO_3 solutions by accelerating proton-transfer reactions and carbonate-bicarbonate interchange. NMR-based speciation studies show that organic amines in AAAS stimulate amino acid profiles and improve the process of bicarbonate formation, which is especially advantageous when carbonate-based systems are involved, where bicarbonate is the major taken-up solution [35, 36]. Nevertheless, in certain systems, partial neutralization and the formation of competing carbamates may cause decreasing returns on the effective use of amino acid functionality at higher promoter concentrations [35, 36]. Moreover, although AAAS uses less energy to regenerate compared to MEA and AAS, it can still be highly desirable to have higher desorption temperatures than optimized carbonate systems [29, 124]. In general, the AAAS is clearly positioned as a high-performance, next-generation promoter of K_2CO_3-based CO_2 capture. Their high-speed kinetics, low volatility, resistance to precipitation, and lower energy requirements make them particularly appealing in post-combustion systems where long-term solvent stability is very important and robust operation is crucial. Table 2 shows the previous studies regarding TSILs, TASK-DESs and AAASs solvents which show high efficiency (as single solvents) in CO_2 absorption. Table 3 provides an additional comparison of emerging proposed K_2CO_3-based carbon dioxide capture systems promoter class based on individual performance.

Table 2 Previous studies on the performance of traditional potassium carbonate solution and the performance of modern solvents as single solvents.

Solvent Type	**Name**	**ID**	**Operating Condition**	**Loading $mol_{CO2}/mol_{solv.}$**	**Ref.**
Conventional Potassume Carbonate	Potassume carbonate	K_2CO_3	353 K 101.3 KPa	0.10	[46]
Conventional	Potassume carbonate	K_2CO_3	113 K	1	[125]

Potassume Carbonate			1090 KPa		
Conventional Potassume Carbonate	Potassume carbonate	K_2CO_3	333 K 1120 Kpa	0.82	[125]
TSILs	Tetramethylammonium glycinate	[N1111][Gly]	298–318 K 10-300 KPa	0.85	[126]
TSILs	Imidazolium taurinate	[aemmim][Tau]	303.15 K 0.1 MPa	0.9	[32]
TSILs	Tetraethylammonium tetrafluoroborate	[TETAH] [BF4]	293 K 1atm	0.96	[127]
TSILs	Butylmethyl imidazolium arginate	[bmim][ARG]	298 K 2 bar	0.62	[128]
TSILs	Butylmethyl imidazolium	[bmim][LYS]	298 K 2 bar	0.48	[128]
TSILs	1,5-diazabicyclonon-5-enium imidazolate.	[DBNH][Im]	298 K 1 bar	0.82	[129]
TASK-DESs	1,5-Diazabicyclonon-5-ene1-butyl-3-methylimidazolium chloride Imidazole	DBN-BmimCl-Im (1:1:1)	298 K 1 bar	1.02	[129]
TASK-DESs	1,5-Diazabicyclonon-5-ene1-butyl-3-methylimidazolium chloride Imidazole	DBN-BmimCl-Im (1:2:1)	298 K 1 bar	1.07	[129]
TASK-DESs	1,5-Diazabicyclonon-5-ene1-butyl-3-methylimidazolium chloride Imidazole	DBN-BmimCl-Im (1:1:2)	298 K 1 bar	0.97	[129]
TASK-DESs	Triethylenetetramine chloride ethylene glycol	[TETA]Cl-EG DES (1:3)	313 K 1 atm	1.456	[130]
TASK-DESs	Choline chloride Ethanolamine	ChCl-EA (1:7)	298.15 K 2.015 MPa	0.401	[131]
AAASs	Piperazine Lysine salt	PZ-Lys	303.15K 0.1MPa	1.454	[33]
AAASs	Piperazine Sarcosyne salt	PZ-Sar	303.15K 0.1MPa	0.893 mol/mol	[33]
AAASs	Piperazine Alanine salt	PZ-Ala	303.15K 0.1MPa	0.850 mol/mol	[33]
AAASs	3-(Methylamino)propylamine Sarcosine salt	MAPA -SAR	313 K 101.13 KPa	0.527	[29]
AAASs	3-(Methylamino)propylamine Glycine salt	MAPA-GLY	313 K 101.13 KPa	0.519	[29]

3.3 Mechanism of Promoter System

The absorption reaction between CO_2 and K_2CO_3 solution is exothermic, and the carbonate transforms into bicarbonate [16, 132]. The overall reaction for the absorption of carbon dioxide using a potassium carbonate, K_2CO_3, solution is described as follows [10, 16, 132-135]:

$$CO_2 + H_2O + K_2CO_3 \leftrightarrow 2KHCO_3$$

or (1)

$$CO_2 + H_2O + CO_3^{-2} \leftrightarrow 2HCO_3^- \quad (2)$$

$$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+ \quad (3)$$

$$CO_2 + OH^- \leftrightarrow HCO_3^- \quad (4)$$

$$H_2O \leftrightarrow H^+ + OH^- \quad (5)$$

$$H^+ + CO_3^{-2} \leftrightarrow HCO_3^- \quad (6)$$

$$H_2O + CO_3^{-2} \leftrightarrow HCO_3^- + OH^- \quad (7)$$

At pH below 8, the principal mechanism is the hydration of dissolved CO_2, with reactions 3, 5, and 6 known as the acidic mechanism. The contribution of the acidic mechanism to the overall rate is negligible unless the solution pH is very low. Almost all industrial absorption processes are performed at high pH (generally pH > 8). Hence, the acidic mechanism can be neglected. Reaction (4) is the rate-controlling step for absorption of CO_2 into hot potassium carbonate solution, while reactions (5 and 7) are instantaneous reactions [16]. In promoted potassium carbonate (K_2CO_3) systems, the enhancement of CO_2 absorption kinetics is achieved through catalytic reaction pathways introduced by chemical activators. Although promoters differ in structure and physicochemical properties, their promotion mechanisms follow a common sequence of elementary steps. In alkaline K_2CO_3 solutions, promoters first undergo deprotonation to form activated species, which are the catalytically active forms responsible for accelerating CO_2 hydration [43].

The general promotion mechanism can be summarized as follows. Upon dissolution, the promoter (Activator) deprotonates to form an activated species (Eq. 1):

$$\text{Promoter} \quad \leftrightarrow \text{Activated promoter} \quad + H^+ \qquad (1)$$

The activated species then reacts rapidly with dissolved CO_2 to form a transient intermediate (Eq. 2):

$$\text{Activated promoter} + \mathrm{CO_2} \rightarrow \text{Intermediate} \qquad (2)$$

Subsequently, the intermediate reacts with water or other basic species present in the carbonate solution, substituting bicarbonate ions and regenerating the original activator (Eq. 3):

$$\text{Intermediate} + \mathrm{H_2O} \rightarrow \text{Promotor} + \mathrm{HCO_3^-} \qquad (3)$$

Through this cyclic mechanism, the promoter acts as a catalyst, increasing the rate of bicarbonate formation without being consumed. The net effect is an acceleration of the overall carbonate-bicarbonate reaction, while the thermodynamic equilibrium of the K_2CO_3 system remains unchanged [10, 16, 132-135]. Figure 4 shows the cyclic mechanism for the promoter.

Table 3 Comparison of emerging catalyst classes for K_2CO_3-based carbon dioxide capture systems based on analysis of their individual performances.

Promoter class	**Representative systems**	**Primary promotion mechanism in K_2CO_3**	**Effect on CO_2 absorption kinetics**	**Impact on regeneration energy**	**Key advantages when used with K_2CO_3**	**Main limitations and risks**	**Overall suitability as K_2CO_3 promoter**	**References**
TASK-Specific Ionic Liquids (TSILs)	Amine-functionalized ILs; amino-acid-based TSILs; dual-functionalized TSILs	Fast, reversible chemisorption via carbamate or stabilized carbamic-acid formation; bypasses rate-limiting CO_2 hydration in carbonate systems	High kinetic enhancement, particularly at low CO_2 partial pressures relevant to post-combustion capture	Moderate increase possible if promoter loading is excessive; reversibility mitigates penalty	Negligible vapor pressure; high thermal and oxidative stability; molecular tunability; strong chemical compatibility with carbonate media	High viscosity; reduced diffusivity at elevated IL fractions; high synthesis cost limits large-scale use	High (as low-dosage catalytic promoter)	[24, 31, 32, 63, 64, 66]
TASK-Specific Deep Eutectic Solvents (TASK-DESs)	Amine-based DESs (TASK-DESs); ChCl-based TASK-DESs	Hydrogen-bond-mediated chemisorption forming transient carbamate or carbonate species within carbonate matrix	Moderate to high enhancement, strongly dependent on viscosity and composition	Can increase regeneration energy if hydrogen-bond network strongly stabilizes absorbed CO_2	Low cost; simple synthesis; negligible volatility; reduced corrosion; good carbonate compatibility	Very high viscosity; mass-transfer limitations; moisture sensitivity in some formulations	High-Moderate (requires careful low-concentration optimization)	[28, 104, 106, 131, 136]
Amine Amino Acid Salts (AAAS)	Piperazine–lysine; SARMAPA; MAPA–Ala	Amine-driven fast kinetics combined with carbamate formation , enhanced bicarbonate formation; accelerates proton-transfer and carbonate–bicarbonate interconversion	Very high kinetic enhancement, comparable to or exceeding MEA-promoted K_2CO_3	Lower than MEA and i AAS due to modified speciation and weaker carbamate stability	Non-volatile; precipitation-resistant; high cyclic capacity; improved oxidative and thermal stability; industrial compatibility	Incomplete neutralization in some systems; diminishing returns at high promoter loadings	Very high (most industrially mature and robust promoter)	[29, 30, 34, 114, 124]

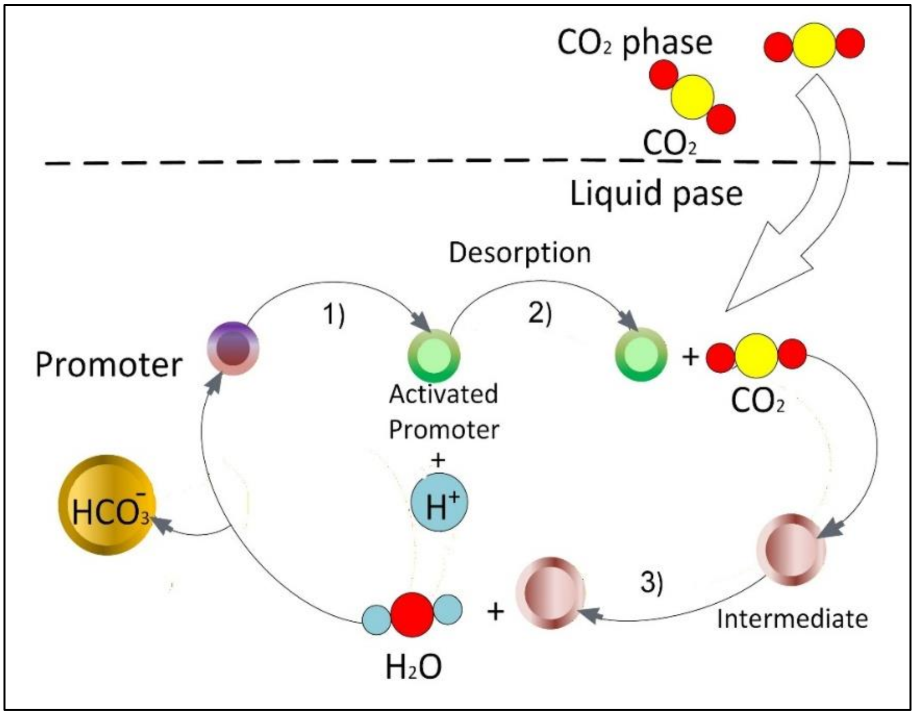

Figure 4. The cyclic mechanism for the promoter.

Despite this heterogeneity in their composition, one of the most common structural features of the promoters is their function as Lewis bases, generally with OH or O functional groups, which interact with CO_2 as Lewis acid. This observation is consistent with previous mechanistic interpretations found in the literature and explains why different promoters give similar overall enhancement effects [21, 43]. In this context, the roles of functional promoter classes suggested previously in this review, namely task-specific ionic liquids (TASK-ILs), task-specific deep eutectic solvents (TASK-DEEPS), and amino acid salts (AAAS), can be clearly interpreted in the same catalytic framework. TASK-ILs promote the CO_2 absorption mainly because of the high strength of reversible Lewis acid-base interactions between CO_2 and functional anions, which enables the rapid formation of intermediates and high thermal and chemical stability in alkaline K_2CO_3 media. TASK-DEEPS facilitate absorption by providing hydrogen-bond-rich microenvironments that stabilize activated CO2 intermediates and enhance proton transfer, thereby accelerating bicarbonate substitution and promoting promoter regeneration. Amino acid salts (AAAS), which have both amine and carboxylate functional groups, favor CO_2 uptake through a combination of high reaction kinetics and low volatility, with excellent compatibility with potassium carbonate solutions, via either a Zwitterionic or base-catalyzed pathway. Collectively, these functional promoters optimize the kinetics of CO_2 hydration and bicarbonate formation without altering the carbonate-bicarbonate equilibrium, making them well-suited for high-temperature, low-energy K_2CO_3-based CO_2 capture processes suitable for industrial application.

4. Factors Affecting CO_2 Absorption Performance in Promoter-Enhanced K_2CO_3 Systems Factors Affecting on the proposed solvent systems

4.1 Effect of Operating Pressure and CO_2 Partial Pressure

The CO_2 partial pressure (pCO_2), which is the main driving force behind carbonate system mass transfer, is directly dependent on the operating pressure. High pressure increases the absorption flux because pCO_2 is maintained above the solution equilibrium, as is also the case in promoted K_2CO_3 systems [16, 137]. Nevertheless, the system's response to pressure changes is altered by the presence of advanced promoters. The kinetic limitation of conventional K_2CO_3 absorption at low pCO_2, characteristic of post-combustion flue gas, is the slow rate of hydration of CO_2. This limitation can be overcome by TASK-ILs, TASK-DESs, and AAAS that chemically bind CO_2 via amine or superbase functionalities. They offer an alternative, quicker chemisorption pathway that relies less on pCO_2 as a driving force than the force-controlled process of traditional K_2CO_3 solvents [25, 35, 36, 69, 103]. For example, amine-functionalized TSILs demonstrate high CO_2 capacity at rather low pressure (almost atmospheric) [25], whereas conventional ILs and un-promoted K_2CO_3 cannot operate at low pressure [9-11, 24]. This renders TSILs especially effective as promoters in low-pressure applications, thereby decreasing the system's sensitivity to pCO_2 fluctuations, and the same applies to TASK-DES and AAAS.On the other hand, the promotion effect can be weakened at higher pCO_2, as the inherent kinetics of carbonate absorption are enhanced and mass transfer constraints prevail [137-139]. The critical point in the TSIL and TASK-DES promoters is that they can enhance the viscosity of solutions, thereby overcoming the advantage of a stronger driving force by restricting diffusion between gases and liquids [28, 72]. Thus, high pressure enhances performance, but the optimum promoter loading should be traded off with hydrodynamic punishments, particularly in viscous TSILs [72, 73].

4.2 Effect of Temperature

The temperature has conflicting effects on the absorption of CO_2: it increases the reaction rate and diffusion rate, while reducing the physical solubility of CO_2. In the case of promoted K_2CO_3 systems, this trade-off is subtle due to the nature of the promoter. High temperatures tend to increase the rate of absorption in K_2CO_3 systems, through the effect of decreasing the viscosity of the solvent and enhancing the rate-limiting steps, which is enhanced by the presence of promotion groups [61], Similar observations were reported by Ramezani and Di Felice [140] for CO_2 absorption in K_2CO_3-DETA solutions, where temperature exerted a positive influence on absorption performance. This enhancement was primarily attributed to reduced solvent viscosity and increased reaction rate constants at higher temperatures. The promoters of AAAS, such as, take advantage of the increased kinetics at higher temperatures, and their ionic character offers better thermal stability than volatile amines, thereby reducing solvent degradation [116-118].The thermal stability of the promoter in itself is, however, vital. TSILs and TASK-DESs have low volatility, yet their functional groups (e.g., amines) may undergo thermal degradation at extremely high temperatures. The literature shows that TSILs and AAAS based on amino acids exhibit increased thermal stability, making them a good choice for normal temperature conditions during K_2CO_3 regeneration [31, 73, 116-118].

4.3 Effect of Promoter Type and Concentration

The type of promoter and its concentration are key factors in determining the overall system performance, including absorption kinetics, cyclic capacity, viscosity, and energy demand.

4.3.1 Effect of Promoter Type

Promoters type with different mechanisms are analyzed in Section 3:

1. **TSILs (e.g., dual-amino functionalized):** Provide high, reversible chemisorption capacity (up to ~1 mol CO_2/mol IL) and negligible volatility, but introduce high viscosity that can hinder mass transfer [31, 64, 72].
2. **Task-DESs:** Fast chemistry pathways and low vapour pressure are introduced, but high viscosity is frequently achieved by hydrogen-bonding networks [28, 103].
3. **AAAS**: Have equilibrium between rapid amine-like kinetics, ionic nature (without being highly volatile), precipitation resistance, and reduced regeneration energy than MEA, and therefore are highly desirable promoters [29, 33, 34]. Promoter selection determines the prevailing absorption pathway (carbamate or bicarbonate) and the resulting speciation that has a direct influence on the cyclic capacity and heat of regeneration [35, 36].

4.3.2 Effect of Promoter Concentration Type

With promoters, high concentration generally increases the rate and capacity by increasing reactive sites as observed with the amine promoters in K_2CO_3 [141]. This is the case with TSILs, TASK-DESs, and AAAS. As an illustration, the more the amines contained, the higher the uptake of CO_2. On critical reflection, however, diminishing returns and trade-offs at high concentrations are noted:

1. **Viscosity Increase:** TSILs and TASK-DESs have a significant limitation. Solutions with high concentrations have a significant adverse impact on CO_2 diffusion rates, reducing kinetic advantages and also increasing pumping costs [28, 72, 73].
2. **Economic limitations:** TSILs are expensive, and should be used at low concentrations as kinetic and not solvents [25, 70, 71, 142].
3. **Speciation and Energy Penalties:** In the case of AAAS, at very high concentrations, amino acid functionalities might become inefficient because of competing carbamate formation with the organic amine base, which might raise regeneration energy [35, 36].

Hence, the literature supports a low-dosage promotion strategy. There is an optimum promoter level, usually low, that provides a disproportionate enhancement of kinetics and cyclic operation without negatively affecting viscosity, price, or the robust thermal and operational properties of the underlying K_2CO_3 solvent.

5. Challenges and Opportunities

The incorporation of sophisticated promoters into aqueous potassium carbonate (K_2CO_3) systems is a very attractive route to improved viability for carbonate-based CO_2 capture. However, this approach is accompanied by unique technical and economic challenges that must be overcome if its promise is to become an industrial reality. Importantly, the present proposal for TSIL, TASK-DES, and AAAS promoters is based primarily on their performance as individual, standalone solvents. On this basis, whilst proving to have intrinsic potential, raises a number of extrapolation issues when these compounds are redesigned to be used as minority additives in K_2CO_3 solvent.

5.1. Key Challenges

Performance Translation from Individual Solvents Most of the promising absorption capacities, kinetics, and cyclic stabilities reported for TSILs, TASK-DESs, and AAAS are based on studies where they were used as the main absorbent. Their behaviour as low concentration promoters in K_2CO_3 solutions can be quite different. Synergistic or antagonistic interactions with carbonate/bicarbonate ions may modify the expected promotion mechanism, equilibrium speciation, and overall system thermodynamics. Therefore, to optimise promoter performance, it is necessary to re-evaluate it within the specific chemical environment of the promoted K2CO3, rather than relying solely on individual solvent data.

1. **Hydrodynamic and Mass Transfer Limitations:** One of the biggest issues in the performance of TSILs and TASK-DESs is their high viscosity, which is frequently worsened in concentrated solutions of aqueous salts, such as K_2CO_3. Elevated viscosity is a serious barrier to gas-liquid mass transfer and to pumping costs, and may partially offset the kinetic benefits derived from chemical promotion. It can also cause operational problems, such as wettability problems in packed columns and solvent circulation problems.
2. **Economic Viability and Scalability:** High synthesis cost of many TSILs, especially those with complex dual-functionalization, is a major hindrance for large-scale deployment. While their use as low-dosage promoters reduces this concern, cost-effective, scalable synthesis routes remain a critical research need. Similarly, while TASK-DESs are generally less expensive, the cost of high-purity components and energy-intensive regeneration of some formulations can be prohibitive.
3. **Long-Term Operational Stability:** The thermal and chemical stability of promoters under actual flue gas conditions is not completely solved. Although AAAS and some TSILs exhibit better resistance to oxidative and thermal degradation than conventional amines, in long-term exposure to trace amounts of oxygen, SOx, and NOx at process temperatures, further validation is required. Solvent loss in aerosol formation or unexpected drying mechanisms in the carbonate medium could affect the process economics and environmental footprint.
4. **System Complexity and Optimization:** Integration of promoters adds new variables to the design of the process. Finding the right type of promoter, the right concentration, and process conditions (e.g., temperature, pressure) is a multi-dimensional challenge. Excessive promoter loading can cause diminishing returns, increased viscosity, and different regeneration energy requirements, requiring advanced modeling and pilot-scale testing to determine the sweet spot.

5.2. Future Opportunities

1. **Rational Design of Next-Generation Promoters:** The basic knowledge of the mechanisms of promotion is a means of blueprint to rationally design additives. Future efforts can be dedicated to the design of "designer promoters" with desired properties that maximize kinetic enhancement in K_2CO_3 without inducing high viscosity, high cost, and high degradation.
2. **Hybrid and Synergistic Formulations:** There are opportunities to examine combinations of various classes of promoters, or multi-functional promoters, to exploit synergistic effects. For example, mixing a low-viscosity AAAS with a highly stable TSIL could be used to balance kinetics and durability. Research on the synergistic effects of various promoters in a carbonate system is still in its early stages.
3. **Process Intensification and Integration**: Promoter-enhanced K_2CO_3 solvents can allow for process intensification. Faster kinetics may permit smaller absorption equipment with consequent reduction in capital cost. In addition to these systems, the reduced regeneration energy of optimized systems, especially those with AAAS, enables better integration with power plant cycles, thereby improving overall plant efficiency.
4. **Exploitation of Unique Promoter Properties:** The negligible volatility of TSILs and TASK-DESs offers a tremendous opportunity to greatly reduce solvent emission and the cost of make-up. This attribute is particularly useful for adhering to strict environmental regulations. Additionally, some promoters exhibit high thermal stability, allowing operation over more flexible temperature regimes.

In conclusion, although the path from individual solvent performance to effective promotion in K_2CO_3 systems presents tangible challenges, there is some opportunity associated with it. A rigorous research effort focused on mechanistic understanding, molecular design, and processing integration is necessary to realize the full potential of promoter-enhanced potassium carbonate technology for efficient and economical post-combustion CO_2 capture.

6. Conclusion

Aqueous potassium carbonate is one of the solvents used for CO_2 capture, as it is inexpensive, thermally stable, has a low overall environmental impact, and has good regeneration properties. However, its large-scale implementation, especially in post-combustion systems with low CO_2 partial pressure, has been hindered by slow absorption kinetics. This review has clarified the strategy of chemical promotion as a key solution to the long-standing limitation. Three main classes of advanced promoters have risen to the fore: task-specific ionic liquids (TSILs), task-specific deep eutectic solvents (TASK-DESs), and amine amino acid salts (AAAS). For example, each class works by introducing alternative, fast-reaction routes (usually via carbamate or carbamic acid formation) that circumvent the rate-limiting CO_2 hydration mechanism inherent in plain K_2CO_3 solutions. While TSILs provide exceptional tunability and stability, their high viscosity and cost make them less suitable for use as a low-dosage additive. TASK-DESs offer a greener and often less expensive synthesis route, but are constrained by concerns about viscosity. AAAS are especially promising because of their combination of rapid amine-like kinetics, ionic character (reducing volatility), lack of precipitation, and low regeneration energy, making them the best candidate, in terms of industrial maturity, for the promoter. The effectiveness of these promoters is controlled by an intricate balancing act of factors such as operating pressure and temperature, and most importantly, the type and concentration of the promoter. An optimal balance is required to achieve significant kinetic enhancement without an unacceptable penalty in viscosity, cost, or regeneration duty. The evidence accepted is that of a "low-dosage promotion" paradigm, where small, catalytic amounts of a promoter can disproportionately enhance system performance while retaining the economic and operational advantages provided by the base K_2CO_3 solvent. Despite the considerable advances documented, issues persist in translating the promising performance of individual promoters into optimized, stable, and cost-effective hybrid systems (K_2CO_3) at scale. The rational design of promoters for the carbonate environment, comprehensive testing of stability over long periods of time under realistic conditions, and integrated process modeling and pilot-scale validation of these materials are key tasks for future research. By solving these issues, promoter-enhanced potassium carbonate technology can be fully matured into a robust, efficient, and economically attractive technology for large-scale CO_2 capture, making a large contribution to global efforts to reduce CO_2 emissions.

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