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New chemistry for enhanced carbon capture: beyond ammonium carbamates

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Carbon capture and sequestration is necessary to tackle one of the biggest problems facing society: global climate change resulting from anthropogenic carbon dioxide (CO_2) emissions. Despite this pressing need, we still rely on century-old technology—aqueous amine scrubbers—to selectively remove CO_2 from emission streams. Amine scrubbers are effective due to their exquisite chemoselectivity towards CO_2 to form ammonium carbamates and (bi)carbonates, but suffer from several unavoidable limitations. In this perspective, we highlight the need for CO_2 capture *via* new chemistry that goes beyond the traditional formation of ammonium carbamates. In particular, we demonstrate how ionic liquid and metal–organic framework sorbents can give rise to capture products that are not favourable for aqueous amines, including carbamic acids, carbamate–carbamic acid adducts, metal bicarbonates, alkyl carbonates, and carbonic acids. These new CO_2 binding modes may offer advantages including higher sorption capacities and lower regeneration energies, though additional research is needed to fully explore their utility for practical applications. Overall, we outline the unique challenges and opportunities involved in engineering new CO_2 capture chemistry into next-generation technologies.

Introduction

Rising atmospheric levels of carbon dioxide (CO_2) are the major contributor to global climate change, with annual emissions approaching 40 billion tonnes.[1] Nearly two-thirds of anthropogenic CO_2 emissions result from the combustion of fossil fuels, including coal and natural gas, for the global production of electricity.[1] In addition, CO_2 emissions are an inevitable by-product of other industrial processes, including the production of cement, steel, and natural gas.[1] As a result, new technologies are needed to mitigate emissions from these industrial point sources during the gradual transition to cleaner fuels and building materials. One such proposed technology is carbon capture and sequestration or utilization, in which CO_2 is selectively removed from low-concentration emission streams (4–15% CO_2) prior to its permanent storage underground or conversion into more valuable products.[2]

Building upon technology developed in the 1930s to purify crude natural gas, many have shown that aqueous amine scrubbers are currently the most technology-ready sorbents for CO_2 capture from flue emissions on large scale (Fig. 1a).[3] Aqueous amine scrubbers are effective because amines react selectively with CO_2 to produce carbamic acid intermediates, which rapidly react with a second equivalent of amine to produce ammonium carbamates; under aqueous conditions, ammonium carbamates and carbamic acids can further react with water to produce ammonium (bi)carbonates.[4] The captured CO_2 is then desorbed using heat and/or vacuum (temperature and/or vacuum swing), thereby regenerating free amines. Over the last ninety years, there has been significant optimisation of the amine structure to maximize working capacities (*i.e.* the usable amount of CO_2 captured in an actual process) while minimising regeneration energies (*i.e.* the total energy input needed to heat the material and desorb CO_2).[5] However, aqueous amine scrubbers are still faced with several challenges, including: (1) low capacities (<3 mol CO_2 per kg solution or <15 wt%) due to dilution of the corrosive amines with water;[6] (2) poor oxidative stability of amines towards O_2; and (3) degradation in the presence of contaminants such as SO_2, which reacts with amines similarly to CO_2.[7] In addition, one aspect of aqueous amine scrubbers has remained largely constant: the products of their reaction with CO_2.[8] This restriction generally leads to high regeneration energies (≥2.4 MJ kg^{-1} CO_2) and CO_2 desorption temperatures (>100 °C), greatly increasing the cost of carbon capture from flue emissions.[9–11]

Amine-based materials for CO_2 capture

One promising avenue to overcome the challenges associated with CO_2 capture by aqueous amine scrubbers is to employ other types of sorbents, such as porous solids or ionic liquids

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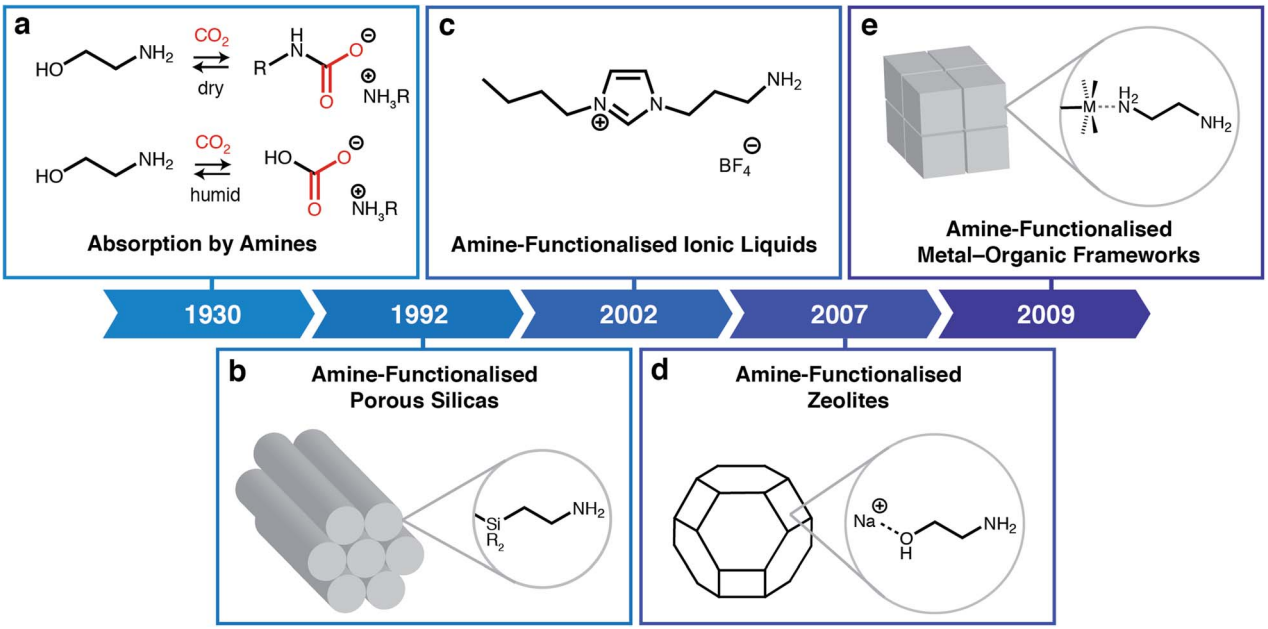

Fig. 1 Classes of amine-based materials for CO_2 capture. (a) Traditional amine chemistry for CO_2 absorption *via* the formation of ammonium carbamates under dry conditions and ammonium (bi)carbonates under humid conditions.[3] (b) Amine-functionalised porous silicas, where amines are either impregnated into or covalently attached to silica supports.[12] (c) Amine-functionalised ionic liquids.[13] (d) Post-synthetically amine-functionalised zeolites.[14] (e) Post-synthetically amine-functionalised metal–organic frameworks.[15]

(ILs). Porous materials such as silicas, carbons, zeolites, metal–organic frameworks (MOFs), porous organic polymers (POPs), and covalent-organic frameworks (COFs), have the potential advantages of higher thermal stabilities and lower heat capacities compared to aqueous amine scrubbers.[16–21] Likewise, ILs are low-melting ionic salts that offer advantages over aqueous amines including non-volatility (preventing release into the atmosphere) and structural tunability. Although hydrophobic porous solids such as silicon-rich zeolites and carbons are capable of scrubbing CO_2 from high-concentration streams (*e.g.* crude biogas),[22] many of these materials cannot remove CO_2 from humid low-concentration streams such as flue gas emissions.[23] This limitation arises because CO_2 and water directly compete for the same physisorption sites in these sorbents. An additional general challenge for porous solid adsorbents that remains to be addressed is their poor thermal conductivity, which complicates adsorbent heating and cooling during adsorption/desorption cycling.

A powerful approach to overcome the poor selectivities of typical sorbents towards CO_2 under humid conditions is to leverage the favourable reactivity of aqueous amine scrubbers in the form of amine-functionalised sorbents (Fig. 1).[24,25] Beginning with the first report of amine-functionalised silicas in 1992 (Fig. 1b),[12,24] a range of amine-functionalized solid adsorbents, including zeolites (Fig. 1d),[14] MOFs (Fig. 1e),[15,19] and carbons[26] have been prepared. Researchers have demonstrated that amine-functionalised porous solids possess the high CO_2 selectivities native to aqueous amines while generally evidencing improved thermal and chemical stabilities. For example, confining amines within a porous support largely eliminates oxidation pathways that are catalyzed by leached metal ions from the absorption columns.[7,27] Similarly, ionic liquids (ILs) can also be functionalised with amine groups to achieve high CO_2 capacities and selectivities without the need for dilution with water (Fig. 1c).[28,29] Numerous *in situ* spectroscopic studies using solution- and solid-state nuclear magnetic resonance (SSNMR) and infrared (IR) spectroscopy combined with theoretical calculations suggest that in most cases amine-functionalised materials produce similar sorption products as aqueous amine scrubbers, namely, ammonium carbamates under dry conditions[13,30,31] and, as confirmed recently, ammonium bicarbonates under humid conditions.[32] As such, the majority of these materials still require high temperatures (>120 °C) to fully desorb CO_2, resulting in high regeneration penalties.[33] In addition, amine-functionalised silicas suffer from oxidative degradation by distinct bimolecular pathways,[34] as well as the irreversible formation of ureas under dry conditions.[35] Overcoming these fundamental limitations is critical to enabling the widespread adoption of carbon capture technologies.

New CO_2 chemisorption pathways in solution and the solid state

An underexplored approach to overcome the fundamental limitations of amine-based materials is not to focus on the development of new materials, but on new chemisorptive pathways for selective carbon dioxide capture. For example, the formation of carbamic acids by CO_2 capture at amine sites is potentially desirable because it involves reaction with CO_2 at only a single amine site, increasing the CO_2 : amine sorption

ratio to 1 : 1.[36] Indeed, unlocking 1 : 1 reaction stoichiometries in general should produce higher gravimetric and volumetric sorption capacities by enabling a higher density of reactive sites within a given volume. Additionally, mechanisms beyond ammonium carbamate formation have been shown to lead to lower CO_2 desorption temperatures in some cases (see below). Importantly, each combination of CO_2 partial pressure (P) and temperature (T) for a given separation (*e.g.* 400 ppm, 25 °C for capture directly from the atmosphere) leads to an ideal differential free energy of sorption ($-\Delta G$) for that separation (*e.g.* -19 kJ mol^{-1} for direct air capture), which is critical to maximising sorption capacities while minimising regeneration energies.[41] New chemisorption pathways should enable more dramatic tuning of the differential enthalpies ($-\Delta H$) and entropies ($-\Delta S$) of sorption to achieve these optimal values. Last, moving away from amines entirely could lead to adsorbents with improved oxidative stabilities, a recurring challenge associated with amine-based materials, although more work is required to characterize the oxidative stability of promising sorbents.[42] Here, we highlight examples of new CO_2 adsorption pathways beyond ammonium carbamates that may ultimately lead to enhanced CO_2 capture.

The unique, highly-charged environment within ILs makes them an ideal setting to unlock new CO_2 reactivity. For example, although carbamic acids are normally disfavoured outside of polar aprotic solvents (*e.g.* dimethyl sulphoxide),[36,43] Schneider, Brennecke, and coworkers found that installing amines onto the anions of amino acid-derived ILs favours CO_2 capture *via* the formation of carbamic acids stabilized by hydrogen-bonding (Fig. 2a).[37] This change in mechanism doubled the molar absorption capacity of these ILs compared to those bearing amine-functionalized cations, which operate by the traditional ammonium carbamate mechanism.[13] In addition, the strong binding of CO_2 within a proline-derived IL ($-\Delta H_{abs} =$ 80 kJ mol^{-1}) led to nearly complete saturation at low pressures of CO_2 (<0.1 bar at 25 °C). Therefore, this switch in chemisorption products demonstrates that the local environment of an amine is a crucial design element for controlling its reactivity towards CO_2.[44]

Following these initial studies, even more unconventional CO_2 absorption pathways began to emerge in ILs. Building upon previous reports,[45] Li, Dai, and coworkers demonstrated that amines can be completely bypassed by capturing CO_2 in ILs bearing alkoxide or phenoxide anions and organic superbase-derived cations, which reversibly capture CO_2 *via* alkylcarbonate formation (Fig. 2b).[38] Similar to carbamic acids (Fig. 2a), this chemistry gives rise to a 1 : 1 reaction stoichiometry and thus higher gravimetric capacities (up to 20 wt%) compared to

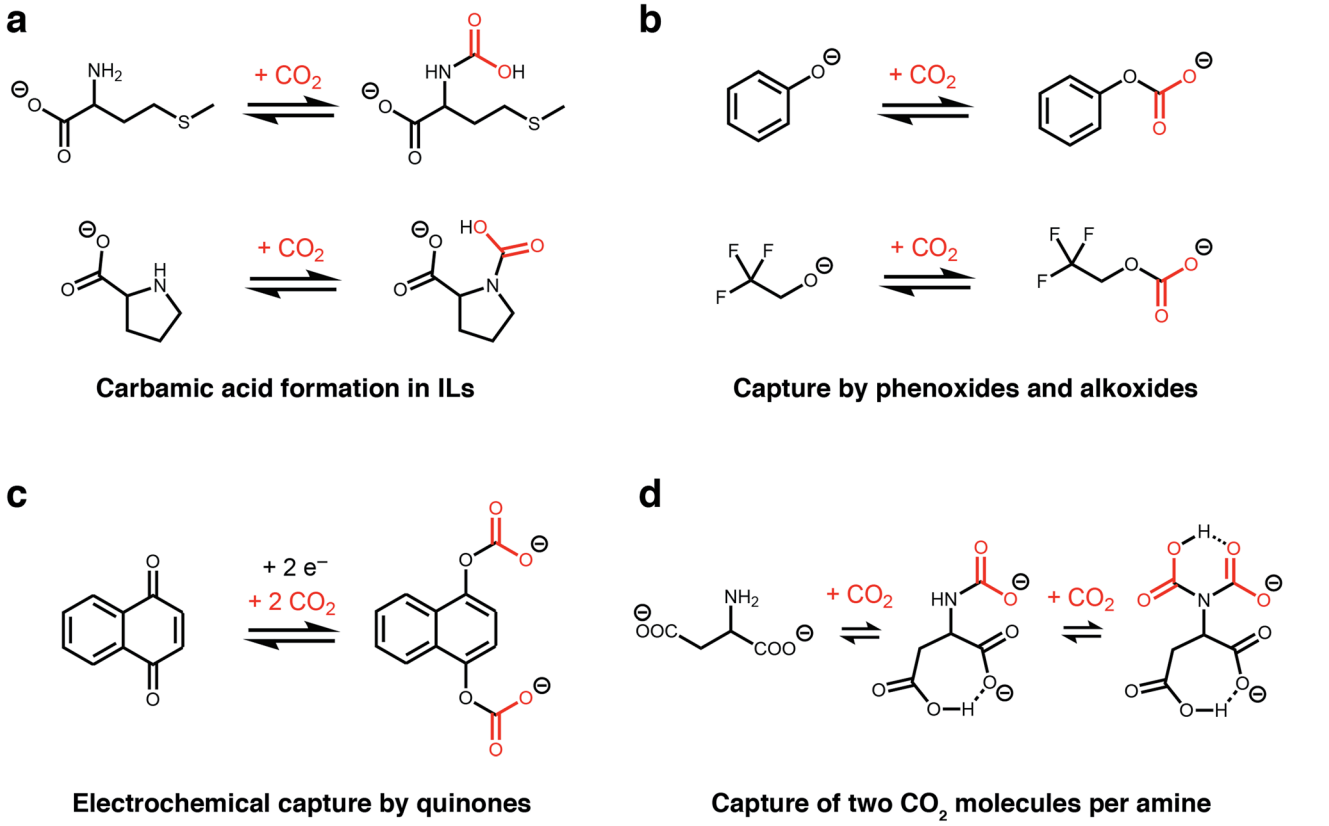

Fig. 2 New CO_2 absorption mechanisms in solution. (a) Proposed formation of carbamic acid in ILs with amine-functionalised anions.[37] (b) Proposed absorption mechanism by phenoxide and alkoxide ILs.[38] (c) Proposed mechanism for electrochemical CO_2 capture by 1,4-naphthoquinone.[39] (d) Proposed absorption mechanism for an IL with an aspartate dianion.[40] In all cases, the corresponding cations are omitted for clarity.

traditional IL sorbents (<10 wt%). Importantly, alkoxide-based ILs also possess low viscosities and rapid absorption kinetics (saturation in less than 5 minutes at room temperature), overcoming common challenges that plague traditional amine-functionalized ILs.[38] Subsequently, Kim and coworkers demonstrated that similar reactivity at oxygen could be achieved in water-lean alcoholamines bearing sterically-hindered amines and that the resulting ammonium alkylcarbonates desorb CO_2 more readily than ammonium carbamates.[50]

Another route to generate oxyanion nucleophiles for rapid CO_2 capture *via* carbonate formation is by the electrochemical reduction of quinones, as demonstrated by Hatton and others (Fig. 2c).[39] Promising results with electrochemically-reduced quinones have been observed in the presence of water and oxygen, although some loss in capacity was observed due to re-oxidation of the nucleophile by oxygen.[51] This electrochemical approach has subsequently been expanded to other nucleophiles, such as reduced sulphides, suggesting it may be a general strategy to expand the scope of nucleophiles for CO_2 capture.[52] An advantage of this approach is that electrochemical regeneration of the quinone (electrochemical swing adsorption) leads to energy savings over traditional temperature or pressure swing processes.

Recent work has revealed that CO_2 capacities approaching a remarkable 2 : 1 reaction stoichiometry can be accessed in ILs, representing a four-fold increase compared to the traditional ammonium carbamate mechanism (Fig. 2d).[40] Specifically, Wang and coworkers found that an ionic liquid with an aspartate dianion was able to reversibly bind 1.96 mol CO_2 per mol IL at 30 °C and 1 atmosphere CO_2, which was hypothesised to occur *via* two subsequent reactions at a single amine site to form both a carbamate (calculated $\Delta E_{abs} = -69$ kJ mol^{-1}) and a carbamic acid (calculated $\Delta E_{abs} = -54$ kJ mol^{-1}).[40] This proposed absorption pathway was supported by ^{13}C NMR measurements as well as density functional theory (DFT) calculations, with the latter ruling out reaction of CO_2 at the carboxylate groups as proposed for related ILs.[53] A similar 2 : 1 absorption mode was also evidenced in an earlier organic chemistry study. The observation of a triplet in solution ^{15}N NMR studies of selected primary amines in the presence of $^{13}CO_2$ and a base confirmed the reaction of 2 CO_2 molecules with a single amine group at −30 °C.[53] The high capacity offered by this absorption mode makes it a very attractive target for CO_2 capture applications.

Although ILs and water-lean solvents represent a unique platform for the discovery of new CO_2 capture products, they are not without their own challenges. For example, the absorption capacities of most ILs are relatively low (<20 wt%) compared to amine-functionalized solids.[13,28] In addition, the viscosities of ionic liquids are relatively high and tend to increase upon CO_2 adsorption (in some cases up to 200-fold), which represents a significant process challenge.[28,54] While molecular engineering allows access to CO_2-loaded ILs with viscosities as low as 650 mPa s,[55] these values are still significantly higher than CO_2-loaded 30% aqueous monoethanolamine solution (4 mPa s).[56] Last, the CO_2/N_2 absorption selectivities, kinetics, desorption conditions, and long-term cycling stabilities of ILs remain poorly characterized in many cases. Addressing these challenges is critical to advancing the commercial viability of IL-based sorbents.

An emerging alternative approach is to engineer new CO_2 capture mechanisms within the controlled pore environments of crystalline porous materials, such as MOFs. The arrangement of functional groups in an ordered fashion within the pores of MOFs presents a potential opportunity for unlocking new CO_2 capture chemistry.

One of the earliest demonstrations of CO_2 chemisorption in MOF adsorbents involved CD-MOFs (Fig. 3a; CD = γ-cyclodextrin).[46,57] These MOFs demonstrate strong adsorption of CO_2 at low partial pressures (<2 mbar), leading to excellent CO_2/CH_4 selectivity (estimated to be >3000) in this regime.[46] Using SSNMR measurements, the authors proposed the formation of carbonic acids or alkylcarbonates; however, the exact chemisorption pathway in this material remains unclear. Nonetheless, the strong bonding of CO_2 in CD-MOF-2 (>1 mmol CO_2 per g MOF adsorbed at 10 mbar and 30 °C) makes this a promising potential material for flue gas capture applications. Analysis of the thermodynamics of CO_2 chemisorption in this material by calorimetry revealed a moderate enthalpy of adsorption at intermediate loadings ($-\Delta H_{ads} = 65$ kJ mol^{-1}), enabling easier desorption of CO_2 from the strong-binding sites compared to amines.[58,59] However, the poor water stability of these MOFs necessitates the translation of this chemisorption mechanism to more stable materials for practical applications.[46]

Carbamic acids have long been invoked as intermediates and products upon CO_2 capture in amine scrubbers,[4] amine-functionalized silicas[30,60] and amine-functionalized MOFs,[61,62] as suggested by NMR and IR spectroscopies. For example, Ho and coworkers found that hydrazine-functionalized variants of the MOF Mg_2(dobdc) (dobdc^{4-} = 2,5-dioxido-1,4-benzenedicarboxylate) exhibit incredibly strong and selective binding of CO_2 (3.89 mmol g^{-1} at 25 °C and 0.4 mbar of CO_2), which they ascribe to highly favourable carbamic acid formation ($-\Delta H_{ads} = 90$ kJ mol^{-1}) within the framework pores.[62] However, until recently there remained little crystallographic evidence for this elusive adsorption product in the solid state. Long and coworkers identified variants of the MOF M_2(dobpdc) (dobpdc^{4-} = 4,4′-dioxidobiphenyl-3,3′-dicarboxylate) functionalised with the diamine 2,2-dimethyl-1,3-diaminopropane (dmpn) as promising adsorbents for post-combustion CO_2 capture owing to their exceptional hydrothermal and oxidative stability (Fig. 3b and c).[47,48] Exposure of single crystals of dmpn–Zn_2(dobpdc) to 1 bar of CO_2 induced the formation of carbamic acid pairs bridging two adjacent amine sites in the framework, as confirmed by SCXRD and SSNMR (Fig. 3b).[47,48] In this structure, the normally disfavoured formation of carbamic acids is facilitated by well-defined hydrogen-bonding interactions, corroborated by the presence of strong $^{1}H_{(COOH)}\cdots{}^{13}C$ correlations in 2-dimensional SSNMR experiments. Notably, carbamic acid pairs were actually predicted computationally in related frameworks before they were observed experimentally.[63]

Building upon this work, the same group demonstrated that dmpn–Mg_2(dobpdc) chemisorbs CO_2 by another distinct

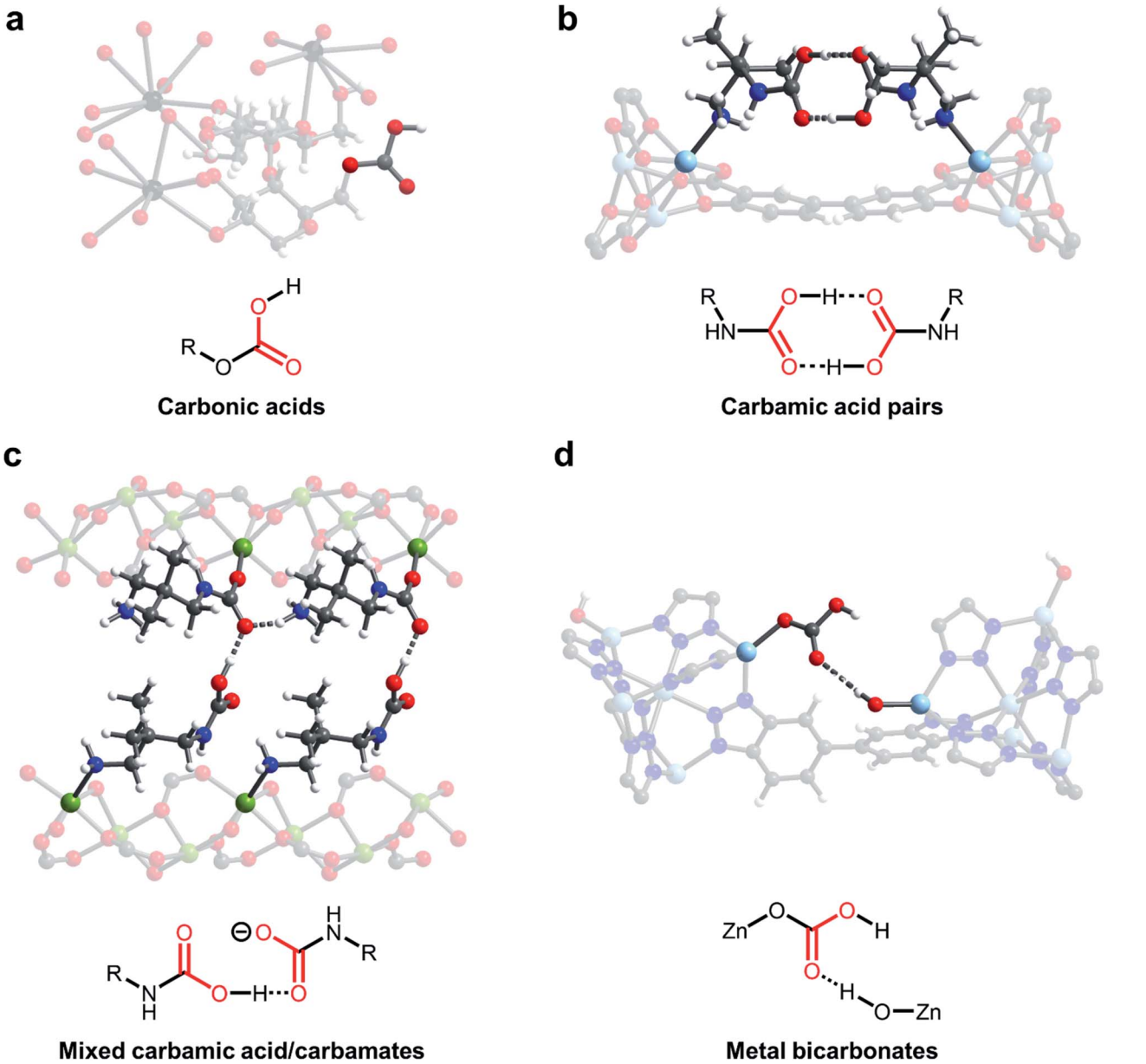

Fig. 3 New CO_2 adsorption mechanisms unlocked in MOFs. (a) Proposed formation of carbonic acids in CD-MOF-2 (CD = cyclodextrin).[46] (b) Crystallographically confirmed formation of carbamic acid pairs in dmpn–Zn_2(dobpdc) (dmpn = 2,2-dimethyl-1,3-diaminopropane; dobpdc^{4-} = 4,4′-dioxidobiphenyl-3,3′-dicarboxylate).[47] (c) Proposed formation of mixed carbamic acids and ammonium carbamates in dmpn–Mg_2(dobpdc).[48] (d) Proposed formation of metal bicarbonates in $Zn(ZnOH)_4(bibta)_3$ (bibta^{2-} = 5,5′-bibenzotriazolate).[49] Gray, white, red, black, dark blue, sky blue, and green spheres correspond to carbon, hydrogen, oxygen, rubidium, nitrogen, zinc, and magnesium, respectively.

pathway: the formation of both ammonium carbamates and carbamic acids (Fig. 3c).[48] In-depth DFT calculations and 2-dimensional SSNMR experiments support the formation of ammonium carbamate chains that interact with carbamic acids *via* hydrogen-bonding in this material. The advantage of this mechanism lies in its high enthalpy of adsorption (ΔH_{ads} = −74 kJ mol^{-1}) coupled with a large entropic penalty ($-\Delta S_{ads}$ = 204 J mol^{-1} K^{-1}), which reduces the temperature required to desorb CO_2 in a temperature-swing adsorption process to <100 °C, potentially enabling adsorbent regeneration with low-grade steam.[47] These thermodynamic parameters enable adsorbent regeneration with an estimated energy of 2.5 MJ kg^{-1} CO_2, comparable to the best-in-class aqueous amine scrubbers such as Mitsubishi KS-1 (2.4 MJ kg^{-1} CO_2).[10,64] Therefore, this finding highlights the potential to overcome thermodynamic trade-offs of carbon capture processes by tuning the adsorption pathway. In addition, this adsorption mode leads to faster adsorption kinetics than ammonium carbamate formation in related materials and a high non-competitive CO_2/N_2 selectivity (880) under the conditions relevant for CO_2 capture from coal flue emissions (150 mbar CO_2, 750 mbar N_2, 40 °C).[65]

A further promising avenue to unlock new selective CO_2 capture reactivities in porous materials is to look to nature for inspiration. For example, carbonic anhydrase enzymes are responsible for the transport of CO_2 in the human body. Many members of this family operate by the reversible reaction of a zinc-hydroxide species (Zn–OH) with CO_2 to form a zinc-bound bicarbonate species (Zn–OCO_2H).[66] In an early study, Zhang and coworkers demonstrated that high-valent monodentate metal hydroxides in the water-stable MOFs $Mn^{II}Mn^{III}(OH)Cl_2$(bbta) and [$Co^{II}Co^{III}(OH)Cl_2$(bbta)] (bbta^{2-} = dihydrobenzo[1,2-*d*:4,5-*d*′]bis([1,2,3]triazolate)) strongly bind CO_2 with high CO_2/N_2 selectivity (>250), even under humid conditions.[67] These materials exhibit highly exothermic capture of CO_2 at low loadings ($-\Delta H_{ads}$ > 100 kJ mol^{-1}), necessitating regeneration using flowing N_2 at 85 °C (simulating a temperature-vacuum swing process). A regeneration energy of 2.7 MJ kg^{-1} CO_2 was calculated for [$Co^{II}Co^{III}(OH)Cl_2$(bbta)], which is comparable with best-in-class aqueous amines. Closely mimicking the mechanism of carbonic anhydrase enzymes, Wade and coworkers subsequently found that Zn–OH centers in the air-stable MOF $Zn(ZnOH)_4$(bibta)$_3$ (bibta^{2-} = 5,5′-bibenzotriazolate) strongly bind CO_2 to form metal-bound bicarbonates with adsorption capacities of 2.2 mmol g^{-1} at 27 °C and 0.4 mbar of CO_2, suitable for direct air capture (Fig. 3d).[49] Interestingly, DFT calculations suggest that these metal-bound bicarbonates hydrogen-bond with adjacent Zn–OH centers, stabilizing the adsorption product ($-\Delta H_{ads}$ = 71 kJ mol^{-1}) and leading to steep uptake of CO_2 at low pressures. Dincă and coworkers demonstrated a similar bioinspired approach to CO_2 capture in ($Zn_5(OH)_4$(btdd)$_3$) (btdd = bis(1,2,3-triazolo[4,5-*b*],[4′,5′-*i*])dibenzo[1,4]dioxin), a hydroxide-substituted variant of the MOF MFU-4*l*.[68] This framework was found to exhibit stronger CO_2 binding ($-\Delta H_{ads}$ = 81 kJ mol^{-1}) compared to $Zn(ZnOH)_4$(bibta)$_3$, albeit with a lower adsorption capacity at low pressures (0.9 mmol g^{-1} at 25 °C and 23 mbar of CO_2). In all of these studies, the formation of metal-bound bicarbonates was validated primarily by *in situ* IR spectroscopy and DFT calculations. Subsequent work by Wade and coworkers has highlighted the importance of metal identity on CO_2 adsorption in M–OH MOFs, unveiling a potential handle for tuning the thermodynamics of chemisorption.[69,70] In a similar vein, Wang and Lackner have found that hydroxide-functionalised ion-exchange membranes are promising for energy-efficient moisture swing sorption processes, demonstrating that ammonium cations can be used as an alternative to metal ions to prepare hydroxide-rich materials.[71] The capture of CO_2 with oxygen-based nucleophiles in both adsorbents (Fig. 3a and d) and solution (Fig. 2b and c) represents a promising solution to overcome the inherent limitations of amine-functionalised materials; however, more work is required to map out the stability of these materials and their performance under realistic conditions.

The vast majority of CO_2 capture processes discussed above operate *via* the addition of nitrogen- or oxygen-based nucleophiles to CO_2. Recently, the range of nucleophiles that can reversibly react with CO_2 has been expanded to include electrochemically-generated sulphides,[52] frustrated Lewis pairs,[72] and *N*-heterocyclic carbenes,[73] among others.[74] In addition, electrochemistry has emerged as a powerful tool to expand the scope of CO_2 capture processes. For example, Hamelers and coworkers have shown that capacitive charging and migration of bicarbonate/carbonate ions through ion exchange membranes can drive a CO_2 capture process with a low energy requirement of 40 kJ mol^{-1} CO_2 captured.[75] Similarly, Landskron and coworkers have developed a related process in which a supercapacitor device reversibly adsorbs CO_2 (<0.1 mmol g^{-1}), although the exact adsorption mechanism remains unclear.[76] Finally, electrochemically driven pH swings are also being investigated as a new energy-efficient CO_2 capture strategy.[77] These recent directions represent an exciting opportunity to unlock new carbon capture chemistry.

Opportunities and challenges for next-generation CO_2 capture

The foregoing examples highlight the unique opportunities offered by new CO_2 capture pathways. Potential advantages of new sorption modes include lower regeneration energies, higher working capacities, and access to a wider range of sorption enthalpies compared to traditional ammonium carbamate formation. Despite this promise, there remains a great need for additional research to assess the application of novel sorption pathways in industrial processes. Key materials challenges (Fig. 4) that remain critically underappreciated include: (i) rapid sorption kinetics, (ii) large working capacities under realistic mixed-gas conditions, (iii) sufficient material stability to survive long-term exposure to reactive contaminants in target gas streams, such as water, oxygen, sulphur dioxide, and hydrogen sulphide, among others depending on the process,[23,24] (iv) adsorbent development and structuring to overcome issues with low thermal conductivities and heat management during highly exothermic sorption processes, and (v) sustainable and scalable materials synthesis. As an example, the hydroxide-based MOF [$Co^{II}Co^{III}(OH)Cl_2$(bbta)] has a promising working capacity and regeneration energy for a flue gas capture process, but its stability in the presence of oxygen and other contaminants remains unknown.[67] Moreover the very large heat of CO_2 adsorption at low loadings ($-\Delta H_{ads}$ > 100 kJ mol^{-1}) suggests that heat management will be an important challenge for this material. Promising strategies to aid heat management include the development of structured hollow fibre adsorbents and the design of carbon-based materials that have inherently larger thermal conductivities.[78]

Exploration of entirely new CO_2 capture pathways beyond those described in this perspective should also lead to further advances. Recent studies have highlighted the promise of large-scale computational screenings in the search for new CO_2 capture materials. For example, Smit and coworkers recently reported the screening of over 300 000 theoretical MOFs and identified classes of physisorption sites, termed "adsorbophores", that endow high CO_2 selectivities to frameworks.[79] The guided synthesis of optimised materials for operation under humid conditions was achieved by selecting candidates with

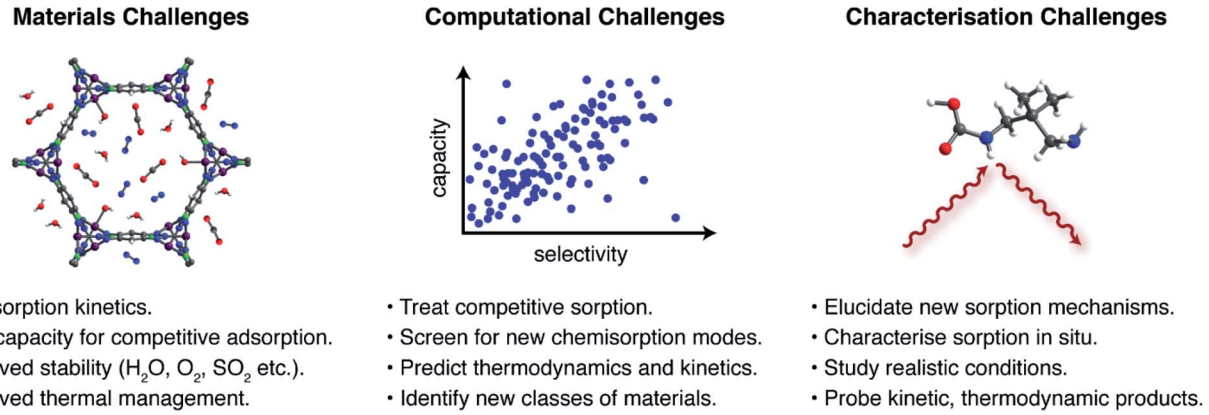

Fig. 4 Grand challenges for next-generation sorbents for CO_2 capture.

hydrophobic adsorbophores to maximize the adsorption of CO_2 under humid conditions. However, the capacities and CO_2/N_2 selectivities reported for best-in-class physisorbents are typically lower than those reported for chemisorptive materials. Similar computational screens to predict chemisorption—for example, using a higher level of theory to account for bond-breaking and – forming processes—remain rare but have the potential to be transformative.[63,80] Similarly, calculations that can predict chemisorption thermodynamics under realistic mixed gas conditions should lead to promising materials for real-world applications.[79] Due to the complex processes inherent to chemisorption, an additional challenge for computational analyses is to predict transition states relevant to sorption kinetics. A promising strategy to address these computational challenges may be to use machine learning to guide the search for new chemisorbent materials.[81]

In order to elucidate and ultimately build upon new CO_2 capture chemistry, advanced characterisation methods are also needed. These methods serve to both validate and discover new chemisorption products when unexpected sorption properties arise. Recent years have seen significant advances in the characterisation of CO_2 capture pathways through *in situ* spectroscopic and X-ray diffraction experiments.[30,32,47,48] These experiments must now be adapted to study conditions that more closely mimic envisaged industrial applications and, in particular, must address mixed gas conditions rather than pure CO_2.[32,48] Furthermore, experiments must not be restricted to studying static/equilibrium conditions and should probe the dynamic conditions associated with practical sorption processes.

Conclusions

New CO_2 sorption pathways such as those recently uncovered in appropriately-functionalised ILs and MOFs may offer improved performance for CO_2 capture compared to traditional sorbents, including higher capacities and lower regeneration costs. Many of these binding modes do not readily occur in aqueous solution and instead arise from the unique opportunity to precisely install chemical functional groups with a controlled spatial arrangement and carefully tuned local environment. For many of these prospective sorbents, more work is needed to assess their sorption kinetics, selectivities, stabilities, and thermal conductivities. This mechanistically-focused line of sorbent discovery is still in its infancy, and a new generation of computational, analytical, and synthetic chemistry is needed to design transformative materials – and sorption mechanisms – for reducing anthropogenic CO_2 emissions.

Conflicts of interest

The authors declare the following competing interest: P. J. M. is listed as an inventor on several patents related to the preparation of metal–organic frameworks for CO_2 capture.

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