Frontiers in Nanotechnology

TYPE Original Research
PUBLISHED 24 February 2025
DOI 10.3389/fnano.2025.1525106

CO_2 capture from indoor air for human comfort and sequestration or reuse: a promising step toward sustainable CO_2 removal

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RECEIVED 08 November 2024
ACCEPTED 03 January 2025
PUBLISHED 24 February 2025

CITATION
Maity K, Bhadirke SD, Wijewardane S and Goswami DY (2025) CO_2 capture from indoor air for human comfort and sequestration or reuse: a promising step toward sustainable CO_2 removal.
Front. Nanotechnol. 7:1525106.
doi: 10.3389/fnano.2025.1525106

Concentration of CO_2 in an indoor environment can be four to five times higher than the outdoor air. This higher indoor concentration of CO_2 reduces the work efficiency of individuals working indoors and negatively impacts human health. However, the elevated concentration also makes it easier to capture CO_2 from indoor air. This study examines the performance of monoethanolamine (MEA) and L-arginine (Arg) solutions for indoor carbon dioxide (CO_2) capture through experimental screening. Key parameters evaluated include CO_2 absorption and desorption capacity, absorption kinetics, and the impact on relative humidity (RH) and total volatile organic compound (TVOC) concentrations. Two solvent formulations were employed in this study: one utilizing pure water as the solvent and the other incorporating a water-glycol mixture. The aqueous Arg solution demonstrated minimal to no detectable increase in VOC levels and exhibited lower evaporation rates than the benchmark aqueous MEA solution. Microwave (MW) heating was utilized to facilitate rapid CO_2 desorption from saturated solutions. The regeneration efficiency, solvent loss, and energy consumption were found to be dependent on the MW desorption time. Optimizing the desorption resulted in faster and almost complete regeneration, minimized solvent loss, and reduced overall energy consumption. The incorporation of glycol minimized evaporation during absorption, decreased the likelihood of complete drying during desorption, and improved solution regeneration. Cyclic absorption-desorption experiments were conducted to evaluate the long-term stability and kinetic performance of the solutions. While the aqueous MEA solution experienced significantly larger declines of 54.3% in CO_2 absorption capacity and 34.24% in absorption kinetics, the water-PG-based Arg solution demonstrated promising performance, with a smaller reduction of 31.24% in CO_2 absorption and a 2.13% decrease in kinetics after ten cycles. Additionally, the water-PG-based Arg solution resulted in lower volatile organic compound (VOC) levels and provided more effective control over relative humidity. These findings underscore the potential of the water-PG-based Arg solution for cyclic CO_2 absorption and microwave-assisted regeneration processes.

KEYWORDS

CO_2 capture, indoor air, monoethanolamine, L-arginine, microwave regeneration, relative humidity, total volatile organic compounds

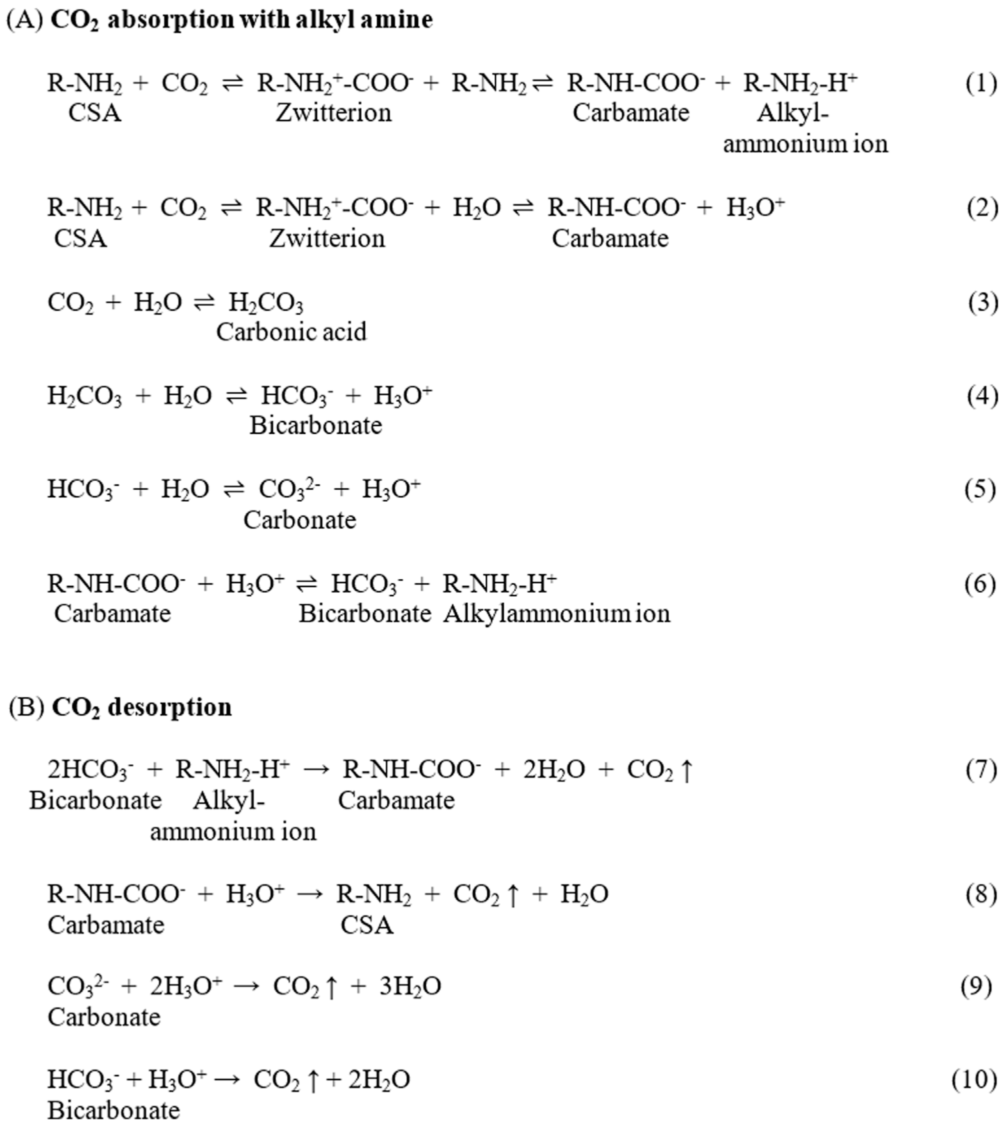
1 Introduction

The fight against rising CO_2 emissions has become a global race, with researchers focusing on two key fronts: reducing dependence on fossil fuels by making renewable energy more accessible and efficient, and advancing direct air capture (DAC) and carbon capture and storage (CCS) technologies to remove CO_2 from the atmosphere. These efforts are not just about slowing emissions but also about reversing their impact—aiming to achieve net-zero CO_2 emissions by 2050 and preventing global temperatures from exceeding the critical 1.5°C threshold (Ma et al., 2022; Chen et al., 2023). According to the Global Monitoring Laboratory of the National Oceanic and Atmospheric Administration, the average global CO_2 concentration in 2023 was 420 ppm (0.042%), which is considered safe for humans (Global Monitoring Laboratory-NOAA, 2023). Nevertheless, indoor CO_2 concentrations, especially in workplaces like offices and conference halls, often surpass recommended limits due to occupant's exhalation, placing increased demands on heating, ventilation, and air conditioning (HVAC) systems to maintain indoor air quality (Young et al., 2024). Prolonged exposure to elevated CO_2 levels can lead to health issues such as respiratory acidosis, increased heart rate, cognitive decline, and hypercapnia (Azuma et al., 2018; Jacobson et al., 2019). The Occupational Safety and Health Administration (OSHA) has established a maximum permissible exposure limit of 5,000 ppm over an 8-h workday (Young et al., 2024). However, relying solely on ventilation to meet this standard can significantly increase the system's carbon footprint (Young et al., 2024). Additionally, research indicates that keeping CO_2 levels below specific thresholds enhances the occupants' cognitive functions and productivity (Kuramochi et al., 2023). Therefore, capturing CO_2 is the only viable option to keep the CO_2 level within the acceptable limit in indoor spaces. Since the concentration of CO_2 in indoor air can be four to five times higher than that in outdoor air, capturing CO_2 directly from indoor air can be easier than from outdoor air. The benefits of capturing CO_2 from indoor air are twofold: first, it removes CO_2 from the atmosphere, and second, it improves the health and work efficiency of individuals working indoors.

Chemical absorption is one of the most promising technologies for CO_2 capture due to its high selectivity and scalability opportunities (Tsubaki et al., 2020). This process employs various absorbing agents, including aqueous alkali solutions (Zeman, 2007), amines (Kim et al., 2013), ionic liquids (Zhao and Baker, 2023), amine-functionalized adsorbents (Lee and Park, 2015), and amino acid solutions (Aronu et al., 2010; Wei et al., 2023), to chemically extract CO_2 from air or gas streams. Among these methods, amine-based technology remains the most widely used. Researchers have shown that the interaction between CO_2 and aqueous amines follows the zwitterionic mechanism. The nucleophilic lone pair on the nitrogen atom of the amine attacks the electrophilic carbon of CO_2, forming zwitterionic adduct ($R\text{-}NH_2^+\text{-}COO^-$), which stabilizes into carbamate ($R\text{-}NH\text{-}COO^-$) and an alkylammonium ion ($R\text{-}NH_2\text{-}H^+$) upon deprotonation (Reaction 1) (Masiren and Harun, 2017; Lv et al., 2015; Said et al., 2020). As absorption progresses, the pH and absorption rate decrease due to the depletion of the CO_2 scrubbing agent (CSA), weakening Reaction 1 (Lv et al., 2015). This favors hydration reactions (Reactions 2–5), resulting in the formation of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) (Lv et al., 2015). Additionally, as the pH drops, carbamate formed in Reactions 1 and 2 decomposes into bicarbonate, as shown in Reaction 6 (Lv et al., 2015; Said et al., 2020). This process is reversible during desorption, as shown in Reactions 7–10 (Lv et al., 2015). The full sequence of absorption and desorption reactions is outlined in Figure 1:

Alkanolamines are preferred over alkylamines for CO_2 capture due to their higher boiling points and lower volatility (National Library of Medicine–Ethylamine, 2024; National Library of Medicine–Monoethanolamine, 2024), which reduces the emission of VOCs during absorption and desorption processes. Monoethanolamine (MEA) is used as a benchmark solvent due to its affordability, high water solubility, and rapid CO_2 absorption rate (Chai et al., 2022). However, it still has drawbacks, such as volatility that can lead to higher TVOC emissions and may limit indoor use, along with a high energy demand for regeneration. Furthermore, it is prone to thermal and oxidative degradation, which results in increased viscosity, solution fouling, and corrosion of downstream equipment (Chai et al., 2022; Custelcean, 2022). These challenges highlight the need for alternative CSA for indoor CO_2 capture. Aqueous amino acids are emerging as promising alternatives. Known for their high surface tension, they offer comparable CO_2 absorption capacity with negligible vapor pressure and greater resistance to degradation (Mai et al., 2023). These properties make them well-suited for capturing CO_2 in indoor applications (Mai et al., 2023; Sang Safidi and Luis, 2019), providing a viable path forward in overcoming the limitations of conventional absorbents like MEA. Arginine (Arg) specifically offers several advantages over traditional absorbents like MEA, including greater resistance to thermal and oxidative degradation. This allows the Arg solution to undergo multiple absorption-desorption cycles, reducing costs associated with frequent solution replacement. Its higher surface tension also minimizes evaporation losses during both CO_2 capture and release, and its biodegradability makes Arg a more environmentally sustainable option (Guo et al., 2018). However, despite these promising attributes, only a limited number of studies have explored the role of Arg in CO_2 capture (Mahmud et al., 2017; Wei et al., 2023). To the best of our knowledge, no research to date has specifically addressed CO_2 capture from indoor air while simultaneously controlling TVOC and humidity levels. Maintaining optimal levels of both TVOCs and humidity is essential for safeguarding respiratory health and ensuring thermal comfort for occupants. This study aims to develop efficient and affordable CO_2 capture solutions specifically designed for indoor use, with added functionality for managing TVOCs and humidity to enhance overall indoor air quality.

This study explores the potential of various CO_2 capture solutions, including aqueous MEA, aqueous Arg, and water-glycol-Arg solutions, to enhance indoor air quality by regulating CO_2 levels, RH, and TVOC concentrations. Through experimental evaluations, the solutions' desorption capabilities, including regeneration efficiency, solvent stability, and visual integrity post-desorption, were analyzed using microwave irradiation at varying exposure times. A subsequent cyclic study was performed to assess the stability, safety, and long-term performance of aqueous MEA and water-PG-Arg solutions. This investigation advances our



(A) CO_2 absorption with alkyl amine

$$\underset{\text{CSA}}{\text{R-NH}_2} + CO_2 \rightleftharpoons \underset{\text{Zwitterion}}{\text{R-NH}_2^{+}\text{-COO}^{-}} + \text{R-NH}_2 \rightleftharpoons \underset{\text{Carbamate}}{\text{R-NH-COO}^{-}} + \underset{\text{Alkyl-ammonium ion}}{\text{R-NH}_2\text{-H}^{+}} \quad (1)$$

$$\underset{\text{CSA}}{\text{R-NH}_2} + CO_2 \rightleftharpoons \underset{\text{Zwitterion}}{\text{R-NH}_2^{+}\text{-COO}^{-}} + H_2O \rightleftharpoons \underset{\text{Carbamate}}{\text{R-NH-COO}^{-}} + H_3O^{+} \quad (2)$$

$$CO_2 + H_2O \rightleftharpoons \underset{\text{Carbonic acid}}{H_2CO_3} \quad (3)$$

$$H_2CO_3 + H_2O \rightleftharpoons \underset{\text{Bicarbonate}}{HCO_3^{-}} + H_3O^{+} \quad (4)$$

$$HCO_3^{-} + H_2O \rightleftharpoons \underset{\text{Carbonate}}{CO_3^{2-}} + H_3O^{+} \quad (5)$$

$$\underset{\text{Carbamate}}{\text{R-NH-COO}^{-}} + H_3O^{+} \rightleftharpoons \underset{\text{Bicarbonate}}{HCO_3^{-}} + \underset{\text{Alkylammonium ion}}{\text{R-NH}_2\text{-H}^{+}} \quad (6)$$

(B) CO_2 desorption

$$\underset{\text{Bicarbonate}}{2HCO_3^{-}} + \underset{\text{Alkyl-ammonium ion}}{\text{R-NH}_2\text{-H}^{+}} \rightarrow \underset{\text{Carbamate}}{\text{R-NH-COO}^{-}} + 2H_2O + CO_2\uparrow \quad (7)$$

$$\underset{\text{Carbamate}}{\text{R-NH-COO}^{-}} + H_3O^{+} \rightarrow \underset{\text{CSA}}{\text{R-NH}_2} + CO_2\uparrow + H_2O \quad (8)$$

$$\underset{\text{Carbonate}}{CO_3^{2-}} + 2H_3O^{+} \rightarrow CO_2\uparrow + 3H_2O \quad (9)$$

$$\underset{\text{Bicarbonate}}{HCO_3^{-}} + H_3O^{+} \rightarrow CO_2\uparrow + 2H_2O \quad (10)$$

FIGURE 1
(A) Reaction between CO_2 and amine, presence and absence of water (Lv et al., 2015) (said et al., 2020). **(B)** Regeneration of amine (Lv et al., 2015) (said et al., 2020).

understanding of CO_2 capture kinetics and positions Arg as a promising, sustainable alternative to traditional absorbents like MEA.

2 Materials and methods

2.1 Reagents

MEA (purity ≥98%), L-arginine (purity ≥98%), triethylene glycol (purity ≥98%), dipropylene glycol (purity ≥99%), diethylene glycol (purity ≥99%), and ethylene glycol (purity ≥99%) were procured from ThermoFisher Scientific. Propylene glycol (purity ≥99.8%) was sourced from Millipore Sigma. All the solutions were prepared using Milli-Q water, and the CO_2 gas (purity ≥99.999 mol%) was obtained from the Airgas company.

2.2 Experimental setup and procedure

The CO_2 scrubbing solutions (CSS) were formulated by adding 0.05 mol of CSA to 50 mL of solvent. For the aqueous CSS, Milli-Q water was used as the solvent, while the water-glycol-based CSS was prepared by mixing water and glycol in a 1:1 volumetric ratio based on the solubility of Arg in water.

The CO_2 absorption setup consisted of a 100 mL two-neck round-bottom flask filled with the prepared CSS and connected to a condenser to minimize the loss of water and amine vapors. This setup was placed inside a sealed steel chamber measuring 32 × 33 × 36 inches (Supplementary Figure S1A), equipped with a 12 V fan to ensure thorough mixing of air within. CO_2 was introduced from the top of the chamber until the concentration stabilized between 1,000 and 1,100 ppm.

The air inside was bubbled through the solution using a micro air pump during the CO_2 absorption process. The experiments were performed under laboratory conditions at atmospheric pressure, with an initial relative humidity of 54% ± 5%. Changes in C_{CO2} (ppm), RH (%), and TVOCs (ppb) were continuously monitored using Graywolf IQ-610 sensors and logged at 30-s intervals with an advanced sense meter. As per the guidelines from Graywolf Sensing Solutions, the TVOC sensor operates accurately within a relative humidity (RH) range of 0%–90%, becoming unreliable beyond this threshold. Consequently, in our study, TVOC data were recorded until the RH reached 90%. The VOCs generated inside the chamber were collected by passing the air through 20 mL of Milli-Q water for 60 min. The resulting solution (referred to as the TVOC solution) was analyzed using Triple Quadrupole Liquid Chromatography-Mass Spectrometry (LC-QqQ-MS) and Headspace Solid-Phase Microextraction Gas Chromatography-Mass Spectrometry (HS-SPME-GC-MS), with the instruments shown in Supplementary Figure S13, S14, respectively. The operating conditions of both instruments are provided in Supplementary Figure S15, S16.

Once the CO_2 absorption process was complete, water was added to replenish the solution that had evaporated due to vaporization. The solution was then transferred to a 500 mL conical flask, and a few small porcelain boiling chips were added to ensure smooth boiling and prevent bumping during the regeneration process. MW-assisted regeneration of the saturated scrubbing solution was performed using the setup shown in Supplementary Figure S2B. Initially, the temperature of the solution, along with the C_{CO_2}, RH, and TVOC values, were recorded. The solution was then heated using a Panasonic 1200 W MW oven at heating power level 10 for varying time periods. The temperature and volume of the solution were recorded right after heating, whereas other parameters, such as TVOC and RH, were measured 5 minutes later after they had stabilized. Rather than using one prolonged MW heating duration, the desorption process was broken into shorter sessions to ensure that the solution did not dry out completely.

2.3 Quantitative analysis and kinetics

The CO_2 loading (α_{abs}) is defined as the moles of CO_2 absorbed per unit moles of CSA, while the CO_2 unloading (α_{des}) represents the reverse process (Song et al., 2012). These values were calculated using the following formula based on the initial and final CO_2 concentrations.

$$\mathbf{CO_2\ loading\ or\ removed}\ (\alpha) = \frac{\mathbf{Moles\ of\ CO_2\ absorbed\ or\ desorbed}}{\mathbf{Moles\ of\ CO_2\ scrubbing\ agent}}\ (\mathbf{mol})$$

$$\mathbf{Moles\ of\ CO_2\ absorbed\ or\ desorbed}\ (\mathbf{n_{co_2}}) = \frac{\Delta C}{1000000} \times \frac{1}{M_{CO_2}} \times \rho_{CO_2} \times 1000 \times V_c\ (\mathbf{mol})$$

$$\Delta C = \mathbf{Initial\ Conc.\ of\ CO_2\ (ppm) - Final\ Conc.\ of\ CO_2\ (ppm)}$$

$$\mathbf{Moles\ of\ CO_2\ absorbed\ or\ desorbed} = \frac{\mathbf{Mass}}{\mathbf{Molecular\ weight}}\ (\mathbf{mol})$$

Where ΔC is the concentration gradient, M_{CO_2} = 44 g/mol and $\rho_{CO_2} = 1.96 \times 10^{-3}$ g/mL are the molecular weight and density of CO_2, respectively, and V_c = 623 L is the chamber volume. The amount of CO_2 absorbed or desorbed (in mg) depends on the moles of CO_2 absorbed or desorbed (n_{CO_2}) and can be calculated using the following formula:

$$\mathbf{Amount\ of\ CO_2\ absorbed\ or\ desorbed} = \mathbf{n_{CO_2}} \times \mathbf{M_{CO_2}} \times \mathbf{1000}\ (\mathbf{mg})$$

Additionally, based on the CO_2 absorption experimental data, the integrated rate law equation for a second-order reaction was used to model the kinetics of gas-liquid absorption reactions. The reaction rate constant (K″) was determined from the slope of the linear regression plot of $1/C_{CO_2}$ versus time.

3 Results and discussion

The performances of aqueous MEA and aqueous Arg solutions in terms of CO_2 absorption, kinetics, and their impact on RH levels and TVOC concentrations were evaluated. Although the aqueous Arg solution showed a lower capacity for CO_2 absorption (α = 0.31 mol/mol) and slower kinetics ($K'' = 1.80 \times 10^{-6}$ ppm^{-1} min^{-1}) compared to the aqueous MEA solution (α = 0.40 mol/mol and $K'' = 2.57 \times 10^{-6}$ ppm^{-1} min^{-1}) (Figure 2A; Supplementary Figure S3), presumably due to Arg's larger molecular size (Suleman et al., 2020) affecting solution viscosity and hindering CO_2 diffusion, it still presents notable advantages over MEA, particularly concerning VOC emissions and RH behavior. The aqueous MEA solution caused a significant increase in TVOC levels during the absorption process, as shown in Figure 2B, whereas the aqueous Arg solution produced minimal to no detectable rise in TVOCs. Qualitative analysis of the VOCs emitted from the aqueous MEA solution using LC-QqQ-MS identified MEA as the primary volatile component (Supplementary Figure S4), as its higher vapor pressure likely contributed to elevated TVOC levels, highlighting a potential drawback of using MEA for CO_2 absorption. In contrast, the aqueous Arg solution demonstrated lower vapor pressure, as evidenced by the RH profiles. Analysis of the RH slopes revealed that the Arg solution took longer to reach 90% RH compared to the MEA solution, indicating a lower vaporization rate (Supplementary Figure S5). These findings indicate that, while the aqueous Arg solution has slightly lower CO_2 absorption capacity and slower kinetics, it is a more environmentally sustainable option due to its minimal VOC emissions, especially indoors. To further evaluate the practical application of these solutions, MW regeneration experiments were conducted to assess their sustainability for continuous absorption-desorption cycles.

Microwave heating was employed for CO_2 desorption due to its faster process, lower energy consumption, and simpler setup compared to conventional heating (McGurk et al., 2017). The irradiation process was optimized to achieve full solution regeneration with minimal microwave irradiation time and solvent loss; to this end, a series of absorption-desorption studies were conducted using aqueous MEA solutions. The first MW irradiation time was adjusted by careful inspection of the solution during the MW session to avoid excessive boiling and bumping of the solution inside the MW chamber, while achieving maximum CO_2 desorption possible. As shown in Figures 3A, B, it was observed that increasing the first MW session beyond 150 s led to excessive solvent loss and worse CO_2 desorption outcome. The

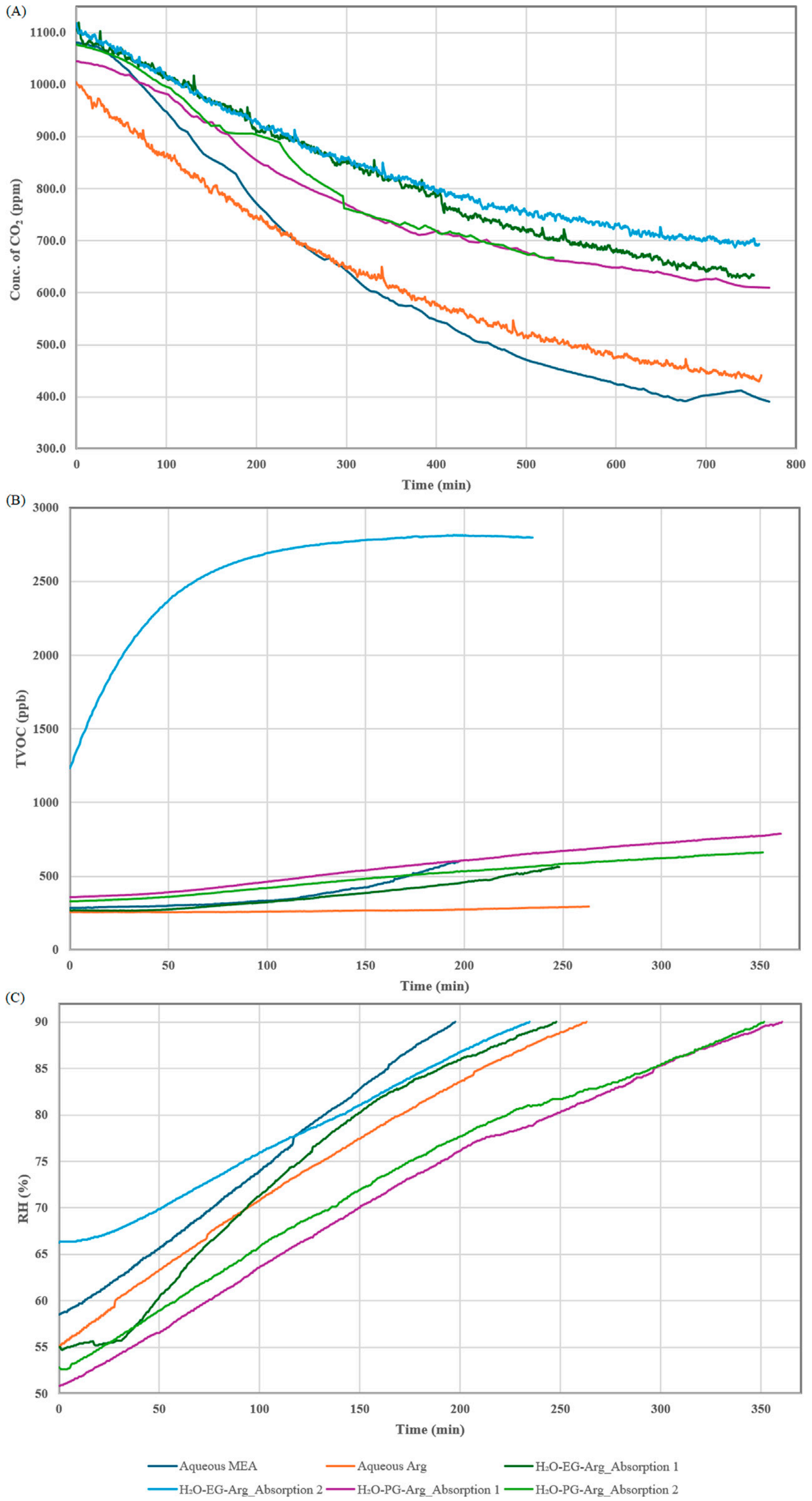


FIGURE 2
(A) CO_2 absorption, **(B)** TVOC concentration and **(C)** RH levels during the CO_2 absorption process for aqueous MEA, aqueous L-arginine, H_2O-EG-Arg, and H_2O-PG-Arg solution. Absorption 2 refers to the second cycle after the initial absorption-desorption cycle.

optimum MW irradiation profile was found to be an initial MW session of 150 s followed by another session of 60 s, achieving near-complete regeneration by desorbing 589 mg (99.5%) of CO_2 from 592 mg absorbed, while limiting solvent loss to just 37 mL.

While the optimal MW irradiation times of 150 s for the first session and 60 s for the second session were effective for aqueous MEA, they proved insufficient for aqueous Arg solution. Only 436 mg (63.5%) of CO_2 was desorbed from the 687 mg absorbed in the first session.

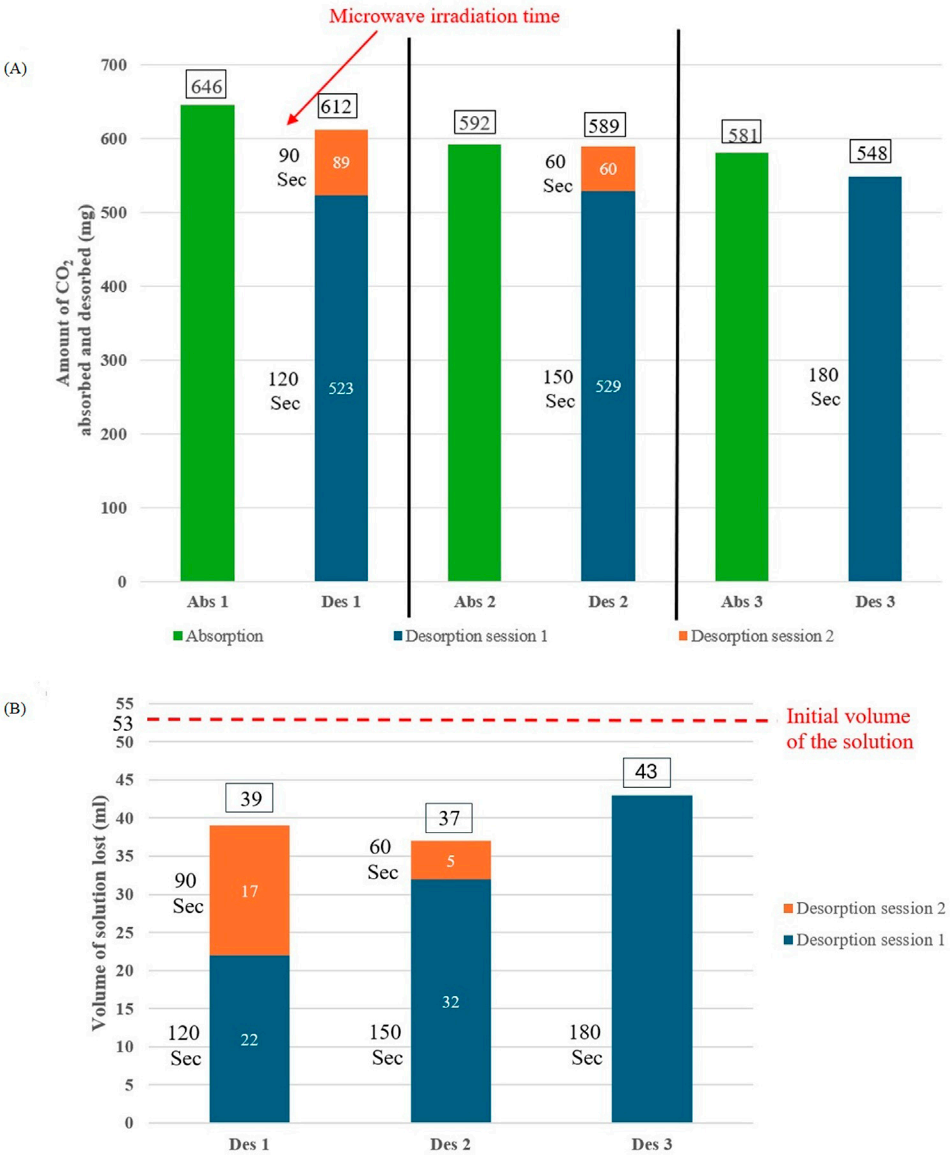


FIGURE 3
(A) Effect of MW irradiation time on CO_2 desorption for aqueous MEA solution. **(B)** Effect of MW Desorption Time on volume of the solution for aqueous MEA solution.

Extending the second session to 90 s released an additional 82 mg, totaling 518 mg (75.4%), showing that the desorption remained incomplete. Prolonged MW irradiation also caused complete solvent evaporation, leaving behind solid Arg crystals, as shown in Supplementary Figure S6. To address this issue and maintain the solution in liquid form, a water-glycol-based Arg solution was formulated.

The choice of glycol with a higher boiling point was intended to manage the RH during the absorption process and to reduce complete evaporation of the solution during the desorption process. To formulate the water-glycol-based CSS, water and glycol were mixed in an optimized 1:1 volumetric ratio. A comprehensive evaluation of some commonly used glycol compounds (Taylor et al., 2024; Garg et al., 2019) was conducted, focusing on key properties such as low vapor pressure, appropriate viscosity, and high molecular weight, as shown in Supplementary Table S1. Among these, the water-EG-Arg and water-PG-Arg solutions exhibited better Arg solubility (Supplementary Figure S2) and were thus chosen for further studies.

While the water-PG-Arg solution initially showed slightly lower CO_2 absorption capacity (α = 0.24 mol/mol, K'' = 1.15 × 10^{-6} ppm^{-1} min^{-1}) than the water-EG-Arg solution (α = 0.26 mol/mol, K'' = 0.95 × 10^{-6} ppm^{-1} min^{-1}) (Table 1), it exhibited comparable kinetics and offered better RH control, taking longer to reach 90% RH during absorption (Figure 2C). Qualitative analysis using LC-QqQ-MS and HS-SPME-GC-MS identified only propylene glycol among the emitted VOCs, with no trace of Arg in the case of water-PG-Arg solution (Supplementary Figures S9, S10). It is worth mentioning that PG, as a VOC, is odorless, non-toxic, and has a Workplace

TABLE 1 CO_2 absorption and reaction kinetics of aqueous MEA and aqueous Arg solutions. Rate Constant (K″) is based on second-order kinetics.

Solution	Amount of CO_2 absorbed (mg)	Rate constant K`` x 10^{-6} (ppm^{-1} min^{-1})	CO_2 abs. time (min)	Initial TVOC at RH 54% ± 5% (ppb)	Final TVOC at RH 90% (ppb)
H_2O (50 mL) + MEA (3 g)	860	2.57	819	285	601
H_2O (50 mL) + Arg (8.71 g)	687	1.80	752	255	293
H_2O (25 mL) + EG (25 mL) + Arg (8.71 g)	582	0.95	754	269	562
H_2O (25 mL) + PG (25 mL) + Arg (8.71 g)	531	1.15	771	358	789

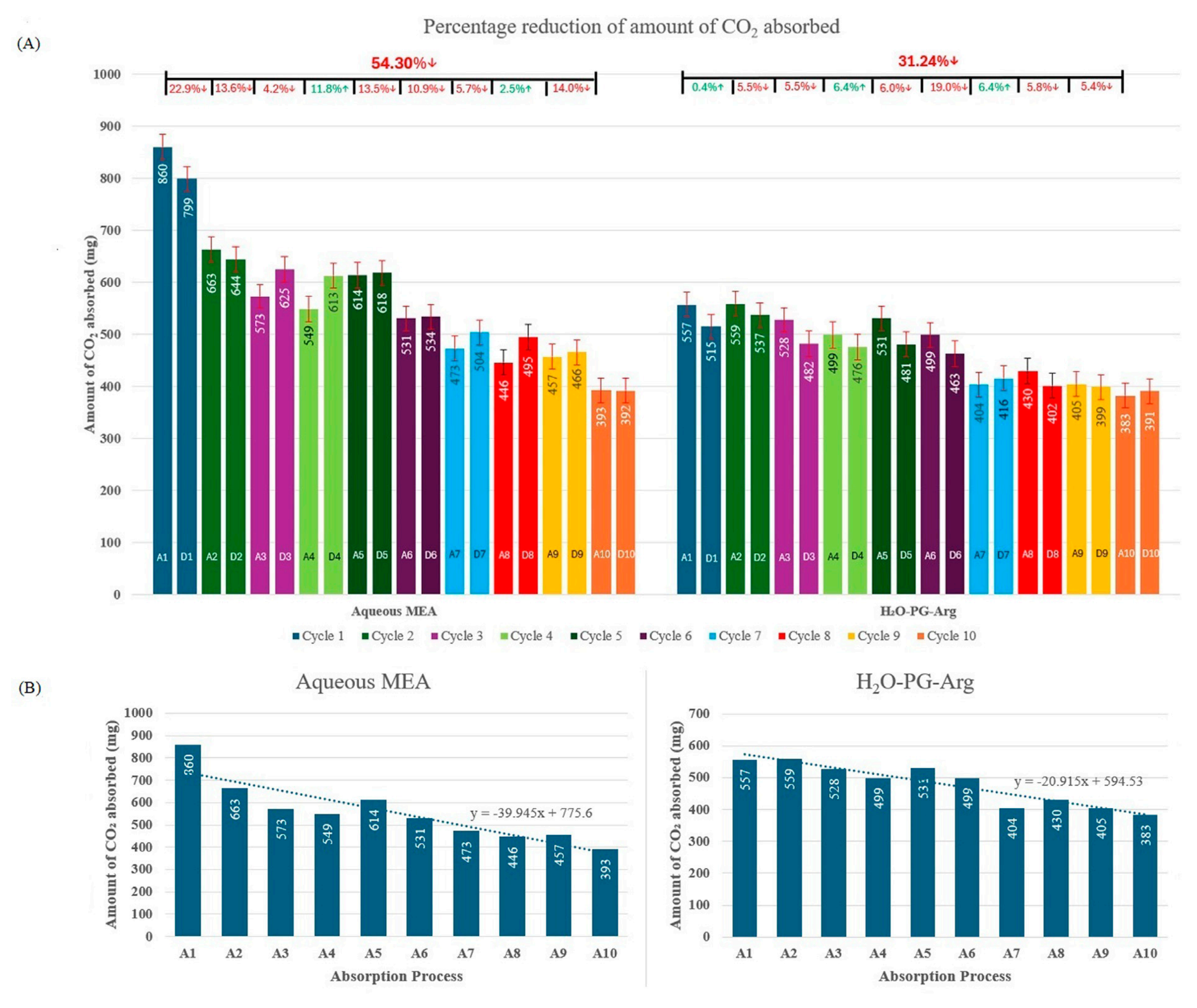


FIGURE 4
(A) Absorption-desorption performance over ten cycles of aqueous MEA and H_2O-PG-Arg solution. The percentage reduction of the amount of CO_2 absorbed after each absorption process, as well as the cumulative reduction after ten cycles, is shown at the top of the figure. **(B)** Absorption-desorption performance over ten cycles of aqueous MEA and H_2O-PG-Arg solution with trendline.

Environmental Exposure Limit (WEEL) of 3,200 ppb, averaged over an 8-h work shift, as set by the American Industrial Hygiene Association (AIHA) (New Jersey Department of Health, 2009). This limit is at least five times higher than the levels detected in our experiment. During desorption, the water-PG-Arg solution achieved ~90% regeneration in a shorter time, reducing energy consumption by 29% (Supplementary Table S2). Additionally, no visible color change was observed in the water-PG-Arg solution after

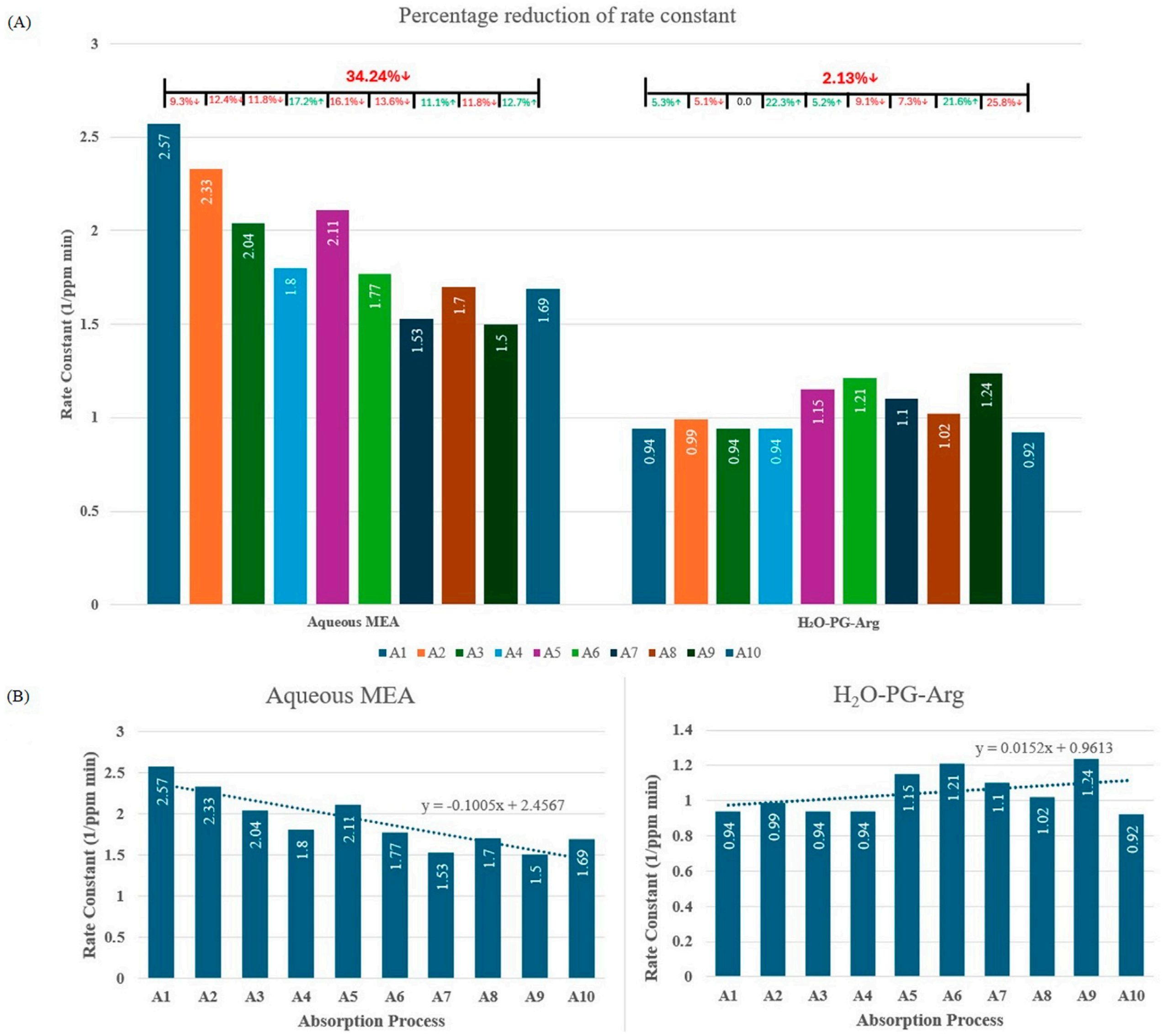


FIGURE 5
(A) Reaction rate constant over ten cycles of aqueous MEA and H_2O-PG-Arg solution. The percentage decrease in the rate constant in each absorption process, as well as the cumulative reduction after ten cycles, is shown at the top of the figure. **(B)** Reaction rate constant over ten cycles of aqueous MEA and H_2O-PG-Arg solution with trendlines.

the first desorption process (Supplementary Figure S7), whereas the water-EG-Arg solution exhibited a shift from transparent to amber, indicating possible degradation (Supplementary Figure S8).

In subsequent cyclic test, the water-PG-Arg solution demonstrated improved stability with consistently lower TVOC emissions during absorption (Figure 2B) and no color change (Supplementary Figure S7) after desorption processes. The water-EG-Arg solution, however, emitted notably higher TVOCs with an unpleasant pungent odor throughout the cyclic study, and its color gradually deepened to a darker red after each desorption process (Supplementary Figure S8). This degradation was likely driven by elevated temperatures during desorption processes, reaching 156°C in the first cycle and 176°C in the second, suggesting potential side reactions and thermal degradation (Supplementary Tables S4, S5). In contrast, the water-PG-Arg solution exhibited lower temperature increases during desorption (Supplementary Tables S6–S15), attributed to the higher specific heat capacity of PG (Supplementary Table S3). Additionally, PG's lower polarity and dielectric constant limited the absorption of MW energy, reducing excessive heat generation (Sengwa, 2003; Gabriel et al., 1998). Thus, the thermal stability, improved absorption performance, and reduced energy consumption of the water-PG-Arg solution highlight its potential for long-term CO_2 capture applications. These findings support further investigation into its cyclic performance over multiple absorption-desorption processes.

The cyclic performances of aqueous MEA and water-PG-Arg solutions were evaluated over ten absorption-desorption cycles, as shown in Figures 4A, B. The reaction rate constants for both solutions across these cycles are presented in Figures 5A, B.

Although the aqueous MEA solution initially exhibited higher CO_2 absorption, its performance declined significantly over time, with a 54.3% reduction in CO_2 absorption after ten cycles. In contrast, the water-PG-Arg solution demonstrated greater stability, with only a 31.24% decline over the same period, becoming increasingly more consistent as our study progressed. The steeper downward trend observed in the MEA solution (Figure 4B) highlights its limitations for long-term CO_2 capture applications. The effectiveness of the aqueous MEA solution declines over time because of oxidative and thermal degradation, leading to a reduced concentration of MEA available for CO_2 absorption. The degradation products, such as ammonia, acetaldehyde, and acetone (Chanchey et al., 2011), may pose potential risks to indoor environments. As a result, the reaction rate constant of the aqueous MEA solution decreased by 34.24% after ten cycles, compared to only a 2.13% reduction for the water-PG-Arg solution. These findings highlight the superior stability and long-term viability of the water-PG-Arg solution for indoor CO_2 capture applications.

4 Conclusion and future works

This study evaluated seven CSS, focusing on their appearance, CO_2 absorption-desorption performance, reaction kinetics, and effects on RH levels and TVOC concentrations. Aqueous MEA showed high CO_2 absorption and faster reaction kinetics but proved less suitable for indoor air capture due to elevated VOC emissions compared to aqueous Arg. Although the aqueous Arg solution performed better than aqueous MEA in terms of TVOC and RH control, it faced challenges with incomplete regeneration and significant solvent vaporization, limiting its use in continuous cycles. To address these issues, we introduced a water-PG-Arg solution, which demonstrated promising results by outperforming aqueous MEA in stability, safety, and long-term efficiency. The inclusion of PG effectively regulated RH during absorption and maintained the solution's liquid state during desorption. Overall, the water-PG-Arg solution exhibited consistent CO_2 absorption and reliable cyclic performance, positioning it as a viable and sustainable solution for indoor CO_2 capture. In our preliminary testing, the integration of an activated charcoal canister within the absorption setup further stabilized RH levels and reduced TVOC concentrations, as illustrated in Supplementary Figures S11A, 11B. As we progressed through the cyclic study, the water-PG-Arg solution's capacity to control RH was slowly impacted (Supplementary Figure S12A), presumably due to the loss of PG to evaporation primarily during the desorption processes, leading to a reduced mole fraction of PG in the resulting solutions, which can be attributed to a gradually lower TVOC generation (Supplementary Figure S12B) during the subsequent absorption processes. Future studies will investigate the use of alternative CSA and less viscous solvents to develop improved CSS that can effectively manage relative humidity across multiple cycles while achieving even lower TVOC emissions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KM: Conceptualization, Investigation, Methodology, Writing–original draft, Writing–review and editing, Formal Analysis, Validation. SB: Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. SW: Validation, Writing–review and editing. DG: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing–review and editing, Writing–original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. Funding for this research was provided by the TECO Clean Energy Research Center (CERC) at the University of South Florida (USF).

Acknowledgments

We would like to thank the following staff and students at the University of South Florida (USF) for their assistance: Dr. Laurent Calcul for assistance and training on Liquid Chromatography-Mass Spectrometry Tripple Quad (LC-MS-QqQ) and Headspace-Solid Phase Micro Extraction-Gas Chromatography-Mass Spectroscopy (HS-SPME-GC-MS); Mr. Timothy Mead for preparing the required experimental setup.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnano.2025.1525106/full#supplementary-material

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Nomenclature

HVAC	Heating, Ventilation, and Air Conditioning system
OSHA	Occupational Safety and Health Administration
NOAA	National Oceanic and Atmospheric Administration
$\mathbf{C_{CO_2}}$	Concentration of CO_2
CSS	CO_2 scrubbing solution
CSA	CO_2 scrubbing agent
MW	Microwave
TVOCs	Total Volatile Organic Compounds
RH	Relative Humidity
ppm	parts per million
Ppb	parts per billion
LC-MS-QqQ	Liquid Chromatography Mass Spectroscopy triple quadruple
HS-GC-MS	Headspace Gas Chromatography Mass Spectroscopy
Arg	L-arginine
MEA	Monoethanolamine
PG	Propylene Glycol
EG	Ethylene Glycol