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Design and Implementation of Direct Air Capture Systems Based on Moisture Swing Adsorption for Efficient Caron Dioxide Removal

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Abstract: Direct air capture (dac) is necessary for achieving negative emissions and meeting the temperature targets outlined in the paris agreement. However, challenges of scalability and energy demands persist. This paper presents a comprehensive design framework for large-scale dac systems utilizing moisture swing adsorption (msa), an innovative method that leverages humidity cycles to regenerate sorbents with near-isothermal energy, thereby reducing energy penalties by 50-70% compared to thermal swing alternatives. The study proposes an architecture combining modular air contractors, structured sorbent monoliths using anion exchange resins, co2 compression trains, and controlled humidification chambers, enabling continuous cyclic operation in various climatic conditions. Governing equations for momentum balance, mass transfer, and adsorption kinetics inform finite element simulations and computational fluid dynamics, which are validated against laboratory-scale experimental data. Key findings reveal 1.2-1.8 mmol co2/g working capacities with 1-5 t h2o/t co2 and levelized costs of $150-300/t co2 at current scales, which are projected to decline to $8-150/t with deployment learning. The framework addresses critical scale-up considerations, including environmental variability, material durability, and infrastructure integration. In practice, msa-dac is positioned as a viable negative emissions technology (net) for integrating renewable energy, modular deployment, and carbon utilization, supporting global decarbonization objectives.

Keywords: *Direct Air Capture (DAC), Moisture Swing Adsorption (MSA), Negative Emissions, Carbon Dioxide Removal, Techno-Economic Analysis.*

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I. INTRODUCTION

➢ *Climate Change and Negative Emission Technologies*

Climate change refers to the variation in climate patterns primarily due to greenhouse gas emissions produced from human activities and natural systems (Fawzy et al., 2020). Climate change mitigation efforts aim to reduce or prevent greenhouse gas (GHG) emissions. According to Panepinto, Riggio, & Zanetti (2021), mitigation can imply the use of new technologies and renewable energies for more efficient use of older equipment, a change in consumer behavior, or management practices. Negative emission technologies have been identified as a way of removing carbon dioxide (CO_2) directly from the atmosphere to reduce global warming. This describes the various types of ideas categorized under the concept before their potential impact on maintaining below 1.5 ºC global warming is examined, alongside their estimated costs and technical effectiveness (Bellamy, 2020). In line with the 2015 Paris Agreement, which specified the goal of international climate policy to enhance the global response to climate change by reducing the average global warming to less than 2 ºC while pursuing efforts to reduce it even further to 1.5 ºC, Otto et al. (2021) argued that negative emissions technologies are introduced to meet these temperature targets.

In its submission on policymaking, the Intergovernmental Panel on Climate Change (IPCC) noted that Anthropogenic greenhouse gas emissions have

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worsened since the pre-industrial period, largely driven by population and economic growth (Baki iz, 2022). This has resulted in unprecedented concentrations of carbon dioxide, nitrous oxide, and methane, with their collective efforts identified throughout the climate system, and they are likely to have been the major cause of the warming (Filonchyk et al., 2024). Specifically, advanced satellite technology observations from global carbon dioxide (CO_2) concentrations revealed gas variations at different planetary scales and timescales (Jiang & Yung, 2019).

In response, net-zero commitments have increasingly been emphasized by countries in communicating long-term climate targets. While it is not specifically clear to what extent traditional emissions reductions and CO_2 removal will help to achieve net-zero (Merfort et al., 2025), carbon removal methods are being explored as pathways to enhance the land sink, engineered removal methods, biomass-based carbon capture and storage, and ocean-based carbon removal (Herzog & Mac Dowell, 2025). The goal is to maintain temperature rise below 2 ^{o}C above pre-industrial levels while pursuing efforts to limit the temperature rise to 1.5 ^{o}C above pre-industrial levels as postulated by the Paris Agreement (Lee, Fyson, & Schleussner, 2021). Adun et al. (2024) opined that this deep decarbonization process is critical for meeting the Paris Agreement goals.

Fuhrman et al. (2021) stated that, based on recent advancements in direct air capture systems and their commercialization, direct air capture with carbon storage could be viable for CO_2 removal from the atmosphere with significantly lower land intensity, despite higher energy demands. Several forms of these systems are being developed, with various energy inputs and costs, and potential for performance improvements and future costs. In addition, Direct Air Capture (DAC) presents a promising solution for removing atmospheric carbon dioxide, also known as negative emissions (Beuttler, Charles, & Wurzbacher, 2019). Experts believe that DAC will only be relevant if it scales rapidly, especially due to the amounts required to be removed using carbon dioxide removal technologies (McQueen et al., 2021).

- *Overview of Direct Air Capture (DAC)*

Direct Air Capture (DAC) technology is essential for reducing atmospheric CO_2 (Zhao et al., 2025). This is based on the premise that climate change poses a risk to human civilization owing to its global and profound impacts. Jha & Dev (2024) explained that while traditional greenhouse gas reduction approaches have offered some progress, they are equally limited, prompting an urgent need for more scalable and innovative solutions to minimize atmospheric CO_2 concentrations and achieve global climate targets. The emergence of DAC as a flexible carbon removal technique, operating independently of emission sources, is effective for capturing CO_2 directly from the air through regenerative sorbent methods (Li & Yao, 2024). DAC is characterized by a location-agnostic and modular nature, allowing for collocation with renewable energy and storage sites, while avoiding long-distance CO_2 transport (Zhao et al., 2025). Apart from fostering carbon management, the potential of DAC extends to its alignment with broader sustainable development objectives. Meanwhile, despite its prominent and widespread benefits, its large-scale deployment faces challenges, including operational costs, high energy consumption, and slow material development.

- *Direct Air Capture [DAC] vs point-source capture*

The rapid increase in the level of atmospheric carbon dioxide and other noxious gases has led to numerous human and animal health issues. Okesola et al. (2018) explained that a process of directly capturing carbon dioxide from the atmosphere will help to make the world a healthier and safer space for its inhabitants. One of the processes and methods postulated to mitigate climate change is by reducing the level of carbon dioxide in the atmosphere through direct air capture (DAC). This proves to be a sustainable, cheap, and affordable method, capturing the CO_2, concentrating it, and pressurizing it for storage or future use. This is distinct from the process of carbon capture from point sources such as industries or power plants. Puxty, Maeder, & Moore (2025) stated that point source carbon capture refers to a technology that aims to separate CO_2 from gas mixtures before its emission to the atmosphere. This technology is considered vital for managing carbon dioxide emissions from power & industrial processes and fossil fuel-based heat as part of emission mitigation approaches.

In general, in line with achieving the IPCC's goal of limiting global temperature to 1.5 oC through massive expansion of negative emissions technologies (NETs), while point-source carbon capture has been widely recognized and deployed as a carbon dioxide removal method, it is limited in its potential to achieve negative emissions (Murawczyk & Stern, 2023). Direct air capture (DAC) is a newer form that fosters true negative emissions.

Experts believe that the current atmospheric concentration of carbon dioxide is higher than it has ever been in the past 800,000 years. Data suggests that present-day CO_2, at approximately 420 ppm, exceeds the highest levels ever experienced on the earth, at least since the Miocene, which further highlights the recent disruption of CO_2 trends in the atmosphere (Cui, Schubert, & Jahren, 2020). Given the energy intensity problem, devising means to reduce this is essential for sustainable economic growth, especially in non-OECD nations. High energy demands are a barrier to implementing DAC systems (Kotowicz, Niesporek, & Baszczenska, 2025). Although research is ongoing on developing alternative technologies and cost-effective sorbents to reduce energy intensity, Azhgaliyeva, Liu, & Liddle (2020) explained that policy instruments such as standards, strategic planning, fiscal measures, government investment, and grants are reliable and effective means.

- *Benefits of Moisture Swing Adsorption*

Moisture swing adsorption is a fast-rising aspect of direct air capture (DAC) technology. Moisture swing adsorption plays a key role in capturing CO_2 efficiently from multiple gas streams, for lower energy consumption than is obtainable in traditional methods (Sun et al., 2021). Moisture swing adsorption reduces energy consumption in DAC technology using moisture control, synergistic

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temperature, and humidity regulation. Consequently, this helps to cut energy consumption by 28% (Xie et al., 2024). The demonstrations of dynamic experiments show the uptake capacity changes of CO_2 with relative humidity while achieving a maximum working capacity for the gas (Wang et al., 2025). Therefore, moisture swing adsorption offers benefits including low thermal energy requirement, passive regeneration, and suitability for arid and semi-arid regions (Weng et al., 2024).

➢ *Research Gap*

Despite the potential of moisture swing adsorption for direct air capture (DAC), some gaps persist in translating laboratory-designed prototypes to industrial systems. The paucity of large-scale design frameworks capable of addressing scalability challenges, including the deployment of cost-optimized material and modular integration, is a major concern. While some studies have detailed the potential of moisture swing adsorption, they equally highlight the absence of requisite, standardized frameworks for large-scale deployment, which consequently limits commercial viability.

In addition, predictive optimization is impeded by insufficient integration of modelling, comprising life-cycle assessments, simulations, and techno-economic analyses. In a recent study by Qadeer et al. (2021) and Xie et al. (2024), most moisture swing adsorption models ignore humidity interactions and energy penalties, resulting in incomplete forecasts of performance. These issues are largely compounded by the lack of strategic evaluations, failing to account for grid interactions and regeneration cycles, among other ancillary components, based on the variability in real-world applications. These fragmented evaluations would be tantamount to overlooking important metrics such as environmental footprints and the level-based cost of CO_2 capture. Thus, this study will bridge the gaps via a unique integrated framework.

➢ *Research Aim and Objectives*

The aim of this study is to design and implement an integrated framework for large-scale direct air capture (DAC) systems with moisture swing adsorption, while addressing gaps for efficient and cost-effective removal of carbon dioxide.

- To develop a comprehensive design framework for moisture swing adsorption (MSA)-based DAC systems for modular scalability
- To evaluate various adsorption and desorption kinetics under different conditions, while optimizing sorbent materials for efficient CO_2 capture
- To assess economic viability and scalability via life-cycle assessment and techno-economic analysis, where metrics such as energy penalties and levelized cost of CO_2 capture are quantified.

II. LITERATURE REVIEW

➢ *Overview of DAC Technologies*

Direct air capture (DAC) technologies are effective for removing (or extracting) CO_2 from ambient air, providing a complementary approach to mitigating climate change besides emissions reduction. Based on their designs, these systems must get rid of the challenge of low atmospheric CO_2 concentrations at approximately 420 ppm, and thus require energy-based processes for extraction, separation, and regeneration (Schaller et al., 2022).

Early commercial deployments are dominated by liquid solvent systems, particularly potassium hydroxide (KOH) or sodium hydroxide (NaOH). When air comes in contact with the alkaline solution, producing carbonate or bicarbonate, regeneration takes place through electrochemical means or via heating, as is seen in Carbon Engineering's process (Sharifian et al., 2021). While high purity is achieved, it faces high water usage and energy demands of about 8-10 GJ/tonne CO_2.

Amine-functionalized materials, including silica or metal-organic frameworks (MOFs), are used by solid sorbent systems, binding CO_2 via vacuum swing adsorption or temperature. They offer lower regeneration temperatures while suffering from sorbent degradation and humidity sensitivity (Hack, Maeda, & Meier, 2022). On the other hand, electrochemical DAC adopts pH swings or electrolyte-based redox reactions to capture and release CO_2, which potentially integrates them with renewables for lower heat needs. This is exemplified in Sustaera and Verdox, with its scaling still in its budding stage.

Also, selective polymers form the basis of membrane-based approaches, which can likewise be used to permeate CO_2 via facilitated transport. However, its efficiency is limited by low fluxes and high pressures (Rafiq, Deng, & Hagg, 2016).

Table 1 A Summary of Direct Air Capture (DAC) Technologies

Liquid Solvent (KOH/NaOH)	**Carbonate formation**	**Commercial (1 Mt/year)**	**8-10 thermal**	**Carbon Engineering, 1Point1**	**Water use, high CAPEX**
Solid Sorbent (Amine)	Chemisorption TVSA	Pilot/Commercial (0.01 Mt/year)	6-9 thermal/electric	Climeworks, Global Thermostat	Degradation, humidity
Electrochemical	pH/redox swing	Lab/Pilot	5-8 electric	Verdox, Sustaera	Scalability, stability
Membrane	Pressure/sweep driven	Lab	>10 electric	MTR, Dioxide Materials	Low flux, fouling

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➢ *Fundamentals of Adsorption-Based DAC*

Adsorption-based DAC relies on the gas-solid relationships, which differentiate physisorption from chemisorption. Physisorption implies weak van der Waals forces with a low heat of around 20-40 kJ/mol, while chemisorption refers to the presence of stronger chemical bonds with higher heat of up to 50-100 kJ/mol (Alsharif, 2025). Although physisorbents such as zeolites are effective for rapid cycling, they have low capacity at dilute CO_2, while chemisorbents such as amines thrive in selectivity (Victor et al., 2022).

Meanwhile, isotherms are modelled in equilibrium, with Langmuir assuming monolayer adsorption on homogenous sites, and Freundlich capturing heterogeneity, which fits irregular or multilayer surfaces much better. Hybrids, such as Langmuir-Freundlich, simplify complex predictions of DAC sorbents (Ng et al., 2017; Saleh, 2022).

Column saturation is demonstrated in breakthrough curves, with initial steep uptake flattening with increasing effluent CO_2. This is quantified by working capacity and time taken to attain saturation, while dynamic experiments reveal the absence of kinetics in isotherms (Abin-Bazaine, Olmos-Marquez, & Campos-Trujillo, 2024). On the other hand, the adsorption cycle is slowed down by mass transfer limitations, including pore diffusion, film diffusion, and surface resistance, often described in linear driving force models. Humidity complicates this effect in DAC due to the adsorption of water, which changes and usually reduces the rate of adsorption (Zhu et al., 2022).

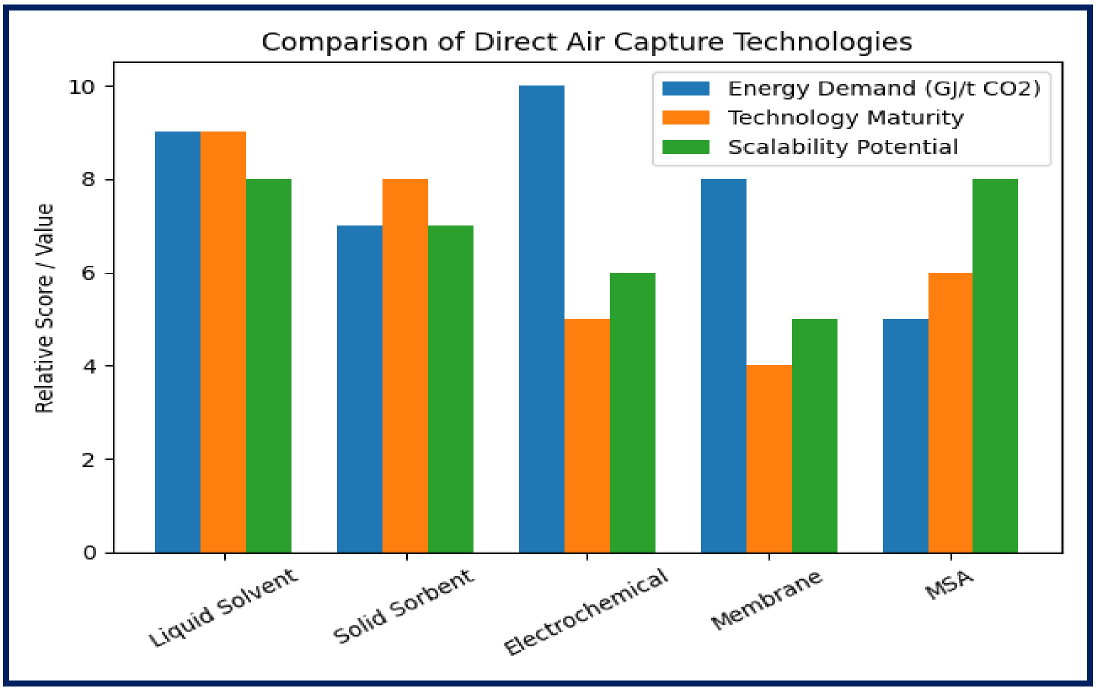

Fig 1 Comparison of DAC technologies

➢ *Moisture Swing Adsorption (MSA)*

Moisture Swing Adsorption (MSA) exploits humidity to enhance CO_2 binding, capturing and releasing dry air in humid conditions, minimizing thermal energy. Meanwhile, ion exchange resins, especially strong-base anion exchangers such as IRA-900, are the foundation of pairing quaternary ammonium sites with bicarbonate (Ji et al., 2025; Wang et al., 2025).

This mechanism typically functions on humidity equilibrium, where dry conditions are favourable for CO_2 binding as low water activity (bicarbonate), while humidification protonates, transforming to volatile hydroxide and CO_2 (Kolle, Fayaz, & Sayari, 2021). Here, the capacities reach up to 1.5-2 mmol/g at 20-80% RH. In the pioneering work by Wang et al. (2024), MSA cycles were recommended to be combined with weak-base resins. The study on IRA-900 variants was advanced, achieving a 1.92 mmol/g uptake, while integrating 6-step thermodynamics for efficiency.

➢ *Material Science Developments*

Moisture swing adsorption (MSA) is dominated by anion exchange resins (AERs), where quaternary ammonium (QA) groups facilitate carbon/bicarbonate chemistry as shown in the equation:

$$\mathbf{CO_2 + OH- + H2O = HCO3-.}$$

Through modifications, such as triazine anions, users can improve capacity by up to 4 mmol/g (Liu et al., 2019). Moreover, carbonate/bicarbonate shifts promote selectivity, especially as humidity contributes to decomposition to gaseous CO_2, while optimization emphasizes high porosity and basicity (Ray, Churipard, & Peter, 2021). In general, sorbent degradation is attributed to AQ Hofmann elimination at > 60 ºC or oxidation, which reduces capacity by 20-50% within cycles (Huang et al., 2025). Nowadays, stability enhancements comprise siloxane crosslinking, and lifetimes exceed 10,000 cycles in laboratory tests. In recent AERs, reports show <5% loss after a few cycles in ambient air.

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➢ *Limitations*

Current studies reveal some limitations. For example, most research on DAC is confined to validation within a small laboratory, which implies small-scale grams to kg sorbent, and overlooks losses due to scale-up in heat transfer and pressure drops (Pisciotta, 2024). There is also a 20-30% loss of efficiency in pilot plants such as Climeworks (Nilsson, 2024). In addition, real-world environmental data ignores variable temperature or humidity, consequently degrading performance (Mennitto et al., 2025). Poor techno-economic integration fragments analysis persists. Thus, based on the need for policy for viability, especially for scaling, among other aforesaid limitations, there is a need for integrating frameworks as is the purpose and focus of this study.

III. THEORETICAL PRINCIPLES OF MOISTURE SWING ADSORPTION

➢ *Chemical Reaction Mechanism*

Moisture swing adsorption (MSA) is a thermodynamically viable approach for direct air capture (DAC). This section provides the chemical, kinetic, and thermodynamic principles that underscore and govern the performance of Moisture Swing Adsorption (MSA). MSA is inherent in CO_2 pH-sensitive equilibrium with hydroxide-functionalized AERs. This involves initiating the primary reaction with CO_2 ionization and hydration, as in the equation below, where CO_2 from the atmosphere diffuses into the aqueous microenvironment of the resin and forms a bicarbonate through nucleophilic attack by tethering hydroxide ions to quaternary ammonium sites (R_4N^+ OH) (Wheatley, 2017).

Under dry conditions, this zwitterionic intermediate deprotonates rapidly, producing R_4N^+ HCO_3^- with an approximate 1-2 mmol/g capacity.

$$CO_2 + OH^- \rightleftharpoons HCO_3^-$$

The reaction is mediated by water molecules, both as reactant and solvent. In the full mechanism, the equation goes as follows: $CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^-$, although localized high pH (>12) accelerates bicarbonate formation in AERs, which bypasses slow uncatalyzed hydration at k ~ 0.03 s-1. Moreover, humidity plays a significant role in modulating water activity (a_w), with low relative humidity (RH < 30%) dehydrating the Donnan gel phase to stabilize charged HCO_{3-} pairings while suppressing desorption (Zhou et al., 2025). On the other hand, higher RH above 70% submerges the polymer, diluting ions and shifting equilibria to the left side through Le Chatelier's principle (Liu & May, 2024).

The landscape is further complicated by the carbonate equilibrium as in $2HCO_3^- = CO_3^{2-} + H_2O + CO_2$ (g), which favours bicarbonate in acidic and dry microenvironments, and carbonate in alkaline thrives in wet types. This dual occupancy of HCO_3^-/CO_3^{2-} promotes capacity by 20% boost, although it demands precise RH control to avoid premature release of CO_2 (Nakao et al., 2019). In addition, by crosslinking resin, such as in 8% DVB, water clusters are confined, and selectivity over N_2/O_2 is amplified.

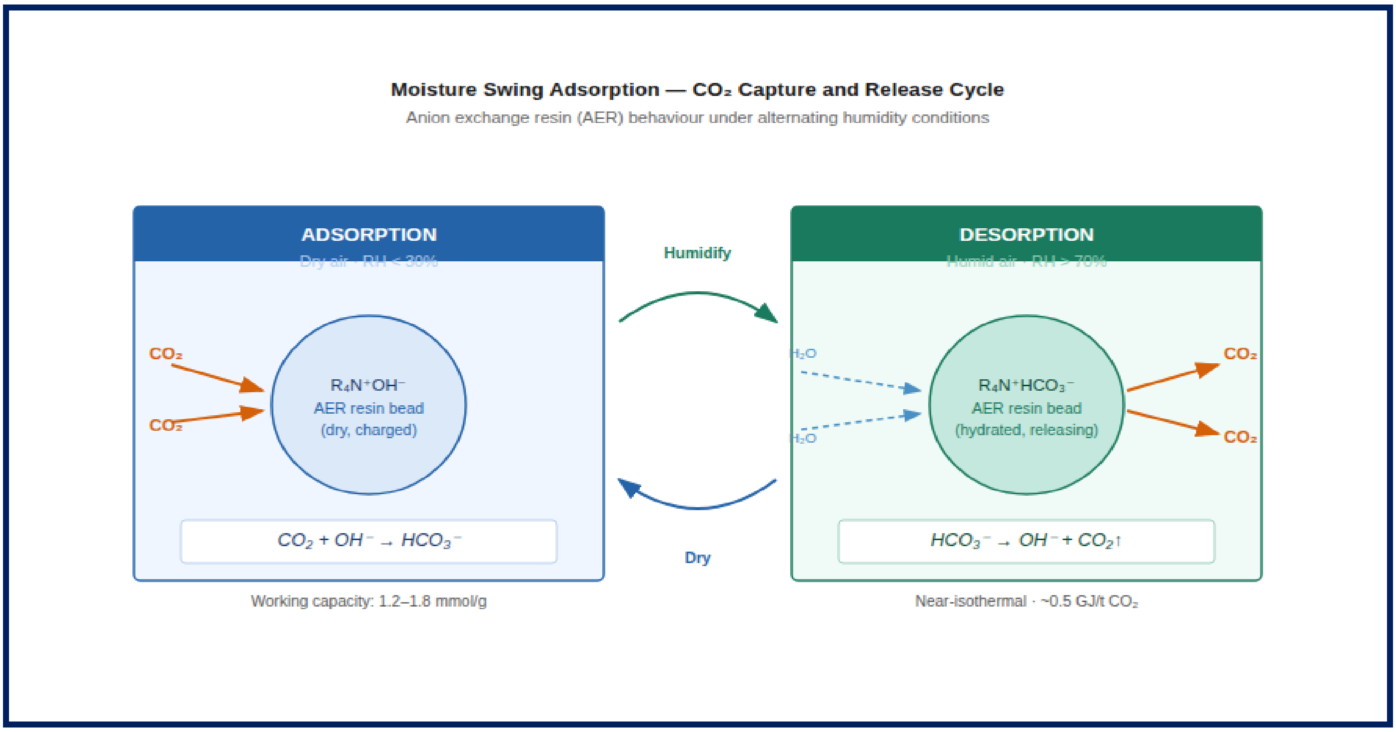

Fig 2 Moisture Swing Adsorption (MSA) Humidity Swing Cycle Diagram [Process/Flow Diagram]

➢ *Thermodynamics of Humidity Swing*

Moisture swing adsorption (MSA) is effective for direct air capture because it is produced from humidity-based Gibbs free energy (ΔG) modulation, hence near-isothermal regeneration (Xie et al., 2024). To calculate the binding energy for CO_2 on AERs, the expression holds as follows:

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$$\Delta G = \Delta H - T\Delta S,$$

Where exothermic adsorption (ΔH ~ -40 to -60 kJ/mol) is offset due to entropy losses from ordering. Water co-adsorption is minimized by dry conditions, providing $\Delta G < 0$ for capture, while humid swings increase sorbate entropy, which flips $\Delta G > 0$ for release without the need for heat (Elfving, 2021).

Equilibrium constants (K_eq) show a strong dependence on R in the formula:

$$K\_eq(RH) \propto \exp(-\Delta H\_w / RT) / a\_w.$$

Here, ΔH_w refers to water sorption enthalpy, such that at 25 ºC and 400 ppm CO_2, uptake increases to 10-20% RH for Δq ~ 1.8 mmol/g, increasing above 80% RH with decomposing bicarbonate for pK_a HCO_3^-/CO_3^{2-} = 10.3. According to Van't Hoff's analysis, humidity is the major driver, with $\partial \ln K/\partial \ln RH \approx -2$ to -4, which exceeds temperature effects (Salthammer & Morrison, 2022). Moreover, nonlinearities are introduced by temperature-humidity coupling, where increased T, such as at 40 ºC exacerbates desorption through an increase in vapor pressure (P_sat), and shortens cycles while risking sorbent dehydration (Hraiech et al., 2025). Isotherms, however, show a sweet spot around 20-30 ºC and 15-50% RH swing, where ΔG_hysteresis enhances and maximizes the cyclic capacity. By mapping feasible operating windows with phase diagrams, 90% regeneration is predicted at a minimal energy penalty of ~0.5 GJ/t CO_2 electric for dehumidification (Zhu et al., 2022).

- *Adsorption Kinetics*

Moisture swing adsorption (MSA) kinetics combine surface reactions with transport, whose limitation is the intraparticle diffusion in resin beads at 50-500 µm (Mejbel, 2021). CO_2 ingress is governed by Fickian diffusion, with $J = -D\_eff\ \nabla C$, where $D\_eff = D\_pore\ \varepsilon\_p / \tau$ (ε_p ~0.4, tortuosity τ ~3-5) (Rezk et al., 2021). D_eff refers to effective diffusivity, and pore sizes between 10-100 nm facilitates Knudsen diffusion at low P, but water clustering halves D_eff in humid swings.

- *Sorbent Performance Parameters*

The effectiveness of moisture swing adsorption (MSA) systems can be determined using various key performance parameters governing material selection and system design. At equilibrium capacity, which is typically between 1.5-2.5 mmol CO_2/g under 20-30% RH dry conditions, the moisture swing adsorption uptake reaches a maximum value at partial temperature and pressures (Vu, 2019). Cyclic productivity, which is the difference between adsorption and desorption loading, is evaluated by the working capacity, where MSA materials demonstrate about 1.2-1.8 mmol/g swings between humid and dry conditions (Fakhraddinfakhriazar, Molina-Fernandez, & Leonard, 2026).

Selectivity coefficients justify the preference of the sorbent for CO_2 over competing gases such as O_2 or N_2, where amine-functionalized resins demonstrate CO_2/N_2 selectivity that exceeds 1000 as a result of chemisorption mechanisms (Elfving, 2021). The duration to 10% of the inlet is indicated by the breakthrough time, measurable during fixed-bed operation, which directly correlates with the efficiency of bed utilization and length of mass transfer zone (Mesfer et al., 2020).

In addition, kinetic rate constants derived from linear driving force models range from 0.01-0.05 s-1 for commercial AERs and are influenced by pore architecture and particle size. Long-term stability measurements include contaminants' tolerance (NO_x, SO_x, particulate matter) and capacity retention after accelerated cycling (more than 90% after 10,000 cycles). Regeneration energy, sensible heat requirements, and humidity swing work collectively to help achieve a 2-4 GJ/t MSA, which is widely lower than thermal swing alternatives (Wang, Wang, & Zhuo, 2025).

IV. SYSTEM DESIGN AND ENGINEERING CONSIDERATIONS

- *Conceptual System Architecture*

The moisture swing adsorption (MSA)-based direct air capture system architecture comprises different subsystems designed for cyclic, continuous operation. The primary interface between the sorbent medium and atmospheric air is the air contractor, which is designed to minimize pressure reduction and maximize exposure (Shi et al., 2020). Meanwhile, multiple configurations also exist, including vertical parallel plate designs and horizontal cross-flow arrays, whose selection is governed by available land area and site-specific wind patterns.

Air contactor design is in line with modular principles, comprising standardized units of 2-4 m height containing packed beds or sorbent panels in stacks. Louvered inlets are used by contractors for passive dust exclusion, while adjustable dampers allow for control of flow (Song et al., 2020). The framework facilitates sorbent modules and accommodates maintenance access and thermal expansion. This involves targeting approximately 200-400 m^2/m^3 surface area-to-volume ratios to ensure balanced costs and capture kinetics.

In addition, moisture control chambers are useful for managing the humidity environment for both phases – adsorption and desorption. During the former, dried air of 15-30% RH extracted from upstream dehumidification units goes through sorbent modules, while the latter phase employs 70-95% RH humidified air (Chatterjee, 2025), generated through membrane humidifiers and water spray systems, where the flow direction is reversed to maximize concentration gradients. In this case, the chamber materials function with corrosion resistance to alkaline conditions from decomposed bicarbonate (Zheng et al., 2019).

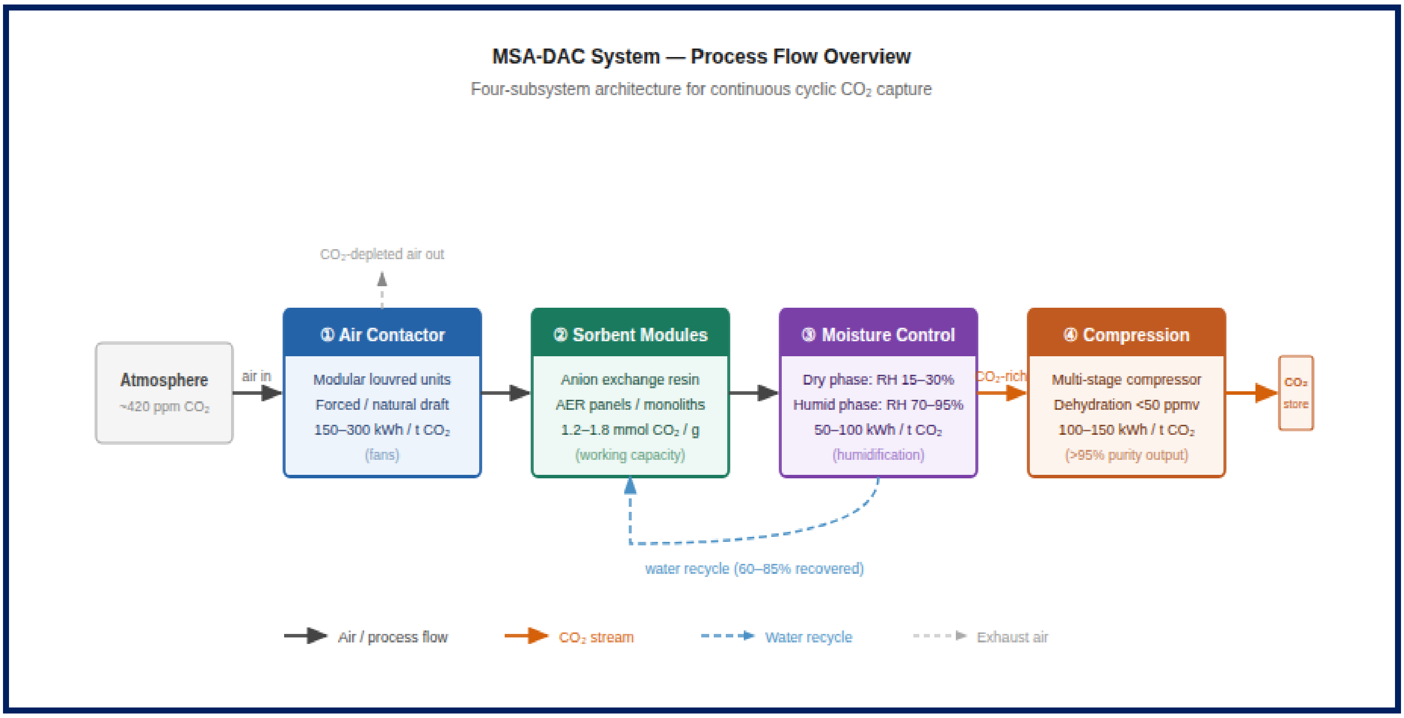

Fig 3 System Architecture Diagram

The fourth subsystem is the CO_2 collection and compression, which starts with the humid, CO_2-rich effluent produced from desorption cycles, and contains 2-5% CO_2 at near-ambient pressure. Entrained water droplets are removed with gas-liquid separators before compressing them to a pipeline pressure of 15-25 MPa via the multi-stage compressor with intercooling (Witkowski et al., 2015). Product purity implies more than 95% CO_2 after dehydration to pipeline specifications of at least 50 ppm H20, which is required for utilization pathways or geological storage.

- *Airflow Management*

A fundamental design decision with major capital and energy implications is presented by natural draft compared to forced convection. Natural draft systems depend on wind-powered flow via contractor arrays, which require little fan energy, depending on varying meteorological conditions (Muchiri, 2024). Studies on computational fluid dynamics reveal that optimized louver geometries can achieve up to 70-85% design flow rates at 3-5 m/s moderate wind speeds, although scholars believe that supplementary fans are necessary for calm periods (Han, 2025).

Parasitic loads are dominated by fan energy requirements in forced convection designs. Axial fans at contractor outlets or inlets provide 50-100 m^3/s flow rates per unit of 200-400 Pa static pressure. Fan power specifically ranges from 0.15-0.30 kWh per 1000 m3 of air processed, which translates to 150-300 kWh/t CO_2 for systems operating at 400 ppm inlet concentration. Variable frequency drives enable turndown at low-demand periods while facilitating response to real-time electricity pricing (Garcia, Ruiz, & Aguila, 2025; Mwasilu, Justo, & Bansal, 2026).

Optimized pressure drops balance gas capture kinetics versus energy consumption. In Darcy-Forchheimer's relationship, the flow through porous sorbent bends is described, with linear pressure drop with velocity and bed depth, while increasing quadratically at higher Reynolds numbers (Dupre, 2020). Multi-objective optimization identifies optimal face velocities of 0.5-1.5 m/s for packed beds and 1.5-3.0 m/s for monoliths, which achieves 50-70% capture efficiencies per pass and limits pressure drop to 150-300 Pa.

- *Humidity Cycling Mechanism*

Passive moisture swing takes advantage of natural humidity gradients across geographic locations or between day and night. An example of this approach is in desert coastal installations, where daytime low humidity (10-20% RH) drives adsorption, and night-time marine inflow (70-90% RH) propels desorption (Ottmann, 2025). Essentially, passive systems eliminate active humidification equipment, which reduces capital costs by an average of 20%, although capture rates are unstable due to seasonal and diurnal patterns.

Likewise, controlled humidification chambers provide consistent cycling that is independent of ambient conditions. High-pressure spray nozzles or ultrasonic atomizers produce a fine water mist of 10-50 µm droplets, evaporating quickly into process air streams (Gemci & Chigier, 2016). With the humidification energy averaging 50-100 kWh/tonne CO2 for evaporation, compressor intercooling, or low-grade sources of waste, promote heat recovery to minimize primary energy consumption.

Moreover, the water loop is closed by water recovery systems, particularly in arid regions with scarce makeup water. The condensation of heat exchangers helps cool humid exhaust streams below the dew point, where 60-85%

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of injected water is recovered. Membrane contractors provide alternative recovery methods with lower temperature requirements but higher capital costs (Matthee, 2020). With integrated designs, up to 1-3 tonnes H2O/tonne CO_2 captured of total water consumption is achievable, which is lower than what is obtainable in solvent-based DAC systems.

- *Sorbent Bed Design*

For sorbent bed design, packed beds versus structured monoliths are distinct techniques with performance and cost trade-offs. Packed beds of 0.5-2 mm diameter spherical resin beads achieve a high sorbent density of up to 500-700 kg/m3 and simple construction while the pressure reduces by 500-1000 Pa/m (Sarbanha, 2024). Structured monoliths are designed by 3D printing or extrusion of sorbent-polymer composites, providing a lower pressure drop between 100-300 Pa/m. While it equally guarantees uniform flow distribution, it also offers lower volumetric sorbent loading and higher fabrication costs (Lawson et al., 2021).

Meanwhile, optimizing the surface area extends beyond mere geometric considerations to accessible sorption sites. The combination of micropores (<2 nm) and macropores (>50nm) with mesopores and rapid transport in hierarchical pore structures provides up to 3-5 times more effective diffusivities than uniformly microporous materials (Schneider et al., 2016). This balances site availability against pore blockage through surface functionalization density controlled by animation conditions, including optimal loadings of 2-4 mmol N/g support.

Cycle times and productivity are governed by heat and mass transfer considerations. While adsorption exotherms of 40–60 kJ/mol CO_2 elevate sorbent temperature by 2–5 °C in well-designed systems, they diminish equilibrium capacity to some extent (Soto, 2021). More importantly, water adsorption or desorption carries latent heat of up to 44 kJ/mol H_2O, which can potentially cause temperature swings of 5-10 ºC if unmanaged (Kim, 2018). Within sorbent beds, integral heat exchangers using liquid or air coolant maintain near-isothermal operation and stabilize cyclic performance.

- *Thermal Management*

Thermal management involves avoiding unwanted heating, which helps to preserve the thermodynamic advantage of moisture swing adsorption (MSA) over thermal swing techniques (Xie et al., 2024). Some examples of passive cooling strategies include selecting reflective materials with 0.7-0.9 solar reflectivity, shading structures to reduce solar gain, and nocturnal radiative cooling of constructed surfaces. When required, active cooling utilizes air-side heat exchangers with minimal pressure penalty or ground-coupled heat exchangers by leveraging stable subsurface temperatures (Tong, 2018).

It also encompasses ambient temperature variability across geographic locations and seasons, necessitating adaptive control strategies. Within Arrhenius relationships, 5-15% capacity reduction per 10 ºC temperature increase is predicted, while cold temperatures slow temperature (Sang et al., 2026), and risk forming in humidification equipment. Flow rates, cycle timing, and humidity setpoints are adjusted by model predictive control algorithms based on weather forecasts to maintain yearly capture efficiency within 15% of design maximum.

However, its integration with renewable energy aligns DAC operation with sustainable power sources, ensuring that photovoltaic arrays are sized to meet compression loads and peak fan, enabling daytime operation with abundant solar radiation (Li & Yao, 2024). Intermittent renewable supply is complemented by thermal energy storage in phase-change materials, and hydrogen from electrolysis during surplus periods drives combustion engines for non-stop compression (Jarvinen et al., 2025). Grid-interactive systems provide demand response services, which reduce net electricity costs by 20-40%.

- *CO_2 Handling and Storage*

Compression of CO_2 captured to pipeline specifications is carried out in stages with cooling at each stage to ensure isentropic efficiency. Centrifugal compressors are used for large flows of more than 100t CO_2/day and 85-90% adiabatic efficiency (Freeman, 2020; Titcombe, 2025). Reciprocating units suit smaller installations. Specific compression work represents 15-25% of total system energy demand, ranging from 100-150 kWh/t CO_2 to deliver at 15 MPa.

When pipelines are unavailable, liquefaction enables temporary storage and movement. Refrigeration cycles using CO_2 or ammonia as working fluids cool CO_2 to achieve liquid densities of 900-1000 kg/m3 while liquefaction energy contributes 80-120 kWh/t CO_2, which is partly offset by reduced transport costs compared to compressed gas (Wilkes, 2024).

For integrated transport, connectivity to existing CO_2 infrastructure is essential. While pipeline transport provides the lowest unit costs, dedicated right-of-way and continuous flow are major requirements. On the other hand, ship transport is useful in coastal locations with 50-200 kt/year capacity, while truck and rail transport provide flexible alternatives for pilot or small-scale deployments at higher unit costs (Miu et al., 2021).

V. MODELLING, SIMULATION, AND PERFORMANCE EVALUATION

- *Governing Equations*

CO_2 transport and accumulation within sorbent beds are described in mass balance equations (Amponsah et al., 2025). The conservation equation combines sorption, dispersion, and convection kinetics for a differential element as shown:

$$\partial(\varepsilon C)/\partial t + \nabla\cdot(uC) = \nabla\cdot(D\nabla C) - (1-\varepsilon)\rho\_s\ \partial q/\partial t$$

Here, ε = bed porosity, C gas-phase CO_2 concentration in mol/m3, u = superficial velocity (m/s), D axial dispersion coefficient (m2/s), ρ_s sorbent density (kg/m3), and q = adsorbed phase concentration (mol/kg).

The sorption rate ∂q/∂t follows linear driving force as in:

$\partial q/\partial t = k\_LDF\ (q^* - q)$, where k_LDF is the mass transfer coefficient (s-1) and q* is the equilibrium loading at local conditions.

For momentum balance, Darcy's law is employed and extended for inertial effects at higher Reynolds numbers. The Ergun equation shows the relationship between pressure gradient and velocity for packed beds:

$$-\partial P/\partial z = 150\mu(1-\varepsilon)^2u/(d\_p^2\varepsilon^3) + 1.75\rho(1-\varepsilon)u^2/(d\_p\varepsilon^3)$$

Here, μ represents gas velocity (Pa · s), d_p is the particle diameter (m), and ρ gas density (kg/m3). For monolithic structures, the friction factor correlations are based on channel hydraulic diameter, replacing the Ergun formulation.

The mass balance is extended by the species transport equations, accounting for multicomponent adsorption competition. The ideal adsorbed solution theory (IAST) predicts equilibrium for $CO_2/N_2/H_2O$ mixtures from single-component isotherms, while extended Langmuir models provide computationally efficient alternatives (Li et al., 2018) as in:

$$q\_i^* = q\_max,i\ b\_i\ P\_i / (1 + \Sigma\ b\_j\ P\_j)$$

Here, the temperature-dependent affinity parameters are b_i = b_O,I exp (-ΔH_i/RT).

- *Computational Modelling*

Velocity and concentration distributions are resolved by CFD modelling of airflow in contractor geometries. Here, Reynolds-averaged Navier-Stokes (RANS) equations with k-ε turbulence closure captures macroscopic flow patterns, and large eddy simulation (LES) is functional for resolving transient eddies that affect local mass transfer. Porous medium submodels are indicative of sorbent regions with user-defined momentum sources and species sinks, which reduces computational cost and preserves essential physics (Nadamani, Shadloo, & Dbouk, 2025). Mesh independence studies cater to solution accuracy, which requires 2-5 million cells for full-scale simulations.

Finite element (FE) modelling of sorption kinetics couples intraparticle diffusion with surface reaction rates. The multicomponent diffusion in resin beads is described by the dusty gas model, which accounts for Knudsen and molecular diffusion regimes (Dale, Markovski, & Hristovski, 2016). Parameter estimation using experimental breakthrough curves validates the kinetic parameters via inverse modelling mechanisms (Soeiro et al., 2024).

Through sensitivity analysis, critical parameters governing performance are identified. For instance, local sensitivity methods are used to examine responses to +/-10% differences in input parameters, and global techniques such as Morris screening explore full parameter spaces. Major sensitivities include mass transfer coefficients, equilibrium capacity, and pressure drop correlations, as the results guide design optimization and experimental prioritization.

- *Key Performance Indicators*

CO_2 capture rate, measured in kg/day, integrates performance over cyclic operation. In continuous systems, capture rate is expressed as: η_capture · Q_air · C_in · M_CO_2 · (t_ads/t_cycle).

Here, η_capture = single-pass efficient

- Q_air = volumetric flow rate (m^3/s)
- C_in = inlet concentration (mol/m^3)
- M_CO_2 = molar mass (kg/mol)
- t_ads/t_cycle = adsorption time fraction

Commercial-scale modules target 500-2000 kg CO_2/day/100 m^2 footprint.

All parasitic loads normalized to product CO_2 are aggregated by energy consumption, measured in kWh/t CO_2. The breakdown shows 150-300 kWh/t fans, 100-150 kWh/t compression, 50-100 kWh/t humidification, and 20-50 kWh/t auxiliary systems. Thermal energy for regeneration is indirectly generated via humidity generation, where electrical equivalents using the coefficient of performance (COP) conversions foster direct comparison with thermal swing systems (Wu et al., 2025).

Cycle time, in minutes to hours, determines equipment utilization and productivity. Adsorption continues until loading approaches equilibrium or until breakthrough, which typically takes between 30 and 120 minutes, depending on the flow rate and bed geometry. Desorption requires 15-60 minutes to complete the regeneration process (Rezai & Allahkarami, 2024), and total cycle time dictates the number of parallel units required for continuous operation.

- *Validation Approaches*

This will be validated with lab-scale prototype testing and comparison with published datasets. The purpose of lab-scale prototype testing is to establish baseline performance given controlled conditions. Heat and mass transfer models are validated using temperature and humidity probes that monitor internal bed conditions, while parametric studies explore the effects of humidity, temperature, cycle timing, and flow rate on capture performance (Bihani et al., 2025). For consistency with wider literature, this will be compared with published datasets. Equilibrium isotherms compared with published data for similar AER materials verify experimental methods, while breakthrough curve shapes and timescales are benchmarked against studies from independent laboratories to confirm kinetic parameters (Wilkins, Rajendran, & Farooq, 2021). Realistic cost projections are assured through techno-economic assumptions cross-referenced with peer-reviewed assessments.

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VI. IMPLEMENTATION CHALLENGES AND SCALE-UP CONSIDERATIONS

➢ *Material Durability*

Sorbent degradation techniques compromise economic viability and long-term performance. In the elimination of quaternary ammonium groups above 50 ºC, ion exchange declines by 0.1-0.5% per cycle due to thermal stress (Matsumoto et al., 2019). However, amine functional groups are attached by oxidative degradation from NOx (5-20 ppb) and atmospheric ozone (20-40 ppb), forming stable amides and nitrosamines that reduce CO_2 affinity. Under realistic ambient conditions, accelerated aging tests are projected to 15-25% capacity loss, hence the need for periodic sorbent replacement (Rochelle, 2024).

Moreover, pore access is blocked, given a corresponding increase in pressure drop due to the accumulation of fouling by atmospheric particulates on sorbent surfaces. Industrial and urban locations experience an approximate of 20-100 µg/m3, where 0.5-2 g/m^3 is deposited on contractor surfaces on a daily basis. Consequently, a significant quantity of incoming particles is removed through prefiltration with fibrous media (MERV 13-16) or electrostatic precipitators, simultaneously adding at least 50 Pa pressure drop while requiring regular replacement or cleaning (Afshari et al., 2020).

Packed beds are also deformed over time due to the effect of polymer creep under gravitational load, thus creating channelling and voids that reduce the efficiency of gas capture. Overall, while structured monoliths are more resistant to mechanical degradation, they require that the thermal expansion coefficients of substrate and sorbent are carefully matched (Lawson et al., 2021).

➢ *Environmental Variability*

Continuous, uninterrupted operation in continental climates is challenged by seasonal fluctuations in humidity. During summer, humidity of 60-90% RH may prevent complete drying during adsorption, reducing working capacity by 50% (Zhang et al., 2025). On the other hand, during winter, humidity of 10-30% RH enhances high uptake, which can freeze in humidification systems. Seasonal storage of captured CO2 provides buffers against reductions in winter demand, while maintaining the performance of hybrid sorbent blends across broader ranges of humidity (Zhang et al., 2025).

Furthermore, dust contamination from wind-blown particulates settles on contractor surfaces, especially in agricultural regions or deserts. Sorbent pores are blinded by dust loading rates, raising pressure drop, and thus require more frequent washing with demineralized water (Yonkofski et al., 2018). Dust adhesion is also reduced by hydrophobic coatings on contractor surfaces, despite the durability of the coating under abrasion and UV exposure being unproven at scale.

Similarly, extreme temperatures beyond the design range have a negative impact on performance and risk damage to the equipment. Specifically, heat waves that exceed 45 ºC reduce equilibrium capacity and accelerate chemical degradation. On the other hand, cold spells under -20 ºC freeze water in recovery and humidification systems, requiring freeze protection strategies and heat tracing. Climate-adaptive designs adopt wider operating envelopes at modest prices, but improve reliability across various deployment sites (Waibel et al., 2024).

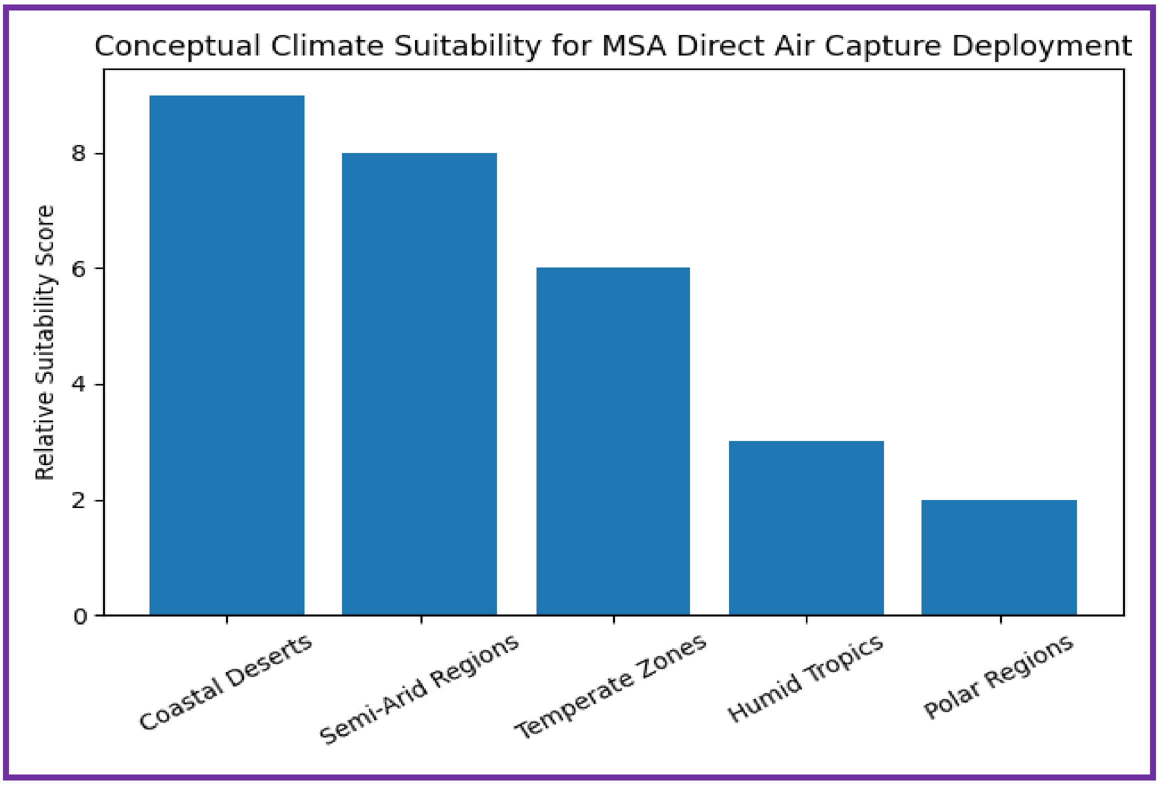

Fig 4 Geographic Suitability Map [Region-Based]

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➢ *Land Use and Siting*

There are distinct trade-offs between urban and desert installations. Urban sites offer proximity to CO_2 utilization markets and existing infrastructure while contending with stricter zoning, higher land costs, and community acceptance issues (Sharifi, 2020). Brownfield and rooftop installations adopt underused space but with limited module sizes (500-2000 t CO_2/year per hectare) (Raj, 2025). In desert locations, abundant low-cost land and high solar resources for renewable energy are achievable, although they need long transport pipelines for CO_2. They also face challenges, including extreme temperatures, dust, and water scarcity (Al-Addous et al., 2024).

By integrating this with renewable energy farms, users can leverage synergies between clean power generation and DAC. In essence, direct DC coupling is achievable by co-locating with solar photovoltaic plants, which avoids grid connection costs and inversion losses. Likewise, wind farm integration complements the process, providing support for continuous operation through nighttime wind power (Chinaris et al., 2025). Installing DAC units between wind turbines or solar panels through land sharing increases the efficiency of land use by 50-100% compared to separate installations.

➢ *Infrastructure Integration*

Grid connection requirements depend on operational strategy and scale. For instance, grid-connected systems ranging from 10 to 100 kt CO_2/year require medium-voltage connections capable of supplying 2-10 MW peak demand, with backup transformers to ensure reliability (Mrad, 2019). Islanded renewable-powered systems require 4-8 hours of battery storage capacity to buffer intermittent generation, resulting in additional $200-400/kWh investment costs (Sharma et al., 2025). Connection chargers can, however, be minimized through grid-interactive systems with demand response capabilities via interruptible load agreements.

CO2 transport pipelines are a key infrastructure investment for large-scale deployment. Trunk pipelines of 12–24-inch diameter move 0.5-5 Mt CO_2/year across hundreds of kilometres at $1-4 million/km installed cost. Distributed DAC facilities are connected to trunk lines through gathering networks, which requires route optimization through populated areas, including some permitting challenges (Alsayyed et al., 2025). Dehydration to <50 ppmv H_2O and selection of corrosion-resistant or stainless-steel alloys in high-risk sections are necessary due to a corroded pipeline from wet CO_2.

Through modular deployment strategies, users can reduce financial risk while accelerating learning. The time and cost of field construction are also minimized by truck-transported and factory-fabricated standardized 1000-5000 t/year modules. Adding incremental capacity matches demand growth and generates operational data for next-generation designs while intrasites module commonality fosters economies of scale in manufacturing and maintenance despite diverse deployment conditions.

VII. TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

➢ *Capital Expenditure (CAPEX)*

The majority of the total capital cost for MSA-DAC systems comprises contactor units, including fabricated costs for modular contactor ($200-500/m^2 of frontal area), depending on the type of materials and wind load (Sabatino et al., 2021). A 1000 t/year module with 200 m^2 frontal area requires up to $40,000-100,000 contactor capital, and scaling to 1 Mt/year facilities is essential for reducing cost to $150-300 per m2 through optimized fabrication and bulk purchasing.

Sorbent materials make up to 15-25% of CAPEX at current production scales. The cost of commercial AERs stands at $10-30/kg, where a 1000 t/year module needs 10-20 tonnes sorbent inventory. Learning curve projection suggests the drop in costs to $5-15/kg by 2035 with manufacturing capacity of 10-100 kt/year. The frequency of replacement is determined and influenced by the sorbent lifetime within 3-7 years, treated as an operating expense in discounted cash flow analysis.

➢ *Operational Expenditure (OPEX)*

Fan energy makes up most of the operating costs at 150-300 kWh/t CO_2. Fan OPEX ranges between $7.5-45/t CO_2 with industrial electricity prices of $0.05-0.15/kWh. Consumption is reduced by 15-25% at 10-20% higher capital cost through high-efficiency motors and variable frequency drives. The time-of-use pricing strategies convert operations to low-cost periods, thereby reducing electricity expenses by a significant amount.

Maintenance costs increase with environmental conditions and system complexity. Annual maintenance at 3-6% of capital caters to routine inspections, minor repairs, lubrication, and filter changes, while major overhauls every 5-8 years replace valves, pumps, and fans, including other wear components at 15-25% of initial capital. Ahuja & Gupta (2024) wrote that unplanned labor costs and downtime can be minimized through predictive maintenance algorithms and remote monitoring.

The costs of water usage vary per location. While municipal water at $1-5/m^3 adds $1-25/t CO_2 for 1-5 m^3/t net consumption, desalinated water in coastal locations costs $0.5-2/m^3 and water-scarce inland sites may cost up to $5-15/m^3. Water recovery investments to reduce consumption to <1 m^3/t are economically viable at water prices above $3/m^3.

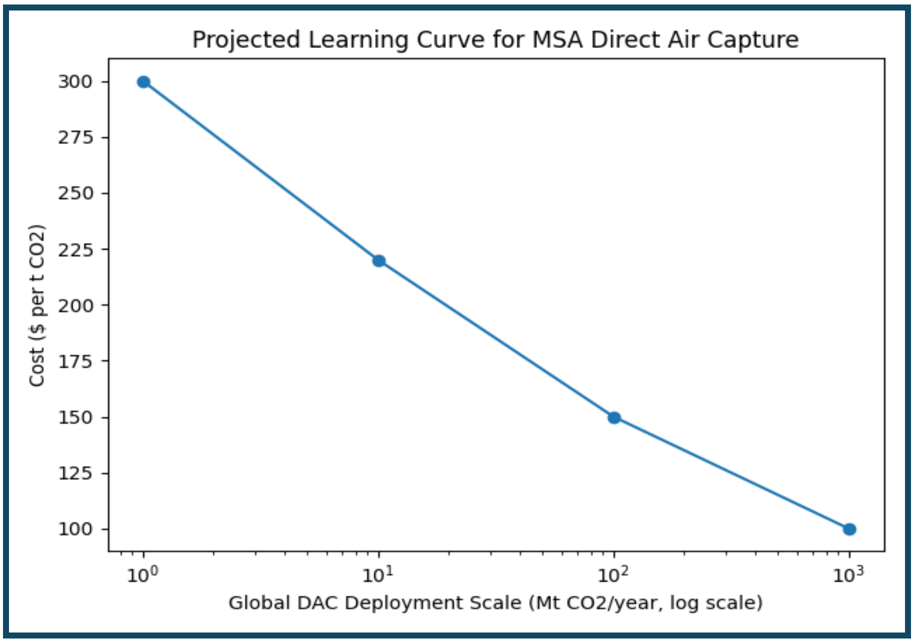

Fig 5 Projected Learning Curve

➢ *Cost per Ton of CO_2 Captured*

The comparison with solvent DAC shows the cost position of MSA. Experts noted that current MSA costs are estimated to be higher than commercial solvent DAC (An, Farooqui, & McCoy, 2022). The component breakdown is as follows: fan energy (15-25%), CAPEX (25-35%), sorbent replacement (10-20%), compression (10-15%), OPEX (10-15%), and water (5-10%). Nature MSC costs $80-150/t CO_2 at a 1 Mt/year scale, which is competitive with solvent DAC projections of $100-200/t.

Through sensitivity analysis, key cost drivers are identified, with electricity price dominating at +/-$0.05/kWh, changing the levelized cost by +/-$20-35/t. The cost is altered by +/-$10-20/t with sorbent lifetime variation of +/-2 years, while capital cost uncertainty of +/-25% propagates to +/-$15-30/t at 10% discount rate. Fan energy and water trade-offs are affected by humidity assumptions as optimal RH swings minimize combined costs.

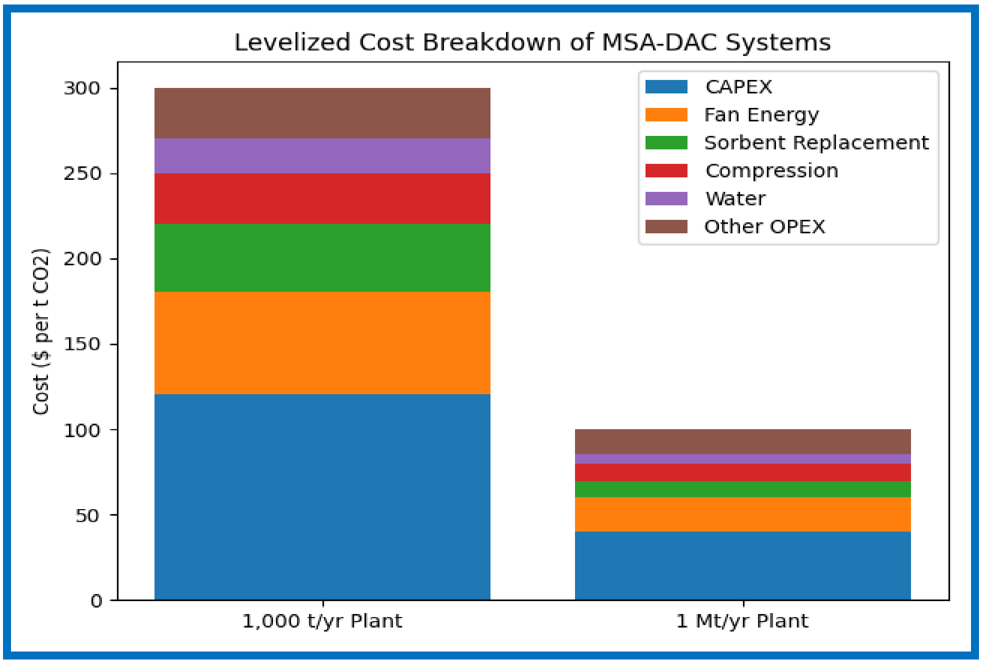

Figure 6: Levelized cost breakdown and learning curve of MSA-DAC systems

➢ *Life Cycle Assessment (LCA)*

Capture operations will be essential for repaying embodied carbon from construction and manufacturing. Aluminium and steel structures embody 10-20 t CO_2 e/t material, including a 1000 t/year facility with 20 t aluminium and 50 t steel with 500-1500 t CO_2 e. For initial fill, sorbent production embodies 5-15 kg CO_2 e/kg, adding 50-300 t CO_2 e, and the total embodied carbon of 1000-2000 t CO_2 e requires 1-3 years of operation to repay at 80% capacity factor (Kar, 2020).

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The benefit of climate is measured by net carbon removal efficiency after taking into account all emissions. A net removal of 800-950 t CO_2 e results from the subtraction of embodied carbon amortization, water-related emissions, and operational energy emissions from gross capture yields. Net efficiency of 80-95% positions MSA among negative emission technologies (NETs) (Santos, Goncalves, & Pires, 2019; Ishaq & Crawford, 2025)

Water footprint goes beyond direct consumption to supply chain impacts. 1-3 L water per kWh is required to generate electricity for compression and fans in thermal plants, contributing an additional 0.5-2 m3/t CO_2 to indirect water use. Sorbent manufacturing consumes up to 10-50 L of water per kg, adding 0.1-0.5 m3/t amortized over the lifetime. The direct and supply chain impacts are addressed by comprehensive water stewardship.

VIII. FUTURE RESEARCH DIRECTIONS

For future research, advanced sorbent materials beyond AERs have great potential for step-change performance improvements. Metal-organic frameworks (MOFs) with coordinatively unsaturated sites achieve 4-6 mmol/g capacity at 400 ppm CO_2, although humidity stability remains a challenge. On the other hand, covalent organic frameworks (COFs) provide tunable pore chemistry and hydrothermal stability, with early demonstrations of 3-4 mmol/g capacity and 10,000-cycle durability.

Regarding AI-driven airflow optimization, which employs machine learning for real-time performance maximization, reinforcement learning algorithms trained on operational data and historical weather optimize cycle timing, humidity setpoints, and fan speeds under varying conditions. Here, neural network surrogate models increase the speed of CFD simulations, enabling full-system optimization that was previously prohibitive. Computer vision systems identify sorbent degradation and dust accumulation, prompting maintenance before performance declines.

Decentralized DAC units provide modular, containerized designs for distributed markets. 10-100 t/year units shipping containers foster rapid deployment at farms, industrial sites, or communities. Standardized interfaces for water, power, and CO_2 connections help simplify installation, and remote monitoring encourages centralized fleet management (Mishra & Singh, 2023). In future research, focus should be on distributed deployment, especially since it accelerates learning via diverse operating conditions and offers grid services through aggregated demand response.

Hybrid humidity-temperature swing systems combine thermal assistance and MSA benefits for challenging conditions. Regeneration in cold climates increases with mild heating during desorption, where humidity swings alone do not suffice. Therefore, temperature-assisted MSA maintains the design capacity at 5 ºC compared to the average capacity for pure MSA, including an energy penalty of 0.5-1 GJ/t. Seasonal hybrid operation optimizes annual performance, with humidity swing in mild seasons and temperature-assisted swing in extreme conditions.

IX. CONCLUSION

This study presents a comprehensive design and implementation framework for DAC systems based on moisture swing adsorption, which addresses critical gaps in translating laboratory prototypes to industrial-scale deployment. Theoretically, the study contributes a profound elucidation of MSA chemical mechanisms, kinetic models governing the transport and sorption of CO_2, and thermodynamic foundations of humidity-based regeneration. The principles establish moisture swing adsorption as a quality approach to achieve near-isothermal regeneration with reduced energy penalties compared to thermal swing alternatives.

Findings from the engineering design insights reveal a balanced capture efficiency and capital & operating costs through optimal system architectures. Policy relevance emerges from techno-economic assessment, showing levelized costs at current scales, which decline with scale and learning. This positions MSA-DAC competitively within the negative emission technologies (NETs) portfolio required to meet the Paris Agreement targets.

Scalability potential is derived from incremental capacity expansion, modular architecture for factory fabrication, and adaptation to local conditions. Established supply chains for ion exchange resins and material lifetimes exceeding 5 years support rapid scale-up. Integrating with renewable energy and CO_2 utilization pathways promotes economic viability and contributes to wider decarbonization objectives.

In conclusion, MSA-based DAC is a technically feasible and economically promising approach to removing atmospheric carbon dioxide. Performance improvement and cost reduction will be achieved with sustained and continuous advancement in sorbent materials, deployment experience, and system optimization, which establishes moisture swing adsorption as a fundamental technology for achieving net-zero emissions and stabilizing the global climate.

REFERENCES

[1]. Abin-Bazaine, A. A., Olmos-Marquez, M. A., & Campos-Trujillo, A. (2024). A fixed-bed column sorption: breakthrough curves modeling. Sorption-New Perspectives and Applications, 1, 53.
[2]. Adun, H., Ampah, J. D., Bamisile, O., Hu, Y., Staffell, I., & Gilani, H. R. (2024). Near-term carbon dioxide removal deployment can minimize disruptive pace of decarbonization and economic risks towards United States' net-zero goal. Communications Earth & Environment, 5, 770.
[3]. Afshari, A., Ekberg, L., Forejt, L., Mo, J., Rahimi, S., Siegel, J., & Zhang, J. (2020). Electrostatic precipitators as an indoor air cleaner—a literature review. Sustainability, 12(21), 8774.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26apr580

[4]. Ahuja, A., & Gupta, M. (2024). Optimizing predictive maintenance with machine learning and IoT: a business strategy for reducing downtime and operational costs.
[5]. Al-Addous, M., Bdour, M., Rabaiah, S., Boubakri, A., Schweimanns, N., Barbana, N., & Wellmann, J. (2024). Innovations in solar-powered desalination: a comprehensive review of sustainable solutions for water scarcity in the Middle East and North Africa (MENA) region. Water, 16(13), 1877.
[6]. Alsayyed, M. M., Manickam, S., Wulandari, E. R. N., Widia, I. D. M., & Karuppayah, S. (2025). A review of applicable technologies, routing protocols, requirements, and architecture for disaster area networks. IEEE Access.
[7]. Alsharif, M. A. (2025). Understanding adsorption: theories, techniques, and applications. In Adsorption-Fundamental Mechanisms and Applications. IntechOpen.
[8]. Amponsah, J., Archibong-Eso, A., Fiagbe, Y., Opoku, D. O., Apatika, A., Adorkor, E., & Ekpenyong, U. (2025). Coupled transport and reaction modeling of sorbent particle size effects in nonisothermal packed-bed CO2 adsorption. ACS Omega, 10(32), 35988–36002.
[9]. An, K., Farooqui, A., & McCoy, S. T. (2022). The impact of climate on solvent-based direct air capture systems. Applied Energy, 325, 119895.
[10]. Bâkiiz, H. (2022). The evolution of large-scale variations in globally averaged atmospheric CO2 concentrations since 1830. All Earth, 34(1), 16–26. https://doi.org/10.1080/27669645.2022.2058688
[11]. Bellamy, R. (2020). Negative Emissions Technologies.
[12]. Beuttler, C., Charles, L., & Wurzbacher, J. (2019). The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. Frontiers in Climate, 1, 10. https://doi.org/10.3389/fclim.2019.00010
[13]. Bihani, R., Tan, X., Saha, P., Abedi, M., Klausner, J., & Benard, A. (2025). Modeling and validation of heat and mass transfer in a direct contact packed bed crossflow humidifier. Applied Thermal Engineering, 268, 125961.
[14]. Chatterjee, A. (2025). Measuring the environmental impact of a carbon capture system integrated with a dehumidification system.
[15]. Chinaris, P. P., Psarros, G. N., & Papathanassiou, S. A. (2025). Hybridization of wind farms with co-located PV and storage installations. Renewable Energy, 240, 122057.
[16]. Dale, S., Markovski, J., & Hristovski, K. D. (2016). Modeling packed bed sorbent systems with the Pore Surface Diffusion Model: Evidence of facilitated surface diffusion of arsenate in nano-metal (hydr)oxide hybrid ion exchange media. Science of the Total Environment, 563, 965–970.
[17]. Dupre, K. R. (2020). Relating porous media structure to the Darcy-Forchheimer model [Doctoral dissertation, Boston University].
[18]. Elfving, J. (2021). Direct capture of CO_2 from air using amine-functionalized resin—Effect of humidity in modelling and evaluation of process concepts.
[19]. Fakhraddinfakhriazar, S., Molina-Fernández, C., & Léonard, G. (2026). Stability of adsorbents for direct air capture (DAC): challenges and perspectives. Energy & Fuels.
[20]. Farahani, P., Meier, C., & Wilke, J. (2017). Digital supply chain management agenda for the automotive supplier industry. In G. Oswald & M. Kleinemeier (Eds.), Shaping the Digital Enterprise. Springer.
[21]. Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: A review. Environmental Chemistry Letters, 18, 2069–2094.
[22]. Filonchyk, M., Peterson, M. P., Zhang, L., Hurynovich, V., & He, Y. (2024). Greenhouse gases emissions and global climate change: Examining the influence of CO_2, CH4, and N2O. Science of The Total Environment, 935, 173359.
[23]. Freeman, B. (2020). Bench-scale development of a hybrid membrane-absorption CO_2 capture process (No. 373-Final-Report-Rev-May2020). Membrane Technology and Research, Inc.
[24]. Fuhrman, J., Clarens, A., Calvin, K., Doney, S. C., Edmonds, J. A., O'Rourke, P., Patel, P., Pradhan, S., Shobe, W., & McJeon, H. (2021). The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5°C and +2°C futures. Environmental Research Letters, 16(11).
[25]. García, E., Ruiz, M., & Aguila, A. (2025). Stochastic optimization of real-time dynamic pricing for microgrids with renewable energy and demand response. Energies, 18(24), 6484.
[26]. Gemci, T., & Chigier, N. (2016). Atomization, spraying, and nebulization. In Production, Handling and Characterization of Particulate Materials (pp. 201–256). Springer.
[27]. Hack, J., Maeda, N., & Meier, D. M. (2022). Review on CO_2 capture using amine-functionalized materials. ACS Omega, 7(44), 39520–39530.
[28]. Han, H. (2025). Design for comfort: A parametric workflow study on wind environment mitigation in Helsinki's Kalasatama area.
[29]. Herzog, H. J., & Mac Dowell, N. (2025). Carbon Removal.
[30]. Hraiech, I., Zallama, B., Belkhiria, S., Zili-Ghedira, L., Maatki, C., Hassen, W., & Kolsi, L. (2025). Experimental characterization of silica gel adsorption and desorption isotherms under varying temperature and relative humidity in a fixed bed reactor. Scientific Reports, 15(1), 29041.
[31]. Huang, X., An, S., Wang, R., Liu, Z., Li, S., Li, Q., & Wang, L. (2025). Anti-degradation biphasic absorbent for efficient and stable CO_2 capture. Environmental Science & Technology, 59(24), 12108–12120.
[32]. Ishaq, H., & Crawford, C. (2025). Negative emission technologies: a way forward? RSC Sustainability, 3(9), 3652–3680.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26apr580

[33]. Järvinen, M., Turunen, K., Seppälä, A., Hirvonen, J., Garg, N., & Santasalo-Aarnio, A. (2025). Energy storage systems. In Designing Renewable Energy Systems within Planetary Boundaries: A Textbook for Energy Engineers (pp. 545–653). Springer Nature Switzerland.

[34]. Ji, Y., Chen, S., Xie, R., Zhang, Y., Yu, K., Wang, T., & Jiang, L. (2025). Cost-effective direct air capture by exceptionally active moisture swing sorption film. Nexus, 2(3).

[35]. Jha, M. K., & Dev, M. (2024). Impacts of climate change. In Smart Internet of Things for Environment and Healthcare (pp. 139–159). Springer Nature Switzerland.

[36]. Jiang, X., & Yung, Y. L. (2019). Global patterns of carbon dioxide variability from satellite observations. Annual Review of Earth and Planetary Sciences.

[37]. Kar, S. (2020). Analysis methods for lifecycle assessment of energy systems and nutrient recovery, in relevance to environmental policies [Doctoral dissertation, Drexel University].

[38]. Kolle, J. M., Fayaz, M., & Sayari, A. (2021). Understanding the effect of water on CO_2 adsorption. Chemical Reviews, 121(13), 7280–7345.

[39]. Lawson, S., Li, X., Thakkar, H., Rownaghi, A. A., & Rezaei, F. (2021). Recent advances in 3D printing of structured materials for adsorption and catalysis applications. Chemical Reviews, 121(10), 6246–6291.

[40]. Lee, K., Fyson, C., & Schleussner, C. F. (2021). Fair distributions of carbon dioxide removal obligations and implications for effective national net-zero targets. Environmental Research Letters, 16.

[41]. Li, G., & Yao, J. (2024). Direct air capture (DAC) for achieving net-zero CO_2 emissions: advances, applications, and challenges. Eng, 5(3), 1298–1336.

[42]. Li, L., Wong-Ng, W., Huang, K., & Cook, L. P. (Eds.). (2018). Materials and processes for CO2 capture, conversion, and sequestration. John Wiley & Sons.

[43]. Liu, M., Guo, L., Jin, S., & Tan, B. (2019). Covalent triazine frameworks: synthesis and applications. Journal of Materials Chemistry A, 7(10), 5153–5172.

[44]. Liu, Z., & Ma, Y. (2024). Chemical recycling of step-growth polymers guided by Le Chatelier's principle. ACS Engineering Au, 4(5), 432–449.

[45]. Maina, J., Kibuine, M. K., & Mugambi, H. N. (2025). Influence of digital divide on procurement performance of textiles manufacturing SMEs in Nairobi County, Kenya. Journal of Business Management and Innovation, 2(10), 49–65.

[46]. Matsumoto, K., Hwang, J., Kaushik, S., Chen, C. Y., & Hagiwara, R. (2019). Advances in sodium secondary batteries utilizing ionic liquid electrolytes. Energy & Environmental Science, 12(11), 3247–3287.

[47]. Matthee, F. (2020). Membrane module development for water recovery from humid gas.

[48]. McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. (2021). A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Progress in Energy, 3(3), 032001.

[49]. Mejbel, M. (2021). Numerical simulation of moisture swing absorption model for carbon dioxide capture [Master's thesis, Arizona State University].

[50]. Mennitto, R., Blom, R., Dörr, M., Rosental, M., & Rettenmaier, N. (2025). Solid sorbents for direct air capture: a technological and environmental perspective. Current Opinion in Chemical Engineering, 50, 101195.

[51]. Merfort, A., Strefler, J., Abrahao, G., Bauer, N., Dorndorf, T., Kriegler, E., Luderer, G., Merfort, L., & Edenhofer, O. (2024). Separating CO2 emission from removal targets comes with limited cost impacts. Nature Communications, 16, 5298.

[52]. Mesfer, M. K. A., Danish, M., Khan, M. I., Ali, I. H., Hasan, M., & Jery, A. E. (2020). Continuous fixed bed CO_2 adsorption: breakthrough, column efficiency, mass transfer zone. Processes, 8(10), 1233.

[53]. Mishra, P., & Singh, G. (2023). Energy management systems in sustainable smart cities based on the internet of energy: A technical review. Energies, 16(19), 6903.

[54]. Miu, L., Nazare, D., Cătuți, M., Postoiu, C., & Dudău, R. (2021). Assessment of current state, past experiences and potential for CCS deployment in the CEE region. CCS4CEE.

[55]. Mrad, A. (2019). On the reliability of small-scale solar systems: Design of a stand-alone system in rural countries.

[56]. Muchiri, K. (2024). Development of a wind-solar PV hybrid system for small-scale power generation in low wind speed regimes in Kenya [Doctoral dissertation, JKUAT-COPAS].

[57]. Mwasilu, F., Justo, J. J., & Bansal, R. C. (2026). Reliability, market dynamics, and energy trading with AI in wind energy. In Advanced Wind Energy Systems: Grid Integration, Markets, and Sustainable Infrastructure (pp. 267–298). IGI Global Scientific Publishing.

[58]. Nadamani, M. N., Shadloo, M. S., & Dbouk, T. (2025). A review on theoretical and computational fluid dynamics modeling of coupled heat and mass transfer in fixed beds of adsorbing porous media. Energies, 18(24), 6418.

[59]. Nakao, S. I., Yogo, K., Goto, K., Kai, T., & Yamada, H. (2019). Advanced CO_2 capture technologies: absorption, adsorption, and membrane separation methods. Springer.

[60]. Ng, K. C., Burhan, M., Shahzad, M. W., & Ismail, A. B. (2017). A universal isotherm model to capture adsorption uptake and energy distribution of porous heterogeneous surface. Scientific Reports, 7(1), 10634.

[61]. Nilsson, M. (2024). Advancing carbon neutrality: Techno-economic analysis of direct air capture at commercial scale.
[62]. OECD. (2022). Public procurement for innovation: Good practices and strategies. Organisation for Economic Co-operation and Development. https://www.oecd.org
[63]. Oputa, J. E., Ogbaini, C. A., Akpor, A., Marvis-Bello, V., Oboh, R., & Okafor, N. (2024). Strategic procurement practices and organizational performance: A study of manufacturing firms in Lagos State, Nigeria. International Journal of Economy Development Research, 3(2), 37–45.
[64]. Otto, D., Thoni, T., Wittstock, F., & Beck, S. (2021). Exploring narratives on negative emissions technologies in the post-Paris era. Frontiers in Climate, 3, 684135. https://doi.org/10.3389/fclim.2021.684135
[65]. Ottmann, D. A. (2025). Oasis by the sea: Design matrix for shaping microclimates in hot coastal cities. In Amphibious Concepts at the Edge of the Sea (pp. 163–190). Springer Nature Singapore.
[66]. Panepinto, D., Riggio, V. A., & Zanetti, M. (2021). Analysis of the emergent climate change mitigation technologies. International Journal of Environmental Research and Public Health, 18, 6767. https://doi.org/10.3390/ijerph18136767
[67]. Pisciotta, M. (2024). A multifaceted approach to CO2 emissions reductions and removals [Doctoral dissertation, University of Pennsylvania].
[68]. Precious, O., Enyinna, G. C., & Oswagwu, J. C. (2025). The effects of electronic procurement on building construction projects in Rivers State, Nigeria. International Journal of Emerging Trends in Engineering Research, 13(2).
[69]. Qadeer, K., Ahmad, A., Qyyum, M. A., Nizami, A. S., & Lee, M. (2021). Developing machine learning models for relative humidity prediction in air-based energy systems and environmental management applications. Journal of Environmental Management, 292, 112736.
[70]. Rafiq, S., Deng, L., & Hägg, M. B. (2016). Role of facilitated transport membranes and composite membranes for efficient CO2 capture—a review. ChemBioEng Reviews, 3(2), 68–85.
[71]. Raj, I. W. (2025). Biodiversity impacts and gains at UK solar farms—present and future scenarios [Doctoral dissertation].
[72]. Ray, B., Churipard, S. R., & Peter, S. C. (2021). An overview of the materials and methodologies for CO2 capture under humid conditions. Journal of Materials Chemistry A, 9(47), 26498–26527.
[73]. Rezai, B., & Allahkarami, E. (2024). Desorption/regeneration of adsorbents and their performance. In Sustainable Remediation Technologies for Emerging Pollutants in Aqueous Environment (pp. 263–283). Elsevier.
[74]. Rezk, M. G., Foroozesh, J., Abdulrahman, A., & Gholinezhad, J. (2021). CO2 diffusion and dispersion in porous media: Review of advances in experimental measurements and mathematical models. Energy & Fuels, 36(1), 133–155.
[75]. Rochelle, G. T. (2024). Air pollution impacts of amine scrubbing for CO2 capture. Carbon Capture Science & Technology, 11, 100192.
[76]. Sabatino, F., Grimm, A., Gallucci, F., van Sint Annaland, M., Kramer, G. J., & Gazzani, M. (2021). A comparative energy and costs assessment and optimization for direct air capture technologies. Joule, 5(8), 2047–2076.
[77]. Saleh, T. A. (2022). Isotherm models of adsorption processes on adsorbents and nanoadsorbents. In Interface Science and Technology (Vol. 34, pp. 99–126). Elsevier.
[78]. Salthammer, T., & Morrison, G. C. (2022). Temperature and indoor environments. Indoor Air, 32(5), e13022.
[79]. Sang, W., Yang, H., Feng, W., Chen, H., Tang, J., & Chen, S. (2026). Unlocking the impact of temperature and salinity on greenhouse gas emissions from estuarine salt marsh soils. Earth's Future, 14(2), e2025EF006912.
[80]. Sarbanha, A. A. (2024). Marinization of bubbling fluidized beds visualization and hydrodynamics.
[81]. Santos, F. M., Gonçalves, A. L., & Pires, J. C. (2019). Negative emission technologies. In Bioenergy with Carbon Capture and Storage (pp. 1–13). Academic Press.
[82]. Sarbu, M. (2021). The impact of industry 4.0 on innovation performance: Insights from German manufacturing and service firms. Technovation, 113.
[83]. Schaller, R., Markus, T., Korte, K., & Gawel, E. (2022). Atmospheric CO2 as a resource for renewable energy production: a European energy law appraisal of direct air capture fuels. Review of European, Comparative & International Environmental Law, 31(2), 258–267.
[84]. Schneider, D., Mehlhorn, D., Zeigermann, P., Kärger, J., & Valiullin, R. (2016). Transport properties of hierarchical micro–mesoporous materials. Chemical Society Reviews, 45(12), 3439–3467.
[85]. Sharma, K., Kumar, A., Yadav, V., & Banerjee, D. K. (2025). Green ammonia.
[86]. Sharifian, R., Wagterveld, R. M., Digdaya, I. A., Xiang, C. X., & Vermaas, D. A. (2021). Electrochemical carbon dioxide capture to close the carbon cycle. Energy & Environmental Science, 14(2), 781–814.
[87]. Sharifi, A. (2020). Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. Journal of Cleaner Production, 276, 122813.
[88]. Shi, X., Xiao, H., Azarabadi, H., Song, J., Wu, X., Chen, X., & Lackner, K. S. (2020). Sorbents for the direct capture of CO2 from ambient air. Angewandte Chemie International Edition, 59(18), 6984–7006.
[89]. Soeiro, W. F., Moura, C. H. R., Dias, C. S., Rodrigues, E. C., Da Costa, D. S., Viegas, B. M., & Estumano, D. C. (2024). Mathematical evaluation of direct and inverse problem applied in

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26apr580

breakthrough models of metal adsorption. Applied Sciences, 14(12), 5035.
[90]. Song, J., Radic, S. O., Hammon, N., Slagle, T., Fang, K., & Barbakh, A. (2020). Carbon Catcher Design Report.
[91]. Soto, A. (2021). Carbon capture, utilization, and storage (CCUS) and how to accelerate the development and commercialization of carbon base products in the European and US market.
[92]. Titcombe, A. A. (2025). Techno-economic assessment of carbon capture for integrated steel mills in Canada.
[93]. Tong, C. (2018). Advanced materials enable renewable geothermal energy capture and generation. In Introduction to Materials for Advanced Energy Systems (pp. 321–377). Springer.
[94]. Victor, E., Chukwuemeka, K., Adeniji Blessing, O., Chibuzor Success, I., Chisom, O., Bernard Chukwuemeka, E., & Uchenna Christian, N. (2022). A concise review of sorbent materials for carbon dioxide capture and storage. Journal of Materials Science Research and Reviews, 10(1), 72–98.
[95]. Vu, T. Q. (2019). Development of amine-impregnated adsorbents for carbon dioxide capture.
[96]. Waibel, N., Roberts, W. O., & Differentiated, H. C. T. B. (2024). Environmental factors heat, cold, altitude, humidity. In Pediatric Sports Medicine: Essentials for Office Evaluation (p. 60).
[97]. Wang, S., Wang, S., & Zhuo, Y. (2025). The comparison of regeneration energy of different solid adsorbents in temperature swing adsorption process: A review. Adsorption Science & Technology, 43, 02636174251385608.
[98]. Wang, W., Zhang, X., Liu, J., Liang, C., Niu, J., & Wang, F. (2024). Review of moisture swing sorbents for carbon dioxide capture from ambient air. International Journal of Global Warming, 32(2), 119–147.
[99]. Wang, Y., Kim, J., Marreiros, J., Rangnekar, N., Yuan, Y., Johnson, J. R., & Lively, R. P. (2025). Investigation of moisture swing adsorbents for direct air capture by dynamic breakthrough studies. ACS Sustainable Chemistry & Engineering, 13(18), 6554–6564.
[100]. Wheatley, J. E. (2017). Fundamental chemistry of carbon dioxide capture [Doctoral dissertation, University of Leeds].
[101]. Wilkes, M. D. (2024). Techno-economic analysis of CO2 capture technologies for small-scale dispatchable gas turbines [Doctoral dissertation, University of Sheffield].
[102]. Wilkins, N. S., Rajendran, A., & Farooq, S. (2021). Dynamic column breakthrough experiments for measurement of adsorption equilibrium and kinetics. Adsorption, 27(3), 397–422.
[103]. Witkowski, A., Rusin, A., Majkut, M., Rulik, S., & Stolecka, K. (2015). Advances in carbon dioxide compression and pipeline transportation processes. Springer.
[104]. Wu, F., Huang, X., Zhang, L., Gao, J., Sun, Y., Zhao, Y., & Zhang, X. (2025). Performance evaluation of solar and condensing heat recovery systems for air reheating and humidification in industrial buildings. Energy Conversion and Management, 341, 120057.
[105]. Xie, R. Y., Chen, S., Yong, J. Y., Zhang, X. J., & Jiang, L. (2024). Moisture swing adsorption for direct air capture: Establishment of thermodynamic cycle. Chemical Engineering Science, 287, 119809.
[106]. Yonkofski, C. M., Appriou, D., Song, X., Downs, J. L., Johnson, C. D., & Milbrath, V. C. (2018). Water application for dust control in the central plateau: impacts, alternatives, and work strategies (No. PNNL-28061). Pacific Northwest National Laboratory.
[107]. Zhang, D., Wang, T., Zhou, B., Zhang, P., & Yang, J. (2025). An analytical review of humidity-regulating materials: performance optimization and applications in hot and humid regions. Buildings, 15(23), 4376.
[108]. Zhao, Y., Zheng, B., Zhang, J., & Xu, H. (2025). Research on direct air capture: A review. Energies, 18(24), 6632. https://doi.org/10.3390/en18246632
[109]. Zheng, F., Hao, L., Li, J., Zhu, H., Chen, X., Shi, Z., & Fan, Y. (2019). Corrosion characteristics of aluminum in sodium bicarbonate aqueous solution at 50°C. International Journal of Electrochemical Science, 14(8), 7303–7316.
[110]. Zhou, R., Hu, Y., Xiao, P., Gu, J., & Chen, T. (2025). Advances in hygroscopic polymer gels toward efficient atmospheric moisture capture and management. Advanced Science, 12(48), e18062.
[111]. Zhu, X., Xie, W., Wu, J., Miao, Y., Xiang, C., Chen, C., & Wang, R. (2022). Recent advances in direct air capture by adsorption. Chemical Society Reviews, 51(15), 6574–6651.