Journal of Zhejiang University-SCIENCE A

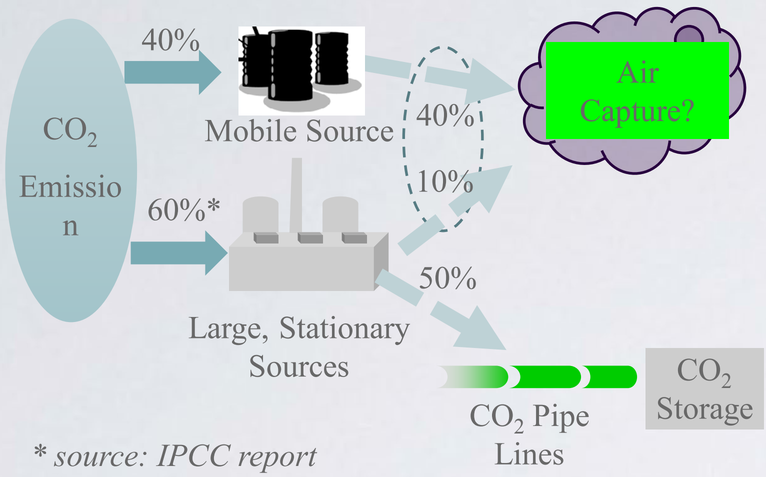
Cite this as: Cheng-long HOU, Yu-song WU, You-zhou JIAO, Jie HUANG, Tao WANG, Meng-xiang FANG, Hui ZHOU, 2017. Integrated direct air capture and CO_2 utilization of gas fertilizer based on moisture swing adsorption. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 18(10):819-830.
http://dx.doi.org/10.1631/jzus.A1700351

Integrated direct air capture and CO_2 utilization of gas fertilizer based on moisture swing adsorption

Key words:

Direct air capture; Desorption kinetics; Greenhouse; CO_2 fertilizer; Cost analysis

Background



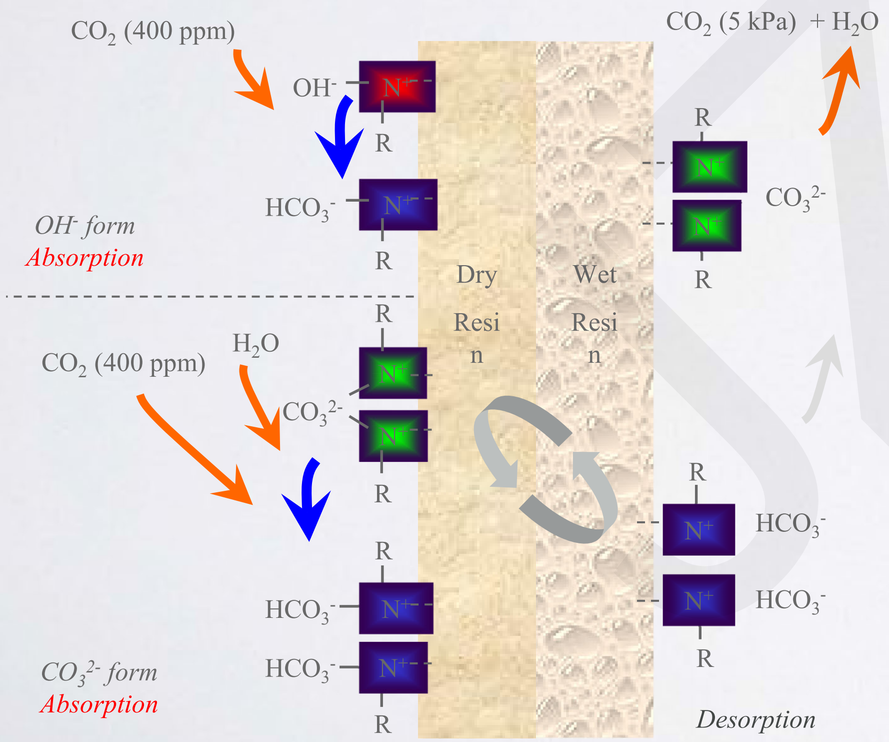
** source: IPCC report 2005*

Carbon Capture and Sequestration (CCS)

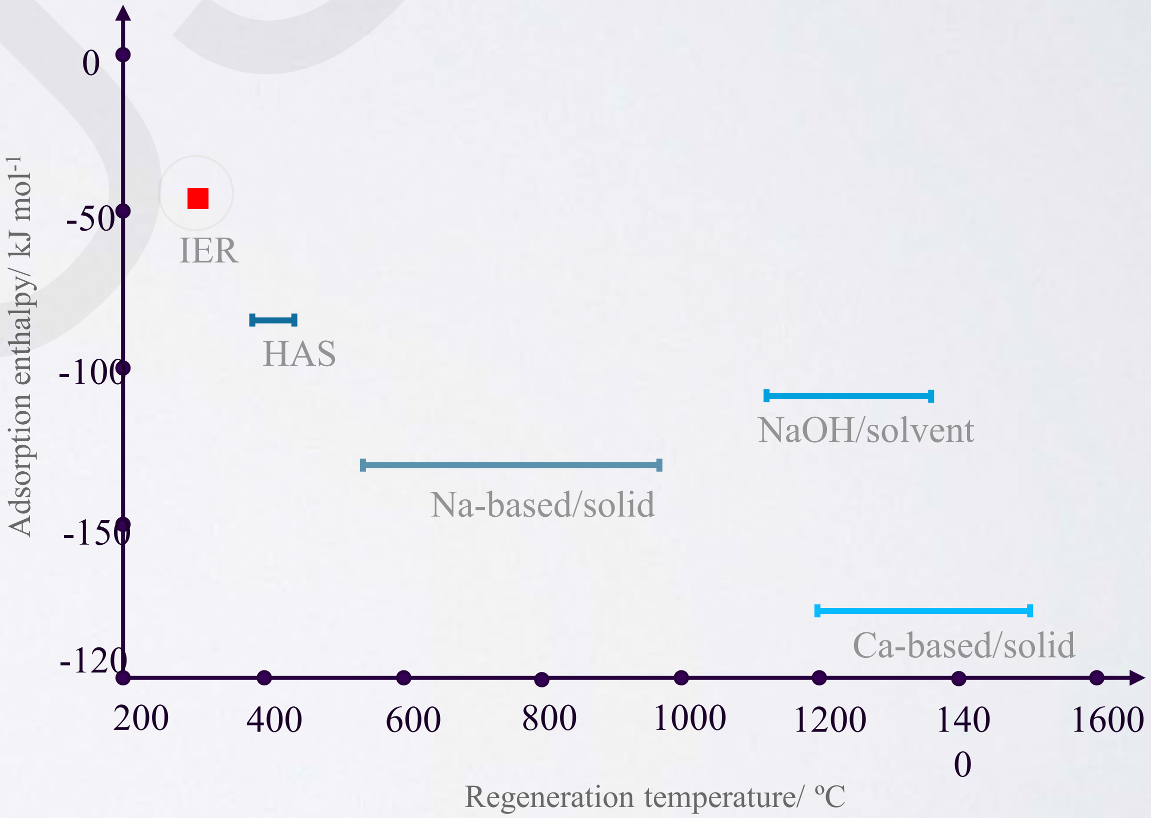
Direct capture of CO_2 from ambient air

- Works for any emission, regardless of location and timing
- Eliminates CO_2 transportation cost
- Closed carbon cycle fuel synthesis technology

Moisture Swing

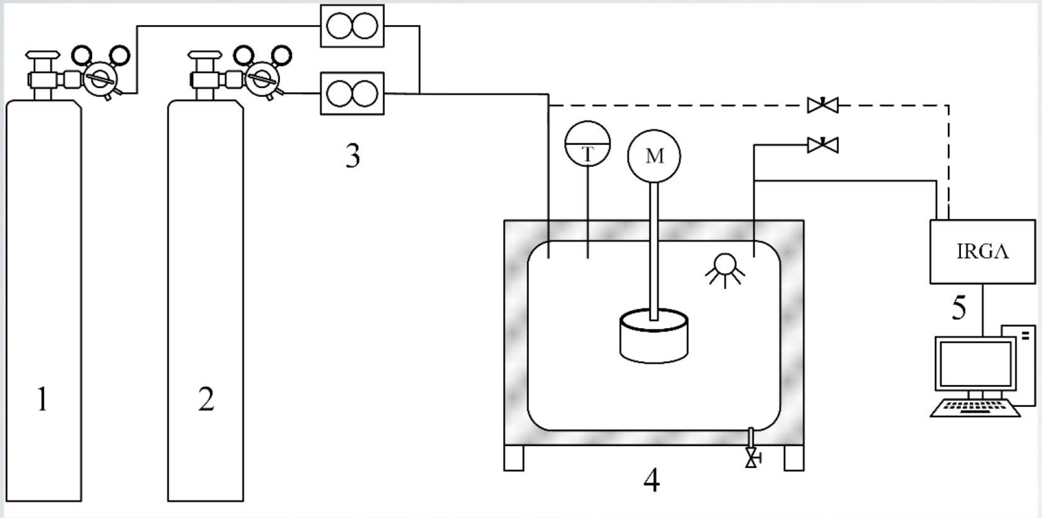


$$CO_3^{2-}(R^+)_2 \bullet xH_2O_{(h)} + CO_2 \leftrightarrow 2[HCO_3^-R^+ \bullet yH_2O_{(h)}] + (x-2y-1)H_2O_{(g)}$$



- Much lower regeneration temperature
- Low adsorption enthalpy (high selectivity)
- Low energy consumption

Experiments and Models

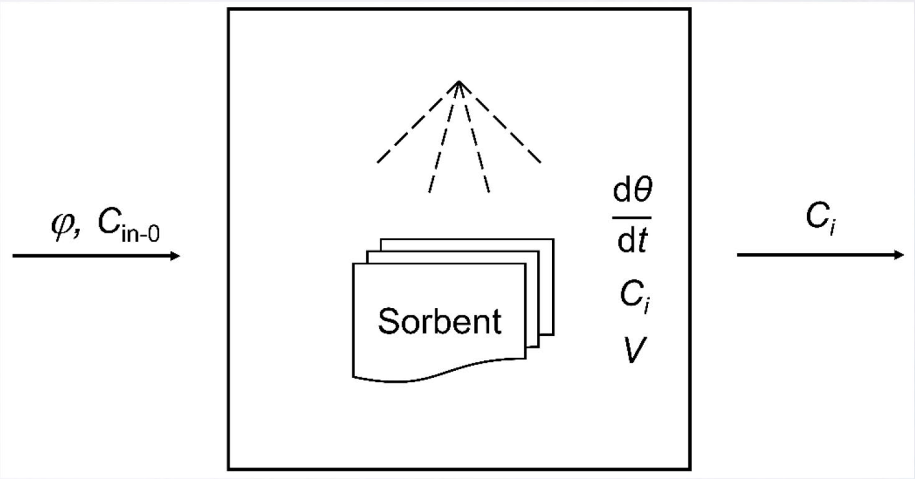


- The desorption reactor set-up consists of a 1.05 L chamber equipped with a rotating sample holder and a water sprayer.
- During the desorption process, the gas was cycled with a peristaltic pump and the concentration of CO_2 in the chamber was logged every second by an infrared gas analyzer.
- The chamber temperature was controlled and kept constant by a water bath system with the fluctuation of ± 0.5 °C.

Atmospheric parameters for cultivations

Parameter	Germination and initial cultivation	Accelerated cultivation
Temperature (°C)	25.0	25.0
Humidity (%)	60.0-65.0%	60.0-65.0%
Light intensity (lux)	48000	18000-98000
CO_2 concentration (ppm)	480	400-3000

Zero dimensional model of a DAC desorption unit



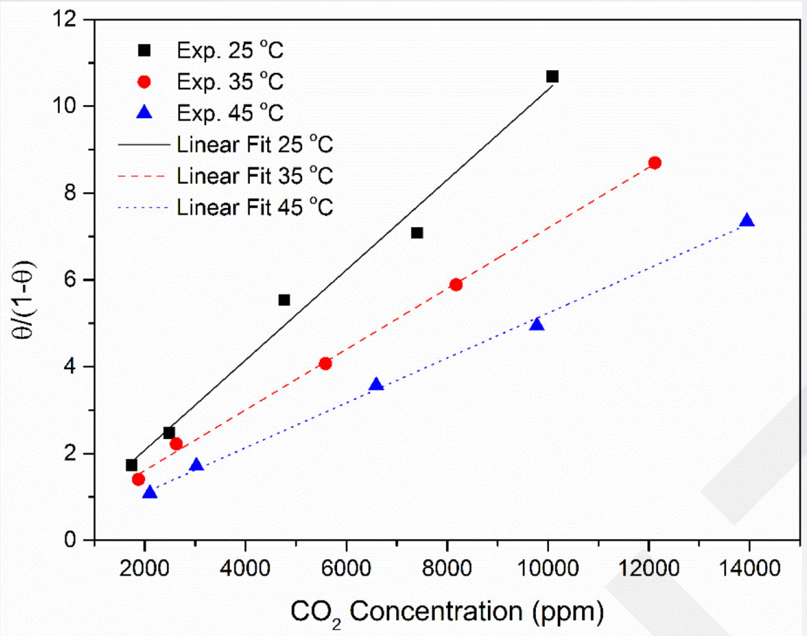
$$\frac{d\theta}{dt} = k_a(1-\theta_i)C_i - k_d\theta_i$$

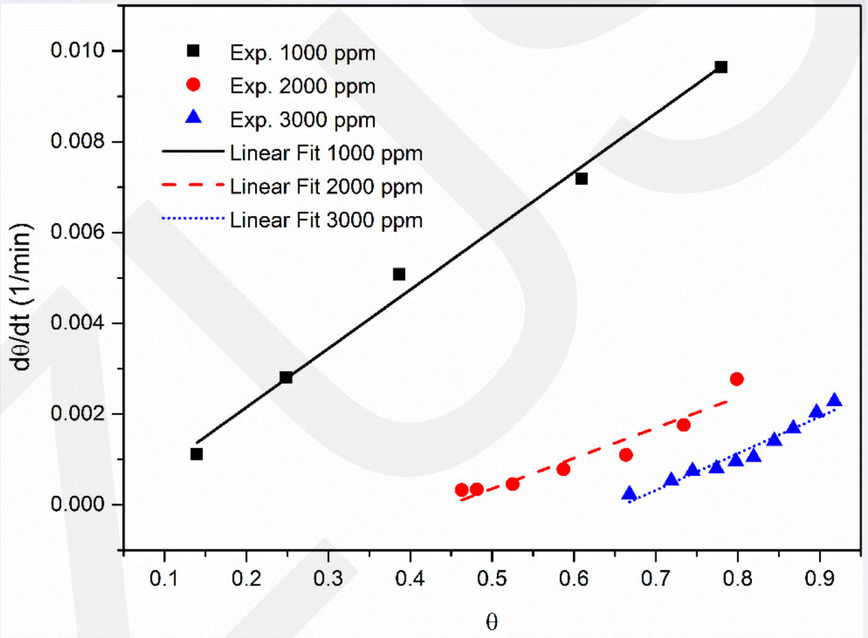
$$C_{i+1} = C_i + [-mq_0 \frac{d\theta}{dt}\frac{22.4}{1000} + \varphi(C_{in-0} - C_i)]\Delta t / V$$

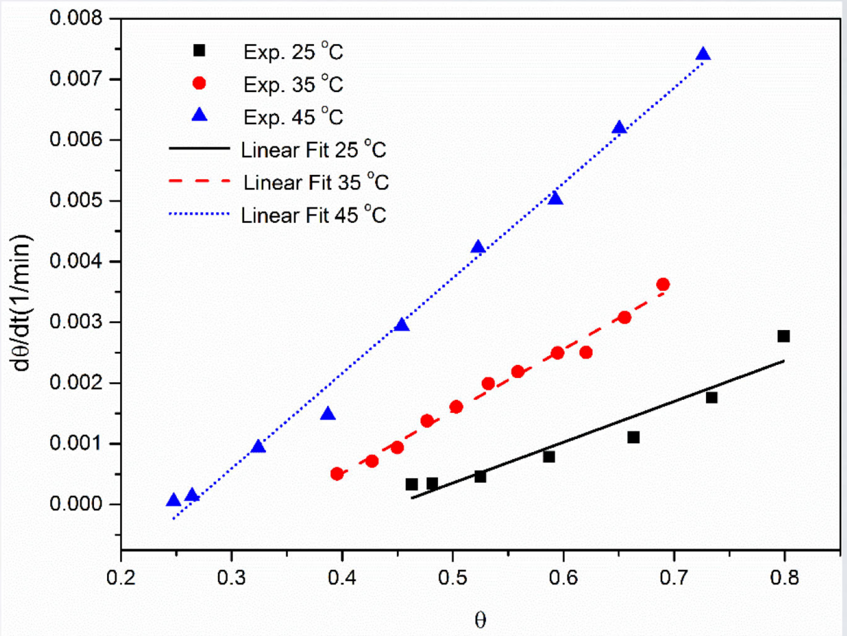
$$\theta_{i+1} = \theta_i + \frac{d\theta}{dt}\Delta t$$

CO_2 desorption performance

- Desorption data has a good fitting to Langmuir model. Desorption ratio can be significantly enhanced by increasing desorption temperature from 25 °C to 45 °C.
- The desorption rate constants increase significantly with increased temperature.



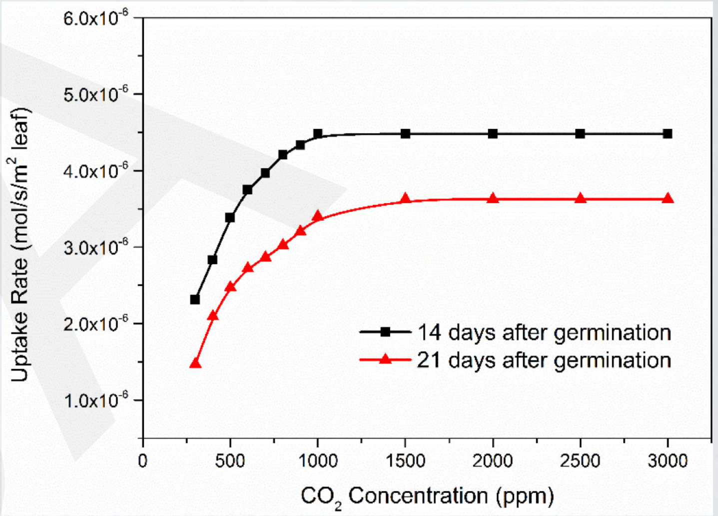


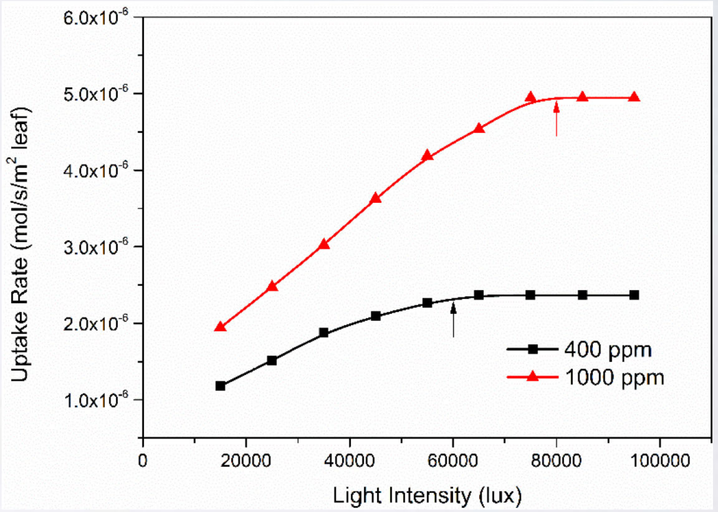


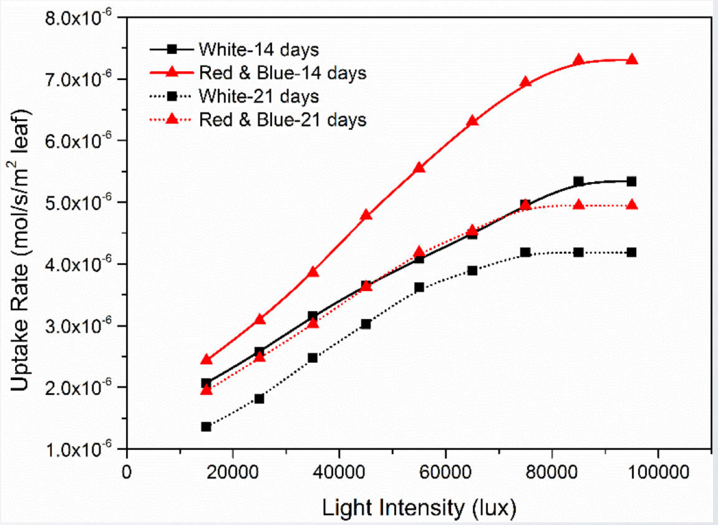
	25 °C	35 °C	45 °C
K_d ($\times 10^{-4}$)(r)^a	10.43(0.98)	7.23(0.99)	5.29(0.99)
(1-θ)^b	67.1%	59.1%	51.4%
k_a(1/(Pa·s))	8.90×10^{-6}	1.25×10^{-5}	2.00×10^{-5}
k_d(1/(Pa·s))	8.50×10^{-4}	1.72×10^{-3}	3.78×10^{-3}
T_d^c(min)	57.1	76.8	97.6
q_{cyc}^d(%)	10.5	14.6	19.0

Accelerated cultivation by CO_2 fertilization

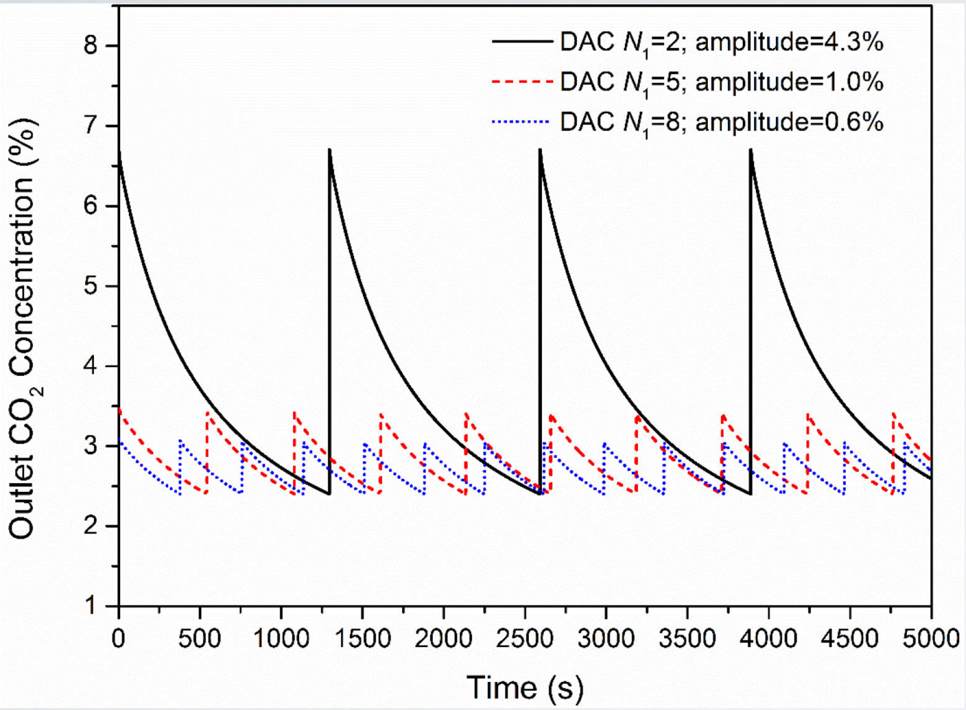
- CO_2 uptake rates both increase dramatically as the CO_2 concentration increases from 400 ppm to 1000 ppm and then reach a plateau.
- The CO_2 uptake rate also increases with increased light intensity and then reach a plateau.
- The light saturation point can be extended from 60000 lux to 80000 lux by elevating the CO_2 concentration from 400 ppm to 1000 ppm.
- Compared to white spectrum, the spectrum of red & blue can enhance the CO_2 uptake rate by 18.2% and 42.8% for lettuces of 14 days and 21 days after germination, respectively.

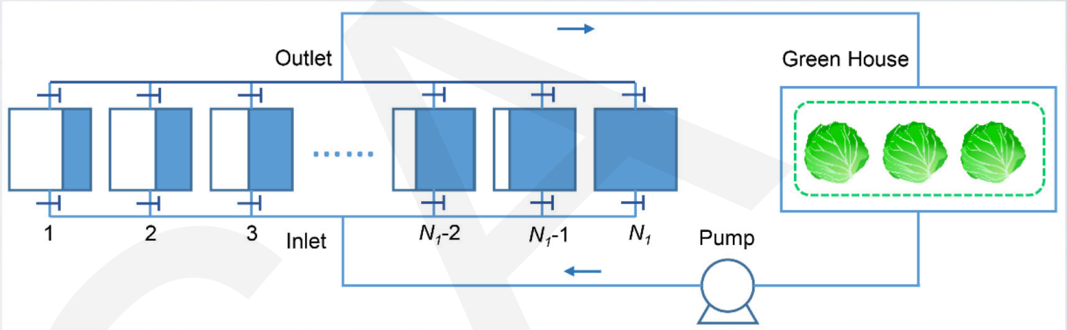






Multi-beds desorption model





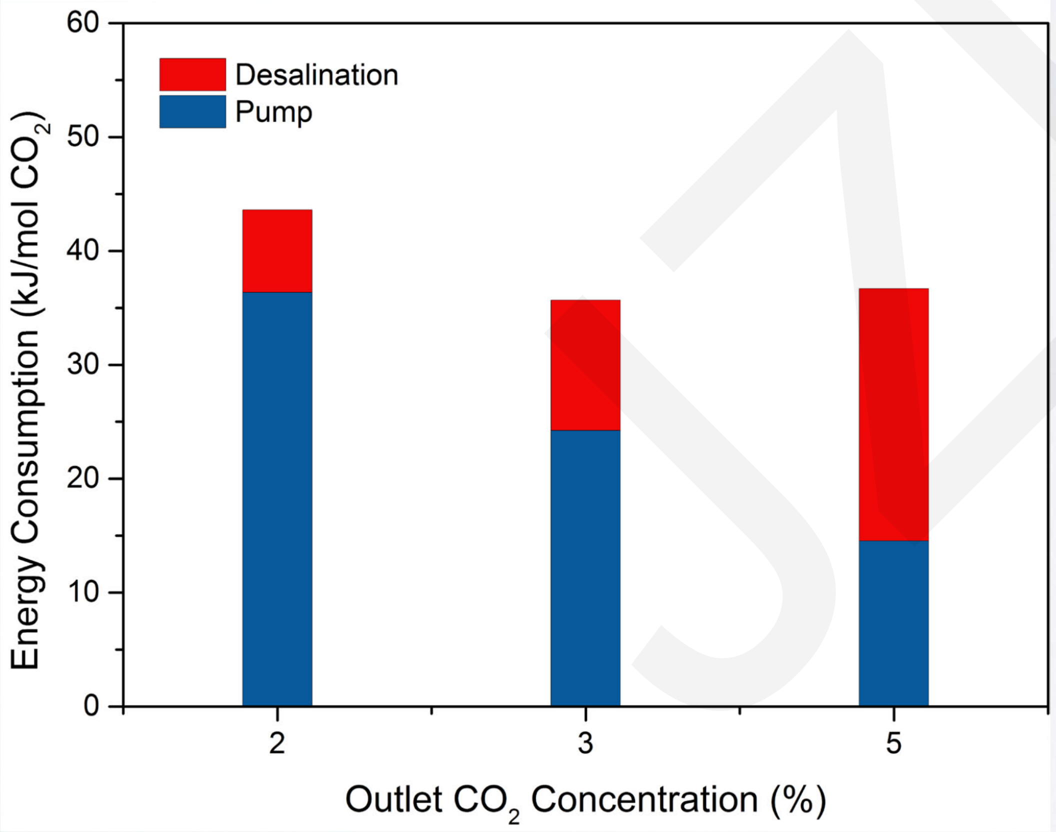
A multi-beds desorption system is proposed with the constant total sorbent amount of 250 kg. The increased unit number N_1 could reduce the fluctuation of CO_2 concentration at the outlet.

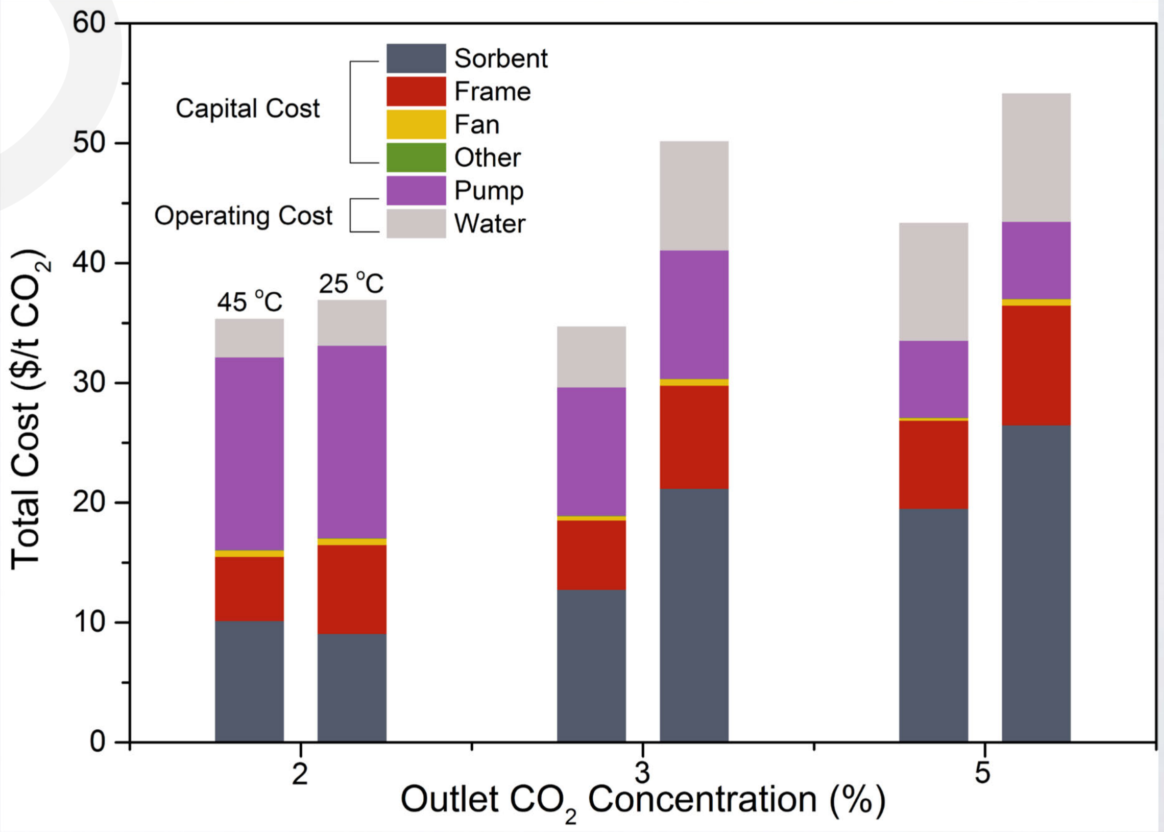
Temperature (°C)	CO_2 concentration	N_1	N_1+N_2/weight (kg)	t_{des} (s)	t_{int} (s)
45	2%	11	20/454.55	8580	780
	3%	7	16/571.43	5530	790
	5%	4	14/875	2800	700
25	2%	8	13/406.25	11200	1400
	3%	5	19/950	2650	530
	5%	4	19/937.5	1960	490

- Higher desorption temperature or kinetics can significantly reduce the requirement of sorbent material.
- Fewer desorption units N_1 are required for higher CO_2 concentration while the desorption time for single unit and interval time between two neighbor units turn out to be shorter. This would result in larger DAC unit number N_2 for absorption.

Energy and cost analysis

- The total energy consumption illustrates an optimal condition of 3% CO_2 concentration at 45 °C with the energy consumption of 35.7 kJ (electricity)/mol CO_2.
- 3% is calculated as the optimal outlet CO_2 concentration at 45 °C, with a total cost of US \$34.68/t CO_2. Comparing with CO_2 capture from flue gas and transportation which cost is around US \$67.6/t CO_2 (Knoope *et al.*, 2014), DAC is competitive as a carbon source for gas fertilizer.





Conclusions

- Desorption isotherms of a moisture-swing CO_2 sorbent are described by the Langmuir model. The equilibrium constant, K_d, decreases from 10.43×10^{-4} to 5.29×10^{-4} as temperature increases from 25 °C to 45 °C. The adsorption rate constant (k_a) and desorption rate constant (k_d) increase with increasing temperature.
- For lettuce accelerated cultivation, the optimal CO_2 concentration level for the growth rate was found to be optimal at around 1000 ppm. The effect of light intensity on the growth rate of the lettuce was found to be optimal at around 8000 lux.
- An integrated system was proposed, where a set of DAC units circularly provide CO_2 to the plant factory with the volume of 3000 m^3.
- From the analysis of material utilization and cost, 45 °C of desorption temperature and 3% of outlet CO_2 concentration are chosen as the optimal conditions with minimum energy requirements and an estimate of 35.67 kJ/mol CO_2 and US \$34.68/t CO_2, respectively.
- The present results demonstrate that atmospheric CO_2 capture is a competitive, sustainable option for gas fertilizer in agriculture.