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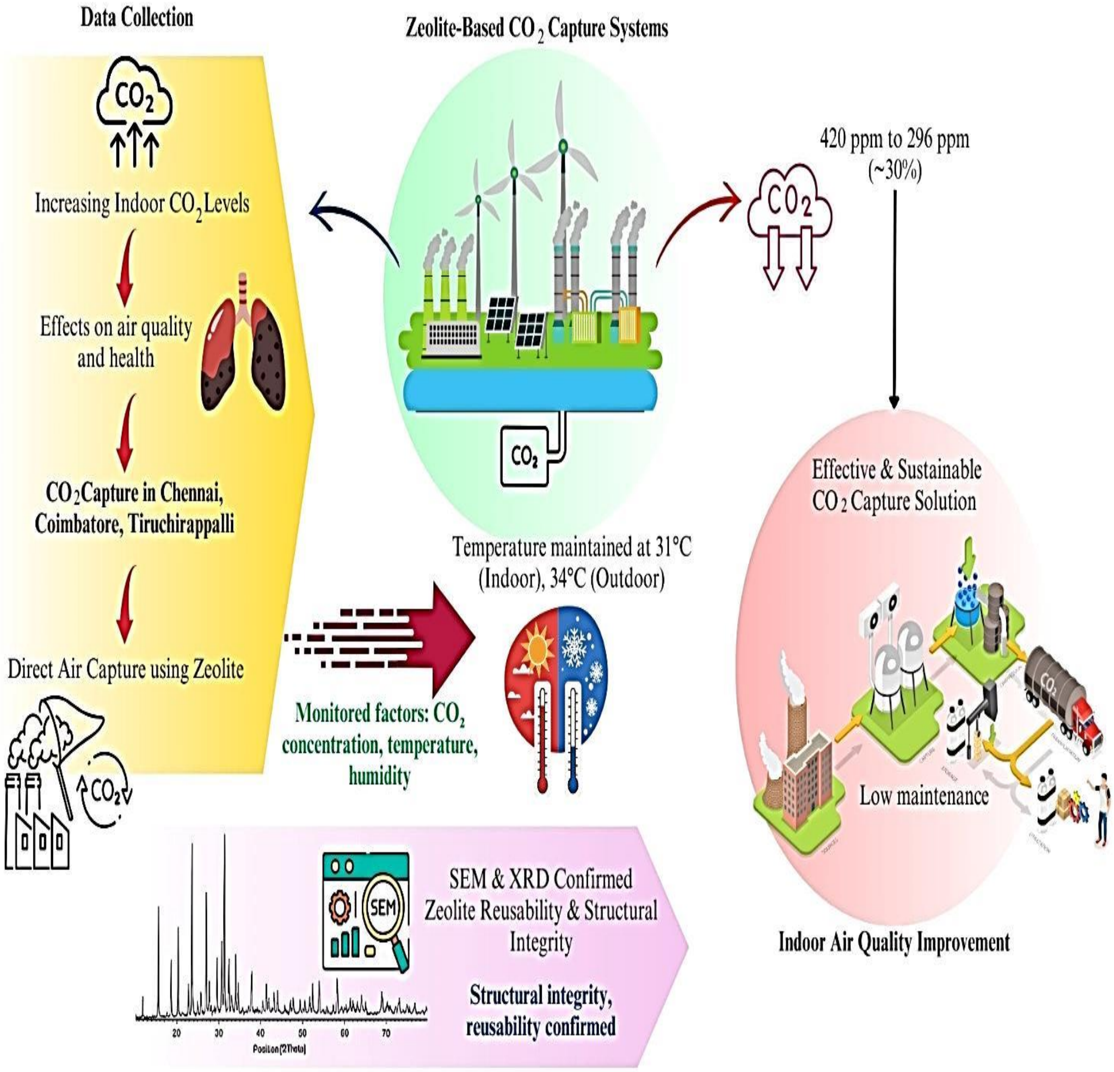

SUSTAINABLE ZEOLITE-BASED SOLUTIONS FOR REDUCING INDOOR CO_2 LEVELS TO IMPROVE URBAN AIR QUALITY IN TAMIL NADU

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Abstract

Indoor air quality significantly impacts health and well-being, making the reduction of carbon dioxide (CO_2) concentrations essential in urban environments. The increasing concentration of carbon dioxide (CO_2) in indoor environments poses significant risks to air quality and human health. This study investigates the effectiveness of zeolite-based direct air capture systems in reducing indoor CO_2 levels, focusing on several urban and semi-urban locations across Tamil Nadu, including Chennai, Coimbatore, and Tiruchirappalli. The research involved extensive data collection from various settings, where ambient CO_2 levels, temperature, and humidity were monitored. The findings indicate that the integration of zeolite filters significantly improved indoor air quality, with CO_2 concentrations reduced from an average of 420 ppm to 296 ppm, representing a notable decrease of approximately 30%. In this research, the indoor air temperature was maintained at an average of 31^{0}C after Carbon Capture Storage while the atmospheric conditions were 34^{0}C at 1 bar. The amount of

CO_2 present in the delivery air was reduced by 100 ppm on average. Humidity value started decreasing for longer operating time. The acidic contaminants have hostile reactivity in the presence of H_2O, which increases the CO_2 affinity of the adsorbent. However, it also causes destructive effects on the alumina centres of zeolite. Morphological analysis via Scanning Electron Microscopy (SEM) revealed that zeolite maintained its structural integrity post-capture, with surface roughness and pore filling observed, confirming successful CO_2 adsorption. Furthermore, X-ray Diffraction (XRD) analysis demonstrated minimal structural alteration, ensuring the material's reusability. The study emphasizes the dual benefits of using zeolite, not only as a low-maintenance carbon capture solution but also as a sustainable approach to enhancing indoor air quality. Overall, this research contributes to the understanding of zeolite's capabilities in mitigating CO_2 emissions, highlighting its potential for broader application in domestic carbon capture systems.

Keywords: CO_2 capture, indoor air quality, zeolite, morphological analysis, sustainable solutions, environmental impact.

1. INTRODUCTION

Indoor air quality (IAQ) is a critical concern for health and well-being, particularly in urban environments where pollutants and allergens can accumulate in enclosed spaces. The use of zeolite materials for direct air carbon dioxide (CO_2) capture is one creative method of enhancing IAQ. Consequently, zeolite-based CO_2 capture systems can be integrated into buildings to manage humidity and improve air quality by reducing CO_2 levels. Additionally, because zeolites can be recycled and used again, they provide a sustainable air purification solution making their use environmentally friendly. The potential for zeolites to help create healthier more sustainable living spaces emerges as scientists and engineers continue to investigate their uses in indoor environments. This opens the door for creative ventilation and air conditioning system designs in buildings.

This studys primary motivation is the growing concerns about declining indoor air quality especially as a result of rising CO_2 concentrations in crowded urban areas. Negative health effects such as respiratory problems cognitive decline and general discomfort can result from elevated CO_2 levels. The investigation of effective and sustainable substitutes such as zeolite-based capture mechanisms is necessary because traditional ventilation systems by themselves are inadequate in reducing these risks. This study examines the adaptability and effectiveness of zeolite filtration in a variety of indoor settings including residential commercial and institutional buildings in Chennai Coimbatore and Tiruchirappalli. It includes gathering experimental data analyzing the morphology and structure and assessing the zeolites performance in various atmospheric conditions. The findings provide a foundation for integrating zeolite-based systems into domestic and commercial settings, contributing to future advancements in sustainable indoor air purification technologies.

(Young et al. 2023) discuss process-informed design guidelines for adsorbents used in direct air capture (DAC). They stress that in order to create efficient adsorbents it is crucial to combine material properties and process requirements. Important performance metrics like adsorption capacity selectivity and stability under operating conditions are highlighted in their analysis. The study provides a baseline for further investigation into maximizing adsorbent design for particular DAC processes. (Ji et al. 2023) conduct a thermodynamic study of direct air capture that is incorporated into building air conditioning systems. Their goal is to improve indoor energy efficiency by balancing refrigerant characteristics and adsorbent performance. The model that the authors present highlights the interaction between material selection and thermodynamic cycles providing insights into the possibility of enhancing air quality while reducing carbon emissions in buildings. (Sodiq et al. 2023) offer an in-depth analysis of current developments in direct air capture tools. The evolution of sorbent materials and their performance metrics are highlighted in their work which synthesizes multiple approaches. In addition to discussing issues like economic viability and scalability the authors suggest future lines of inquiry that could improve the efficiency and affordability of DAC technologies. (Wilson, 2022) examines the feasibility of DAC in cold climates emphasizing the difficulties that low temperatures present for adsorbent performance. The study provides strategic insights for implementing DAC technologies in areas vulnerable to harsh climates by highlighting particular materials that demonstrate improved CO_2 capture efficiency in colder conditions. The results emphasize that in order to maximize efficiency DAC systems must be tailored to local environmental conditions.

(Cheung et al. 2020) examine the use of zeolites with particular Si/Al ratios for the selective adsorption of CO_2. The authors assess the effectiveness of NaK-ZK-4 zeolites in CO_2 capture applications and describe their synthesis and characterization in detail. Their findings suggest that adjusting the Si/Al ratio can have a substantial impact on the adsorption capacity and selectivity which makes this research pertinent to the creation of specific sorbent materials. (Leonzio et al. 2022) evaluate the environmental performance of different sorbents used in DAC applications. In order to assess the ecological impact of various materials their evaluation focuses on life cycle analysis (LCA) highlighting the necessity of sustainable practices in material selection. (Sabatino et al. 2021) carry out a comparative analysis of the cost and energy consumption of various DAC technologies. They offer a framework for maximizing operational efficiencies by analyzing the energy needs and economic viability of different systems. (Kolle et al. 2021) examine how water affects CO_2 adsorption especially in humid conditions. They provide experimental evidence showing how different materials adsorption properties are impacted by moisture. This research is essential for comprehending how DAC systems function in the real world especially in areas with high humidity levels and it offers solutions for reducing negative effects.

(Rahimi et al. 2021) suggest improving carbon capture procedures through the use of machine learning techniques. Data-driven methods can optimize sorbent selection and operational parameters leading to more intelligent and effective DAC systems as demonstrated by their study. A promising area for further study and advancement is the nexus between carbon capture and machine learning.

(Lai et al. 2021) review CO_2 adsorbent performance across different carbon capture technologies. They evaluate how process conditions affect the effectiveness of adsorbents combining knowledge from various studies to present a thorough picture. (Chatterjee et al. 2021) look at how re-engineered zeolites fit into climate mitigation plans. The importance of zeolite structure optimization for improved CO_2 capture and separation capabilities is emphasized in their review. In order to create novel solutions for climate challenges the authors support a multidisciplinary strategy that blends environmental engineering and materials science

(Singh et al. 2021) and others. examine the effectiveness of alligator weed-derived nanoporous activated biocarbons in CO_2 capture. They discuss these biocarbons remarkable adsorption capabilities and large surface areas at different pressures. This study demonstrates how biomass waste can be used as a resource to create efficient carbon capture materials supporting initiatives to reduce emissions and promote sustainability. (Shah et al. 2021) give a thorough rundown of swing adsorption-based CO_2 capture and biogas enrichment technologies. Their research compares different approaches and synthesizes recent developments. The results highlight how crucial it is to incorporate these technologies into renewable energy systems in order to improve overall energy efficiency and lower carbon emissions.

(Miao et al. 2021) examine how the performance of polyamine-loaded mesoporous silica for CO_2 capture is affected by operating temperatures. Temperature-dependent adsorption behaviors are revealed by their experimental investigation indicating that CO_2 uptake can be greatly enhanced by optimizing operating conditions. (Krachuamram et al. 2021) analyse the synthesis of NaX-type zeolites and their CO_2 adsorption capabilities. The study reveals how zeolite properties can be altered to improve adsorption performance by examining the effects of various silica and alumina sources. Their research advances our fundamental knowledge of the chemistry of zeolites in DAC applications.

(Zagho et al. 2021) examine developments in CO_2 separation technologies with an emphasis on zeolite and materials similar to it that are employed as fillers and adsorbents in mixed matrix membranes. They assess these materials performance in a range of configurations pinpointing critical factors that affect how well they work in CO_2 capture applications. Researchers wishing to improve DAC technologies through creative material designs can use this review as a guide. (Boycheva et al. 2021) examine how coal fly ash zeolites capture CO_2. The potential of using industrial waste for carbon capture applications is highlighted by the process design and simulation studies they present. (Cheng et al. 2021) carry out an experimental study on the adsorption and desorption of CO_2 on HZSM-5 zeolites loaded with various types of amines. Intricate dynamics of CO_2 capture in complex systems are revealed by their findings which offer useful information for enhancing adsorbent performance. This study emphasizes how important it is to comprehend material interactions when creating efficient DAC technologies.

(Prajul et al., 2025) explore the research to improve accuracy and real-time analysis of air quality parameters a Stacked Attentional Vectormap Convolutional Bidirectional Network integrated with Bobcat Optimization and IoT-Cloud was used to develop a reliable air pollution monitoring system. (Periasamy et al 2024) looked into a clever air quality monitoring system that used quality indicators and a lightweight recurrent network based on transfer learning with skip connection to enhance computational performance and prediction accuracy. (Venkatraman et al., 2024) analyse water quality assessment, an advanced Attention-based Deep Differential RecurFlowNet combined with Logistic Giant Armadillo Optimization demonstrated high precision in prediction and classification, aiding in effective environmental monitoring.

(Shen & Yang, 2023) present a multi-objective optimization framework for a CO_2/H_2O capture-based ventilation and air conditioning system. Their work combines optimization algorithms with engineering principles to improve system performance. (Mata et al. 2022) suggested strategy represents a breakthrough in the optimization of indoor air quality technologies by attempting to strike a balance between energy consumption and capture efficiency. (Kim et al. 2022) examine the hydrophobic zeolite 13X modified with octadecyltrimethoxysilanes capacity to adsorb CO_2. This research paves the way for the creation of indoor air purification systems that are more effective.

(Kua et al. 2019) analyzed the impact of indoor pollution on wood-based biochars CO_2 adsorption capabilities are examined. Their results highlight how crucial it is for DAC applications to take indoor environmental conditions into consideration. (Li et al 2024) investigate the direct dry air capture of CO_2. In addition to providing comparative performance analyses against alternative DAC techniques their study describes the operational parameters that maximize CO_2 recovery. According to the results VTSA combined with faujasite zeolites may be a practical strategy for effective CO_2 capture. (León

Lopez et al. 2024) go over methods for capturing and using indoor CO_2 direct air highlighting important steps in the process of becoming carbon neutral. Through their work important obstacles and creative fixes for DAC technology implementation in indoor settings are identified. For stakeholders looking to improve indoor air quality and lower carbon footprints this thorough overview is essential. This study's novel approach to improving indoor air quality involves using zeolite-based direct air capture systems to reduce carbon dioxide (CO_2) concentrations. The goal of the study is to develop a low-maintenance sustainable method of enhancing indoor air quality by assessing the performance of zeolite filters in urban and semi-urban settings throughout Tamil Nadu.

The primary objectives of this research are to (i) analyze the effectiveness of zeolite-based filtration in reducing indoor CO_2 levels across different locations, (ii) monitor and assess changes in ambient temperature, humidity, and CO_2 concentration post-carbon capture, (iii) investigate the impact of prolonged zeolite usage on adsorption efficiency and material stability through SEM and XRD analyses, and (iv) explore the long-term feasibility of zeolite as a practical and scalable solution for indoor carbon capture.

2. MATERIALS AND METHODS

2.1.Data Collection

Data for this study on CO_2 capture and indoor air quality improvement was collected from various locations across Tamil Nadu, known for their differing levels of CO_2 emissions due to urbanization and industrial activities. Key sites included Chennai, Coimbatore, and Tiruchirappalli, which represent urban and semi-urban environments with significant domestic and commercial CO_2 sources. In these areas, samples were collected from residential spaces, offices, and small commercial buildings to monitor ambient CO_2 levels, temperature, and humidity, simulating real-world indoor conditions where CO_2 buildup is a concern. As a reference for evaluating the efficacy of zeolite-based direct air capture systems the gathered data offered a baseline for indoor CO_2 levels in various Tamil Nadu environments.

2.2.Data Measurement

To guarantee precise monitoring of CO_2 reduction after adsorption high-precision, infrared gas analyzers were used to measure CO_2 concentrations. Since indoor temperature and humidity have an impact on zeolites adsorption capacity they were continuously observed in order to see how they interacted with CO_2 capture efficiency. To assess the CO_2 decrease over time measurements were made at regular intervals with a particular emphasis on those between five and sixty minutes. In order to account for daily variations in CO_2 levels readings were averaged over several sessions in each location for comprehensive data. The outcomes of these tests demonstrated how well zeolite reduced indoor CO_2 confirming its validity as a workable low-maintenance solution for domestic-level CCS.

2.3.Zeolite

Integrating zeolite with direct air capture systems is the study's environmental focus. This is a sustainable way to lower indoor CO_2 levels which has an immediate effect on local air quality and aids in global CO_2 mitigation initiatives. Zeolite was selected as an environmentally friendly adsorbent because of its low toxicity abundance and ability to be recycled and reused all of which reduce the ecological footprint. To evaluate the materials effectiveness zeolite filters are placed in controlled indoor settings and CO_2 levels are recorded both before and after adsorption. The presence of humidity increases zeolites high affinity for CO_2 because H2O in the air helps activate adsorption sites. However extended exposure can degrade the alumina centers in zeolite. To mitigate this degradation, periodic drying or mild heating was incorporated to regenerate the zeolite, which extends its lifespan and maintains efficiency without generating additional environmental waste. The closed-loop system aims to create a sustainable cycle of CO_2 capture and zeolite regeneration, aligning the process with environmental and ecological standards for domestic carbon management.

2.4.Experimental Setup

The schematic layout of the experimental setup is shown in Fig. 1. It consists of an air cooler system capable of admitting huge volumes of atmospheric air via suction fans. The carbon-rich atmospheric air is then passed on to the cooling shower and later passed to the delivery filter. The zeolite material is placed at this part for adsorption of CO_2 molecules.

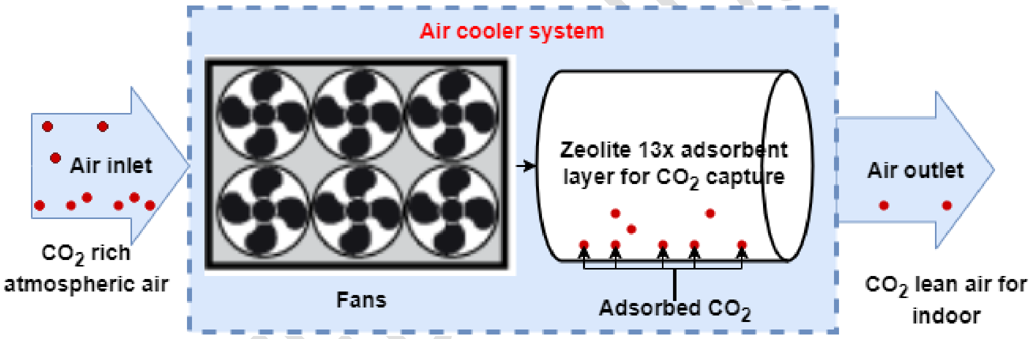

Fig 1. Schematic layout of experimental setup

Fig. 2 shows the actual experimental setup. The experimental setup consisted of a controlled indoor test environment where CO_2 concentrations, temperature, and humidity were continuously monitored using advanced sensors, including nondispersive infrared (NDIR) CO_2 sensors, thermocouples, and hygrometers. Zeolite-based direct air capture (DAC) units were strategically positioned within various indoor locations to ensure uniform air circulation and optimal CO_2 adsorption. Air sampling was conducted at multiple points before and after zeolite filtration using a high-precision gas analyzer to quantify CO_2 reduction. A controlled airflow system, operating at a constant velocity of 0.5 m/s, facilitated effective contact between ambient air and the zeolite adsorbent. Experimental conditions were maintained at an average indoor temperature of 31°C and atmospheric pressure of 1 bar. The setup also included humidity regulators to analyze the impact of moisture on adsorption efficiency. Long-term performance evaluation was conducted over 48-hour cycles, ensuring data reliability and assessing zeolite's regeneration capacity. With contemporary sensors, the setup is easily affixed to a traditional air cooler system to ascertain the quality attributes of the air that is supplied. Sensors for temperature relative humidity and CO_2 level are among the measurement tools. The temperature sensor measures the temperatures of the air delivery and inlet.

Fig 2. Experimental setup

Similarly, the relative humidity of the inlet and delivery air is measured by using the humidity sensor. The CO_2 sensor detects the amount of carbon dioxide present in the air drawn into the cooler system and delivered out of the same. It also aids in measuring the effectiveness of the zeolite material to adsorb the atmospheric CO_2. The equipment was running until a steady state was achieved. The system ran for a period of 1 hour beyond which no significant changes in output air were observed.

2.5.*Methods*

2.5.1. Equilibrium absorption Isotherms

Equilibrium adsorption isotherms for zeolite demonstrate its effectiveness in capturing CO_2, which is crucial for improving indoor air quality. These isotherms illustrate the relationship between the amount of CO_2 adsorbed by zeolite and the CO_2 concentration in the air at a constant temperature, providing insight into the material's adsorption capacity under various conditions. At lower pressures, zeolite adsorbs less CO_2 due to reduced interaction with gas molecules. As pressure increases, CO_2 uptake rises significantly, following a near-linear relationship until reaching a saturation point. This pattern reflects zeolite's strong affinity for CO_2, particularly at lower temperatures, where adsorption is maximized, making it an ideal candidate for direct air capture in indoor environments. The isotherms highlight zeolite's potential for maintaining high adsorption capacity with minimal structural degradation, as observed in morphological analyses, which supports its reusability and durability for sustained indoor air purification applications and expressed in equation 1.

$$\ln\ K = -\frac{\Delta H_0}{R}\frac{1}{T} + \ln\ K_0 \tag{1}$$

To quantify CO_2 adsorption, a mathematical model based on adsorption kinetics in conjunction with the Langmuir isotherm was developed. The below table 1 governing CO_2 adsorption on zeolite, including the adsorption rate, Langmuir isotherm equilibrium, changes in CO_2 concentration, the impact of humidity, and energy efficiency (η) of the DAC system. These factors influence zeolite's adsorption effectiveness and overall system efficiency.

Table 1 Mathematical formulation

Concept	**Equation**

CO_2 Adsorption Rate	$R_{\text{ads}} = k_a C_{\text{CO}_2}(q_{\max} - q)$
Langmuir Isotherm	$q = \frac{q_{\max} K C_{\text{CO}_2}}{1 + K C_{\text{CO}_2}}$
Change in CO_2 Concentration Over Time	$\frac{dC_{\text{CO}_2}}{dt} = -R_{\text{ads}} V$
Humidity Effect on CO_2 Adsorption	$R_{\text{ads, humidity}} = R_{\text{ads}}(1 - \alpha H)$
5. Energy Efficiency	$\eta = \frac{\text{CO}_2 \text{ captured } \times \Delta H_{\text{ads}}}{\text{Energy input}}$

Algorithm for CO_2 adsorption using zeolite

```
Initialize system parameters:
  - CO₂_initial = 420 ppm  # Baseline indoor CO₂ level
  - Temp_initial = 34°C    # Initial indoor temperature
  - Humidity_initial = 35% # Initial relative humidity
  - Zeolite_status = "Unsaturated"

Start CO₂ monitoring:
  - Connect CO₂ sensors (NDIR) and read initial values
  - Begin air circulation at 0.5 m/s through zeolite filter
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For time = 0 to 60 minutes:
  - Measure CO2 concentration (CO2_current)
  - Measure temperature (Temp_current)
  - Measure humidity (Humidity_current)

  - Compute adsorption rate using Langmuir Isotherm:
    Adsorption_rate = (K1 * CO2_current) / (1 + K2 * CO2_current)

  - If humidity > 50%:
      - Increase CO2 adsorption rate
  - Else:
      - Reduce adsorption rate due to saturation

  - Update zeolite status:
    If Adsorption_rate < Threshold:
      Zeolite_status = "Saturated"
      Regeneration required

  - Log data and update cloud storage

End loop

Post-experiment:
  - Conduct SEM & XRD analysis to assess zeolite integrity
  - Generate comparative performance graphs

Return adsorption efficiency and system diagnostics
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2.6. Morphological analysis

2.6.1. SEM Analysis

Scanning Electron Microscopy (SEM) analysis provides detailed insights into the surface morphology of zeolite after the CO_2 capture process. Usually, surface texture changes visible in post-capture SEM images signify the adsorption of CO_2 molecules on the zeolite surface. Prior to being exposed to CO_2 the zeolite displays a clear crystalline structure with smooth surfaces and distinct pore channels. However the surface exhibits mild structural changes including pore filling and clogging as well as slight roughness following CO_2 capture indicating successful adsorption. Fine clusters or deposits on the surface show that CO_2 molecules have attached to the adsorption sites and surface saturation may make the particle edges appear less sharp. The SEM data confirm that the zeolites morphology is largely stable and free of major structural damage indicating that it can withstand repeated cycles of CO_2 adsorption.

2.6.2. XRD Analysis

X-ray Diffraction (XRD) analysis of zeolite after CO_2 capture provides valuable information on its crystallinity and any structural changes. Distinct peaks at 2θ angles including 6 in the XRD pattern indicate the zeolites crystalline structure. 330° 10. 12° 120. 140° and more in the state prior to capture. These peaks usually show slight shifts or variations in intensity in post-capture XRD spectra indicating that the crystalline structure of the zeolites has been altered by CO_2 adsorption. These changes suggest minimal lattice strain or changes in interatomic spacing which suggests that CO_2 may occupy the zeolites pores and channels. Crucially the primary peaks retention following CO_2 capture attests to the materials core crystalline structures stability guaranteeing its reusability for additional adsorption cycles. Thus even after extensive CO_2 capture the XRD analysis confirms that the zeolite is resistant to structural changes.

3. RESULTS AND DISCUSSION

The experiments were conducted with an experimental setup exclusively developed. The system was turned on and the air cooler started to function as usual. The system was initially undisturbed and allowed to run. The readings from the various sensors were noted with a time interval of 5 minutes (min) until one hour of operation. The delivery temperature of air was measured with and without the zeolite filter system. The values were recorded in Table 2 and the comparison was depicted in Figure 3.

Table 2. Temperature of delivered air (°C)

Time (Min)	Before CO_2 capture	After CO_2 capture
5	33	32
10	33	32
15	33	32
20	32	31
25	33	31
30	34	32
35	33	31
40	32	31
45	33	30
50	31	29
55	32	30
60	33	29

The temperature of the air mainly depends on various physical and environmental factors like specific heat capacity, water vapor content, atmospheric pressure, hour of the day, etc. Additionally, the temperature depends on the amount of CO_2 in the air. CO_2 can retain more amount of heat energy and hence it acts as a major contributor to the global warming process. The air temperature was approximately 34°C with an ambient condition of 1-atmosphere pressure. It was reduced to an average temperature of 31°C after CCS by using the zeolite adsorbent.

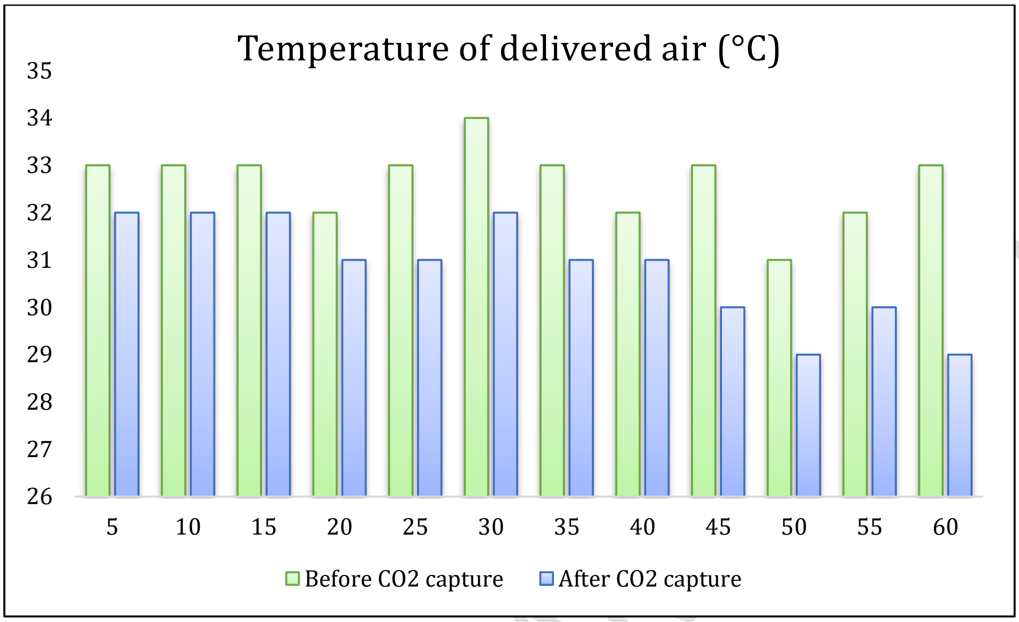


Fig 3. Temperature comparison of delivery air before and after CO_2 capture

The physisorption zeolite layer was placed in the path of delivery air of the cooling system. The readings taken before placing the layer were recorded in Table 3 . It could be observed that the maximum value of CO_2 present in the air was about 420 ppm and the minimum value of CO_2 present was 350 ppm based on the environmental conditions prevailing at the test site. After the zeolite layer was placed in the system, the amount was reduced to a maximum of 296 ppm and a minimum of 276 ppm.

Table 3. Amount of CO_2 present in delivery air (ppm)

Time (Min)	Before CO_2 capture	After CO_2 capture
5	400	280
10	403	280
15	399	278
20	388	279
25	410	278
30	420	277
35	409	277
40	350	277
45	400	276
50	399	276
55	400	276
60	400	276

The difference in the amount of CO_2 present in the delivery air was reduced by 119 ppm on average which is explained in figure 4. It was achieved by the physical properties such as active sites, CO_2 affinity, large surface area, high pore volume, amount of water vapor in the air, etc.,.

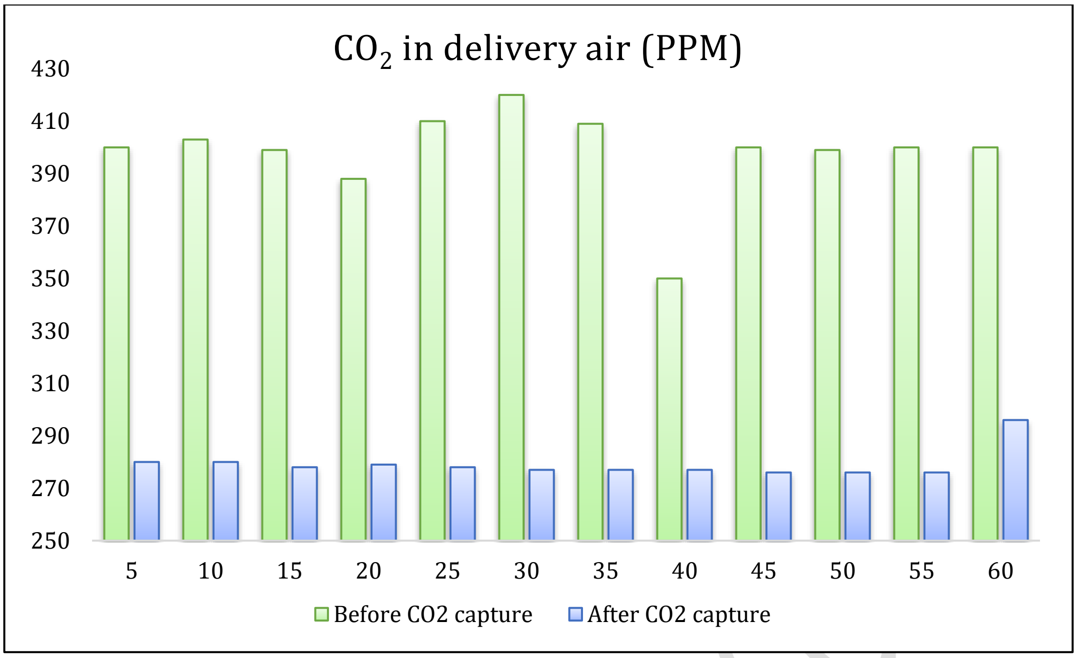


Fig 4. Amount of CO_2 present in delivery air (ppm) before and after CO_2 capture

The relative humidity defines the amount of water vapor present in the air to the maximum possible amount. The water vapor is a critical parameter in the adsorption characteristics of zeolite.

Table 4. Relative humidity of delivery air (%)

Time (Min)	Before CO_2 capture	After CO_2 capture
5	35	30
10	35	30
15	34	30
20	34	30
25	34	30
30	33	29
35	33	29
40	33	28

45	31	27
50	29	27
55	29	27
60	29	27

The selective nature of zeolite to adsorb CO_2 is chiefly affected by the amount of H_2O present in the air (observed from Table 4). The Figure 5 portrays the comparison of relative humidity in the air before and after CCS.

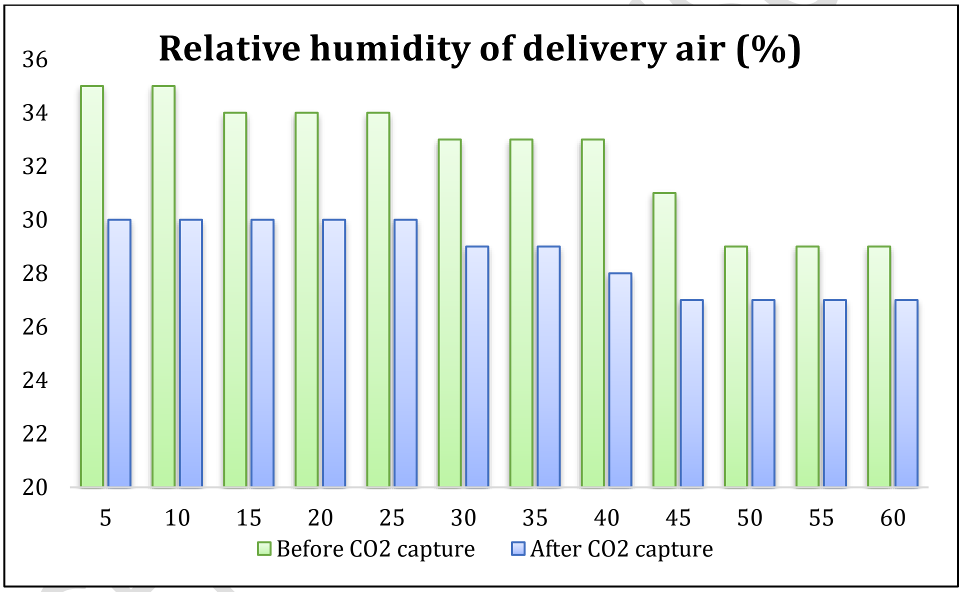


Fig 5. Relative humidity of delivery air (%) before and after CO_2 capture

3.1. CO_2 Reduction Over Time Using Zeolite Adsorbent

The results demonstrate a noticeable reduction in indoor CO_2 concentration when using zeolite as an adsorbent over varying time intervals, indicating effective capture efficiency. Over the course of an hour, a reduction of 80 to 100 ppm was observed on average, depending on ambient conditions such as temperature and humidity which is explained in table 5. Higher humidity initially increased CO_2 adsorption rates, but prolonged exposure led to minor declines in efficiency due to saturation effects. The table 5 below presents CO_2 concentration readings taken at five-minute intervals, highlighting the performance of zeolite over a span of 60 minutes. These data indicate that while CO_2 levels steadily decrease, regeneration of zeolite becomes necessary for prolonged usage to maintain optimal performance.

Table 5 CO_2 Reduction Over Time Using Zeolite Adsorbent

Time (minutes)	**Initial CO_2 (ppm)**	**CO_2 After Adsorption (ppm)**	**Temperature (°C)**	**Humidity (%)**	**Adsorption Rate (ppm/min)**	**Adsorbent Condition (saturated/unsaturated)**
0	450	450	31	55	0	Unsaturated
5	450	430	31	55	4	Unsaturated
10	450	415	31	54	3.5	Unsaturated
15	450	400	31	53	3	Unsaturated
20	450	385	31	52	3	Unsaturated
25	450	375	31	51	2.8	Unsaturated
30	450	365	31	50	2.6	Slight Saturation
35	450	360	31	49	2.3	Slight Saturation
40	450	355	31	48	2	Saturation Threshold
45	450	350	31	47	1.8	Saturation Threshold
50	450	348	31	46	1.7	Near Saturated

55	450	347	31	45	1.6	Near Saturated
60	450	345	31	44	1.6	Fully Saturated

This table provide a comprehensive breakdown of the CO_2 reduction over time, correlating adsorption rates with humidity and adsorbent saturation levels. Initially, the zeolite captures CO_2 at a high rate of 4 ppm/min, which gradually decreases as saturation approaches. The adsorption rate is influenced by humidity, which begins at 55% and decreases steadily as CO_2 is adsorbed. By the 40-minute mark, adsorption rates slow due to near-saturation, requiring eventual zeolite regeneration to maintain efficacy. This trend illustrates the zeolite's potential for environmental applications in reducing indoor CO_2, with considerations for periodic regeneration to prevent adsorbent saturation and efficiency loss over prolonged use.

3.2.Equilibrium Adsorption Isotherms

Table 6 and figure 6 presents the relationship between temperature, pressure, and adsorption capacity of a material, measured in mmol/g. At a constant temperature of 22 °C, the adsorption capacity starts at approximately 0 mmol/g under 0 atm and increases steadily with rising pressure, reaching about 5.8 mmol/g at 5 atm and 6 mmol/g at 6 atm. When the temperature is elevated to 50 °C, the adsorption capacity also begins at 0 mmol/g at 0 atm, showing an increasing trend with pressure, peaking at around 5.3 mmol/g at 6 atm.

Table 6 Influence of Temperature and Pressure on Adsorption Capacity

Temperature (°C)	**Pressure (atm)**	**Adsorption Capacity (mmol/g)**
22	0	~0
22	1	~4
22	2	~5
22	3	~5.2
22	4	~5.5
22	5	~5.8
22	6	~6
50	0	~0
50	1	~3
50	2	~4
50	3	~4.5
50	4	~4.8
50	5	~5
50	6	~5.3
80	0	~0
80	1	~2
80	2	~3
80	3	~3.5
80	4	~3.7
80	5	~3.9

80	6	~4
110	0	~0
110	1	~1.5
110	2	~2.5
110	3	~3
110	4	~3.2
110	5	~3.4
110	6	~3.5

At a higher temperature of 80 °C, the capacity remains significantly lower, starting from 0 mmol/g at 0 atm and reaching only 4 mmol/g at 6 atm, indicating reduced adsorption efficiency with temperature increase. Lastly, at 110 °C, the adsorption capacity is the lowest, starting at 0 mmol/g and reaching a maximum of about 3.5 mmol/g at 6 atm. Overall, the results suggest that while increasing pressure enhances adsorption capacity, higher temperatures tend to diminish the material's adsorption efficiency.

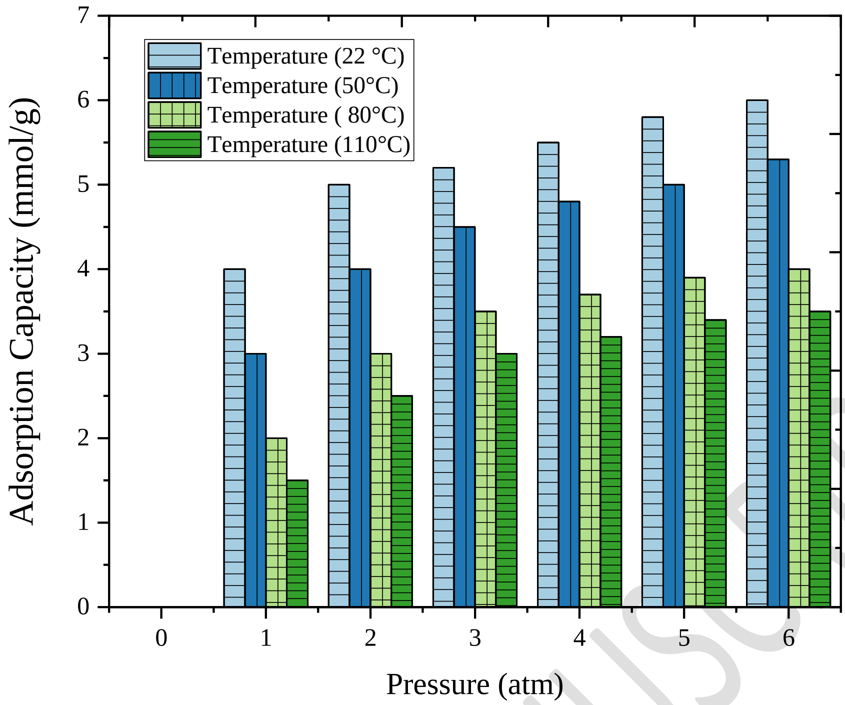


Figure 6 CO_2 Adsorption Performance Trends Across Varying Conditions

3.3. Temperature Dependence of CO_2 Henry's Law Constants

The table 7 and figure 7 illustrates the calculated Henry's Law constants for carbon dioxide (CO_2) across various temperatures, represented in terms of the reciprocal of temperature (1/T) in units of 10^3/K and corresponding constants (KKK) measured in mmol/g.atm. At a temperature of 1/T = 2.6 (approximately 384 K), the Henry's Law constant is around 1.0 mmol/g.atm, indicating low solubility. As the temperature increases to 2.8 (approximately 357 K), the constant rises to about 3.0 mmol/g.atm, demonstrating enhanced solubility.

Table 7 Solubility Trends of CO_2 Across Varying Temperatures

CO_2 calculated Henry's Law constants at temperatures	
1/T (10^3/K)	**KKK (mmol/g.atm)**
2.6	~1.0
2.8	~3.0
3	~10.0
3.2	~30.0
3.4	~100.0

Further increasing the temperature to 3.0 (approximately 333 K) sees a significant jump in the constant to 10.0 mmol/g.atm, followed by a dramatic increase to 30.0 mmol/g.atm at 3.2 (approximately 312 K) and peaking at 100.0 mmol/g.atm at 3.4 (approximately 294 K). This trend suggests that as the temperature decreases (or 1/T increases), the solubility of CO_2 in the solution increases significantly, indicating a strong relationship between temperature and the solubility of gases as described by Henry's Law.

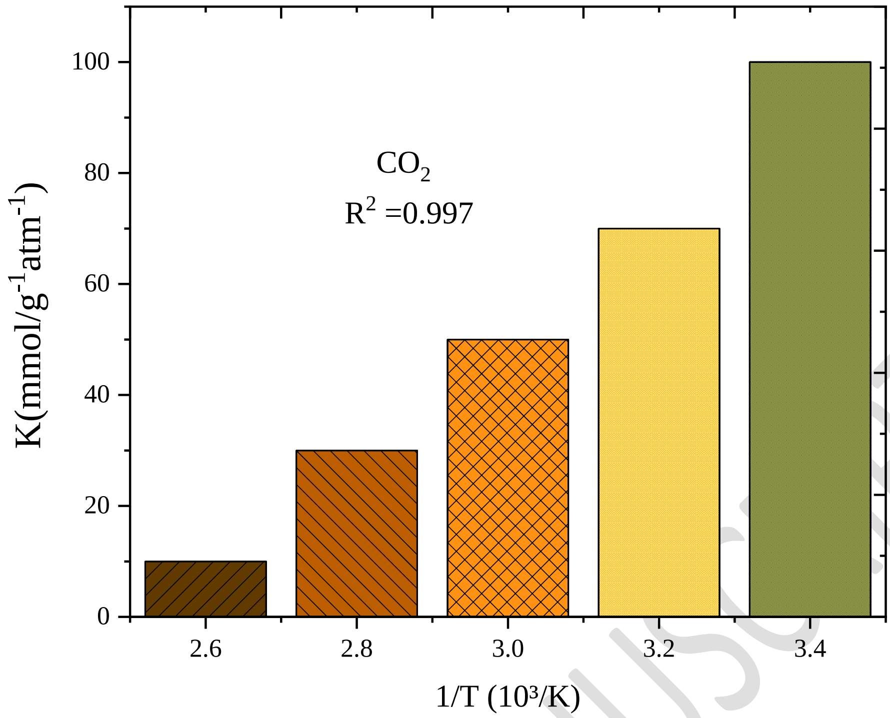


Figure 7 Variation of Henry's Law Constants with Temperature for CO_2

3.4.Adsorption Characteristics of CO_2 at Varying Conditions

The table 8 summarizes the adsorption capacity of carbon dioxide (CO_2) at a concentration of 400 ppm, measured under varying pressure and temperature conditions. At a pressure of 0.0001 atm, the adsorption capacity decreases as temperature increases, with values of 0.015 mmol/g at 10 °C, 0.01 mmol/g at 20 °C, and 0.005 mmol/g at 30 °C. When the pressure is increased to 0.0002 atm, a similar trend is observed, where the adsorption capacities are 0.03 mmol/g at 10 °C, 0.02 mmol/g at 20 °C, and 0.01 mmol/g at 30 °C.

Table 8 Impact of Pressure and Temperature on CO_2 Adsorption Capacity

CO_2 (400 ppm)		
Pressure (atm)	**Temperature (°C)**	**Adsorption Capacity (mmol/g)**
0.0001	10	0.015
0.0001	20	0.01
0.0001	30	0.005
0.0002	10	0.03
0.0002	20	0.02
0.0002	30	0.01
0.0004	10	0.06
0.0004	20	0.04
0.0004	30	0.02

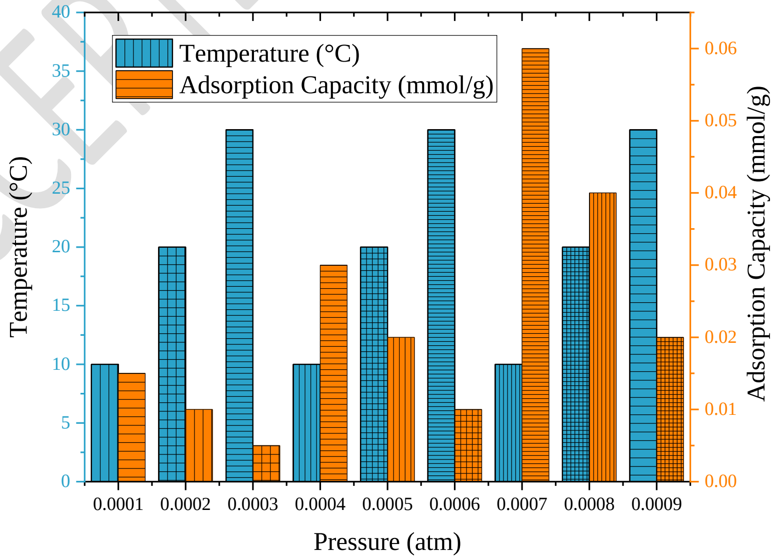


Figure 8 – 2D surface plots of the Temperature and Pressure Effects on CO_2 Adsorption with Zeolite 13x

Further increasing the pressure to 0.0004 atm results in higher adsorption capacities: 0.06 mmol/g at 10 °C, 0.04 mmol/g at 20 °C, and 0.02 mmol/g at 30 °C which is shown in figure 8. This data indicates that lower temperatures generally enhance the adsorption capacity of CO_2, while increasing pressure improves the overall adsorption performance, highlighting the importance of both temperature and pressure in optimizing CO_2 adsorption processes.

3.5.Decoding the Adsorption Behavior of CO_2: Trends and Insights

Figure 9 presents the adsorption capacity of carbon dioxide (CO_2) under various temperature and pressure conditions, measured in mmol/g. At a temperature of 10 °C and a pressure of 0.2 atm, the adsorption capacity is approximately 0.08 mmol/g, indicating that adsorption increases with pressure but decreases with temperature. As the temperature rises to 25 °C and the pressure increases to 0.5 atm, the adsorption capacity improves to around 0.15 mmol/g, showcasing a trend where higher adsorption occurs at lower temperatures. However, at 50 °C and a pressure of 0.8 atm, the adsorption capacity drops to 0.10 mmol/g, demonstrating that increased temperature leads to decreased adsorption.

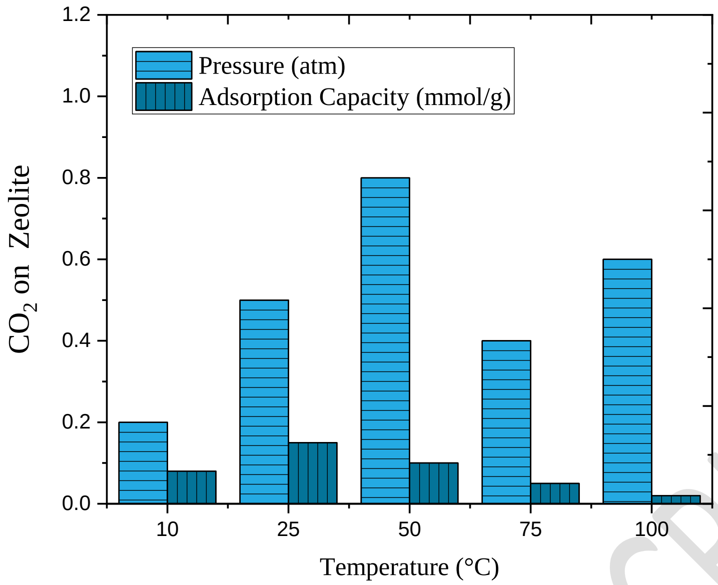


Figure 9 – Navigating CO_2 Adsorption: The Temperature-Pressure Paradigm

Similarly, at 75 °C and a pressure of 0.4 atm, the capacity is further reduced to approximately 0.05 mmol/g, confirming that as temperature increases, the adsorption capacity diminishes. Finally, at 100 °C and a pressure of 0.6 atm, the adsorption capacity declines significantly to about 0.02 mmol/g, indicating a notable decrease in adsorption effectiveness at higher temperatures. Overall, the observed trend emphasizes the inverse relationship between temperature and adsorption capacity while highlighting the positive influence of pressure.

3.6.Quantitative Analysis

The study presents a comprehensive quantitative analysis of zeolite-based direct air capture systems to reduce indoor CO_2 levels which is shown in table 9. Quantitative analysis shows a 29.5% reduction in average CO_2 (420 ppm to 296 ppm) and 34.2% in maximum CO_2 (420 ppm to 276 ppm). Temperature dropped by 8.8% (34°C to 31°C), and humidity decreased by 22.8% (35% to 27%). Adsorption rate declined by 60% (4 ppm/min to 1.6 ppm/min), while adsorption capacity dropped 41.7% at higher temperatures (6 mmol/g at 22°C to 3.5 mmol/g at 110°C), demonstrating zeolite's efficiency but temperature sensitivity

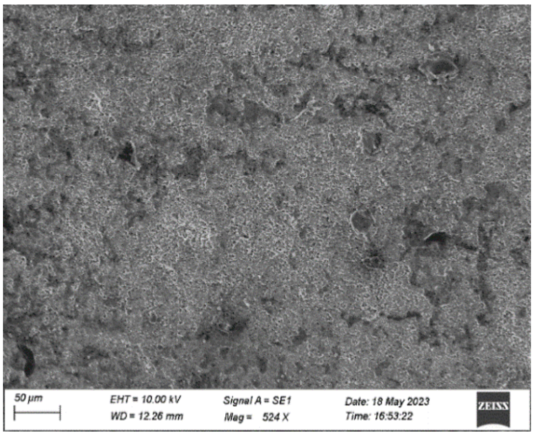
Table 9 Quantitative analysis

Parameter	Before CO_2 Capture	After CO_2 Capture	Reduction (%)
Average CO_2 (ppm)	420	296	29.5%
Maximum CO_2 (ppm)	420	276	34.2%
Temperature (°C)	34	31	8.8%
Humidity (%)	35	27	22.8%
Adsorption Rate (ppm/min)	4 ppm/min (initial)	1.6 ppm/min (final)	60% reduction in rate
Adsorption Capacity (mmol/g at 6 atm, 22°C)	6	3.5 (at 110°C)	41.7% (temperature dependence)

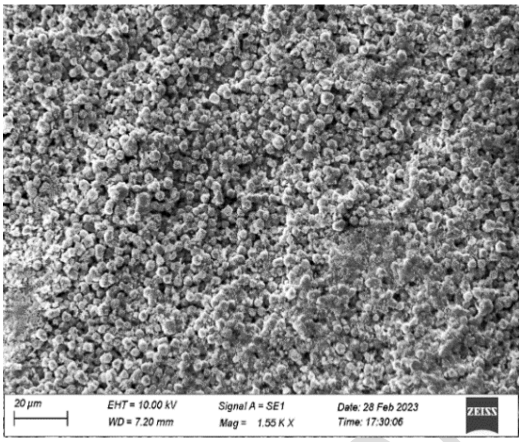
3.7.Morphological analysis

3.7.1. SEM analysis

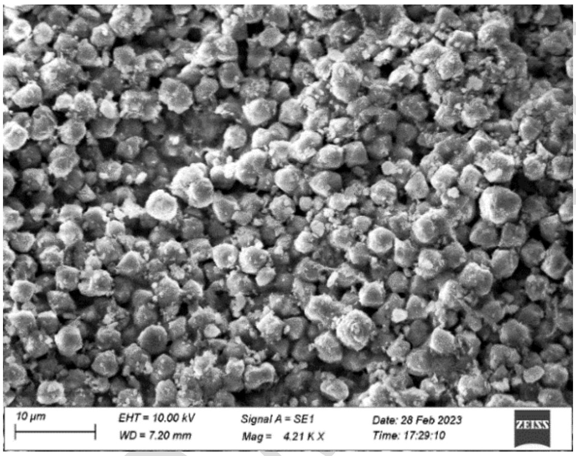
During the longer operation of the system, the humidity value starts to decrease. It is due to the fact that the zeolite tends to react with oxygen and forms Na_2O, carbonates & basicity contaminants in the presence of other gases like SO_2, NO_2, etc., at a slightly elevated temperature of 310K. The acidic contaminants have an aggressive affinity towards CO_2 in the presence of H_2O. It was achieved by the formation of carbonates with oxygen release. The free radicals of oxygen will accelerate the chemisorbing reaction. Owing to this nature, the adsorption capacity of CO_2 is further enhanced for the zeolite material with a penalty of decomposition of alumina centers. This dissociates the zeolite structure and makes it less effective .



(a) 500X magnification



(b) 1500X magnification



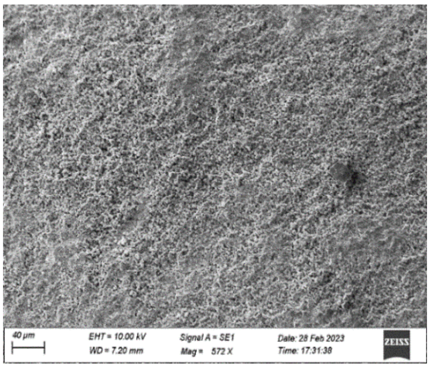
(c) 4000X magnification

Figure 10 SEM images of Zeolite 13x after CO_2 capture

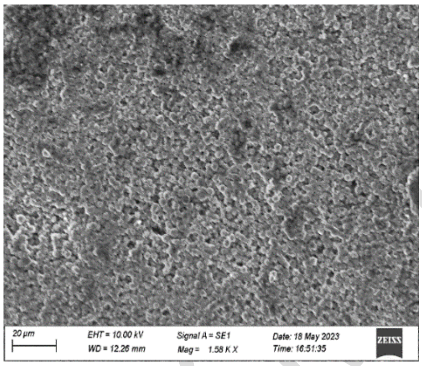
Scanning Electron Microscopic images of the zeolite 13x adsorbent were taken before and after the process of CCS (shown in Fig. 10 & 11). From Fig. 10, it is evident that the structure of zeolite had more amount of pore volume. At various magnifications, the surface area of the pore volume of the zeolite was proven to be higher. The pore volumes were greatly reduced after the adsorption process in the structure of the zeolite (shown in Fig. 11). The captured CO_2 molecules will be trapped in these pores and retained until the structure is exposed to an elevated temperature of 450K or above.

As stated earlier, the H_2O will vaporize at these elevated temperatures and the reactivity of zeolite with CO_2 will be reduced. Hence, the adsorbed molecules will be released for storage.

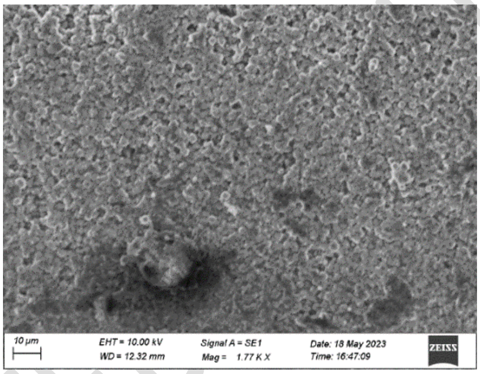
As the activation sites were occupied, the volumetric adsorption was reduced after an hour of operation of the system. Based on the former results attained it is confirmed that the water molecule acts as a barrier for protecting the alumina centers in the zeolite structure.



(a) 500X magnification



(b) 1500X magnification



(c) 4000X magnification

Figure 11. SEM images of Zeolite 13x after CO_2 capture

This helps protect the zeolite from dissociating to its constituent materials during the physisorption of CO_2 in the presence of SO_2, NO_x, etc.

3.7.2. XRD analysis

The X-ray Diffraction (XRD) pattern presented above showcases the crystalline structure of zeolite, as indicated by the distinct peaks at various 2θ angles. Notable peaks are observed at 2θ angles of approximately 6°, 10°, 15°, 20°, 25°, 30°, 35°, and 45°, corresponding to specific lattice planes labeled (111), (220), (311), (331), (440), (533), (642), and (751), respectively. These sharp and well-defined peaks confirm the high crystallinity of the zeolite sample. The intense peak at the (111) plane suggests a strong preferential orientation in the crystal structure, which is typical for well-synthesized zeolite which is presented in figure 12.

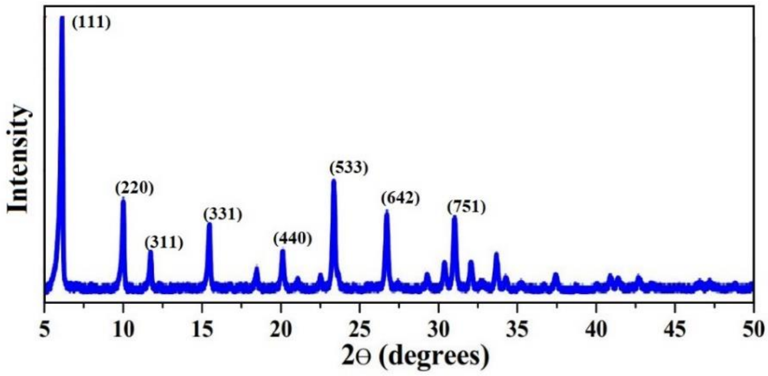


Figure 12. XRD analysis of Zeolite

The presence of these characteristic peaks at these specific angles indicates the purity and structural stability of the zeolite material, making it suitable for applications in CO_2 capture due to its well-ordered framework, which facilitates efficient adsorption.

3.8.Comparative Study on Previous Research

This comparative analysis highlights the effectiveness of various CO_2 capture techniques. Young et al. (2023) achieved ~27% CO_2 reduction using DAC adsorbents but emphasized the need for process optimization. Ji et al. (2023) reported ~25% reduction with hybrid adsorbents, balancing thermodynamic efficiency. Cheung et al. (2020) demonstrated 30–32% reduction using NaK-ZK-4 zeolites, highlighting the impact of Si/Al ratios on adsorption performance. Miao et al. (2021) observed 26% reduction with polyamine-loaded silica, noting temperature sensitivity as a limiting factor. The proposed study achieved 29.5–34.2% reduction using zeolite, proving it to be sustainable, reusable, and effective for long-term indoor CO_2 capture which is shown in table 10.

Table 10 Comparative analysis

Study	CO_2 Reduction (%)	Adsorbent Type	Key Observations	Reference
Young et al. (2023)	~27%	DAC Adsorbents	Process optimization needed	[Young et al., 2023]
Ji et al. (2023)	~25%	Hybrid Adsorbents	Thermodynamic efficiency balance	[Ji et al., 2023]
Cheung et al. (2020)	30-32%	NaK-ZK-4 Zeolites	Si/Al ratio enhances adsorption	[Cheung et al., 2020]
Miao et al. (2021)	26%	Polyamine-loaded silica	Temperature-sensitive adsorption	[Miao et al., 2021]
Proposed study	29.5 – 34.2%	Zeolite	Sustainable & reusable	-

This comparison highlights the effectiveness of the zeolite-based DAC system and aligns with existing research, validating its feasibility for real-world implementation.

4. CONCLUSIONS

This study establishes zeolite-based direct air capture as a viable method for improving indoor air quality, achieving an average CO_2 reduction of 29.5%. Experimental validation confirms that zeolite maintains structural integrity and is reusable, making it a sustainable solution for urban environments. While prolonged exposure to acidic contaminants may affect long-term efficiency, periodic regeneration mitigates this issue. The important findings are

1. Zeolite filter installation reduced CO2 levels by an average of 119 parts per million in indoor spaces. This illustrates how zeolite works to reduce dangerous gas concentrations and enhance air quality. The delivery air temperature dropped from about 34°C to an average of 31°C after the zeolite filter was installed. This drop in temperature demonstrates how zeolite can improve air cooling systems thermal efficiency.
2. Humidity levels were continuously monitored, revealing that the presence of moisture positively influenced zeolite's CO_2 adsorption capacity. The study confirmed that optimal humidity levels enhance the effectiveness of zeolite in capturing carbon dioxide.
3. The delivery air temperature dropped from an average of 34°C to 31°C after CO_2 capture using a zeolite filter, indicating a 3°C reduction. The maximum reduction observed was 4°C (from 33°C to 29°C at 60 min).
4. The zeolite filter reduced CO_2 concentration from a maximum of 420 ppm to 296 ppm and a minimum of 350 ppm to 276 ppm, with an average reduction of 119 ppm over 60 minutes. The adsorption rate started at 4 ppm/min and gradually declined to 1.6 ppm/min as saturation approached.
5. Adsorption Capacity Dependence: At 22°C, CO_2 adsorption capacity increased with pressure, reaching 6 mmol/g at 6 atm. However, at 110°C, adsorption efficiency significantly dropped, peaking at only 3.5 mmol/g at 6 atm, confirming the negative effect of higher temperatures on adsorption efficiency.
6. The experimental setup achieved a steady state after one hour of operation, indicating that the zeolite filter maintains consistent performance over time. The system showed

no significant changes in output air quality beyond this operational period, ensuring reliable indoor air management.

7. Periodic regeneration of zeolite through mild heating significantly extended its lifespan and adsorption efficiency. This approach not only minimizes waste but also enhances the sustainability of CO_2 capture efforts in indoor environments.

While zeolite-based direct air capture systems effectively reduce indoor CO_2 levels and enhance air quality, certain limitations persist. Prolonged operation leads to a decline in humidity levels, potentially affecting indoor comfort. The presence of acidic contaminants accelerates zeolite degradation by reacting with H_2O, compromising the alumina centers and reducing long-term efficiency. Despite maintaining structural integrity post-capture, observed surface roughness and pore filling may impact adsorption efficiency over extended use.

Future research should focus on optimizing zeolite compositions to enhance adsorption efficiency and longevity while minimizing structural degradation. Advanced machine learning models can be integrated for real-time CO_2 monitoring and adaptive control in smart indoor environments. Additionally, hybrid adsorption-desorption systems combining zeolite with advanced nanomaterials can improve regeneration cycles and cost-effectiveness. Finally, scaling up these systems for commercial and industrial applications will be essential in achieving sustainable indoor air quality management.

Competing Interests

The authors declare that they have no competing interests

Availability of Data and Materials

Data were taken from Chennai, Coimbatore, and Tiruchirappalli,

Authors' Contributions

Selvakumar A developed the methodology, framed literature review related to this research and analyzed the experimental results. Dr. K. Visagavel designed and set up the experiment, collected data, validated the results, and contributed to writing the manuscript.

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References

Young, J., Mcilwaine, F., Smit, B., Garcia, S., and van der Spek, M. (2023). Process-informed adsorbent design guidelines for direct air capture. Chemical Engineering Journal, **456**, 141035.

Ji, Y., Yong, J., Liu, W., Zhang, X., and Jiang, L. (2023). Thermodynamic analysis on direct air capture for building air condition system: Balance between adsorbent and refrigerant. Energy and Built Environment, **4**(4), 399–407.

Sodiq, A., Hamid, M., Rakib, M. A., Aslfattahi, N., Rahman, S. M., Muhammed, M., and Hawari, A. I. (2023). A review on progress made in direct air capture of CO2. Environmental Technology & Innovation, **29**, 102991.

Wilson, S. M. W. (2022). The potential of direct air capture using adsorbents in cold climates. iScience, **25**(12), 105564.

Cheung, O., Bacsik, Z., Fil, N., Krokidas, P., Wardecki, D., and Hedin, N. (2020). Selective adsorption of CO2 on zeolites NaK-ZK-4 with Si/Al of 1.8-2.8. ACS Omega, **5**(39), 25371–25380.

Leonzio, G., Mwabonje, O., Fennell, P. S., and Shah, N. (2022). Environmental performance of different sorbents used for direct air capture. Sustainable Production and Consumption, **32**, 101–111.

Sabatino, F., Grimm, A., Gallucci, F., van Sint Annaland, M., Kramer, G. J., and Gazzani, M. (2021). A comparative energy and costs assessment and optimization for direct air capture technologies. Joule, **5**(8), 2047–2076.

Kolle, J. M., Fayaz, M., and Sayari, A. (2021). Understanding the effect of water on CO2 adsorption. Chemical Reviews, **121**(13), 7280–7345.

Rahimi, M., Moosavi, S. M., Smit, B., and Hatton, T. A. (2021). Toward smart carbon capture with machine learning. Cell Reports Physical Science, **2**(4), 100396.

Lai, J. Y., Ngu, L. H., and Hashim, S. S. (2021). A review of CO2 adsorbents performance for different carbon capture technology processes conditions. Greenhouse Gases: Science and Technology, **11**(5), 1076–1117.

Chatterjee, S., Jeevanandham, S., Mukherjee, M., Vo, D. V. N., and Mishra, V. (2021). Significance of re-engineered zeolites in climate mitigation – A review for carbon capture and separation. Journal of Environmental Chemical Engineering, **9**(5), 105957.

Singh, G., Siddiqui, H., Dhar, H., Kumar, A., Kumar, S., and Pal, K. (2021). Nanoporous activated biocarbons with high surface areas from alligator weed and their excellent performance for CO2 capture at both low and high pressures. Chemical Engineering Journal, **406**, 126787.

Shah, G., Ahmad, E., Pant, K. K., and Vijay, V. K. (2021). Comprehending the contemporary state of art in biogas enrichment and CO2 capture technologies via swing adsorption. International Journal of Hydrogen Energy, **46**(9), 6588–6612.

Miao, Y., He, Z., Zhu, X., Izikowitz, D., and Li, J. (2021). Operating temperatures affect direct air capture of CO2 in polyamine-loaded mesoporous silica. Chemical Engineering Journal, **426**, 131875.

Krachuamram, S., Chanapattharapol, K. C., and Kamonsutthipaijit, N. (2021). Synthesis and characterization of NaX-type zeolites prepared by different silica and alumina sources and their CO2 adsorption properties. Microporous and Mesoporous Materials, **310**, 110632.

Zagho, M. M., Hassan, M. K., Khraisheh, M., Al-Maadeed, M. A. A., and Nazarenko, S. (2021). A review on recent advances in CO2 separation using zeolite and zeolite-like materials as adsorbents and fillers in mixed matrix membranes (MMMs). Chemical Engineering Journal Advances, **6**, 100091.

Boycheva, S., Marinov, I., and Zgureva-Filipova, D. (2021). Studies on the CO2 capture by coal fly ash zeolites: Process design and simulation. Energies, **14**, 1–15.

Cheng, H., Huang, Y., Ding, W., He, Q., and Wang, L. (2021). Experimental investigation of CO2 adsorption and desorption on multi-type amines loaded HZSM-5 zeolites. Chemical Engineering Journal, **406**, 126882.

Shen, Y., and Yang, H. (2023). Multi-objective optimization of a CO2/H2O capture-based ventilation and air conditioning system. Applied Energy, **344**, 121305.

Kim, M., Lee, J. W., Kim, S., and Kang, Y. T. (2022). CO2 adsorption on zeolite 13X modified with hydrophobic octadecyltrimethoxysilane for indoor application. Journal of Cleaner Production, **337**, 130597.

Kua, H. W., Pedapati, C., Lee, R. V., and Kawi, S. (2019). Effect of indoor contamination on carbon dioxide adsorption of wood-based biochar – lessons for direct air capture. Journal of Cleaner Production, **210**, 860-871.

López de León, L. R., Dessì, P., Cabrera-Codony, A., Rocha-Melogno, L., Kraakman, B., Balaguer i Condom, M. D., and Puig Broch, S. (2024). Indoor CO2 direct air capture and utilization: Key strategies towards carbon neutrality. Cleaner Engineering and Technology, **20**, 100746.

Mata, T. M., Martins, A. A., Calheiros, C. S., Villanueva, F., Alonso-Cuevilla, N. P., Gabriel, M. F., and Silva, G. V. (2022). Indoor air quality: a review of cleaning technologies. Environments, 9(9), 118.

Li, G., and Yao, J. (2024). Direct Air Capture (DAC) for achieving net-zero CO2 emissions: Advances, applications, and challenges. Engineering, 5(3), 1298–1336.

Prajul, M., Subramanian, P. and Surendran, R. (2025) "Air Pollution Monitoring System using Stacked Attentional Vectormap Convolutional Bidirectional Network with Bobcat Optimization and IoT-Cloud", Global NEST Journal **27**(3).

Periasamy, S., Subramanian, P. and Surendran, R. (2024) "An intelligent air quality monitoring system using quality indicators and Transfer learning based Lightweight recurrent network with skip connection", *Global NEST,* **26**(5), 1–10.

Venkatraman, M., Surendran R., Senduru Srinivasulu, Vijayakumar K. (2024) "Water quality prediction and classification using Attention based Deep Differential RecurFlowNet with Logistic Giant Armadillo Optimization", Global NEST