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Bio-based CO_2 adsorbent from puffed rice waste: Optimization and experimental evaluation

Abeer DAR SALEH[1,a *], Maatouk KHOUKHI[1,b], Ameera MOHAMMAD[1,c], and Ali AL MARZOUQI[1,d]

[1]United Arab Emirates University, Al Ain, UAE

[a]201870084@uaue.ac.ae, [b]mkhoukhi@uaeu.ac.ae, [c]a.fares@uaeu.ac.ae, [d]hassana@uaeu.ac.ae

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Abstract. The urgent need for effective carbon dioxide (CO_2) capture strategies extends beyond industrial emissions to enclosed built environments, where elevated CO_2 concentrations impair occupant health, cognitive function, and overall productivity. This research introduces a bio-based adsorbent derived from thermally puffed and chemically modified waste rice, designed for high-performance indoor CO_2 capture. The material was evaluated in a custom-built 1 × 1 × 1 m controlled environmental chamber simulating classroom conditions, under systematically varied parameters of temperature (20–30 °C), relative humidity (45–65%), and surface coverage (35–55%). Using Response Surface Methodology (RSM), the study optimized these parameters to achieve a reduction of over 300 ppm within four hours, corresponding to a CO_2 removal rate of 79.25 ppm·h^{-1} and a first-order kinetic rate constant of 0.0952 h^{-1}. The optimized model demonstrated strong predictive power ($R^2 > 0.98$) for both removal efficiency and kinetic behavior. The adsorbent exhibited a competitive uptake capacity of ~4.6 mmol·g^{-1} at a low activation temperature (~260 °C), enabling low-energy regeneration cycles. Beyond its adsorption performance, the material's lightweight structure and ease of integration into building interiors allow passive, scalable deployment without modification to existing HVAC systems. This positions the technology as a dual-impact solution advancing CCU goals through renewable, low-cost sorbents while supporting sustainable building innovations that improve indoor air quality in educational and commercial spaces.

Introduction

Modern lifestyles result in individuals spending approximately 80–90% of their daily lives indoors [1]. This raises serious concerns regarding the health impacts of indoor air pollution, which is now recognized as posing greater risks to human health than outdoor pollution [2]. A large-scale study involving 9,196 participants revealed that nearly 87% of indoor time occurs in residential buildings, office spaces, restaurants, malls, educational institutions, and other enclosed settings [3].

Indoor air quality (IAQ) has therefore become a critical determinant of comfort, health, and productivity. Improved IAQ is strongly associated with enhanced cognitive function, reduced prevalence of respiratory illnesses, and increased workplace performance [4]. Conversely, poor IAQ contributes to respiratory and cardiovascular diseases, allergic responses, and in severe cases, life-threatening conditions.

Indoor environments are characterized by a complex mixture of pollutants, including CO_2, volatile organic compounds (VOCs), particulate matter (PM), and bioaerosols, originating from human occupancy, building materials, combustion processes, and outdoor infiltration [5]. Among these, CO_2 is of particular concern, as human respiration alone releases ~37 g/h per person [6].

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Elevated CO_2 levels in classrooms and workplaces have been shown to impair decision-making, cognitive performance, and overall productivity, with reductions of up to 6–9% observed at concentrations between 1000 and 2500 ppm compared to baseline levels near 600 ppm [7–9].

Conventional carbon capture technologies remain poorly suited for indoor applications, where CO_2 concentrations are lower than in industrial flue gases but remain persistently elevated (1000–2000 PPM). This limitation highlights the need for low-cost, sustainable adsorbents specifically designed for enclosed environments [10]. Biomass-derived sorbents have emerged as promising alternatives due to their abundance, renewability, and tunable surface functional groups that enable pollutant adsorption. Recent studies have demonstrated that tailoring porosity and surface chemistry can enhance the capacity for CO_2 uptake, positioning biomass as a viable solution for both indoor air purification and sustainable carbon management [11–16].

This paper aims to investigate the performance of a bio-based adsorbent derived from thermally puffed and chemically modified waste rice for indoor CO_2 capture. Specifically, the study evaluates the adsorption efficiency of the material in a customized 1 × 1 × 1 m controlled environmental chamber simulating classroom conditions, optimizes key operational parameters using Response Surface Methodology (RSM), and demonstrates its potential as a scalable and sustainable solution for improving IAQ in built environments.

To achieve this aim, the research pursues the following objectives:

- To evaluate the adsorption performance of the puffed rice–based material under systematically varied environmental conditions of temperature, relative humidity, and surface coverage in a customized chamber.
- To optimize the operational parameters affecting CO_2 removal efficiency and kinetic behavior using Response Surface Methodology (RSM).
- To assess the practical feasibility of the developed adsorbent as a low-cost, sustainable, and scalable solution for integration into building interiors without modification of existing HVAC systems.

Methodology

This study adopts a systematic experimental framework to evaluate the performance of a bio-based purification material derived from treated puffed rice media for indoor CO_2 reduction. The methodology is based exclusively on laboratory-scale experimentation conducted in a customized 1 × 1 × 1 m controlled environmental chamber designed to simulate classroom conditions.

The methodological approach is organized into three key phases:

- Controlled chamber experiments

The puffed rice–based adsorbent was installed on the interior surfaces of the customized chamber. Environmental parameters were systematically varied, including temperature (20–30 °C), relative humidity (45–65%), and surface coverage ratio (35–55%). A baseline CO_2 concentration of approximately 1000 ppm was established through controlled injection, after which concentration decay was monitored for up to four hours.

- Data collection and validation

CO_2 concentration levels were continuously monitored using calibrated non-dispersive infrared (NDIR) CO_2 sensors, with additional logging of temperature and relative humidity. Each run was repeated to ensure data reliability, and adsorption behavior was quantified in terms of removal rate and kinetic constants.

- Response surface methodology (RSM) optimization

The experimental data served as the input for statistical modeling using Minitab software [17]. A Central Composite Design (CCD) was employed to evaluate the influence of independent variables (temperature, relative humidity, coverage %) on CO_2 removal efficiency. Analysis of

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Variance (ANOVA) was used to validate the model's significance, while response surfaces were employed to determine the optimal operating conditions for maximum CO_2 adsorption.

This structured methodology ensures that the adsorption behavior of the bio-based material is evaluated under realistic indoor conditions. At the same time, statistical modeling provides predictive insight into its performance and scalability for practical building applications.

Results and Discussion

Experimental Setup Result

To evaluate the CO_2 absorption performance of the developed circular purification media under controlled conditions, a laboratory-scale simulation chamber was designed and constructed. This experiment aimed to quantify the percentage of CO_2 absorbed after 4 hours of continuous exposure under varying operational conditions. The study used an RSM design matrix comprising 18 experimental runs, each varying three parameters:

- Temperature (T),
- Relative Humidity (RH),
- Material Coverage Ratio (applied on the internal wall and ceiling surfaces).

Each run was carried out by introducing an initial CO_2 concentration of 1000 ppm into the chamber and recording the average CO_2 level after 4 hours. The CO_2 absorption percentage was then calculated as follows, Eq.1:

$$CO_2\ Adsorption\ \% = \left(\frac{C\ initial - C\ final}{C\ initial}\right) \times 100 \quad (1)$$

The CO_2 concentration profiles recorded across the 18 experimental runs over 4 hours revealed significant variations in adsorption performance depending on temperature, relative humidity, and coverage percentage, as shown in Table 1. Among all the tested conditions, run 6 demonstrated the most efficient performance, reducing CO_2 concentration from 1001 ppm to 684 ppm. This run was conducted at a moderate temperature of 25°C, relative humidity of 55%, and material coverage of 45%, which appeared to be optimal for achieving sustained CO_2 reduction over time.

Similarly, runs 4, 7, 8, and 10 also showed strong performance, each achieving more than 300 ppm of CO_2 removal, indicating that maintaining moderate temperature and relative humidity levels, combined with 45% coverage, creates favorable conditions for adsorption. These conditions likely balance the material's surface activation, pore accessibility, and the diffusion rate of CO_2 into the adsorbent.

In contrast, run 5 exhibited the poorest performance, with a minimal reduction from 986 ppm to 880 ppm. This run was conducted at 25°C and 55% RH, but with a low coverage of 35%, which appears insufficient to support effective gas–solid interactions. Additionally, runs 9, 18, and 17 also displayed relatively low reductions, suggesting that either high or low extremes in relative humidity or insufficient surface area due to lower coverage can hinder the CO_2 uptake capacity. Overall, the results indicate that a coverage ratio between 45–50%, moderate temperatures (25–30°C), and relative humidity in the range of 50–60% provide the best operational window for the developed purification material. These findings are crucial for informing us of practical deployment strategies in real indoor environments, where fine-tuning parameters can significantly influence air quality outcomes.

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Table 1. Summary of CO_2 absorption performance across RSM experimental runs.

Run	0-15 min	60-75 min	120-135 min	180-195 min	225-240 min
1	987	934	881	829	790
2	998	940	889	833	792
3	994	940	892	838	799
4	991	909	826	746	683
5	986	961	930	904	880
6	1001	914	830	748	684
7	985	905	825	743	683
8	998	916	833	750	686
9	990	962	929	903	878
10	991	910	828	746	686
11	999	946	897	846	806
12	987	936	888	839	804
13	989	936	890	842	805
14	982	938	889	863	809
15	999	947	893	840	802
16	981	902	825	747	690
17	991	943	895	846	811
18	984	955	927	898	872

Adsorption Kinetics and Isotherm Modeling

To assess the time-dependent behavior of CO_2 removal, first-order kinetic modeling was applied to the 4-hour concentration data of all 18 experimental runs. The concentration profiles, recorded at 15-minute intervals, were fitted using the exponential decay mode Eq. 2:

$$C_{(t)} = C_0 \cdot e^{-kt} \quad (2)$$

Where:

- $C_{(t)}$ is the CO_2 concentration at time t,
- C_0 is the initial concentration,
- k is the rate constant (hr^{-1}).

The rate constant (k) was calculated for each run using the starting and final concentrations, as shown in Table 2. The fit quality was validated using the coefficient of determination R^2, and the average CO_2 reduction rate (ppm/hour) was calculated over the 4-hour duration. Fig. 1 shows that Run 6 had the highest performance, with an average reduction rate of 79.25 ppm/hr, a rate constant of 0.0952 hr^{-1}, and an R2 of 0.9947, indicating a very strong model fit. Similarly, runs 4, 7, 8, and 10 exhibited high reduction rates, all above 75 ppm/hr, with comparable rate constants and excellent R2 values above 0.993. On the other hand, runs 5, 9, and 18 demonstrated significantly slower rates, with average reductions around 27 ppm/hr, and lower rate constants in the range of 0.028–0.030 hr^{-1}.

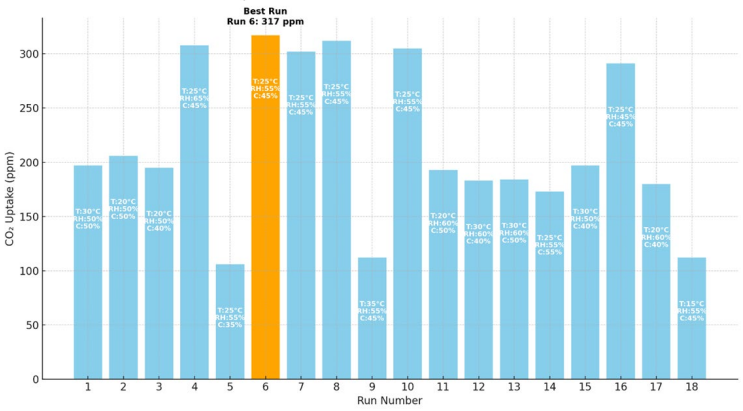


Figure 1. CO_2 uptake across all experimental runs with embedded experimental parameters.

The values of the rate constant k indicate how quickly each configuration removes CO_2 from the air, with higher values reflecting faster adsorption kinetics. Across all runs, the R2 values exceeding 0.98 demonstrate that the pseudo-first-order model accurately captured the reduction behavior in every scenario. A clear trend was observed where runs conducted under moderate temperature (25–30°C), relative humidity (50–60%), and material coverage between 45–50% exhibited higher rate constants and faster CO_2 reduction. In contrast, runs with low coverage or extreme humidity levels were consistently among the slowest performers, suggesting that these environmental and deployment parameters play a critical role in optimizing the material's effectiveness.

Table 2. Summary of CO_2 reduction performance and kinetic parameters for all experimental runs.

Run	Initial ppm	Final ppm	CO_2 Uptake (ppm)	Rate Constant k (hr^{-1})	R^2	Average Rate (ppm/hr)
1	987	790	197	0.0557	0.9945	49.25
2	998	792	206	0.0578	0.9939	51.5
3	994	799	195	0.0546	0.9959	48.75
4	991	683	308	0.0931	0.9958	77
5	986	880	106	0.0284	0.9913	26.5
6	1001	684	317	0.0952	0.9947	79.25
7	985	683	302	0.0915	0.9939	75.5
8	998	686	312	0.0937	0.9948	78
9	990	878	112	0.03	0.9913	28
10	991	686	305	0.092	0.9952	76.25
11	999	806	193	0.0537	0.9924	48.25
12	987	804	183	0.0513	0.9889	45.75
13	989	805	184	0.0515	0.989	46
14	982	809	173	0.0484	0.9918	43.25
15	999	802	197	0.0549	0.9927	49.25
16	981	690	291	0.088	0.9942	72.75
17	991	811	180	0.0501	0.9926	45
18	984	872	112	0.0302	0.9911	28

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To identify the most suitable kinetic model, additional fits were performed using pseudo-second-order and linear isotherm equations. Although these models provided acceptable approximations in some cases, the pseudo-first-order model consistently achieved the highest coefficient of determination (R^2) across all 18 runs. It effectively captured early-phase reduction trends and reflected the expected physical behavior of CO_2 interaction with the developed bio-based material. The model's simplicity and strong statistical performance confirm it as the most reliable and representative approach for describing the observed adsorption kinetics.

To assess long-term performance, the pseudo-first-order model from Run 6 was extrapolated to 48 hours. As illustrated in Fig. 2, CO_2 concentration continued to decline, with the model predicting levels below 200 ppm after roughly 16 hours. This indicates that the material performs efficiently in the short term and maintains purification capacity over extended periods, supporting its potential for deployment in real indoor environments requiring sustained air-quality control.

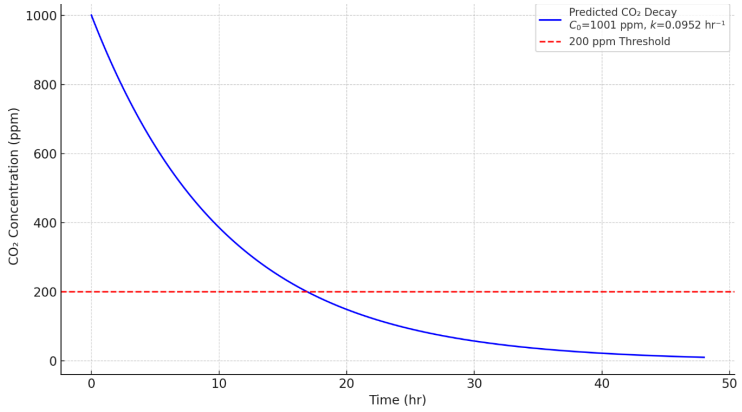


Figure 2. Predicted CO_2 concentration over 48 hours for run 6 using the pseudo-first-order model.

Although the experiments were conducted in a sealed chamber, the derived adsorption kinetics and scaling analysis indicate that under continuous occupancy the material would operate in a dynamic equilibrium, offsetting occupant-generated CO_2 rather than achieving complete removal. Given the low short-term capacity utilization and long predicted saturation time at room scale, regeneration can be performed periodically during unoccupied hours without disrupting building operation.

Material Scaling from Chamber to Room-Level Application

To evaluate the long-term performance and scalability of the developed CO_2 purification material, a two-phase approach was adopted: small-scale controlled chamber testing, followed by predictive modeling for full room application. Initial testing was conducted in a controlled 1×1 m experimental chamber designed to replicate indoor environmental conditions. Circular material samples (10 cm diameter, 1.2 cm thickness, 9 g per unit) were uniformly installed to cover 45% of the chamber's surface area, equivalent to 0.45 m^2. Over a 4-hour testing period (Run 6), a reduction in CO_2 concentration from 1001 ppm to 684 ppm was recorded equivalent to a removal of approximately 28.5 grams of CO_2. Based on the estimated adsorption capacity of 500 mg CO_2 per gram of material, each 9 g sample adsorbed up to 4.5 g of CO_2 before saturation.

Based on the lab experiment, it was determined that approximately 57 circular samples were used to achieve 45% coverage in the chamber. This provided a total theoretical adsorption capacity of ~257 grams, of which only ~5 mg per sample was utilized during the 4-hour test. This indicates

that the material operated well below its saturation limit, demonstrating suitability for longer-term use without immediate regeneration.

For assessing a real-world applicability, the model was extended to a typical classroom-sized space (5 × 5 m area with 3 m height). The total internal surface area, including walls, ceiling, and floor, was calculated as 110 m². A 45% coverage scenario consistent with the effective range from chamber testing was assumed, resulting in 49.5 m² of treated surface area, summarized in Table 3. Given the surface area of each circular sample, approximately 6,303 material units would be required to achieve this coverage. In the room-scale extrapolation (5 × 5 × 3 m classroom), the floor area was deliberately excluded from the treated-surface calculations because of practical considerations related to abrasion, cleaning requirements, and potential moisture exposure, which would limit the durability of the installed material. Consequently, the internal envelope considered consisted only of the four vertical walls (60 m² in total) and the ceiling (25 m²), resulting in a cumulative surface area of 85 m² rather than the full 110 m² if the floor had been included.

Table 3. Comparison of chamber and room-scale co_2 purification setup (at 45% coverage.

Parameter	Chamber (1 m²)	Full room without the floor
Treated Surface Area (m²)	0.45	38.25
Total Internal Surface (m²)	1m	85
Material Coverage (%)	45%	45%
Sample Weight (g)	9	9
Number of Samples Used	~57	~4,870
Estimated Time to Saturation	~9 days	~770 days

A brief comparative analysis with commonly reported bio-based and activated carbon sorbents indicates that the proposed puffed rice–based material exhibits a competitive CO_2 adsorption capacity (~4.6 $mmol \cdot g^{-1}$) under indoor-relevant conditions, comparable to coconut-shell and bamboo-derived activated carbons. The adsorption behavior is dominated by physisorption, enhanced by surface hydroxyl and alkali-induced functional groups that promote weak acid–base interactions with CO_2. Unlike many conventional bio-adsorbents requiring high activation temperatures (≥600–900 °C), the developed material is activated at a substantially lower temperature (240–280 °C), reducing processing energy demand [18] and supporting lightweight, passively integrated indoor air purification applications.

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