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Article

Lithium-Containing Sorbents Based on Rice Waste for High-Temperature Carbon Dioxide Capture

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Abstract: This article studies the influence of the nature of the carrier from rice wastes on the sorption properties of lithium-containing sorbents, and also considers the impact of the modifying additive (K_2CO_3) and adsorption temperature on their characteristics. It has been shown that the sorption capacity of 11LiK/SiO_2 at 500 °C reached 36%, which is associated with the formation of lithium orthosilicate in the sorbent composition, as well as with an increase in the specific surface area of the sorbent. After 12 cycles of sorption–desorption, it was found that the sorption capacity of 11LiK/SiO_2 for CO_2 decreased by only 8%. Rice waste-based sorbents have a high sorption capacity for CO_2 at high temperatures, which allows them to be used for carbon dioxide capture. The results of this study indicate the prospects of using agricultural residues to create effective adsorbents that contribute to reducing environmental pollution and combating global warming.

Keywords: capture; carbon dioxide; sorption; sorbent; rice waste

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1. Introduction

Mitigating the effects of global climate change is one of the most pressing challenges of our time [1–3]. At the Climate Change Summit held on 23 September 2019, it was announced that 77 countries, 10 regions, and more than 100 cities had committed to achieving net-zero carbon emissions by 2050 [4,5]. Achieving this ambitious goal requires the development of zero- and low-carbon energy technologies, which remains a top priority for these pioneering nations [6]. Among the key strategies to reduce carbon emissions is the advancement of carbon capture, utilization, and storage (CCUS) technologies, which are essential as fossil fuels will likely continue to play a major role in global energy consumption in the near future [7].

Carbon capture technologies can be categorized into three main approaches based on the point of carbon dioxide capture within fossil fuel power plants: pre-combustion, post-combustion, and oxy-combustion [8]. Historically, amine-based solvents have been widely used for capturing CO_2 from flue gases [9]. While effective, this method demands high energy for solvent regeneration and poses environmental concerns due to the release of hazardous by-products during the process. These drawbacks have shifted the focus of researchers towards solid adsorbents as a more sustainable alternative [10–12].

Solid adsorbents have gained renewed attention due to their lower energy requirements, environmental safety, faster adsorption kinetics, and greater stability under extreme conditions compared to liquid absorbents [13–15]. However, the capture and separation of CO_2 from large volumes of flue gas remain energy-intensive and costly. This has made the development of efficient sorbents crucial, especially for concentrated gas flows, to reduce the overall cost of the adsorption process. Despite advancements, particularly in post-combustion CO_2 capture, no ideal sorbent has yet been identified. Current materials face significant challenges, including their low CO_2 capture capacity, poor selectivity under real pressure conditions, high costs, slow adsorption kinetics, and sensitivity to moisture [16]. Therefore, research efforts are increasingly focused on developing sorbents with lower regeneration energy, faster adsorption/desorption rates, and greater stability, aiming for more economically viable carbon capture technologies [17].

The scientific problem addressed by this study is the development of more efficient and cost-effective high-temperature CO_2 sorbents with improved stability over multiple cycles. Existing calcium-based sorbents suffer from significant degradation after 20–30 cycles of use, mainly due to abrasion and sintering, which reduce their overall effectiveness [18]. In contrast, lithium-based sorbents, particularly lithium orthosilicate (Li_4SiO_4), have demonstrated higher stability at elevated temperatures (550–700 °C) and are more effective for CO_2 capture in this temperature range [19]. However, lithium-based sorbents still face challenges related to adsorption kinetics and regeneration efficiency [20–22]. This research introduces rice waste as a sustainable source of silica and carbonized silica to enhance the sorption properties of lithium-containing materials. By investigating the comparative influence of silica and carbonized silica derived from rice waste on the high-temperature CO_2 sorption properties of lithium-based sorbents, this study aims to address these limitations and contribute to the development of more effective carbon capture technologies.

One effective solution to improve the performance of lithium-based sorbents involves doping with small amounts of alkali metal carbonates, such as K_2CO_3 or Na_2CO_3 [23]. Research has shown that doping Li_4SiO_4 with potassium or sodium carbonates enhances the CO_2 sorption capacity, although Na_2CO_3 doping can lead to sintering after multiple cycles [24,25]. The performance of Li_4SiO_4 is also strongly influenced by the synthesis method and the nature of the silicon precursor. Studies have demonstrated significant differences in the purity, crystallite size, crystallinity, and specific surface area of Li_4SiO_4 synthesized from different raw materials [26,27]. A cost-effective and abundant source of silicon oxide is rice waste, which is rich in silica.

This study investigates the comparative influence of carriers derived from rice waste, such as silicon oxide and carbonized silicon oxide, on the physicochemical properties and high-temperature CO_2 sorption performance of lithium-based sorbents. By utilizing rice waste, this research not only explores an eco-friendly and economically viable material for sorbent production but also seeks to improve the performance of lithium-containing sorbents for high-temperature CO_2 capture.

2. Materials and Methods

2.1. Synthesis of Silicon Oxide and Carbonized Silicon Oxide from Rice Wastes

Rice wastes (rice husks and stems) from the Kyzylorda region of the Republic of Kazakhstan were used as raw materials for obtaining silicon oxide (SiO_2) and carbonized silicon oxide. The process of obtaining SiO_2 from rice husks involved several steps of pretreatment and heat treatment. First, the rice husks were cleaned of dust and sand by washing them multiple times with distilled water, followed by drying at 120 °C for 4 h. After drying, the husks were mixed with concentrated hydrochloric acid (HCl) in a 1:10 ratio and heated at 90 °C for 24 h. The purpose of adding HCl at this stage is to remove metallic impurities (such as iron and calcium) and organic residues that can affect the purity of the SiO_2. The resulting mixture was filtered, washed several times with distilled water, dried again at 120 °C for 4 h, and calcined at 600 °C for 4 h. After calcination, a white powder (ash) was obtained, consisting mainly of SiO_2. To further increase the purity of the SiO_2, the ash was dissolved in a 2M NaOH solution at 90 °C for 2 h while being stirred on a magnetic stirrer. This step converts the SiO_2 into sodium metasilicate, a soluble form of silicon. Afterward, concentrated HCl was added to the solution. The second addition of HCl is necessary to neutralize the sodium metasilicate and precipitate the SiO_2 as a solid. The resulting solution was filtered through a vacuum filter, and the solid SiO_2 was washed with hot distilled water and dried at 120 °C for 12 h, resulting in highly purified SiO_2. The elemental composition of the obtained sample consists of 99.4% SiO_2, 0.4% K_2O, and 0.2% CaO. The specific surface area of the obtained sample is 150 m^2/g. To obtain carbonized silicon oxide (SiO_2 + C), rice waste (rice husks, stems) were crushed to the size of 0.25 mm particles. The pellets were obtained by adding a binder to the milled rice waste. The resulting pellets were placed in a tubular furnace, hermetically sealed, and filled with gaseous nitrogen grade A. The carbonization process was carried out with a temperature rise rate of 10 °C per minute up to 500 °C and held at this temperature for 100 min. Activation was carried out with water vapour at a temperature of 850 °C in a high temperature vacuum tube furnace of the BR-12 NFT series under the optimal conditions previously identified by us. The elemental composition of the obtained sample consists of 63% SiO_2, 34% C, and 3% Na_2O. The specific surface area of the obtained sample is 273.5 m^2/g.

2.2. Preparation of Sorbents

The sorbents used in this work were synthesized by the mixing method. Samples of 10Li/SiO_2 and 10Li/SiO_2 + C were prepared by mixing Li_2CO_3 and amorphous SiO_2 and/or SiO_2 + C in a ratio of 1:9. Samples of 11LiK/SiO_2 and 11LiK/SiO_2 + C were prepared by mixing Li_2CO_3 and K_2CO_3 with amorphous SiO_2 and/or SiO_2 + C in the ratio of 1:0.1:8.9.

After complete stirring, the mixture was dried at 200 °C for 2 h and then subjected to heat treatment at 750 °C for 3 h. The resulting sorbents were moulded into tablets with a diameter of 2–3 mm, then placed in a reactor and the CO_2 capture study was carried out.

2.3. Evaluation of CO_2 Sorption

The synthesized sorbents were tested in carbon dioxide capture at atmospheric pressure. To determine the sorption capacity, the composite sorbent (1 g) was placed in a fixed bed reactor, the reactor was placed in an electric furnace. Before starting the experiment, the samples were degassed at 200 °C for 60 min. Then, 100% carbon dioxide was supplied to the sorbent at a rate of 15 mL/min for 30 min at a specific temperature, from 100 to 500 °C. After that, the gas composition was changed to pure helium to remove gaseous CO_2 from the reactor and the temperature of the reactor was raised to 750 °C.

The efficiency of cyclic sorption was tested using 12 sorption/desorption cycles. The CO_2 sorption/desorption process was carried out at 500 °C in 100 vol.% CO_2 (15 mL/min) for 30 min and 750 °C in 100 vol.% helium for 30 min.

The exhaust gasses were analyzed using a Chromos GC-1000 (Russia, Novosibirsk) gas chromatograph equipped with a thermal conductivity detector (TCD).

2.4. Investigation of the Physico-Chemical Characteristics of Samples

Physico-chemical characterization of the sorbents was carried out by XRD, Raman spectroscopy, SEM, etc. The spent sorbents were investigated in adsorption at 500 °C and desorption at 750 °C.

X-ray diffractometric analysis was carried out on an automated diffractometer DRON-3 with CuKa -radiation, β-filter. Conditions of diffractograms shooting were the following: U = 35 kV; I = 20 mA; shooting θ-2θ; detector 2 deg/min. X-ray phase analysis on a semi-quantitative basis was performed on powder sample diffractograms using the method of equal suspensions and artificial mixtures. Quantitative ratios of crystalline phases were determined. The interpretation of diffractograms was carried out using the ICDD file data: PDF 2 (Powder Diffraction File) Release 2022 and the HighScorePlus programme. Content calculations were performed for the main phases.

A JEOL JSM-6390 LA model scanning electron microscope (JEOL, Tokyo, Japan) with a JED 2300 energy dispersive X-ray detector was used to investigate the morphology of the composite. The composites were imaged on carbon tape where micrographs were taken at an accelerating voltage of 30 kV. The distribution of elements on the surface of the composites was performed with Analysis Station software version 3.62.07 (JEOL Engineering, Freising, Germany) using the standardless ZAF method.

To determine the structure of the formed carbon on the composites, measurements were performed on a Raman spectrometer Solver Spectrum (NT-MDT Company, Moscow, Russia) with excitation laser radiation of 473 nm. The laser was focused on the sample using a 100× objective to a spot with a diameter of 2 micrometres. A 600/600 diffraction grating with a spectral resolution of 4 cm^{-1} was used to record the signal. The signal accumulation time was 60 s.

IR spectra were recorded and processed on a VERTEX 70 FT-IR spectrometer (Bruker VERTEX, Ettlingen, Germany) in the frequency range from 4000 to 500 cm^{-1} and using a PIKE MIRacle ATR single impaired internal total reflection (SIRIR) attachment with a germanium crystal. The results were processed using the software OPUS 7.2.139.1294. Attenuated total internal reflection (ATR) is the most popular infrared spectroscopy technique because it is easy to use and provides high-quality spectra without prior sample preparation. ATR is used for the analysis of solids, liquids and gels. The sample is placed, pre-degreased with alcohol, on the ATR attachment of the IR spectrometer. The sample is placed horizontally on the surface of the optical material. To record the spectrum, it is enough to ensure contact between the sample under study and the crystal of the attachment. Observe the spectrum acquisition process. ATR spectra are practically no different from the absorption spectra obtained by the classical method and are easily identified from spectral libraries.

3. Results

Pre-Sorption Analysis

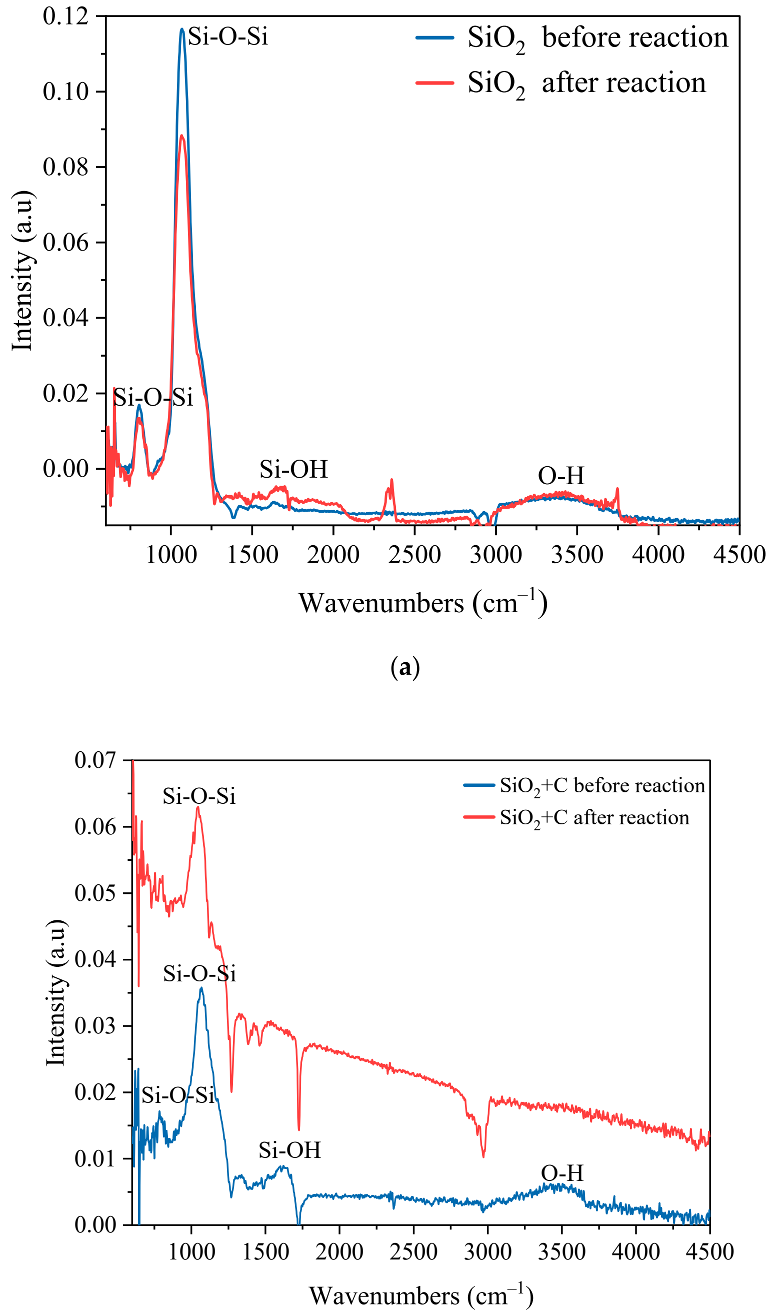
The FTIR spectra of fresh and spent silicon oxide and carbonized silicon oxide in the sorption and desorption of CO_2 are shown in Figure 1.

In the spectra of fresh carbonized silicon oxide, a wide absorption band is observed at 3500 cm^{-1}. According to the literature [28], absorption bands in the range of 3600–3100 cm^{-1} are attributed to OH- stretching vibrations caused by surface hydroxyl groups and chemisorbed water. Low-intensity peaks are observed at ~1580 and ~2730 cm^{-1}, which are attributed to graphite-like carbon. In addition, there is a spectrum at 1050 cm cm^{-1} related to the vibration of the Si-O bond in silicon oxide.

In the spectra of silicon oxide, an intense peak is observed at ~1050 cm^{-1} related to silicon oxide. In samples of carbonized silicon oxide and silicon oxide after the adsorption and desorption of CO_2, the intensity of the peak related to SiO_2 decreases, which may be due to a change in the dispersity of the samples after the adsorption/desorption of CO_2 [29]. The phase analysis of composite sorbents based on silicon oxide is presented in Figure 2.

On the XRD profile of the 10Li/SiO_2 sorbent before and after adsorption at 500 °C, reflections are observed at 20°, 26.6° and 50°, which belong to SiO_2, and at 18.8°, 26.9° and 55.5°, which belong to the Li_2SiO_3 phase. On the sorbent, after CO_2 adsorption at 500 °C and desorption at 750 °C, the intensities of the peaks related to the Li_2SiO_3 and SiO_2 phases decrease and intense peaks appear at 23.8°, 24.7°, and 24.8°, which, according to [30], belong to the $Li_2Si_2O_5$ phase. The formation of the $Li_2Si_2O_5$ phase after CO_2 desorption may be associated with the phase transition of $Li_2SiO_3 + SiO_2 = Li_2Si_2O_5$, confirmed by a decrease in the intensity of the peaks related to Li_2SiO_3 and SiO_2.

Modification of the 10Li/SiO_2 sorbent with potassium carbonate leads to a decrease in the intensity of the peak related to SiO_2 and the formation of the Li_4SiO_4 phase, and the XRD spectrum (Figure 3) of the 11LiK/SiO_2 sorbent shows peaks at 22°, 28.4°, and 35.5°, which, according to [31], correspond to the Li_4SiO_4 phase.



(**a**)

(**b**)

Figure 1. FTIR spectra of fresh and spent silicon oxide and carbonized silicon oxide in the sorption and desorption of CO_2: (**a**) carbonized silicon oxide before and after reaction; (**b**) silicon oxide before and after reaction.

On the 11LiK/SiO_2 sorbent after CO_2 adsorption at 500 °C and desorption at 750 °C, a decrease in the intensity of the Li_4SiO_4 peak and an increase in the intensity of the SiO_2 peak are observed, which may indicate phase transitions through the following reactions [32]:

$$Li_4SiO_4 + CO_2 = Li_2SiO_3 + Li_2CO_3 \quad (1)$$

$$Li_2SiO_3 + CO_2 = SiO_2 + Li_2CO_3 \quad (2)$$

The samples after CO_2 desorption do not show Li_2CO_3 reflections, which may indicate the complete desorption of CO_2 from the sorbent. On the XRD profile of the 10Li/SiO_2 + C and 11LiK/SiO_2 + C sorbents, the peaks related to the SiO_2 and Li_2SiO_3 phases are shifted to a lower frequency region, which may be associated with an increase in the dispersion of the particle [33]. The XRD profile of samples of 10Li/SiO_2 + C and 11LiK/SiO_2 + C shows a reflection at 26.6°, which, according to [34], corresponds to the graphitic structure of carbon.

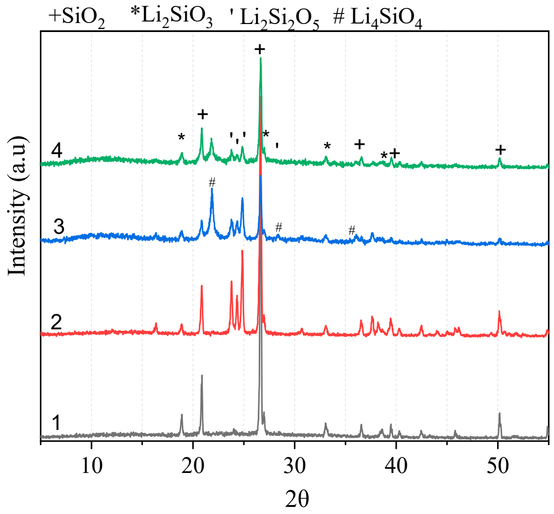


Figure 2. Diffractograms of sorbents: 1—10Li_2O/SiO_2 before adsorption of CO_2; 2—10Li_2O/SiO_2 after adsorption and desorption of CO_2; 3—10Li_2O + K/SiO_2 before adsorption of CO_2; 4—10Li_2O + K/SiO_2 after adsorption and desorption of CO_2.

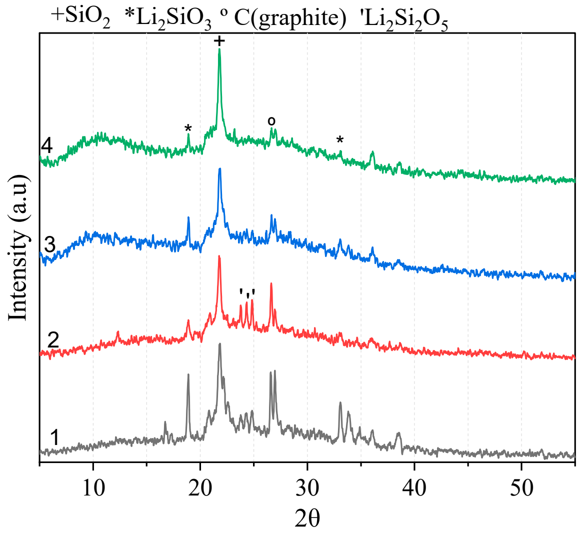


Figure 3. Diffractograms of sorbents: 1—10Li_2O/SiO_2 + C before adsorption of CO_2; 2—10Li_2O/SiO_2 + C after adsorption and desorption of CO_2; 3—10Li_2O + K/SiO_2 + C before adsorption of CO_2; 4—10Li_2O + K/SiO_2 + C after adsorption and desorption of CO_2.

Identification of phases was also carried out using Raman spectroscopy. The results of the samples are presented in Figures 4 and 5. The Raman spectrum of the sorbent 10Li/SiO_2 before the reaction shows bands at 604, 932 and 1094 cm^{-1}, which, according to [35], belong to the Li_2SiO_3 phase. After the sorption and desorption of CO_2 on the spectra of the 10Li/SiO_2 sorbent, in addition to the absorption bands of the Li_2SiO_3 phase, bands at 515 and 1100 cm^{-1} are observed, which belong to the $Li_2Si_2O_5$ phase [36]. The spectra of the K_2CO_3-modified fresh sorbent show spectra at 973 and 1037 cm^{-1}, and according to [37], these absorption bands belong to the Li_4SiO_4 phase. All observed absorption bands are mainly associated with the stretching or vibration of the Si–O bond. In the spectra of the 10Li/SiO_2 + C and 11LiK/SiO_2 + C sorbents, absorption bands related to graphite-like carbon and low-intensity absorption bands of the Si–O bond are observed [38].

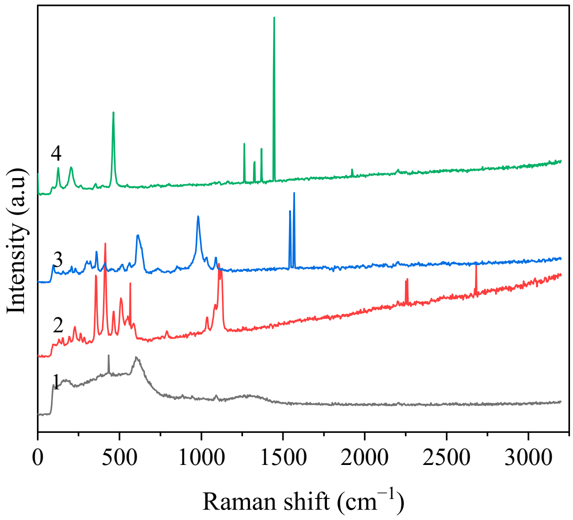


Figure 4. Raman spectra: 1—10Li/SiO_2 before sorption of CO_2; 2—10Li/SiO_2 after sorption and desorption of CO_2; 3—11LiK/SiO_2 before sorption of CO_2; 4—11LiK/SiO_2 after sorption and desorption of CO_2.

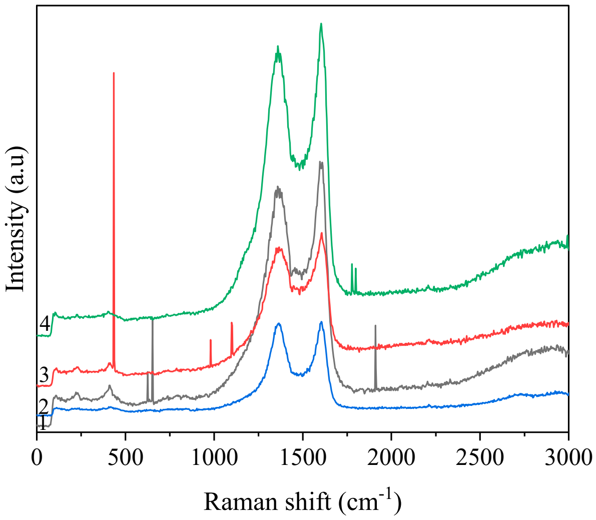
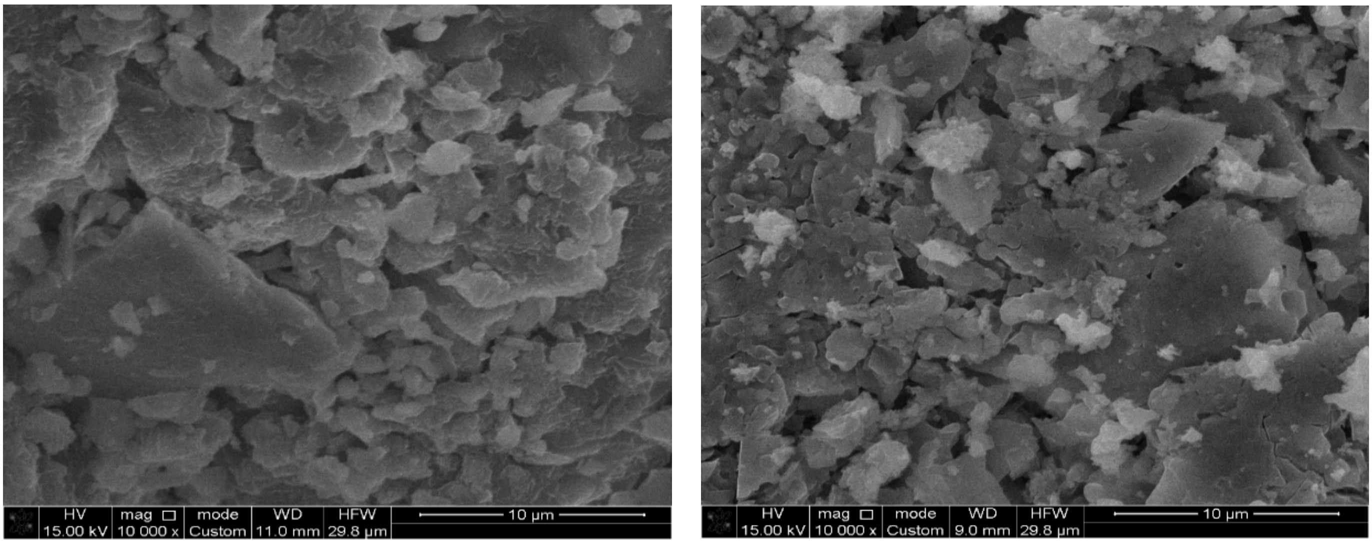


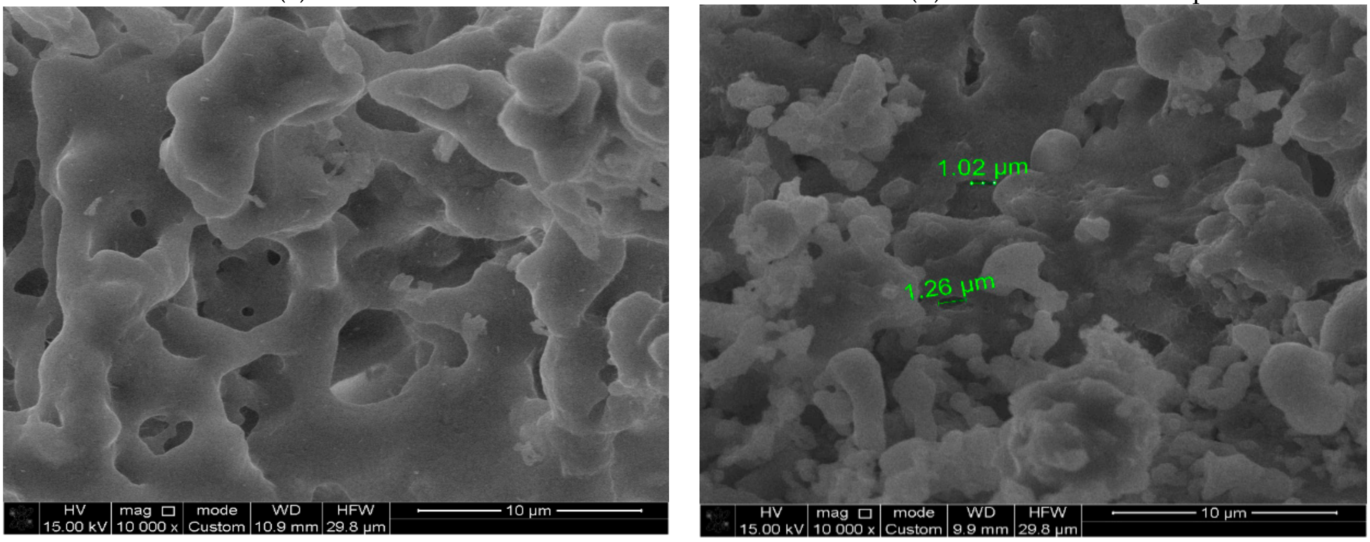
Figure 5. Raman spectra: 1—10Li/SiO_2 + C before sorption of CO_2; 2—10Li/SiO_2 + C after sorption and desorption of CO_2; 3—11LiK/SiO_2 + C before sorption of CO_2; 4—11LiK/ SiO_2 + C after sorption and desorption of CO_2.

The synthesized sorbents were characterized by SEM and the surface morphologies of these sorbents are shown in Figures 6 and 7.

Micrographs of 10Li/SiO_2 are represented by aggregates of different sizes and shapes. After the sorption and desorption of CO_2 on the 10Li/SiO_2 sample, particles appear in the form of plates accumulated in a heap; perhaps these particles belong to the $Li_2Si_2O_5$ phase [39]. Modification of the 10Li/SiO_2 sorbent with K_2CO_3 leads to a change in the morphology of the sorbent, the porosity of the sorbent increases, which is also confirmed by BET results, and the specific surface area increases from 40 to 120 m^2/g (Table 1). After the sorption and desorption of CO_2 on the 11LiK/SiO_2 sorbent, the dispersion of particle size increases, which is also confirmed by XRD results.



(**a**) 10Li/SiO2 fresh (**b**) 10Li/SiO2 after desorption

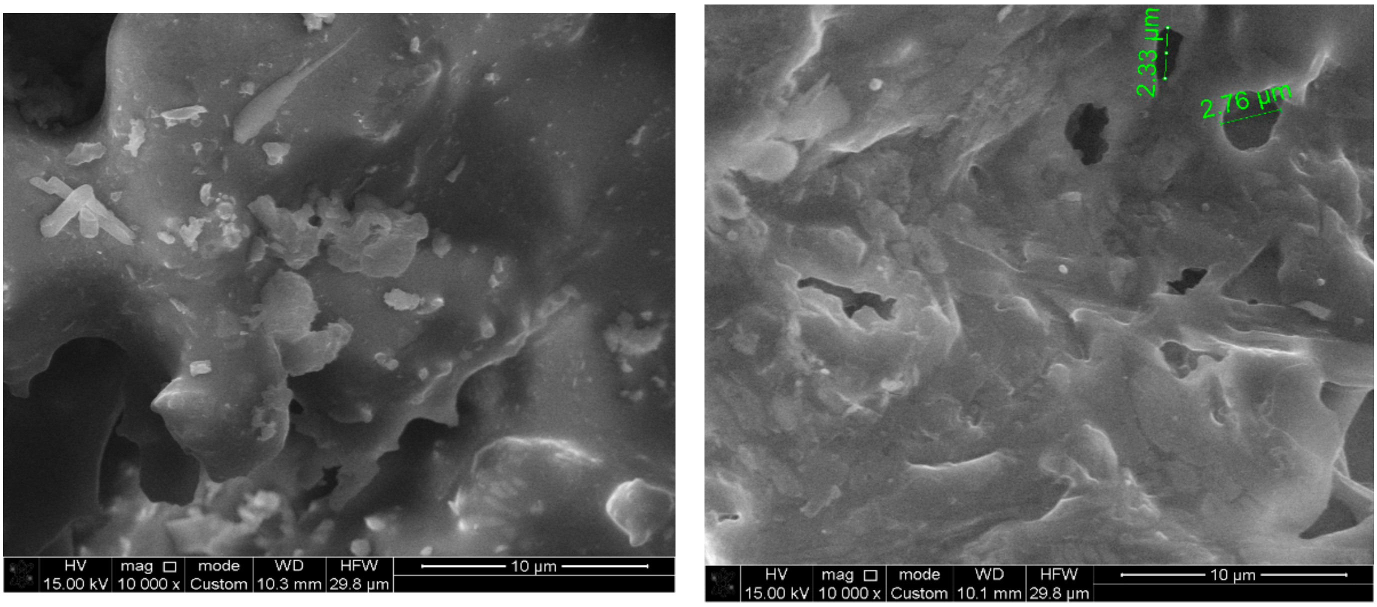


(**c**) 11LiK/SiO2 fresh (**d**) 11LiK/SiO2 after desorption

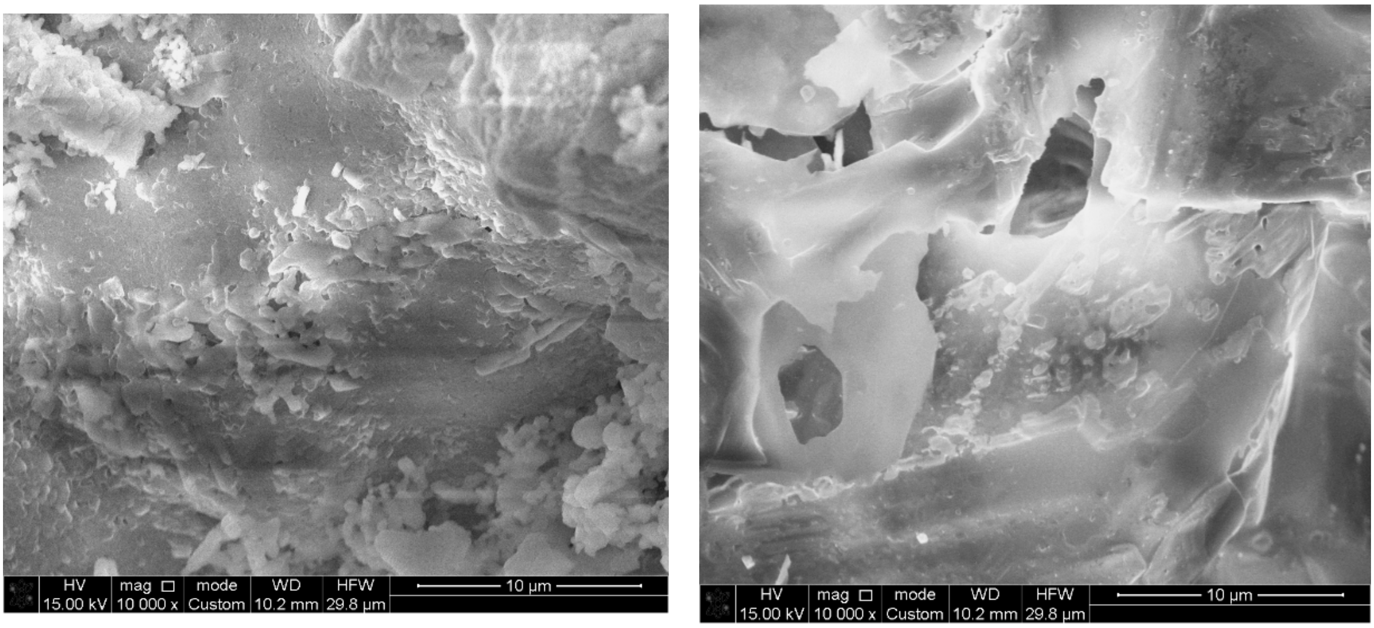
Figure 6. Microphotographs of sorbents before sorption (fresh) and after desorption: (**a**) 10Li/SiO_2 fresh; (**b**) 10Li/SiO_2 after desorption; (**c**) 11LiK/SiO_2 fresh; (**d**) 11LiK/SiO_2 after desorption.

In the micrograph of fresh 10Li/SiO_2 + C, aggregates are observed, with lamellar particles that are close to graphite [40]. In addition, rod-like particles are observed, which can be attributed to silicon oxide or to Li_2SiO_3 [41].

After the sorption and desorption of CO_2 on 10Li/SiO_2 + C, the morphology of the sample changes. Rod-shaped particles are observed in the microphotographs of the sample modified with potassium carbonate 11LiK/SiO_2 + C, which, according to [42], can be attributed to Li_2SiO_3. It is known [43] that the sorption temperature is a critical factor affecting the sorption capacity of sorbents for CO_2. Figure 8 shows the results of the influence of the potassium carbonate modifier and sorption temperature on the sorption properties of sorbents, which were studied by conducting CO_2 sorption experiments for 30 min in a fixed-bed reactor.



(**a**) 10Li/SiO₂ + C fresh (**b**) 10Li/SiO₂ + C after desorption



(**c**) 11LiK/SiO₂ + C fresh (**d**) 11LiK/SiO₂ + C after desorption

Figure 7. Microphotographs of sorbents before sorption (fresh) and after desorption: (**a**) 10Li/SiO_2 + C fresh; (**b**) 10Li/SiO_2 + C after desorption; (**c**) 11LiK/SiO_2 + C fresh; (**d**) 11LiK/SiO_2 + C after desorption.

Table 1. Designation of sorbents.

Composition	Designation	Specific Surface, m^2/g
10 wt. % Li_2CO_3/SiO_2	10Li/SiO_2	40
10 wt. % Li_2CO_3 + 1 wt. % K_2CO_3/SiO_2	11LiK/SiO_2	120
10 wt. % Li_2CO_3/SiO_2 + C	10Li/SiO_2 + C	140
10 wt. % Li_2CO_3 + 1 wt. % K_2CO_3/SiO_2 + C	11LiK/SiO_2 + C	191

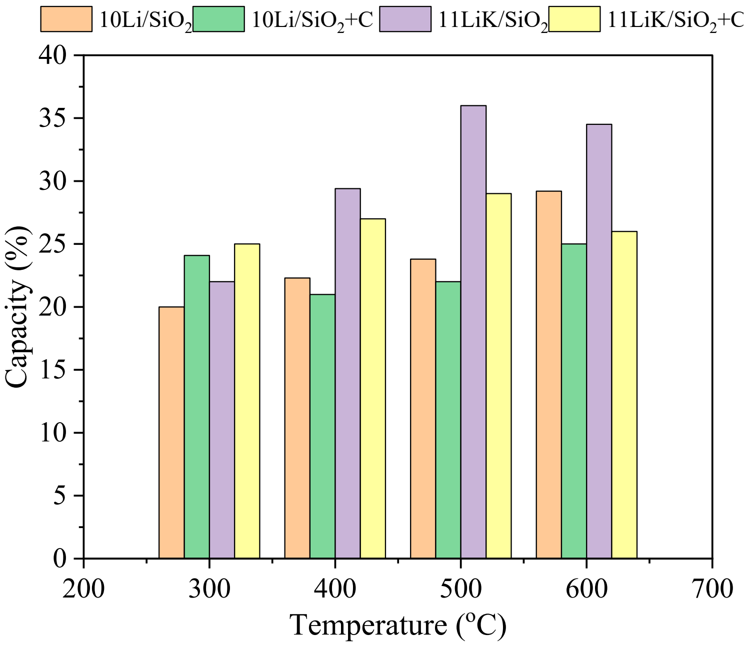


Figure 8. The influence of sorption temperature on the sorption capacity of sorbents for carbon dioxide.

The choice of potassium as a modifier is justified by the fact that the best additives increasing the sorption capacity of lithium-containing sorbents for CO_2 are potassium and sodium carbonates, but in the work of Seggiani et al. [44], it was found that the addition of Na_2CO_3 leads to the severe sintering of the sorbent after multiple sorption–desorption cycles. It was shown in [45] that the decrease in the sorption capacity of Li_4SiO_4 was significantly improved after the addition of K_2CO_3. The addition of K_2CO_3 in the amount of 1 wt.% is due to the fact that the addition of a small amount of alkaline elements leads to an improvement in the sorption properties of Li_4SiO_4 [46].

It can be seen from the results that the sorption behaviour of sorbents promoted by potassium at all sorption temperatures differs significantly from the sorbents $10Li/SiO_2$ and $10Li/SiO_2 + C$. At an adsorption temperature of 300 °C, sorbents based on $SiO_2 + C$ show a large sorption capacity.

It is possible that carbon micropores play a role at this sorption temperature, since it is known [47] that micropores with sizes less than 0.54 nm determine the ability to capture carbon sorbents. Starting from 400 °C, SiO_2-based sorbents exhibit a better sorption capacity compared to sorbents based on $SiO_2 + C$, most likely due to the high content of silicon oxide and the formation of silicates, which are sorption centres for CO_2 at high temperatures. Figure 9 shows the cyclic characteristics of $11LiK/SiO_2$ and $11LiK/SiO_2 + C$. After 12 cycles, the sorption efficiency of the $11LiK/SiO_2$ sample was more than 92%, and the $11LiK/SiO_2 + C$ sample was 89%, which indicates the excellent characteristics of the regeneration cycle. Comparison of the sorption capacity of $11LiK/SiO_2$ with other lithium-containing sorbents showed that it has good sorption capabilities compared to other sorbents [48–50] (Table 2).

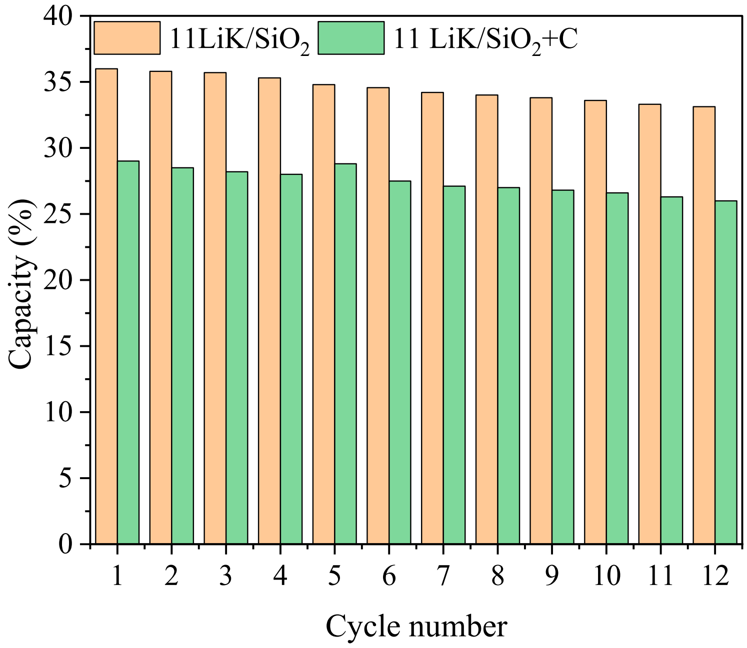


Figure 9. Cyclicity of CO_2 capture by sorbents at a temperature of 500 °C.

Table 2. Comparison of the CO_2 adsorption capacity of lithium-containing sorbents.

Composition of Sorbents	Preparation Methods	CO_2 Sorption Temperature/°C	Sorption Time (min)	Sorption Capacity	Ref./This Work
$Li_2/Na_2/K_2CO_3$	-	580	120	0.179 gCO_2/g sorbent	[44]
NaF-doped Li_4SiO_4	Sacrificial carbon template method	575	30	0.30 gCO_2/g sorbent	[46]
Li_4SiO_4	Solid state reaction process	400	-	31%	[48]
LS-LO10Na	Solid-state reaction method	550	-	0.308 gCO_2/g sorbent	[49]
Li_4SiO_4 with 10 wt% Na_2CO_3 and 5 wt% K_2CO_3	Impregnated suspension method	550	30	0.296 gCO_2/g sorbent	[50]
11LiK/SiO_2	Mixing method	500	30	36%	[This work]

4. Conclusions

In this paper, a comparative study of the influence of the nature of the carrier synthesized from rice waste on the sorption and physicochemical characteristics of lithium-containing sorbents was carried out. The influence of the potassium carbonate-modifying additive and adsorption temperature on the sorption properties of the sorbents was investigated. Firstly, the sorbents show excellent CO_2 sorption properties at high adsorption temperatures. The sorption capacity of 11LiK/SiO_2 at 500 °C reached 36% at atmospheric pressure, which is due to the formation of lithium orthosilicate in the sorbent composition, as well as to the increase in the specific surface area of the sorbent. After 12 cycles of sorption–desorption, it was found that the CO_2 sorption capacity of 11LiK/SiO_2 decreased by only 8%. This shows that the sorbent has good thermal stability. The results showed that rice waste-based sorbents can be used as high temperature sorbents for carbon dioxide capture. Therefore, using agricultural waste to create CO_2 sorbents not only helps reduce pollution from crop waste, but also effectively combats global warming. This is of great significance to the ongoing environmental remediation efforts and promotes the development of the solid waste industry to reduce pollution and carbon emissions. However, additional research is needed to gain a deeper understanding of the processes occurring during the sorption/desorption of CO_2 on sorbents obtained from rice waste.

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