Article

Sewage Sludge Derived Materials for CO$_2$ Adsorption

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Abstract: The study tried to contribute to solving two serious environmental issues: CO$_2$ reducing and sewage sludge disposal. Thus, sewage-sludge-derived materials were obtained in order to be evaluated for CO$_2$ adsorption capacity. Therefore, the char resulted after the sewage sludge pyrolysis was subjected to oxidation and chemical activation processes by using different quantities of alkaline hydroxide. One of the obtained materials, activated with a lower quantity of alkaline hydroxide, was also treated with acid chloride. Further, the materials were structural and texturally characterized, and material treated with acid chloride was used for CO$_2$ adsorption tests, due to high surface area and pore volume. The handmade system coupled to a gas chromatograph allowed the adsorption efficiency evaluation using different feed gases (rich and poor in CO$_2$) by completed purge of pipe line and on-line check. Additionally, the adsorption capacity, separation efficiency, and CO$_2$ recovery were calculated. Taking into account the values for adsorption capacity (separation efficiency and CO$_2$ recovery), it can be concluded that the sewage sludge derived material could be a promising solution for CO$_2$ reduction and waste disposal.

Keywords: adsorbents; carbon dioxide; char; pyrolysis; sewage sludge

1. Introduction

Nowadays, climate change has attracted serious attention. Despite the economic shutdown caused by the coronavirus pandemic response, carbon dioxide emissions, which are main factor in the greenhouse effect (along with methane and nitrous oxide but in a higher concentration), reached a concentration in the atmosphere in 2020 of 414 ppm, constituting a continuous increase according to National Oceanic and Atmospheric Administration Global Monitoring Laboratory [1]. Therefore, different technologies for carbon capture and storage, which involve chemical and physical adsorption, cryogenic distillation, and membrane separation, were proposed [2–7]. These processes have both advantages and disadvantages, such as high energy consumption for cryogenic distillation or the trade-off relation between the membrane permeability and selectivity. The adsorption technique has attracted serious attention due to low energy consumption and cost-efficiency ratio [7–10]. In order to be considered potential candidates for CO$_2$ adsorption, the materials must also possess some properties, such as high surface area, high pore volume, low affinity to moisture, regeneration ability, thermal and mechanical stability, and high selectivity [11]. As a consequence, various materials were obtained and proposed for CO$_2$ adsorption, including activated carbon, zeolites, silica or metal oxides [12–15]. The high demand of activated carbon for pollutants adsorption resulted from different processes and for food or pharmaceutical obtaining can be
justified due their textural properties, availability and low cost [16]. Generally, this type of materials has significant advantages, such as lower regeneration energies compared to others adsorbents [17], ability for functionalisation with different groups [18] and increased capacity to adsorb contaminants from gases and liquids matrices [19].

Commercially available activated carbons were obtained from coal, peat and petroleum coke [11,18]. However, the researchers turned their attention to huge availability of wastes rich in carbon (e.g., plastics, agricultural) as raw materials for activated carbon synthesis, trying to solve two issues at the same time: waste disposal and CO$_2$ capture [20–22]. In this context, the sewage sludge resulting from wastewater treatment plants could be a promising candidate for CO$_2$ adsorbents obtaining and energy or fuel production through different processes, such as pyrolysis [8], gasification [23] or combustion [24].

The pyrolysis products—gas, oil and char—were studied in order to get more information about their potential application and impact on the environment. Usually, the process is performed at 180–550 °C, where the moisture and volatiles losses are reached up to 390 °C and the formation of CO and CO$_2$ occurs due to bond disruption, continuing with the conversion of less reactive compounds up to 550 °C [8,25–27].

During the gasification process, the sludge is converted in synthesis gas, due to high content of moisture [23,28]. The gasification yield and cost-effectiveness were studied by optimization of process conditions [29,30]. Additionally, it was discovered that the use of sewage sludge during coal gasification, a process called co-gasification, contributed to the increase of the calorific value of the resulting gas [31]. Another advantage of this process is the minimization of the pollutant gas emissions [32,33].

Combustion is large-scale process using the sewage sludge as raw material [34]. It is achieved at a temperature above 850 °C in a fluidized bed of inert material. The combustion requires a prior drying, in order to reach a sewage sludge moisture less than 65% [35]. A serious drawback is the high pollutant gas emission, requiring purification systems.

The solid residual char resulting from these processes is rich in metals, and its disposal is an issue that must be solved in terms of the environment protection. Thus, many researchers turned their attention to obtain adsorbents from the solid char resulting from the pyrolysis of different wastes, such as plastics [20] or agricultural [21].

Additionally, activated carbon, for CO$_2$ removal from biogas, was obtained from sewage sludge through physical activation process [36]. It has been shown that the activating temperature and the agent influence the efficiency. Thus, at 600 °C and by using nitrogen as activating agent, the adsorption capacity was higher. In other study, biochar was obtained for the CO$_2$ adsorption through microwave co-torrefaction of various quantities of sewage sludge and Leucaena wood [37]. The adsorption capacity of biochar increased directly with the quantity of the Leucaena wood in mixtures.

Taking into account the above-mentioned aspects, the aim of the study was to transform the sewage sludge into valuable materials with high CO$_2$ retaining capacity.

2. Materials and Methods

The sewage sludge was obtained from a local sewage treatment plant (WWTP Ramnicu Valcea, Romania) after the anaerobic digestion. From the textural point of view, the sewage sludge was similar to plasticine, having high humidity, more than 80 wt % (gravimetrically determined up to constant weight) [38]. Therefore, prior to pyrolysis process, in order to obtain the char, there were two necessary stages (steps) for the material preparation. First, the material was dried using a moisture extractor to achieve a humidity less than 5%, and further it was grounded in a ball mill (Fritsch, Idar-Oberstein, Germany), to obtain a particle size less than 250 µm [38].

A previously developed experimental setup was used for the pyrolysis process [39]. The pyrolysis temperature interval was 23–450 °C, with a gradient of 5 °C/min. The temperature increased after 25 min, resulting in three products: oil, gas and char. Further, an oxidation process was applied to 20 g of solid waste (char) using a sandwich support. This setup facilitated the continuous flow of oxidizing gas (10 vol % O$_2$ in N$_2$). The
oxidation process was achieved in 4 h with a flow rate of 100 mL/min and a gradient of 10 °C/min up to 280 °C. Prior to the oxidation process, an inert atmosphere was insured in the reactor using the same flow rate of the binary gas for 30 min.

After the oxidation, a chemical activation process was performed using KOH (Sigma Aldrich, Darmstadt, Germany). The oxidized SS_PyCHAR and alkaline hydroxide were manually grinded until the mixture became homogenous. In order to assess the influence of KOH, three mixtures were obtained: (i) SS_PyCHAR:KOH (1:1) (further noted I_1); (ii) SS_PyCHAR:KOH (1:2) (further noted I_2); and (iii) SS_PyCHAR:KOH (1:3) (further noted I_3). The first type of mixture, SS_PyCHAR:KOH (1:1), was also treated with 5M HCl (Sigma Aldrich, Darmstadt, Germany) (1 g mixture to 20 mL HCl) by using a known method [40] in order to observe the influence on the material properties (further noted I_4). The obtained solution was filtered (cellulose filter, with 25 µm pore size and 580 mm × 580 mm size-Merck KGaA, Darmstadt, Germany), and its pH was adjusted to 6. The filtrate, together with the filter paper, was placed on the watch glass and dried at 105 °C for 6 h in an oven (Nahita 631, Stuttgart, Germany) without ventilation.

The obtained materials, due to poor content of volatiles, were pelletized by using starch powder as a binder (9:1). The pellets were obtained at 1 g weight by using a pelletizer (IKA, Konigswinter, Germany) and dried at 105 °C for 4 h.

After the pelletizing process, a thermal activation was performed by introducing the pellets into the reactor [17] placed into a calcination oven equipped with PID panel for temperature control. The process was carried up to 750 °C, with an increment of 10 °C/min, under inert atmosphere, by using a flow rate of 100 mL/min N₂ (99.999 vol.%, Messer, Bucharest, Romania).

The obtained pellets were weighted prior to and after these processes, and a mass loss of 30% was noted. The pellets aspect and their physical properties are presented in Figure 1 and Table 1, respectively.

Figure 1. Sewage sludge char pellets.

Table 1. Pellets physical properties.

| Shape (Appearance) | Height (mm) | Diameter (mm) | Weight (g) | Colour |
|--------------------|-------------|---------------|------------|--------|
| circular           | 11.46       | 12.74         | 0.7        | black  |
For CO₂ adsorption tests, two gas mixtures were used: (i) 0.1 vol.% CO₂ in N₂ (Messer, Bucharest, Romania) and (ii) 74 vol.% CO₂ in N₂ (Messer, Bucharest, Romania). The tests were performed three times in order to observe the repeatability and reproducibility.

The morphology of the materials was determined using a Variable Pressure Field Emission Scanning Electron Microscope-FESEM VP (Carl Zeiss, Oberkochen, Germany) with a resolution of 0.8 nm at 30 kV or 2.5 nm at 30 kV in VP mode.

Brunauer–Emmett–Teller (BET)-specific surface and pore diameter distribution were determined from the N₂ adsorption-desorption isotherms, at −196 °C with an Autosorb-iQ-C instrument (Boynton Beach, FL, USA). Prior to sorption analysis, the materials were preheated for 5 h. Initially, the temperature increased up to 180 °C in 1 h and then it was kept constant for 4 h, for degassing. Finally, the material was cooled to room temperature under vacuum.

The IR spectra were recorded in the region 4000–400 cm⁻¹ using Fourier transform infrared spectroscopy (FTIR) on a Cary 630 ATR-FTIR instrument (Agilent Technologies, Inc., Santa Clara, CA, USA). Before the analysis, the samples were grinded in an agate mortar, then dried at 80 °C under vacuum for 3 h, in order to avoid the appearance of physically adsorbed water. Spectral acquisition was carried out by pressing the sample against the diamond crystal using the attached pressure clamp. A slip clutch on the clamp prevented overtightening, collecting spectra (32 scans for background and samples at 8 cm⁻¹ resolution and threshold 0.002) between 4000 and 400 cm⁻¹.

The combustion and the pyrolysis methods coupled with the gas chromatography method (Flash EA2000, Thermo Scientific, Waltham, MA, USA) were used to perform the elemental analysis [37,38]. The metals content was determined by atomic absorption spectrophotometer (NovAA 300, Analytik Jena AG, Jena, Germany).

The experimental setup (Figure 2) consisted of a reactor connected to a supply gas cylinder and to a chromatograph with TCD detector for CO₂ quantification (GC Varian CP 3800, Palo Alto, CA, USA), in order to assess the efficiency of the materials. The reactor was made from stainless steel, with the dimensions 160 mm—length, 27.5 mm—radius, 55.00 mm—internal diameter and 0.38 L—volume. Thus, 200 g of adsorbent material was introduced into sandwich support described in a previous study [41] and then placed into the reactor. The tests were performed in two stages by using firstly the gas mixture with higher concentration in CO₂ (74 vol.%) and after that the second gas mixture with lower concentration in CO₂ (0.1 vol.%). The amount of adsorbent used was 200 g, and the test parameters were feed pressure—5 PSI, flow rate—100 mL/min and temperature—23 °C.

![Figure 2](image-url)
3. Results and Discussion

Table 2 presents the elemental composition from sewage sludge to the obtained materials.

Table 2. The elemental composition.

| Element (wt%) | SS  | SS_PYCHAR | I_1  | I_2  | I_3  | I_4  |
|---------------|-----|-----------|------|------|------|------|
| C             | 34.51 | 29.46    | 10.85 | 8.87 | 6.02 | 31.93 |
| O             | 17.11 | 0.38     | 0.37 | 0.41 | 0.44 | 0.5  |
| N             | 6.26  | 4.13     | 1.67 | 1.28 | 0.66 | 0.65 |
| S             | 0.86  | 0.47     | 0    | 0    | 0    | 0    |
| H             | 5.01  | 1.17     | 2.07 | 2.76 | 2.95 | 2.15 |

Thus, a similar C content for the sewage sludge and for the obtained char treated with KOH and HCl can be observed. High C content was also noticed in the sewage sludge char (29.46 wt.%), which slightly decreased, with about 3 wt.%, after the oxidation process. Additionally, the C content decreased for the materials treated with KOH.

The highest O content was observed in the sewage sludge, about 17 wt.%, which drastically decreased for all obtained materials. The N content slightly decreased. Sulfur element was observed only in sewage sludge and its char. The H content decreased five times for char and oxidized char and about two times for the obtained materials.

Table 3 reveals the evolution of metals content. Enrichment in metals for the char can be observed, with an exception being noticed for Fe. Comparing the SS_PYCHAR with the I_1, I_2, I_3 and I_4, a notable increase for K and Fe can be seen. Additionally, a slight increase was observed for Na in the case of materials treated with KOH, while Cr, Mn, Ni, Cu, Zn, Pb and Si decreased.

Table 3. The elemental content of the obtained materials.

| Sample       | Cr | Fe  | Mn  | Ni  | Cu  | Zn  | K    | Na  | Pb  | Si  |
|--------------|----|-----|-----|-----|-----|-----|------|-----|-----|-----|
| SS           | 0.19 | 28.95 | 0.14 | 0.02 | 0.36 | 0.11 | -    | -   | 0.02 | 144.75 |
| SS_PYCHAR    | 0.45 | 0.09 | 0.26 | 0.23 | 1.64 | 1.52 | 4.70 | 2.65 | 0.06 | 323.32 |
| I_1          | <0.01 | 150.95 | 0.19 | <0.01 | 0.66 | 0.36 | 197.93 | 9.5 | <0.02 | 147.80 |
| I_2          | <0.01 | 9.69 | 0.15 | <0.01 | 0.43 | 0.11 | 169.49 | 6.47 | <0.02 | 146.22 |
| I_3          | <0.01 | 8.15 | 0.11 | <0.01 | 0.13 | 0.11 | 168.99 | 6.06 | <0.02 | 146.00 |
| I_4          | <0.01 | 14.23 | 0.07 | <0.01 | 1.83 | 0.11 | 16.27 | 7.34 | <0.02 | 434.24 |

The scanning electron microscopy (SEM) revealed a homogenous surface for the sewage sludge material (Figure 3A) and a porous surface for the char (Figure 3B). The pyrolysis process was conducted to the formation of different pore sizes, due to the carbonization of the organic matter. Analysing the micrographs of the obtained mixtures (Figure 3C–E), irregular shapes and erosion surfaces can be observed that probably formed after the KOH treatment [42]. The erosion degree increased with the KOH content. Additionally, the HCl contributed to the mixture erosion (Figure 3E).

The surface of I_2, Figure 3D, is similar to a “broccoli bouquet”, with porous convolutions, being strongly physically modified under the influence of alkaline hydroxide. The formation of pores on the surface of materials can be associated with the evaporation of some chemicals that were activated during the thermal process [43], developing a “cavernous” surface. Additionally, the KOH reacts with the mineral, forming CO_2 and H_2O, among others.
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Figure 3. SEM microphotographs of dried sewage sludge (A), SSYPYCHAR (B), I_1 (C), I_2 (D), I_3 (E) and I_4 (F).

The special inorganic compound in the sewage sludge, SiO_2, acts as a built-in template, which prevents agglomeration, resulting in the formation of porous structure. From Figure 3C–E, some sheets can be be observed, representing a mixture of carbon, Cu, Zn, Fe and Si. In comparison with the sewage sludge or SSYPYCHAR, the I_4 (treated with HCl) displayed hierarchical structure with pores, Figure 3F. The sheets were destroyed by the addition of HCl, which led to the transformation of the material surface by increasing the porosity.

Nitrogen (N_2) adsorption-desorption isotherms (Figure 4) revealed a small, specific surface area for the sewage sludge, about 2.97 m^2/g, which increased to 15.61 m^2/g after the pyrolysis process (Table 4), and the same tendency was observed for the pore volume but not for the pores diameter, which slightly decreased for all mixtures (Table 4).
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Table 4. Textural properties of the materials based on sewage sludge (SS).

| Material Type | $S_{BET}$ m$^2$/g | $V$ cm$^3$/g | $d_p$ Å |
|---------------|-------------------|--------------|--------|
| SS *          | 2.972             | 0.030        | 41.666 |
| SS PYCHAR     | 15.608            | 0.042        | 39.250 |
| I$_1$         | 3.305             | 0.008        | 39.256 |
| I$_2$         | 6.447             | 0.017        | 39.252 |
| I$_3$         | 3.618             | 0.014        | 31.308 |
| I$_4$         | 921.013           | 0.657        | 39.306 |

*—dry state.

The highest surface area and pore volume were obtained for I$_4$, while the pore’s diameter remained almost constant, and only in the case of I$_3$ the diameter slightly decreased. In comparison with other studies [40,44–46], the surface area of I$_4$ significantly increased and the pore diameter slightly increased [46].

Regarding the shape of isotherms and hysteresis loops (Figures 4–6), these were Type II with H3 hysteresis according to IUPAC [46,47].

FTIR analysis (Figure 7) was used to identify the typical functional groups of the raw sewage sludge (SS), its char (SS PYCHAR) and activated chars (group I).

The peaks at 2918 cm$^{-1}$ and 2851 cm$^{-1}$ were assigned to CH$_2$ asymmetrical and symmetrical stretching vibration [48], indicating the presence of aliphatic structures in the SS sample. It can be observed that these bands disappeared after pyrolysis, leaving only an imperceptible trace, highlighting total decomposition of aliphatic C-H bonds [49]. The peaks at 1625 cm$^{-1}$ from SS and 1572 cm$^{-1}$ from SS PYCHAR correspond to C=O vibration, indicating the existence of aldehydes and acids from proteins in the raw sewage sludge [25]. The peaks at 3246 cm$^{-1}$, 1400 cm$^{-1}$, 1010 cm$^{-1}$ and 529 cm$^{-1}$ revealed the surface carbon structure, including chain hydrocarbons and functional groups such as hydroxyl and aromatic rings [50,51]. The peak at 3246 cm$^{-1}$ was attributed to O-H stretching vibration, related to water, alcohols or carboxylic acids. The peak from 1400 cm$^{-1}$ corresponded to C-H stretching vibration of CH$_2$ and CH$_3$ groups. The band from 1010 cm$^{-1}$ was attributed...
to C-O and Si-O bonds, indicating the presence of quartz and stable C-O bond [25,49]. The peak from 529 cm\(^{-1}\) corresponded to C-H vibration of alkenes, which almost disappeared in the SS\(_{PYCHAR}\).

**Figure 5.** Adsorption isotherms and pore distribution of I\(_1\), I\(_2\) and I\(_3\) samples.

**Figure 6.** Adsorption isotherms and pore distribution of I\(_4\) sample.
Figure 7. FTIR spectra of the sewage sludge and its activated chars. Compared with the initial SS sample, the peaks of the activated chars with KOH (group I) were stronger, indicating that the abundance of the surface functional group species was higher. For example, the peak from 1625 cm$^{-1}$ from SS, attributed to C=O vibration, suffered a shift and a transformation to a large band in the activated samples, to approximately 1700–1800 cm$^{-1}$ in the samples treated with KOH, indicating the intense presence of these groups at the surface. Additionally, the peaks from 1350–1400 cm$^{-1}$ (group I) were attributed, as in the case of the initial sample, to C-H stretching vibration of
CH\textsubscript{2} and CH\textsubscript{3} groups. The intensity of these peaks for the activated chars highlighted the increased distribution rate of the OH and CH\textsubscript{2} structure. The peaks from 540–570 cm\textsuperscript{-1} (group I), attributed to C-H vibration of alkenes, almost disappeared in the samples I.4, indicating that these samples did not contain primary alkenes.

The material treated with HCl was used for CO\textsubscript{2} adsorption test, due to its high specific surface area. The results are presented in Table 5. Additionally, the adsorption capacity, separation efficiency and CO\textsubscript{2} recovery were calculated [52,53].

Table 5. CO\textsubscript{2} adsorption evolution and separation efficiency.

| Gas Mixture               | Injection Number | Time (min) | CO\textsubscript{2} Evolution (vol.\%) | \(a\) (cm\textsuperscript{3}/g) | \(\eta\) (%) | \(R\) (%) |
|---------------------------|------------------|------------|---------------------------------------|-------------------------------|---------------|-----------|
| 74 Vol % CO\textsubscript{2} balance N\textsubscript{2} | 1 | 8 | 51.19 | 11.87 | 99.68 | 98.11 |
| | 2 | 8 | 38.74 | | | |
| | 3 | 8 | 22.23 | | | |
| | 4 | 8 | 16.88 | | | |
| | 5 | 8 | 6.09 | | | |
| | 6 | 8 | 2.12 | | | |
| | 7 | 8 | 0.23 | | | |
| | 8 | 8 | 9.12 | | | |
| | 9 | 8 | 17.46 | | | |
| | 10 | 8 | 44.27 | | | |
| | 11 | 8 | 67.00 | | | |
| | 12 | 8 | 74.05 | | | |
| 0.1 Vol % CO\textsubscript{2} balance N\textsubscript{2} | 1 | 8 | 0.0076 | 0.92 | 95.00 | - |
| | 2 | 8 | >LOD (4) | | | |
| | 3 | 8 | >LOD | | | |
| | 4 | 8 | >LOD | | | |
| | 5 | 8 | >LOD | | | |

\(a\) = adsorption capacity (cm\textsuperscript{3}/g); \(\eta\) = separation efficiency (%); \(R\) = CO\textsubscript{2} recovery (vol.%); \(LOD\) for CO\textsubscript{2} = 50 ppm.

Prior to adsorption test, the gas mixtures were confirmed through GC analysis. The adsorption capacity, separation efficiency and CO\textsubscript{2} recovery were calculated with the following equations:

\[
a = \frac{Q \cdot p (c_i - c_f) \cdot t}{m} \tag{1}
\]

where: \(Q\) = the flow of the test gas passed over the adsorbent materials, cm\textsuperscript{3}/s; \(p\) = adsorption pressure, bar; \(c_i\) = CO\textsubscript{2} concentration in the cylinder (feed gas), vol.\%; \(c_f\) = CO\textsubscript{2} exit concentration up to adsorbent saturation, vol.\%; \(t\) = breaking time, s; \(m\) = the amount of the adsorbent materials in the reactor, g.

\[
\eta = \frac{c_a}{c_i} \times 100 \tag{2}
\]

where: \(c_a\) = adsorbed CO\textsubscript{2} concentration (vol.%); \(c_i\) = initial CO\textsubscript{2} concentration (vol.%)

\[
R_{CO_2} = \frac{T_{e}(CO_2) - T_{i}(CO_2)}{T_{i}(CO_2)} \times 100 \tag{3}
\]

where: \(T_{e}(CO_2)\) = the average of the CO\textsubscript{2} concentrations until the breaking period at the exit from the adsorbent materials (vol.%); \(T_{i}(CO_2)\) = initial CO\textsubscript{2} concentration (vol.%).

The feed gas flows continuously through installation and every 8 min the output gas was analysed in order to determine the CO\textsubscript{2} content.
As it can be observed (Table 5), in the case of the gas used first, rich in CO$_2$, the saturation occurred after seven injections. The single run time analysis was 8 min, and 12 runs were performed consecutively, until the initial concentration of CO$_2$ in gas was noticed. Then, desorption was achieved through vacuum and the adsorption tests continued with the gas mixture with low concentration of CO$_2$. Even up to five runs, the CO$_2$ was lower than detection limit.

It should be noted that in the case of the second gas mixture, the saturation did not occur even after 100 injections, therefore the degree of recovery was not estimated.

In comparison with other studies [36,37], the adsorption capacity of the adsorbent was similar, even for feed gas with significantly lower content of CO$_2$ (35%) than in this study. It was demonstrated that not only the activation agent influences the adsorption capacity but also the pyrolysis temperature and the heating rate can modify the adsorption [40]. Thus, a higher adsorption capacity was reached by using higher pyrolysis temperature (800 °C). Additionally, the combination of sewage sludge with wood sawdust revealed similar CO$_2$ adsorption capacities, with the values varying with the pressure [54].

From an economic point of view, the technology could be efficient due to waste recycling for value-added applications in concrete CO$_2$ adsorbents that avoid the expensive sewage sludge disposal. We calculated the techno-economic aspects of sewage sludge conversion, with this becoming economically attractive when the value of avoided CO$_2$ emissions reached 30 EUR/t. These results are consistent with the literature, which mentions values of approximately 29 EUR/t [55]. Nowadays, the price on the market of European Union Allowances is about 25 EUR/t CO$_2$ [56].

4. Conclusions

The char resulted after the pyrolysis process of sewage sludge was used to obtain CO$_2$ adsorption materials. Four types of material were obtained with different surface areas and similar pore volumes and diameters. The material treated with HCl presented good properties, such as higher surface area and pore volume, in comparison with the raw materials and treated only with KOH; therefore, it was used further for CO$_2$ adsorption test. The material was pelletized by using starch powder as a binder. For adsorption tests, a handmade installation equipped with a sandwich support in order to avoid the material spread was used. Saturation was achieved after seven injections with gas rich in CO$_2$ (74 vol.%). When the material was tested with the CO$_2$-depleted gas (only 0.1 vol.%), the saturation was not achieved even up to 100 injections. Additionally, in the case of the tests with the gas rich in CO$_2$, the material presented an adsorption capacity of 11.87 cm$^3$/g and a great separation efficiency and CO$_2$ recovery of 99.68% and 98.11%, respectively. Therefore, the obtained material could be a potential adsorbent for CO$_2$ capture and storage even at high concentrations.

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