CARBON DIOXIDE STORAGE USING BIOCHAR ADSORBENT

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Abstract. *Industrialization has led to a surge in carbon dioxide (CO_2) emissions. In Brazil, emissions reached 2.42 billion gross tons of CO_2e in 2021, a 12% increase compared to 2020. This scenario has impacted global warming, resulting in extreme climate change, rising sea levels, and food insecurity. Scientists are exploring alternatives for capturing and storing CO_2, with an emphasis on adsorption capture, using biomass activated charcoal. The transformation of sugarcane bagasse into biochar emerges as a viable alternative for waste management. The production process of activated charcoal involves drying the bagasse, crushing it, and carbonization and activation steps to create a porous structure conducive to adsorption. Tests were conducted to build and analyze a carbon dioxide capture system using biochar produced from sugarcane bagasse residues, calculating the adsorption capacity of the produced charcoal. Also, it was made a particle size analysis, to characterize the charcoal. Although the production yielded 21.45% higher than previous tests, the adsorption values were not as expected (1.51 mmol CO_2/g charcoal compared to 3,29 mmol CO_2/g charcoal), possibly due to moisture adsorbed during storage.*

Keywords. *Charcoal, Adsorption, Sugarcane bagasse, Granulometry.*

Introduction

The emissions of carbon dioxide (CO_2) from industries have been a significant concern in recent decades. The increasing industrialization worldwide has brought numerous economic benefits, but also triggered a substantial rise in CO_2 emissions, one of the main greenhouse gases responsible for global warming. According to the SEEG, Brazil emitted 2.42 billion gross tons of CO_2e in 2021, representing an increase greater than 12% compared to the amount recorded in 2020 (Brotero, 2023). In this scenario, approximately 86% of the world's carbon dioxide emission come from burning fossil fuels to produce energy and materials (BBC News Brasil, 2021). And despite the substantial growth in renewable energy adoption, CO_2 emission related to energy use reached a record of 39.3 billion tons of equivalent carbon in 2022 (a 0.8% increase compared to 2021) (Um Só Planeta, 2023).

In the same way, the increase in carbon dioxide emissions has had a significant impact on the phenomenon of global warming. As concentrations of CO_2 and other greenhouse gases in the atmosphere keep rising, the effects of global warming become increasingly evident and concerning. Examples of the consequences include extreme climate change, rising sea levels, ocean acidification, disruptions to ecosystems and threats to food and water security (Mirzabaev *et al.*, 2023).

For this reason, many scientists and researchers around the world have been researching alternatives to remove or reduce CO_2 levels through capture and storage, using methods such as CCS (Carbon capture and storage) and CCUS (Carbon capture, utilization and storage) (Hussin *et. al.*, 2021). The first involves capturing CO_2 emissions from industrial processes and transporting it to a location for safe storage underground in geological formations. The second, instead of storing carbon, suggests reusing it in industrial processes, converting it into, for example, plastics, concrete or biofuel (National Grid, 2023).

To make the CO_2 sequestration process economically viable, the capture stage must be profitable. In this regard, capture through adsorption seems to be a promising alternative due to its lower energy requirements, cost-effectiveness, and simplicity in use at a broad range of temperatures (Kaur *et al.*, 2019). Research on natural gas storage has also shown that, in comparison to simple compression, the use of an adsorbent substance increased storage amounts. Further increasing storage was achieved via thermal control of the operation. These results inspired further research into the application of comparable technology for carbon capture and storage systems, which could provide CO_2 emission reduction options. However, the main challenge in disseminating this technology is the development of effective and low-cost adsorbents. Several materials for CO_2 adsorption have already been tested, such as amines, zeolites, silicas and activated biomass carbons, for instance.

The use of biomass to produce activated carbon has shown considerable interest due to its high porosity. Furthermore, the charcoal produced has several advantages as a CO_2 adsorbent: low cost, high adsorption capacity and easy regeneration (Ello *et al*, 2013). Examples of biomass that are being used are sugarcane bagasse, coconut shells, açaí residues and pine wood.

Objectives

The research aims to build and analyze a carbon dioxide capture system using biochar produced from sugarcane bagasse residues. The goal is to assemble a system capable of capturing carbon dioxide through adsorption, calculating the adsorption capacity of the produced charcoal. Additionally, it seeks to characterize the charcoal, using a particle size analysis, to assist another research group, which is simulating adsorption in devices of different shapes.

This work intends to study the viability and efficiency of the process using charcoal made from biomass, to ensure that, in the future, adsorption will be more accessible, dispersing the technology. This proposal is aligned with the great challenges proposed by the GCSP program, as it seeks sustainability in industries, by ensuring safe storage of CO_2, or its return to the system. Furthermore, it seeks to promote health, safety and joy of living for future generations, by mitigating the effects of global warming through the containment of greenhouse gases. In this way, some of the consequences of this problem, such as extreme climate change, rising sea levels and disruptions to ecosystems, can be alleviated.

Development

Brazil is the world's largest producer of sugarcane, one of the most important raw materials in the Brazilian agro-industrial sector, responsible for many products supply chain, such as ethanol, sugar, cachaça and rapadura. Sugarcane bagasse has been increasingly produced in larger quantities due to the expansion of cultivated areas and the industrialization of sugarcane, primarily resulting from investments in alcohol production (Venceslau, 2018). It is estimated that approximately 12 million tons of bagasse are generated annually in Brazil, averaging about 280 kg per ton of crushed sugarcane (CONAB, 2023). In this context, the possibility of transforming bagasse into biochar emerges as an alternative to address this waste.

To produce charcoal, initially, the sugarcane bagasse must go through a drying process, to guarantee process efficiency and charcoal quality. Considering that the average moisture content of sugarcane bagasse is 46.2%, while the rice husk is 11.31% and the corncob is 16.93%, the drying stage is essential for the bagasse (Vieira, 2012). When biomass has a high moisture content, more energy is needed to initiate the burning process, in other words, more energy is required to vaporize the water, resulting in less energy available for the actual combustion.

Therefore, the bagasse should be spread on trays (Figure 1) and placed in the dryer for 8 hours at 100°C. Subsequently, it must be placed in a bag and sealed to prevent moisture from entering until the moment of conversion into charcoal.

To obtain activated carbon, the bagasse goes through two stages: biomass carbonization and the activation of the carbonized material. The carbonization step involves the pyrolysis of the precursor at temperatures usually above 473 °K. It is a material preparation stage, in which volatile components and light gases (CO, H_2, CO_2 and CH_4) are removed, producing a mass of fixed carbon and a primary porous structure, which favors the subsequent activation (Teixeira, 2020).

Figure 1 – Bagasse in trays

In the activation process, the carbonized material undergoes secondary reactions, to obtain a porous product with a high surface area by eliminating components that could obstruct the pores, such as tar, creosote and naphthas (Claudino, 2003). Charcoals can be activated through physical, chemical processes, or a combination of both methods. Physical activation involves the carbonization of the material and the subsequent activation at high temperatures, between 800°C and 1,100 ºC, under the flow of gases such as steam and carbon dioxide (Ramos *et al.*, 2009). The idea is to help remove the gases formed during the carbonization step. Since the temperatures are very high, the gas that goes through the system is hardly retained, resulting in carbon free from adsorbed gases. Figure 2 exemplifies the pyrolysis and physical activation process.

Therefore, the already-dried bagasse was ground in a knife mill into pieces up to 1 cm in length (to increase the contact surface) and placed inside a 2.5 L iron pot (Figure 3). Refractory mortar was applied around the lid to enhance system sealing. The goal is to ensure that no oxygen enters, preventing combustion during the process, which reduces the yield of produced charcoal. Soon after, it was placed in the Muffle for the carbonization process for 1 hour, at 750°C, followed by the activation stage for 2 hours, at 850°C.

Figure 2 – Pyrolysis and physical activation process (Teixeira, 2020)

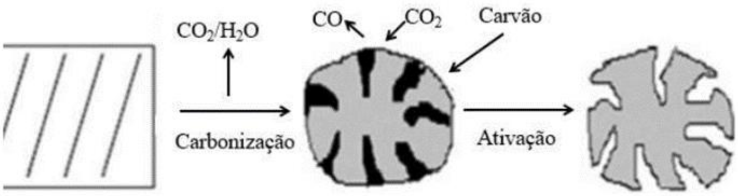


Figure 3 – Iron pot

To prevent damage to the laboratory due to the gases generated during pyrolysis and activation, a gas collection system was implemented. Even though the iron pot has been sealed, some of these gases escape, because the mortar has a certain level of porosity, and the seal is not perfect. Therefore, a 5 L PET bottle collected these gases, directing them through the pipelines via an exhaust fan (Figure 4).

Figure 4 – Muffle and Exhaust fan

To assess the yield of bagasse conversion into charcoal, a gravimetric analysis was carried out, measuring the masses of bagasse before and after the process, and comparing them with the mass of the charcoal produced.

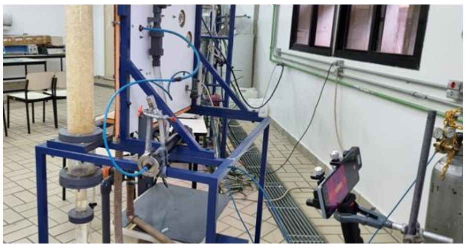
After this step, the adsorption test was done. Adsorption can be considered as the phenomenon that analyzes the adherence of molecules of a component in a fluid phase (liquid or gas) on the surface of a solid. An adsorbent is a material that will adsorb a compound (adsorbate) (Teixeira, 2020).

There are several factors that influence the adsorption process. For the adsorbate, the mass and molecular geometry, solubility and polarity, and for the adsorbent, the porous structure, chemical surface and surface area (Schultz, 2016). For instance, the greater the surface area, the more favorable the adsorption will be.

So, for this process, a device was used (Figure 5), which contained a manometer to check the pressure (on the left) and a tube (on the right) for the entry of carbon dioxide, coming from a CO_2 cylinder. The tube was connected to an adsorption column to ensure a CO_2 flow rate of 2L/min (Figure 6).

Figure 5 – Device for CO2 adsorption

Figure 6 – Assembled system



To analyze the mass of CO_2 adsorbed during the experiment, the initial and final masses of the equipment were weighed. The internal temperature was monitored using an infrared camera (Figure 7), connected to a cell phone. The temperature drops after its significant rise indicated the completion of the adsorption process. This was done to determine the total time of the process. Additionally, the temperature variation was also evaluated based on the analysis of the temperature sensor inserted in the equipment (device located in the middle of the device). This analysis was conducted assuming that the adsorption process, being exothermic, encompassed the greatest temperature variation curve (disregarding the initial temperature increase), to gather initial and final time data (Figure 8).

Following this, an analysis of the adsorption capacity was carried out, comparing the mass of the equipment before and after the process to verify how much carbon dioxide had been adsorbed.

After this process, a charcoal particle size test was conducted to characterize it, enabling future simulation of this charcoal in devices with different shapes. Particle size analysis, known as granulometry, is the relative proportion, in percentage, of different grain sizes that constitute the aggregate. This analysis is widely used in the field of Civil Engineering, in soil classification, for example (SPLABOR, 2018). Concerning activated charcoal, studying granulometry is valid, since the smaller the particle size of the adsorbent material, the greater the contact surface and interaction between particles, resulting in higher adsorption (Diniz & Rocha, 2016).

In this regard, initially, the charcoal mass was weighed on a semi-analytical balance. Afterwards, the charcoal was placed on the top sieve of a set of stacked sieves with particle sizes between 4.0 mm and 100 µm (Figure 9). The system was shaken and the retained mass on each level was recorded, calculating the weighted average to determine the mean particle size.

Figure 7 – Image produced by infrared camera (Xtherm Infrared)

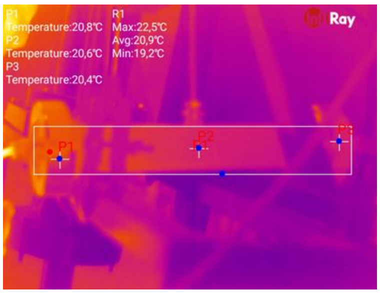


Figure 8 – Data collected by temperature sensor

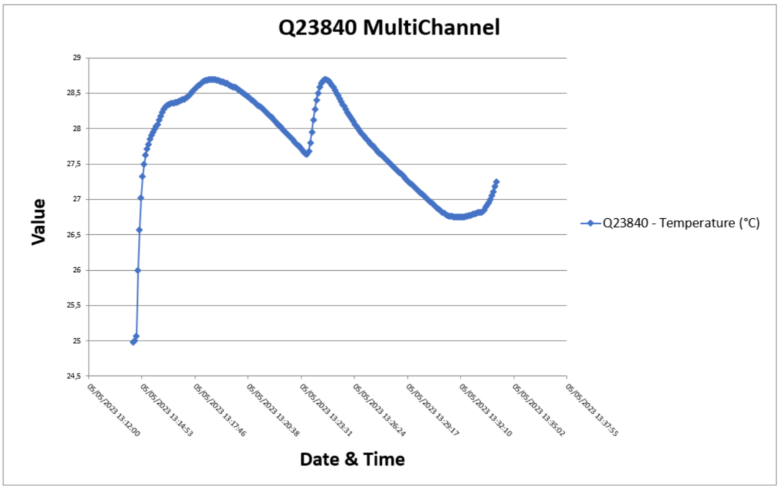


Figure 9 – Set of stacked sieves to determine granulometry

Results and Discussion

From the activated carbon production process, a yield of 21.45% was obtained, higher than the result obtained in a similar test, which was 13.34% (Chedid & Zanone, 2022). One factor that may have influenced this increase is the crushing into smaller parts, which increases the contact surface and the process efficiency. Beyond that, the iron pot could have been better sealed, producing less ashes, increasing yield.

Table 1 – Yield of the charcoal production process

Mass of bagasse used (g)	Mass of charcoal produced (g)	Yield (%)
224.14	48.08	21.45

It is noticeable that the upper layer of the obtained charcoal presents a white surface (Figure 10), indicating probable combustion during activation. In this case, there was a reaction of the bagasse with the oxygen already present in the pot or with the possibly incoming oxygen. This product slightly reduces the charcoal yield, which could be avoided if the process was carried out in an inert atmosphere.

Figure 10 – Result of the biochar

In the adsorption tests (Table 2), it is noticeable that the adsorption value found in the 2nd experiment (1.51 mmol CO_2/g charcoal) is considerably higher than the found in the 1st experiment (0.56 mmol CO_2/g coal). This is because, only before the 2nd test, the charcoal went through a drying process, removing the moisture present in it. Therefore, there was likely water adsorption while the charcoal was being stored, even though it was sealed. The ambient humidity can undesirably influence other properties, such as yield and adsorption capacity (Araújo, 2018). The water takes up the space of CO2 or changes its structure.

Table 2 – Adsorption capacity using the equipment's mass difference

	1º experiment	2º experiment
Mass of charcoal (g)	14.25	30.00
Mass of adsorbed CO2 (g)	0.35	2.00
Number of moles of adsorbed CO2 (mmol)	7.95	45.44
Adsorption (mmol CO2/g charcoal)	0.56	1.51

Furthermore, when compared with the previous result of 3.29 mmol CO_2/g charcoal (Chedid & Zanone, 2022), it is evident that although the 2nd experiment yielded a better result than the 1st, it is still not sufficiently satisfactory. However, it should be considered that the previous test was conducted using a different device (2.0 L PET bottle) with a distinct carbon dioxide source (dry ice), possibly making it less accurate. Also, in the recent test, the CO_2 was inserted in a high flow, while in the first test, it was completely introduced in the beginning of the experiment, enabling a longer adsorption time, which probably increased the outcome.

The number of moles that entered the equipment was also calculated using the initial and final times acquired through the temperature sensor, bearing in mind that the CO_2 flow rate was 2L/min. Based on the results found in Table 3, they were much higher than those obtained using only the equipment's mass difference (in the 1st experiment, 673.82 mmol compared to 0.56 mmol). This shows that not all the CO_2 that entered the equipment was adsorbed. Additionally, the reading on the manometer connected to the device showed a slight increase in pressure, followed by a rapid decrease, while ideally, it should have increased considerably. This suggests that the system was not pressurized enough and that a significant portion of the income CO_2 leaked. After the experiment, it was discovered that there was a safety valve preventing pressurization and releasing CO_2 upon reaching a certain pressure, which should have been removed.

Table 3 – Number of moles of CO_2 that entered the device using the temperature sensor

	1º experiment	2º experiment
Time of adsorption (s)	450	2520
Volume of adsorbed CO2 (L)	15.00	84.00
Mass of adsorbed CO2 (g)	29.65	166.07
Number of moles of adsorbed CO2 (mmol)	673.82	3773.41

In the particle size analysis of the acquired charcoal, keeping in mind that the initial charcoal mass was 50.18 g, the weighted average diameter found was 258.649 µm. Furthermore, the granulometry distribution graph was obtained (Figure 11), which shows that the sieve that retained most charcoal had an opening of 125 µm.

Table 5 – Charcoal granulometry

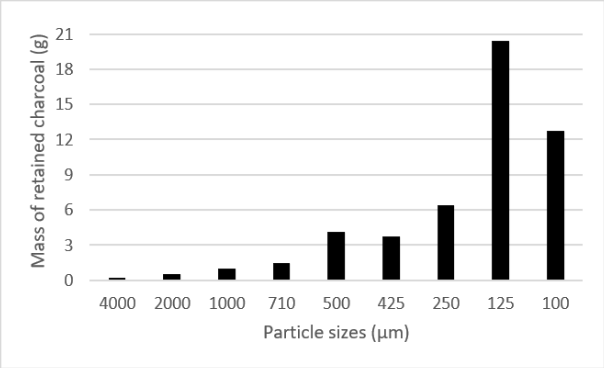
Particle sizes (µm)	Mass of retained charcoal (g)
4000	0,2
2000	0,52
1000	0,99
710	1,48
500	4,13
425	3,77
250	6,42
125	20,4
100	12,76

Conclusion

The production of activated charcoal from bagasse, via traditional process, achieved a suitable yield (21.45%), but the product did not exhibit the expected adsorption values (1.51 mmol CO_2/g charcoal, as opposed to 3.29 mmol CO_2/g charcoal). However, the influence of moisture in this process is probable, reducing approximately 63% of the adsorption capacity. Additionally, the values obtained using data from the temperature sensor showed that not all the CO_2 that entered the equipment was adsorbed, proving the system was not pressurized enough and a significant portion of the income CO_2 leaked.

Moreover, with the data from the granulometry of the produced charcoal, it will be possible to simulate the adsorption capacity more accurately in other devices, with different shapes, for example.

Figure 11 – Granulometry distribution



Finally, with the advancement of this technology, it will be possible in the future to make it more accessible and efficient. Consequently, carbon dioxide will be safely stored or reused in the process, reducing the emission of greenhouse gases into the atmosphere and mitigating the effects of global warming.

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