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Comparative study of cellulosic and carbonaceous biomass modifications for low-temperature CO_2 adsorption

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ABSTRACT

The escalating global energy demand has led to increased fossil fuel combustion, elevating atmospheric CO_2 concentrations and exacerbating climate change. This study investigates the enhancement of CO_2 adsorption capacity in biomass-derived materials through amine functionalization, comparing nanocrystalline cellulose (NCC) and activated carbon (AC). Hairy NCC was synthesized via TEMPO-mediated oxidation of cotton linter, while AC was produced through pyrolysis of elderberry kernels. The amine-modified adsorbents were characterized using FTIR spectroscopy and SEM imaging, with CO_2 capture performance evaluated through thermogravimetric analysis at 25°C and 50°C under varying CO_2 concentrations (10-90 vol.%). Results revealed that at 25°C and 90 vol.% CO_2, unmodified NCC and AC exhibited adsorption capacities of 1.74 and 2.78 mmol/g, respectively. After monoethanolamine (MEA) modification, NCC demonstrated improved performance (2.25 mmol/g), while AC capacity decreased to 1.72 mmol/g due to amine-induced pore blockage. The superior performance of amine-modified NCC highlights its potential as an efficient, sustainable alternative to conventional AC for CO_2 capture applications. This study provides critical insights into biomass-derived adsorbents for mitigating anthropogenic CO_2 emissions, with implications for developing cost-effective carbon capture technologies.

Highlights

- Amine-modified nanocrystalline cellulose and activated carbon were tested for CO_2.
- At 25°C/90% CO_2, aminated-cellulose showed 2.25 mmol/g vs. 1.72 for modified carbon.
- CO_2 levels boosted adsorption, and higher temperatures (25 to 50°C) reduced capacity for both.
- Amine-cellulose outperforms amine-activated carbon, emerging as a sustainable CO_2 adsorbent.

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1. Introduction

Dangerous amounts of CO_2 have been pumped into the atmosphere as a result of fossil fuel addiction. Scientists have proven that rising greenhouse gases (GHG) are overwhelmingly caused by human activity, with carbon dioxide being identified as the primary driver behind the alarming increase in planetary temperatures(Fathalian et al., 2024; Lotfinezhad et al., 2024). Significant environmental consequences have been triggered by these rising concentrations, including global warming and its cascading impacts - glacial melt, sea level rise, shifting climate patterns, and biodiversity decline. To mitigate these challenges before 2050, a substantial reduction in greenhouse gas emissions ranging between 40-70% is required to be achieved(Kumar et al., 2024). Several techniques are employed for CO_2 capture in industrial applications, including solvent-based absorption, solid adsorbent systems, cryogenic distillation, and membrane separation. Due to limitations such as elevated operating costs and solvent degradation encountered in solvent absorption, significant energy requirements and high-pressure necessities to prevent CO_2 phase transition in cryogenic processes, and mandatory pretreatment procedures with limited throughput observed in membrane systems, research efforts are primarily focused on the development and optimization of adsorbent materials that minimize these drawbacks. Among available alternatives, the solid adsorption approach is regarded as particularly promising owing to its demonstrated molecular selectivity, enhanced uptake capacity, and reduced energy

demands during regeneration cycles(Das et al., 2023; Gautam and Mondal, 2023). Activated carbon (Tahmasebpoor et al. 2023), cellulosic materials (Ji et al., 2024), metal-organic frameworks (MOFs) (Vinothkumar et al., 2022), and porous organic polymers (POPs) (Moradi et al., 2023) are widely used components of the solid-state adsorption process. Among biomass-derived materials, cellulosic and carbon-based substances have been extensively investigated in recent years, with significant research efforts being devoted to their applications. Activated carbon is recognized as a microporous material exhibiting unique characteristics, including high adsorption capacity, low production costs, and an extensive specific surface area. These properties have led to its utilization in diverse applications such as solvent recovery, carbon dioxide capture, dye removal, and water purification processes (Melouki et al., 2020). In recent years, various types of biomass such as tea bagsRattanaphan et al. (2020), rice husks Li et al. (2015), and coconut shells Chen et al. (2016) have been used for the synthesis of activated carbon. Cellulose and its derivatives are characterized by high mechanical and thermal stability, along with a three-dimensional network structure that enables combination with diverse materials to yield various composite formulations. Furthermore, the commercial-scale production of cellulose has created new opportunities for modification of existing carbon dioxide capture methodologies (Zhang et al., 2024). Hairy nanocrystalline celluloses (HCNC) are classified as a novel category of nanocelluloses, composed of a crystalline structure resembling nanocrystalline cellulose (CNC) with amorphous cellulose chains interspersed between the crystalline regions. Through periodate oxidation, the C2-C3 bonds of β-D-glucose monomer units in cellulose are selectively converted to 3,2-dialdehyde functionalities. This transformation results in the formation of a cellulose-derived intermediate, designated as dialdehyde-modified cellulose (DAMC), which is obtained under ambient temperature conditions (Muthami et al., 2021). To date, numerous approaches have been developed for adsorbent modification, among which amine functionalization of adsorbent surfaces has been demonstrated as an effective strategy(Abbasi et al., 2019). This technique is widely regarded as particularly promising for CO_2 capture applications, owing to its notable advantages, including the absence of secondary pollution, minimal energy requirements, and sustainable operation (Li et al., 2020). Zhu et al. (2020)functionalized nanocrystalline cellulose through aminosilane modification and subsequently evaluated the modified adsorbent's CO_2 capture performance. Experimental results demonstrated a substantial enhancement in adsorption capacity from 0.2 mmol/g to 1.5 mmol/g, representing an approximately 8-fold improvement. This significant increase has been attributed to the synergistic combination of chemical and physical adsorption mechanisms. In another study, Sepahvand et al. (2020)synthesized cellulose nanofibrils and subsequently modified the adsorbent using phthalimide functionalization. The researchers reported that incorporation of 1.5 wt% phthalimide resulted in a significant enhancement of CO_2 adsorption capacity from 2.2 to 5.2 mmol/g, representing a 136% improvement in capture performance. This study examines the impact of amine functionalization on the CO_2 adsorption performance of two widely used biomass-derived materials: cellulose and activated carbon. Notably, the research presents the first comparative analysis of these modified adsorbents, while simultaneously introducing hairy nanocrystalline cellulose as a novel material for carbon capture applications, an approach previously unreported in the literature.

2. Materials and Methods

2.1 Raw materials

The α-cellulose substrate was sourced from Linterpak Co. (Behshahr, Mazandaran, Iran), characterized by intermediate polymerization degree and fibrous morphology, with senjad additionally procured from local markets in Tabriz. Chemical reagents included sodium metaperiodate ($NaIO_4$), ethylene glycol ($C_2H_6O_2$), hydrochloric acid (HCl, 37%), and monoethanolamine (MEA, C_2H_7NO) from Merck KGaA (Darmstadt, Germany). Supplementary chemicals - sodium chloride (NaCl), 1-propanol (C_3H_8O), potassium hydroxide (KOH), and ethanol (C_2H_5OH) were obtained from Dr. Mojallali Chemical Co. (Iran).

2.2 Preparation of cellulose adsorbent

Four grams of α-cellulose was first manually disintegrated into smaller fibers, then added to an oxidation solution containing 6 g sodium metaperiodate and 16 g NaCl dissolved in 300 ml distilled water. The mixture was immediately protected from light by aluminum foil wrapping and stirred magnetically for some hours at room temperature until the oxidation was quenched with 3 ml ethylene glycol. The resulting dialdehyde-modified cellulose was vacuum-filtered and thoroughly washed with distilled water until a neutral pH was achieved. For HCNC synthesis, the purified DAMC was dispersed in 100 mL distilled water and hydrolyzed at 80 °C for 6 hours under continuous stirring, followed by centrifugation at 3000 rpm for 15 minutes to isolate the solubilized fractions. After measuring the supernatant mass, 1.7-fold excess 1-propanol was added to induce crystallization, and a final centrifugation step (3000 rpm, 15 minutes) yielded the hairy nanocrystalline cellulose product for subsequent characterization (Koshani et al., 2021).

2.3 Preparation of carbon adsorbent

The elderberry kernels were first separated from their shells and mantle, then thoroughly washed with distilled water to remove surface impurities. After drying the cleaned kernels at 100 °C for 24 hours to eliminate moisture, they were carbonized at 600 °C for 2 hours in a muffle furnace and subsequently ground into powder, which was size-homogenized using a 200 µm sieve. For chemical activation, 5 g of the carbonized powder was mixed with KOH at a 2:1 (w/w) ratio and magnetically stirred at 90 °C for 3 hours to ensure proper impregnation. The mixture was then oven-dried overnight at 90 °C before undergoing thermal activation at 600 °C for 1 hour under an inert atmosphere. Following gradual cooling to ambient temperature, the activated material was repeatedly washed with 3M HCl and distilled water until a neutral pH was achieved, removing residual activator. A final drying step at 95 °C for 12 hours preceded another 200 µm sieving, yielding the activated carbon product (designated AC-KOH) ready for subsequent characterization and testing (Nandi et al., 2023).

2.4 Preparation of modified adsorbents

The amine modification was performed by first preparing an ethanol-amine solution, adding 5 mL of absolute ethanol per gram of adsorbent. Monoethanolamine was then introduced at 10 wt% relative to the combined mass of adsorbent and ethanol. This mixture underwent reflux condensation at 75 °C for 3 hours with continuous magnetic stirring to ensure uniform functionalization. The modified adsorbents were subsequently separated by centrifugation and washed with deionized water to remove unreacted MEA. After drying with a vacuum oven, the amine-functionalized materials were named as follows: modified hairy nanocrystalline cellulose (HCNC-MEA) and modified activated carbon (AC-KOH-MEA).

2.5 Characterization of adsorbent properties

To investigate the structure and morphology of the adsorbents, scanning electron microscopy analysis and a MIRA3 FEG-SEM Tescan device made in the Czech Republic were used. About 0.1 g of the dried samples were attached to a silver base with double-sided adhesive and then coated with gold using a Sputter-coating Emitech K550 Telstar device for 30 seconds, and then the relevant images were taken. Also, to investigate the chemical bonds and functional groups formed on the adsorbents, Fourier transform infrared analysis and a Bruker, Tensor27 device made in Germany were used. About 1 g of the adsorbents was powdered with a metal mortar and then placed inside the device to prepare the relevant spectra.

2.6 Adsorption analysis in different cycles

To perform the adsorption analysis to investigate the adsorption capacity of the adsorbents, a TGA/DC1 device made in Switzerland was used at atmospheric pressure. After loading the samples into the device, the temperature of the device was first increased to 120 °C in an N_2 gas environment with a flow rate of 50 ml/min. The purpose of this work is to remove the impurities adsorbed by the samples. Then, to start the first adsorption cycle at the desired temperature, the atmosphere of the device was changed to a mixture of 90 vol.% CO_2 gas and 10 vol.% N_2 gas, and the temperature of the device was also reduced to the desired adsorption temperature. The adsorption process continued for 90 min, and the temperature of the device was again changed to 120 °C, and the atmosphere of the device was changed to N_2 gas. The device remained in this condition for 60 min until the desorption or reduction process was completed. In this way, the first adsorption/desorption cycle was completed at the desired temperature. This process is repeated exactly as three consecutive cycles of adsorption/desorption for all samples at two temperatures of 25 and 50 °C and concentrations of 10 and 90 vol.% CO_2 gas (Nobarzad et al., 2021).

3. Results and Discussion

3.1 Textural properties

3.1.1 FE-SEM analysis

Fig. 1 presents comparative SEM micrographs of both pristine and amine-functionalized adsorbents. As shown in Fig. 1a, the unmodified hairy nanocrystalline cellulose exhibits a characteristically smooth surface morphology with homogeneous texture, demonstrating the absence of significant porosity in its native structure(Heidari Nia et al., 2023; Lessan and Karimi, 2017). In contrast, as can be seen in Fig. 1b, activated carbon has high porosity and many micropores in its structure (He et al., 2021; Yagmur et al., 2020). It seems that the absence of pores in the hairy nanocrystalline cellulose sample compared to activated carbon is likely to be the reason for the low adsorption capacity of the cellulose sample. The image of hairy nanocrystalline cellulose modified with amine (Fig. 1c), shows that the planar structure of cellulose has undergone chemical changes due to the reaction with amine and has become a completely uneven structure. Also, observing the image of the activated carbon sample modified with amine (Fig. 1d) indicates significant changes in the carbon sample with the amine modification process, because most of the pores in the pure sample are filled with amine after modification, and a significant reduction in the surface area is observed. In other words, it can be said that the porosity of the carbon sample has been greatly reduced after the modification process(Kongnoo et al., 2016). This clogging of pores by amine will probably cause a decrease in adsorption capacity, which will be discussed in the following sections. Finally, it can be stated that with amine loading, the activated carbon sample has had its pores filled by amine molecules, but in the case of the cellulose sample, a chemical reaction with amine has occurred on the surface, and the structure of the adsorbent has undergone significant changes as a result of this reaction.

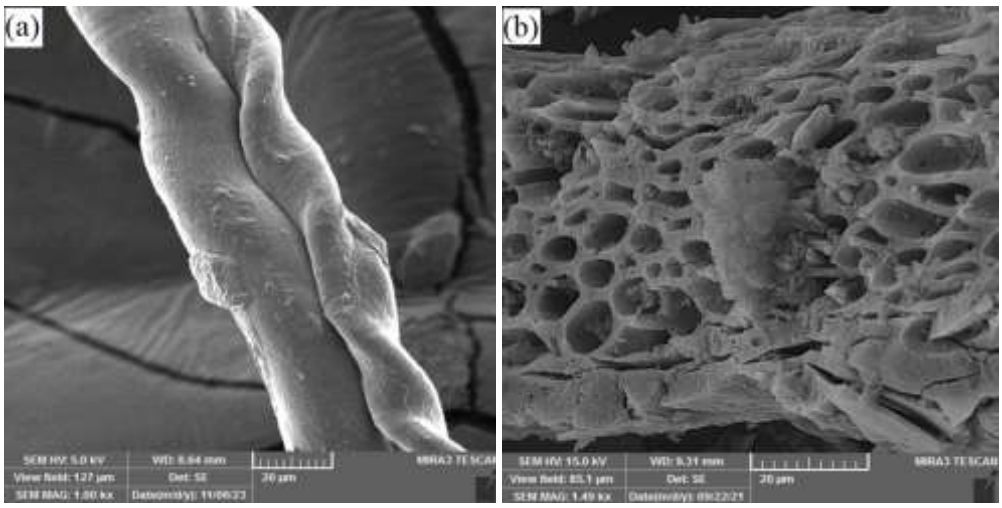
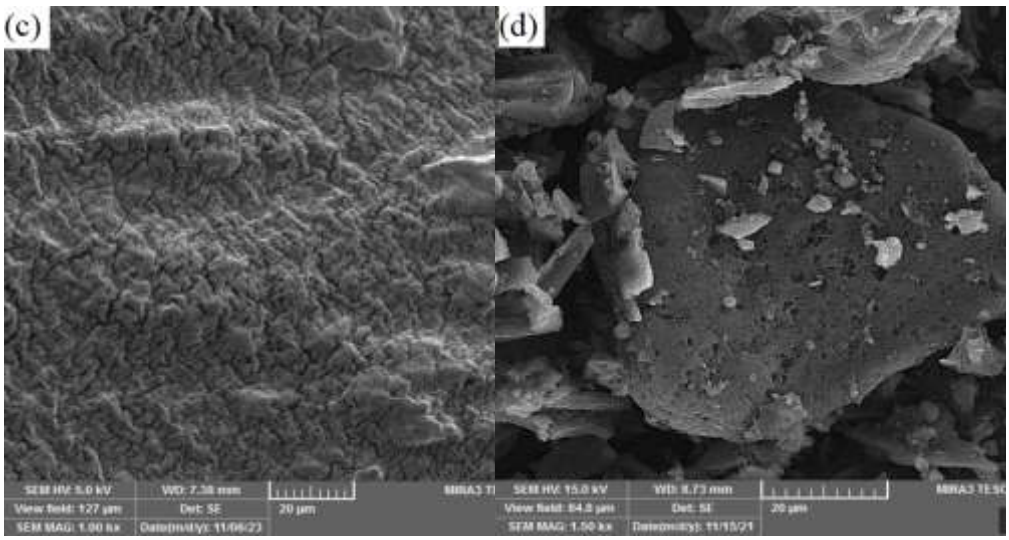


Fig. 1 FE-SEM analysis images of samples: a) Pure hairy cellulose nanocrystals, b) Pure activated carbon, c) hairy cellulose nanocrystals modified with MEA, and d) activated carbon modified with MEA



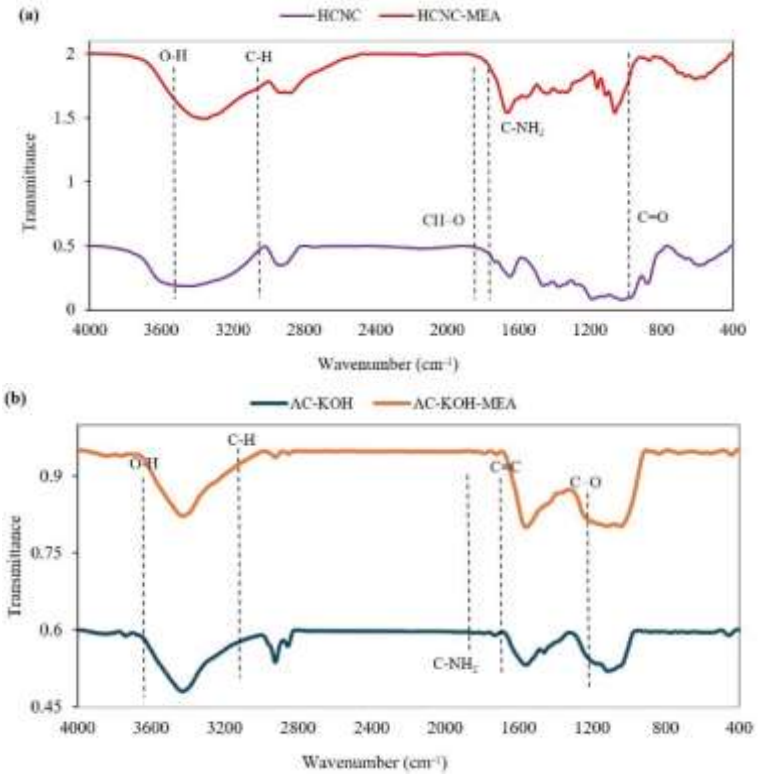


Fig. 2 FTIR analysis of samples: a) Pure hairy cellulose nanocrystals and hairy cellulose nanocrystals modified with MEA, and b) Pure activated carbon and activated carbon modified with MEA

3.1.2 FTIR analysis

The results of FTIR analysis of the cellulose sample and its modified type are presented in Fig. 2a. According to the figure, it can be said that the peaks observed in the region of 3415 to 3450 cm^{-1} are related to O-H stretching vibrations and the peak observed in the region of 2900 cm^{-1} represents C-H stretching vibrations. Considering that the highest adsorption of primary amine groups, which usually appear at about 3250 to 3400 cm^{-1}, overlap with O-H stretching vibrations, for this reason, the amine groups cannot be clearly distinguished. However, the amine-modified hairy nanocrystalline cellulose shows a broad, sharp peak in the region of 1650 to 1660 cm^{-1}, which represents $C-NH_2$ bending vibrations(Liu et al., 2018; Wang and Okubayashi, 2019). In addition, two characteristic peaks of hairy nanocrystalline cellulose at 890 and 1715 cm^{-1} indicate the tensile force of carbonyl groups and hemiacetal bonds formed by aldehyde groups, respectively. The peaks formed in these two regions confirm the oxidation reaction on alpha-cellulose, which resulted in the formation of aldehyde groups(Koshani et al., 2022). As a result of the modification of hairy nanocrystalline cellulose by amine, these two peaks have completely disappeared. This indicates that the chemical reaction between the aldehyde groups of hairy nanocrystalline cellulose with amine and their conversion into amine groups has occurred (Wang and Okubayashi, 2019). Fig. 2b also presents the results of FTIR analysis taken from the activated carbon sample and its modified type. The peaks formed in the region of 3430 to 3450 cm^{-1}, like the cellulose sample, are related to O-H stretching vibrations that are caused by the presence of moisture and hydroxyl groups. The peak observed

in the region of 2923 cm^{-1} represents C-H stretching vibrations. As a result of modification with amine, a peak was formed in the region of 1650 cm^{-1}, which confirms the success of modification with amine. However, it does not seem that the peak formed was caused by the reaction, but only by the filling of the pores (Das and Meikap, 2017). The peaks formed at 1560 and 1050 cm^{-1} are also attributed to the C=C and C=O groups, respectively (Demiral and Demiral, 2008).

3.2 TGA analysis and adsorption capacity

Fig. 3 presents the results of the adsorption capacity study of pure cellulose and activated carbon samples. By carefully examining the results, it can be seen that in all test conditions, AC-KOH has shown a higher average adsorption capacity compared to HCNC. For example, at a temperature of 25 °C and a concentration of 90 vol.% carbon dioxide gas, the average adsorption capacity of AC-KOH is reported to be about 2.78 mmol/g, which is about 60% higher than the average adsorption capacity of the cellulose sample, which is equal to 1.74 mmol/g. It is quite clear that the pores and micropores observed in the SEM analysis for the pure activated carbon sample have caused the high adsorption capacity of this sample compared to the cellulose sample, which does not have significant pores. Of course, the adsorption capacity of HCNC is also acceptable and shows that the presence of aldehyde groups formed as a result of oxidation has been able to compensate for the lack of pores to some extent(Koshani et al., 2022). However, it still has a lower adsorption capacity compared to activated carbon, which has a very high surface area due to the presence of numerous pores.

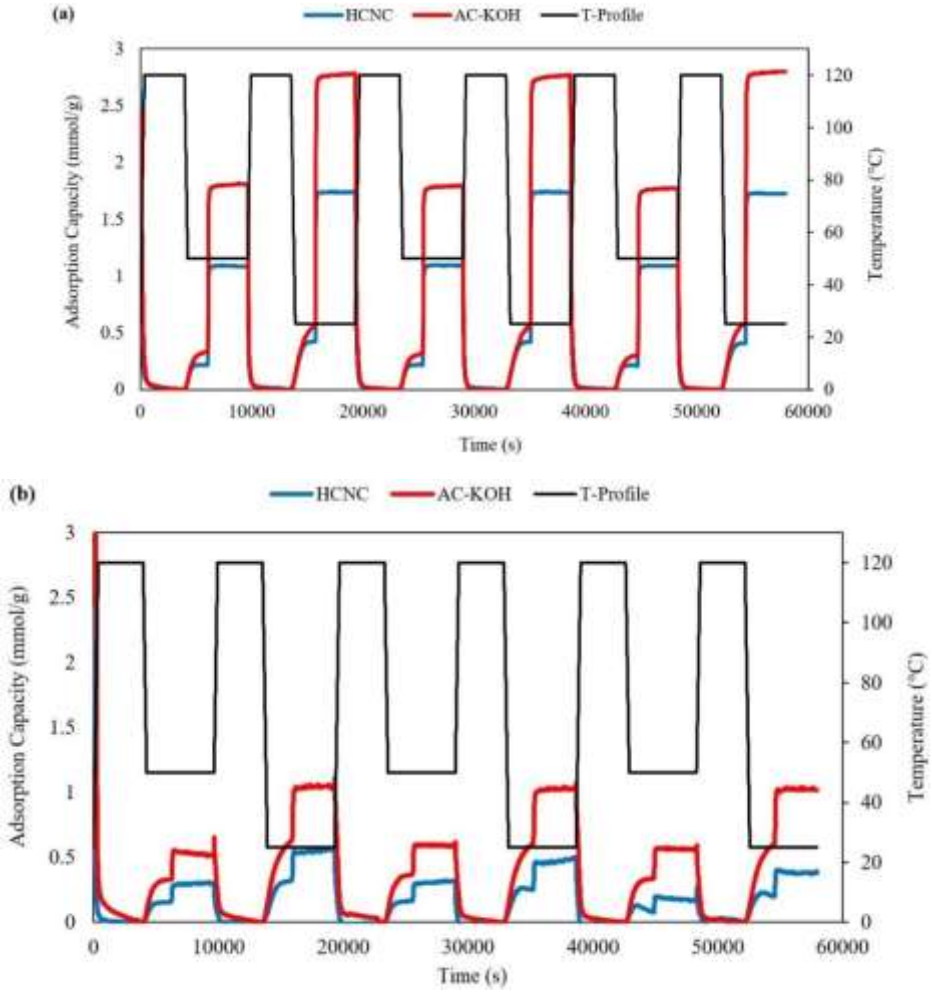


Fig. 3 CO_2 adsorption analysis for samples HCNC and AC-KOH at different temperatures of 25 and 50°C and at two concentrations of: a) 90 vol.% CO_2, and b) 10 vol.% CO_2

3.2.1 Effect of carbon dioxide concentration on adsorption capacity

According to Fig. 3, it is quite clear that for both pure samples and at both temperatures of 25 and 50 °C, the average adsorption capacity of carbon dioxide with a concentration of 90 vol.% is higher than that of 10 vol.% concentration. For example, at a temperature of 25 °C and a concentration of 90 vol.% carbon dioxide gas, the average adsorption capacity for HCNC and AC-KOH was 1.74 and 2.78 mmol/g, respectively. While at the same temperature and a concentration of 10 vol.% carbon dioxide, the average adsorption capacity was reported to be 0.48 and 1.02 mmol/g, respectively. It is clear that with an increase in the concentration of carbon dioxide gas from 10 to 90 vol.%, the number of carbon dioxide molecules per unit volume also increases, and as a result, the number of collisions with the adsorbent surface increases. As a result of this increase in the number of collisions with the surface, the adsorption capacity also increases, and more molecules are adsorbed onto the surface. Increasing the concentration of carbon dioxide increases the amount of contact of this gas with the surface of the adsorbent. Also, considering Henry's law, at

a constant temperature, the amount of gas adsorbed by the adsorbent is equal to the partial pressure of the same gas in the gas phase. That is, with increasing the concentration of carbon dioxide, the partial pressure of this gas in the gas phase increases, and as a result, the adsorption capacity increases (Sepahvand et al., 2020; Tahmasebpoor et al., 2023).

3.2.2 Effect of temperature on adsorption capacity

At a concentration of 90 vol.% carbon dioxide gas, with an increase in temperature from 25 to 50 °C, the average adsorption capacity for HCNC and AC-KOH samples decreased from 1.74 and 2.78 mmol/g to 1.09 and 1.79 mmol/g, respectively, which is equivalent to about 37% reduction for the cellulose sample and about 36% reduction for the carbon sample. As we know, the carbon dioxide adsorption process is exothermic and shows good efficiency at low temperatures. This decrease in adsorption capacity with increasing temperature confirms that the adsorption process by both samples in the pure state is completely physical. With increasing temperature, the kinetic energy of carbon dioxide molecules increases and, overcoming the minimum energy required for adsorption, passes the peak of the adsorption energy and is adsorbed by the adsorbent. However, as mentioned, this process is exothermic and the excess energy is produced in the form of heat, causing an even greater increase in kinetic energy. On the contrary, according to Le Chatelier's principle, the system tries to remove this excess energy. The removal of this energy from the system is manifested as a decrease in the rate of adsorption, so that with this decrease in adsorption, the system returns to equilibrium and the exothermic process of carbon dioxide adsorption stops (Sepahvand et al., 2020; Xu et al., 2021).

3.2.3 Effect of sample modification by amine

The results of the adsorption capacity of cellulose and monoethanolamine-modified activated carbon samples at two temperatures of 25 and 50 °C and concentrations of 10 and 90 vol.% carbon dioxide gas are presented in Fig. 4.

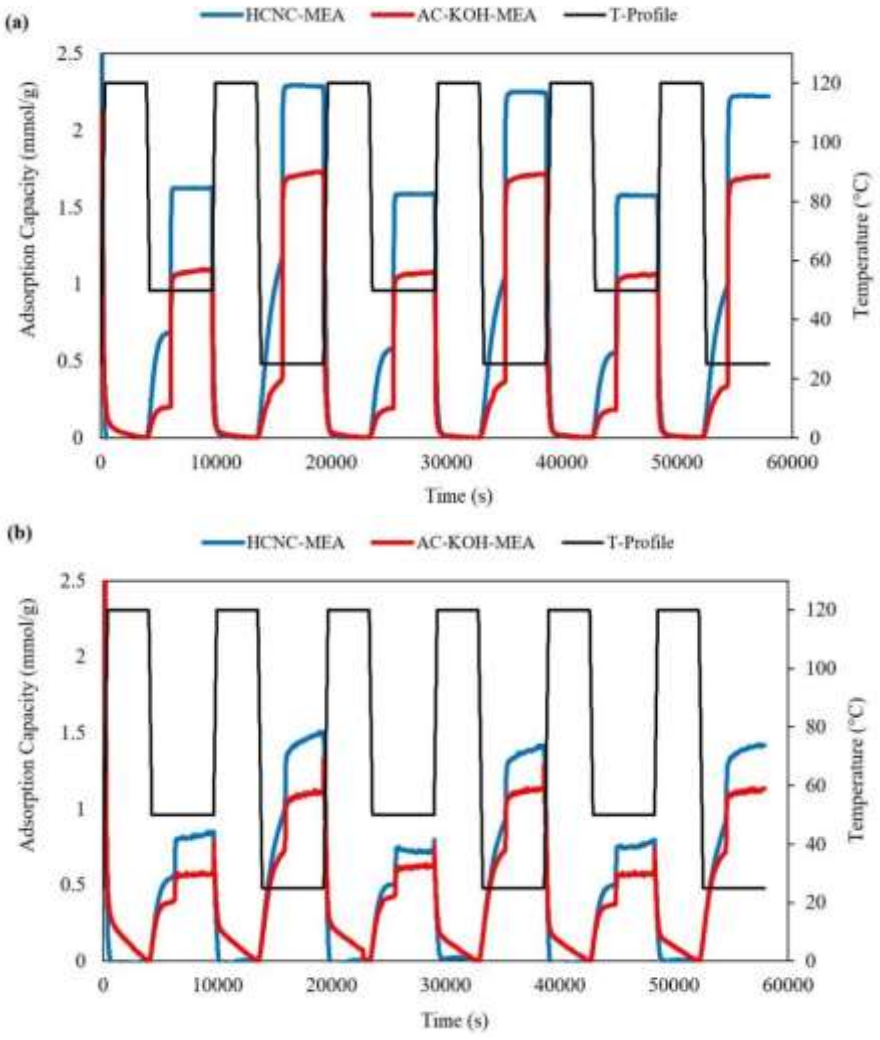


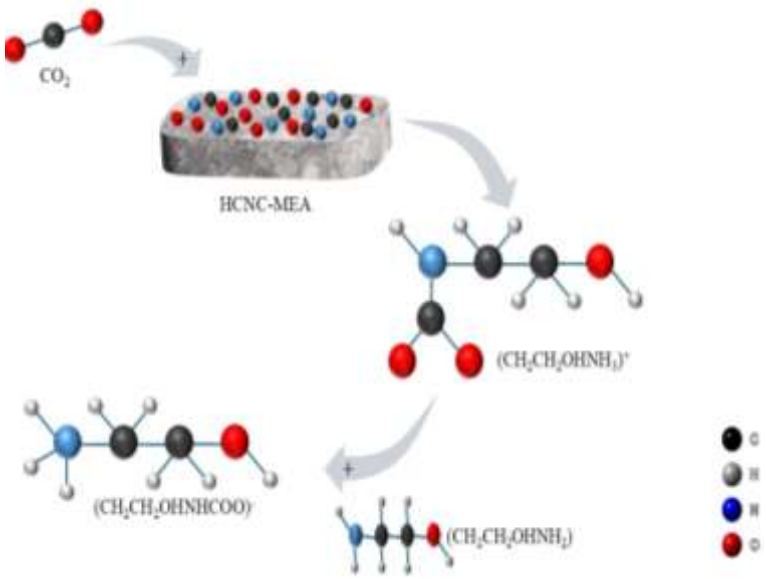
Fig. 4 CO_2 adsorption analysis for samples HCNC-MEA and AC-KOH-MEA at different temperatures of 25 and 50°C and at two concentration of a) 90 vol.% CO_2 and b) 10 vol.% CO_2

The results show that the modification of the cellulose adsorbent by amine (HCNC-MEA sample) increased the adsorption capacity in all experimental conditions, but in contrast, the modification of the activated carbon adsorbent by amine (AC-KOH-MEA sample) decreased the adsorption capacity. So at a temperature of 25 °C and a concentration of 90 vol.% carbon dioxide gas, the average adsorption capacity of the cellulose sample increased from 1.74 to 2.25 mmol/g, while under the same conditions, the average adsorption capacity of the carbon sample decreased from 2.78 to 1.72

mmol/g. In other words, the average adsorption capacity of the cellulose adsorbent increased by about 30% due to amine modification, but the average adsorption capacity of the carbon adsorbent decreased by about 40%. With the modification of activated carbon by amine, chemical adsorption also becomes important, along with physical adsorption. However, it should also be taken into account that, according to the results of SEM analysis, with the addition of amine to activated carbon, most of the micropores of this adsorbent are filled and clogged by amine molecules, and the porosity is significantly reduced. As a result, this filling of physical adsorption drops sharply, and the chemical adsorption that occurs by amine cannot compensate for this drop in physical adsorption. In other words, with the modification of the carbon adsorbent by amine, the adsorbent loses a significant part of its available surface area, and the carbon dioxide adsorption capacity decreases significantly. Physical adsorption plays a key role in activated carbon, the amount of which is greatly reduced by amine modification and reduced adsorbent porosity, resulting in a decrease in the total adsorption capacity (Gholidoust et al., 2017; Kongnoo et al., 2016). In contrast, the adsorption capacity of the cellulose adsorbent, which is devoid of pores, has increased significantly with amine modification only due to the presence of abundant aldehyde groups. Aldehyde groups have a great potential to form bonds with other materials. For this reason, it seems that aldehyde groups have reacted with amine modification, and as a result of this reaction, the adsorption capacity of the HCNC-MEA adsorbent has increased due to modification. Using the method of measuring aldehyde groups, the numerical value of these groups in this study was 7, which, according to the references, is a confirmation of the formation of aldehyde groups (Kim et al., 2000; Yu et al., 2022).

Fig. 4 shows that this improvement in the adsorption capacity of the adsorbent occurred due to the increase in chemical adsorption due to amine modification. This is because the interactions between the basic sites of the amine groups and the carbon dioxide molecules are stronger than the van der Waals forces created in physical adsorption. The interaction between the basic sites of the amine and the acidic CO_2 molecules leads to the production of carbamate. The zwitterion mechanism has been introduced for the formation of carbamates through the reaction between CO_2 and primary or secondary amines. This mechanism consists of two steps, which can be seen in Fig. 5. In the first step, the active electron pair located on the N atom of the primary amine attacks the C atom of the CO_2 molecule and forms the zwitterion. In the second step, another free amine molecule deprotonates the zwitterion formed in the first step, and finally, the carbamate is formed. Given that the deprotonation step is rapid, most reactions only refer to the production of the carbamate and omit this step. The carbamate is formed by the reaction of two primary or secondary amine molecules with a CO_2 molecule (Ahmed et al., 2016; Wu et al., 2018; Zhang et al., 2019).

Fig. 5 Mechanism of the reaction of amine MEA with CO_2



3.2.4 Comparison with other scientific sources

Table 1 briefly presents a comparison between the adsorption capacity of the adsorbents in this study and other studies. According to Table 1, it is possible to understand the different results of the adsorption capacity of activated carbon in different studies. Bezerra et al. (2014) showed that by adding amine to activated carbon, the adsorption capacity decreased, similar to the present study, from 1.202 mmol/g to 0.590 mmol/g. However, Kamarudin et al. (2018) reported an increase in CO_2 adsorption capacity (46% increase for Tetraethylenepentamine and 25% increase for MEA amine) by modifying activated carbon with two different types of amines. A comparison of the results obtained with different sources shows that the results are different, which can probably be attributed to the microstructure of the produced activated carbon. In addition, the comparison results indicate that by modifying the cellulose adsorbent with different amines, the

adsorption capacity has increased, unlike carbon adsorbents, which have different results. For example, Zhang et al. (2019) were able to increase the adsorption capacity of this adsorbent from 0.20 mmol/g to 1.59 mmol/g by modifying nanocrystalline cellulose.

Table 1 Comparison of activated carbon and hairy cellulose nanocrystals synthesized in the present study with other studies

Adsorbent	Amine	CO_2 concentration	Adsorption temp (°C)	Adsorption capacity (mmol/g)	Reference
Commerical AC	- MEA	100	25	1.202 0.590	(Bezerra et al., 2014)
AC-kenaf	- MEA TEPA	100	25	0.624 0.781 0.914	(Kamarudin et al., 2018)
AC-oil sands	- DEA	99.99	50	1.34 5.63	(Gholidoust et al., 2017)
AC-fly ash	- MEA	99.8	30	0.95 1.54	(Maroto-Valer et al., 2008)
CNC	- APTMS	99.9	25	0.100 0.200	(Mohd et al., 2021)
CNC Aerogel	- AEAPMDS	100	25	0.200 1.590	(Zhang et al., 2019)
CNF	- APS	100	25	0.350 1.910	Wu et al., (2018)
CNC/Silica	- TEPA	100	25	0.25 2.25	Zhou et al., (2021)
AC-oleaster kernel	- MEA	90	25	2.780 1.720	Present Study
HCNC	- MEA	90	25	1.740 2.250	Present Study

4. Conclusion

This study aimed to improve the performance of hairy nanocrystalline cellulose and activated carbon adsorbents by using amine modification and investigating the adsorption of these adsorbents. In summary, the following results can be deduced from the present study**:**

1. The average adsorption capacity decreases with increasing temperature from 25 to 50 °C. For HCNC and AC-KOH samples at 90 vol.% CO_2 concentration, it decreased from 1.74 and 2.78 to 1.09 and 1.79 mmol/g, respectively**.**

2. Increasing the carbon dioxide concentration from 10 to 90 vol.% at 25 °C increased the average capacity. The average adsorption capacity of both HCNC and AC-KOH samples increased from 0.48 and 1.02 to 1.74 and 2.78 mmol/g, respectively**.**

3. By modifying the adsorbents with amine at all experimental conditions (temperature 25 and 50 °C, concentration 10 and 90 vol.% CO_2), the adsorption capacity of the cellulose sample increased significantly, but on the other hand, this modification caused a decrease in the adsorption capacity of the carbon sample**.**

Due to the lack of a TGA/DC1 device in the country, it was not possible to perform post-adsorption analyses in this study. Considering the results obtained and the comparison with activated carbon, which is a known adsorbent, it can be stated that the novel hairy nanocrystalline cellulose adsorbent, both in its pure state and modified with amine, can be introduced as a new adsorbent in the field of carbon dioxide adsorption. Aminosilanes can be used to modify hairy nanocrystalline cellulose, and their results can be compared with the sources.

Statements and Declarations

Acknowledgements

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Data availability

Data can be shared by the corresponding author via email (tahmasebpoor@tabrizu.ac.ir) upon reasonable request.

Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

M. Tahmasebpoor: Supervision, Review-Editing; O. Mohammadi Moinalzoafa: Methodology, Investigation, Conceptualization, Writing Original Draft.

AI Use Declaration

This study did not incorporate artificial intelligence techniques; instead, all analyses and optimizations were conducted using conventional and widely accepted analytical methods.

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