Activated porous carbon derived from sawdust for CO₂ capture

S. Foorginezhad a, *, M.M. Zerafat b, **, M. Asadnia c, ***, Gh Rezvannasab b

a Department of Engineering Sciences and Mathematics, Luleå University of Technology, Energy Science, 97187, Luleå, Sweden
b Faculty of Advanced Technologies, Nano-Chemical Engineering Department, Shiraz University, Shiraz, 71348-51154, Iran
c School of Engineering, Macquarie University, Sydney, New South Wales, 2109, Australia

HIGHLIGHTS

• Hierarchical porous carbons are synthesized from cheap and available sawdust.
• Facile activation using CO₂ was applied.
• 9.2 mmol/g CO₂ adsorption uptake and 40.2 CO₂/N₂ selectivity were achieved.
• Recyclability over 10 cycles demonstrates practical application.

ARTICLE INFO

Keywords:
CO₂ capture
Adsorption
Activated carbon
Porous carbon
Selectivity

ABSTRACT

Mitigation of greenhouse gas emissions, especially CO₂, highlights the critical demand for efficient CO₂ capture technologies. This is due to their essential role in climate change and their profound impact on global ecosystems and human well-being. Activated carbons have emerged as promising candidates for CO₂ capture due to their availability, cost-effectiveness, and tunable properties. In this study, activated carbons were synthesized from sawdust carbonized at various temperatures within the 700–1100 °C range and subsequently activated using CO₂. Comprehensive characterization was conducted through SEM, FESEM, XRD, TGA, and FTIR techniques to assess the properties. The results reveal that carbonization at 1000 °C yielded an activated carbon with a hierarchical and microporous structure, featuring surface area, pore volume, and pore size of 1651.34 m²/g, 0.69 cm³/g, and <1.76 nm, respectively. Remarkably, this activated carbon exhibited promising CO₂ uptake of 9.2 mmol/g at 25 °C and 1 bar. Moreover, a remarkable recyclability over 10 cycles demonstrates its potential for practical CO₂ capture applications. Furthermore, the synthesized activated carbon exhibited high selectivity for CO₂ over N₂ (85/15 v/v), reaching 40.2 at 1 bar and 25 °C. These findings underscore the viability of the as-prepared activated carbon as a desired candidate for efficient and selective CO₂ capture, contributing to the ongoing efforts to mitigate the impact of anthropogenic CO₂ emissions to the environment.

1. Introduction

The primary environmental concern contributing to global warming is the rapid increase in greenhouse gas emissions [1]. This surge, which is a consequence of human activities such as fossil fuel combustion, deforestation, and industrial processes, has significantly amplified the natural greenhouse effect. As a result, heat entrapment in the atmosphere leads to a noticeable escalation in global temperatures. This warming trend presents several challenges, including polar ice melt, rising sea levels, altered weather patterns, ecosystem disruptions, and ozone depletion [2,3]. Owing to carbon dioxide’s greenhouse characteristics, resulting from specific human activities, it is recognized as the primary cause of global warming. The World Green Building Council and International Energy Agency reveal that the building sector is responsible for 39% of global carbon emissions. Within this sector, 28% of emissions stem from operational carbon emissions, while the remaining 11% can be attributed to embodied carbon emissions linked to materials, transportation, and construction processes, encompassing the entire life cycle of buildings [4]. The increase in CO₂ concentration is considered as a possible cause for the greenhouse effect that leads to
global warming, and its reduction is a matter of environmental concern [5].

Overall, the release of CO$_2$ resulting from the combustion of fossil fuels and their derivatives remains the pivotal contributor of CO$_2$ source [6]. Estimations point towards a continuous increase in the consumption of fossil fuels for industrial applications in the foreseeable future. Undoubtedly, excessive emissions of CO$_2$ caused by human activities will significantly affect global warming and engender many environmental challenges. Hence, the primary avenue for addressing global warming with efficacy lies in the proficient capture and sequestration of CO$_2$ [7, 8].

1.1. CO$_2$ capture technology and methods

In the context of large-scale CO$_2$ management, three main methods stand out for CO$_2$ separation and capture. These methods are oxy-fuel combustion capture, pre-combustion capture, and post-combustion capture. Each approach plays a vital role in the ongoing effort to decrease CO$_2$ emissions and address the challenge of climate change. In the context of identifying sources and the processes involved in CO$_2$ generation, diverse technological approaches are available for implementing a carbon capture system within both academic and industrial domains. These approaches encompass absorption, adsorption, membrane separation, biological capture, and cryogenic capture techniques. These technologies represent a spectrum of options for capture and mitigate CO$_2$ emissions, catering to various applications and industries [9]. Drawing from the literature review and our present comprehension, absorption, adsorption, and membrane separation technologies have garnered significant focus compared to other methods. In the context of gas mixtures, it is challenging to simultaneously achieve a high degree of CO$_2$ separation and a heightened level of CO$_2$ purity when utilizing a single-stage ceramic or polymeric membrane. This challenge arises due to a trade-off between these two objectives. In comparison, ceramic membranes exhibit low CO$_2$ selectivity over other gases, while they can operate under harsh conditions [10], including elevated temperatures (>350 °C) and corrosive media [11]. It can be seen that the documented literature underscores the increasing prominence of adsorption and absorption techniques in the field of CO$_2$ capture [12].

1.1.1. Absorption

CO$_2$ capture using liquid absorption is considered as the most commercially available and mature technology in various fields, including chemical and petroleum industries [9]. Although considerable attention has been devoted to amine system as a promising candidate to capture up to ~90% of CO$_2$ in flue gas, almost 30% of the plant-produced power is consumed, costing $40–100 per Ton of CO$_2$ [13]. MEA has been widely used for CO$_2$ capture from power plants due to high uptake rates, low cost, and biodegradability. However, several drawbacks such as corrosion, solvent loss, and toxicity raised from degradation and evaporation are inevitable [9, 14]. As the driving force is solubility, it has been illustrated that physical absorption depends on pressure/temperature differences, while acid-based neutralization reaction plays a vital role in chemical absorption [15–17]. Various absorbent solutions have been suggested in the pursuit of solvent-based CO$_2$ capture technologies. Among these options, Ionic Liquids (ILs) are recommended as a promising alternative to conventional solutions due to their distinctive properties, including low volatility, non-flammability, exceptional thermal stability, minimal vapor pressure, and reduced energy requirements for regeneration [18, 19]. However, several weaknesses such as high viscosity, high cost, and low working capacity can limit their utilization [9].

1.1.2. Adsorption

Due to promising advantages, including low energy consumption, insignificant corrosion, and no need for special equipment, adsorption is highly considered for CO$_2$ capture [20]. It is verified that through a reversible process and simple equipment, carbon capture efficiency can be reached up to >85%, while challenges exist in solid handling and low adsorption rate as well as selectivity [21] that need to be addressed. In adsorption, CO$_2$ capture can achieve through either physical (van der Waals bond between the adsorbent and CO$_2$ molecules) or chemical adsorption (chemical bonds between the adsorbent and CO$_2$ molecules) and the most efficient adsorbent is selected according to CO$_2$ adsorption, CO$_2$ selectivity, adsorption/desorption rate, adsorption/desorption temperature, regeneration, mechanical/thermal stability, manufacturing/operation costs, etc. [22]. Up to now, a diverse array of adsorbent materials have been developed for CO$_2$ capture, including metal oxides, metal-organic frameworks (MOFs), zeolite imidazolate frameworks (ZIFs), zeolites, carbon-based materials in various forms, polymeric particles, and other materials like biochar [23, 24]. It is also essential to underscore the paramount importance of the cost-effectiveness of adsorbents, especially in case of considering their deployment at a larger scale in practical applications [25], as some of porous adsorbents are technically inefficient or not economically viable [26].

Activated carbon emerges as a notably advantageous and energy-efficient material which can be derived from recycled materials [27], including agricultural and crop residues, municipal solid waste, industrial byproducts, animal remains, and forestry biomass [27]. Yusof et al. [28] investigated the CO$_2$ adsorption performance of fibrous silica impregnated with CaO, MgO, and CeO$_2$. The highest physical adsorption uptake reached to 0.76 mmol/g at atmospheric pressure and room temperature. In contrast, the most significant chemical adsorption of CO$_2$ was observed for MgO-FL, with an uptake of 9.97 mmol/g. Rouzi et al. [29] employed nano-porous carbon derived from walnut shells for CO$_2$ capture. The as-prepared adsorbent exhibited a CO$_2$ uptake and CO$_2$/N$_2$ selectivity of 7.42 mmol/g and 12.70, respectively at 1 bar and 25 °C. Hamyali et al. [30], synthesized various carbonaceous adsorbents using anthracite coal for CH$_4$, N$_2$, and CO$_2$ capture. The CO$_2$ uptake at 1 and 35 bar was 10.51 mmol/g and 27.58 mmol/g, respectively. Also, the selectivity of CO$_2$/N$_2$ and CO$_2$/CH$_4$ reached 10.17 and 25.67, respectively. Ahmad et al. [31] derived carbon from waste jute and activated it by C/KOH in various ratios (1:1, 1:2, 1:3, and 1:4) to produce CO$_2$ capture nano-adsorbent. At 25 °C, the CO$_2$ uptake reached 9.15 and 26.18 mmol/g at 1 and 35 bar, respectively. Besides, the as-prepared adsorbent depicted CO$_2$/CH$_4$ (10:90) selectivity of 9.28 at 35 bar. Recently, Souza et al. [32] synthesized microporous carbon from Brazil nut shells for carbon capture. Results depicted that the KOH chemically activated carbon exhibited better CO$_2$ uptake of 3.8 mmol/g at 1 bar and 25 °C compared to the physically activated sample.

In the present study, activated carbons were synthesized from sawdust subjected to carbonization over the 700 °C–1100 °C range. The subsequent activation process involved the utilization of CO$_2$ gas. To evaluate the properties of the synthesized activated carbon, SEM (scanning electron microscopy), FE-SEM (field emission scanning electron microscopy), XRD (x-ray diffraction), TGA (thermogravimetric analysis), and FTIR (Fourier transform infrared spectroscopy) were employed. Through controlling the carbonization temperature and employing CO$_2$ activation, the as-prepared activated carbon meets requirements for CO$_2$ adsorption, recycling, and selective capture of CO$_2$ over N$_2$. This work contributes to the body of knowledge in low-cost and sustainable activated carbon synthesis and application in CO$_2$ capture, offering valuable insights and opportunities for further research and development in the field of sustainable and efficient carbon capture technologies.

2. Experimental section

2.1. Materials & methods

2.1.1. Materials

Sawdust was obtained from a local market (Fars, Iran) and sieved. Subsequently, the samples with a particle size <3 mm were selected for
further experiments. Pure CO₂ gas was used as an activating agent and for CO₂ capture. N₂ gas was used to assess the selectivity of the adsorbents.

2.1.2. Characterization techniques

The porous structure of the synthesized activated carbon, along with its pore dimensions and morphology, were analyzed by Scanning Electron Microscopy (SEM) instrument (VEGA3 TESCAN) and Field emission scanning electron microscopy (FE-SEM) micrographs (MIRA3TESCAN-XMU).

Fourier Transform Infrared Spectroscopy (FTIR) was carried out at room temperature (25 °C) using a Nicolet Magna 550 spectrometer to characterize the chemical composition of the synthesized carbon, providing insights into different chemical bonds and the detection of functional groups.

The thermal stability and degradation of the synthesized carbon were studied by conducting Thermogravimetric Analysis (TGA) in an air atmosphere using a TA instrument (model: Q600, USA). Temperature increased at a rate of 10 °C/min, ranging from ambient temperature to 1200 °C.

Diffraction pattern of the synthesized carbon was evaluated through X-ray diffraction (XRD) performed using a Panalytical Xpert PRO X-Ray Diffractometer (Holland) with Cu (λ = 0.154 nm) irradiation at 40 kV and 30 mA in the 20 = 5°–90° range.

Specific surface area, pore size, and pore volume of the synthesized carbon was considered using Brunauer–Emmett–Teller (BET) and Barrett–Joyner–Halenda (BJH) methods (BEL Co., BELSORP MINI II, Japan). The BET analysis was conducted within a relative pressure range of 0.0105–0.1439. The determination of the total pore volume was carried out at a relative pressure ranging up to 0.1214. For the evaluation of pore size distribution, the Non-Local Density Functional Theory (NLDFT) method was applied to the adsorption isotherm data. Regarding the sample preparation, degasification conditions were meticulously controlled at a temperature of 130 °C for a duration of 700 min, under a nitrogen atmosphere, ensuring optimal preparation of the samples for the adsorption tests.

2.2. Synthesis of porous carbons

Sawdust was ground, then dried at 110 °C for 12 h to serve as the starting material for porous carbon production. Following the overall procedure reported by Ello et al. [33], ground sawdust was placed inside a tubular furnace and subjected to heating in the range of 700–1000 °C under N₂ atmosphere. To activate the as-prepared carbon, the flow of nitrogen (N₂) was switched to CO₂ with 140 mL/min rate for 3.5 h, after reaching the desired temperature. Following this, the gas flow was switched back to nitrogen (N₂), while allowing the temperature to decrease gradually to the room temperature. For the purpose of comparison, inspired by a Ello et al. [33], raw sawdust as blank sample was heated to the desired temperature, while exposed to a continuous flow of nitrogen (N₂) gas for 1 h. Subsequently, it was cooled down to the room temperature. The synthesized carbons activated by CO₂ gas flow are denoted as A-CS-X, where X is the carbonization temperature (700–1100 °C).

2.3. CO₂ adsorption and regeneration

The adsorption characteristics were evaluated through Thermogravimetric Analysis (TGA) at different temperatures in the 0–50 °C range, atmospheric pressure (1 bar), and various CO₂ flow rates in the 50–150 mL/min range. The adsorption amount was monitored continuously for a period of 30 min. Before each adsorption experiment, the carbon sample underwent a degassing process at 120 °C under vacuum conditions for 12 h. To assess the recyclability, after achieving adsorption equilibrium at a specific temperature, the sample was heated up to 120 °C and maintained until desorption was accomplished, and a continuous adsorption-desorption cyclic test was conducted for the sample up to 10 cycles. In the desorption process, gravimetric method was also utilized to quantify the amount of CO₂ desorbed from activated carbon.

The adsorption selectivity of the synthesized sample for CO₂ over N₂ at 25 °C was determined using the well-established Ideal Adsorption Solution Theory (IAST) and considering of 1 bar as the total pressure of the CO₂/N₂ mixture, with 15 mol% for CO₂ and 85 mol% for N₂, as described by equation (1) [34,35]:

$$S_{\text{IAST}} = \frac{q_{\text{CO}_2/0.15 \text{ bar}}}{q_{\text{N}_2/0.85 \text{ bar}}} \times \frac{0.85}{0.15}$$

Where \(q_{\text{CO}_2/0.15 \text{ bar}} \) is CO₂ and N₂ uptake (mmol/g) at 0.15 and 0.85 bar partial pressures, respectively.

3. Results and discussion

3.1. Textural properties

Textural characteristics of the as-prepared activated carbons are reported in Table 1. The data clearly reveal a notable variation in the raw sawdust surface area properties and pore characteristics when subjected to varying carbonization temperatures. The raw sawdust initially exhibits relatively low surface area, pore volume, and pore size. However, with the progressive increase in carbonization temperature, these parameters exhibit a substantial growth, reaching their maximum at 1000 °C, where the surface area reaches 1651.34 m²/g, the pore volume increases to 0.68 cm³/g, and the pore size to 1.76 nm. Interestingly, when carbonization temperature is further increased to 1100 °C, there is a decline in the surface area to 1429.18 m²/g at 1050 °C and further to 1163.26 m²/g at 1100 °C. This diminishing trend in surface area contrasts with the behavior of pore volume. A similar trend was documented in the study by Serafin and Cruz Jr [35], where the surface area of activated carbon derived from common oak leaves increased from 1180 m²/g at 600 °C to 1821 m²/g at 800 °C with a subsequent surface area reduction, down to 1382 m²/g. This behavior reflects a common phenomenon in the carbonization process of biomass. Initially, with the elevation of temperature, there is an augmentation in carbonization and the formation of pores, resulting in an expanded surface area. On the other hand, at higher temperatures, supplementary reactions, such as pore collapse or merging, may diminish the overall surface area. This phenomenon is also observable in the SEM images, where it becomes evident that volatile compounds within the sawdust are facilitated to create more pores as the carbonization temperature rises. At higher temperatures, these pores can merge and coalesce, forming larger pores in the material’s structure [36].

Fig. 1 (a) presents the corresponding N₂ adsorption-desorption isotherm for raw sawdust and carbonized samples. Among all the samples, A-CS–1000 was chosen for further experimentation, due to its superior surface area, pore volume, and pore size characteristics. Following the International Union of Pure and Applied Chemistry
(IUPAC) classification, A–CS–1000 exhibits a Type-I isotherm at low relative pressures. Notably, the curve displays a remarkably narrow hysteresis loop, a feature indicative of the presence of narrow micro-pores [37]. This specific isotherm type is characteristic of gas molecules adsorbing onto materials with micro-pores, which are relatively small in size and primarily found on the external surfaces, a feature often observed in activated carbon materials [36,37]. The pore size distribution of A–CS–1000 using nonlinear density functional theory (NLDFT) and N2 isotherm is delineated in Fig. 1 (b). A–CS–1000 reveals a significant predominance of ultra-micropores, characterized by pore diameters falling within the 0.4–1.76 nm range. This intriguing observation points to the fact that the ultra-microporosity of A–CS–1000 is profoundly influenced by the choice of activation temperature and/or the utilization of CO2 as the activating agent. Regarding CO2 uptake of each sample, a notable increase in CO2 capture amount was observed with the increase in specific surface area, up to a maximum amount of 1651.34 m2/g. This trend aligns with the expected behavior that larger surface areas provide an increased number of adsorption sites for CO2 molecules. However, further increase in the sintering temperature resulted in surface area reduction followed by a slight decrease in CO2 uptake. This can be attributed to the change in pore structure and possibly the deterioration of some functional groups at higher temperatures, which are also critical factors influencing CO2 adsorption. These findings highlight the intricate relationship between specific surface area, pore structure, and other material properties in determining the efficiency of CO2 adsorption. Based on the CO2 capture performance and characteristic properties of each sample, A–CS–1000 has been selected for more in-depth analysis and characterizations.

3.2. TGA analysis

TGA was employed to assess the thermal stability of sawdust and A–CS–1000. As for sawdust, Fig. 2 reveals distinct weight loss patterns indicative of sawdust and A–CS–1000 thermal behavior. Initially, as the temperature gradually increased up to 150 °C, a slight weight loss of ~5% was observed. This initial decline can be ascribed to the elimination of physically adsorbed water and the desorption of lightweight molecules that might have been trapped within the activated carbon’s
porous structure [38,39]. Subsequently, a sharp and more substantial decline in weight up to ~72% became evident within the 240–400 °C temperature range, which can be attributed to the thermal decomposition of cellulose and hemicellulose, key constituents of the original raw material [40,41]. It is reported that hemicellulose, cellulose, and lignin degradation occur generally in the 200–700 °C range [42]. Consistent with prior studies, it is evident that the final mass is not absolute zero due to the presence of fixed carbon and ash constituents within the carbon material [39].

The TGA of A–CS–1000 delineated that, within the temperature range of 25 °C–850 °C, a mass loss of 6.6% was observed, indicating the complete decomposition of organic compounds present in the material. This finding aligns well with the outcomes reported in previous studies, affirming the reliability of the results. For example, Thabede et al. [43] synthesized activated carbon from Rose Geranium (Pelargonium graveolens L.) Leaves which showed ~70 wt % and ~15 wt % mass loss for activated carbon and raw precursor, respectively. Furthermore, during the initial heating phase spanning from 25 °C to 150 °C, a minor mass loss of ~1.5% was noted. This loss can be attributed to the desorption of water molecules from the surface of the activated carbon. This behavior is consistent with water desorption phenomenon commonly observed in thermal analysis of porous materials. These TGA result offer valuable insights into the thermal stability of A–CS–1000, affirming its suitability for various applications, including CO₂ capture. TGA analysis revealed that the activated carbon was produced with a ~19% yield. Despite the modest yield, the economic viability and feasibility of the process are enhanced by the availability and low-cost of the raw material employed. The abundant supply and affordability of sawdust mitigate concerns regarding the lower yield, ensuring that the production process remains both economically feasible and sustainable.

### 3.3. FE-SEM and SEM analyses

SEM analysis was conducted to examine the microstructural characteristics of both raw and carbonized sawdust and the results are visually presented in Fig. 3(a–i), providing valuable insights into the structural transformations during the carbonization process. According to Fig. 3 (a) and (b), it can be seen that the surface structure of the raw powdered sawdust exhibits an amorphous structure. Also, surface of the particles is relatively smooth and without pores. In Fig. 3 (c), it is evident that elevating the temperature up to 700 °C followed by CO₂ activation, leads to the development of a limited number of surface pores while some were blocked by ash and by-products. This finding is consistent with the observations reported in a prior study conducted by

![Fig. 2. TGA curve of raw sawdust and A-CS–1000 under N₂ atmosphere.](image)

![Fig. 3. SEM and FE-SEM images of (a) and (b) raw sawdust, (c) A-CWO-700, (d) A-CS–800, (e) A–CS–900, (f) and (g) A–CS–1000, (h) A-CS–1050, (i) A-CS–1100.](image)
Concerning Fig. 3 (d), as the temperature is further elevated to 800 °C, there is a notable increase in porosity and the number of pores. Furthermore, larger pores become apparent on the surface. Additionally, it becomes evident that higher temperatures correlate with a reduction in the quantity of ash and by-products. Subsequently, the porous structure undergoes further development as the temperature is elevated to 900 °C (see Fig. 3 (e)). Notably, the number of pores continues to increase as the temperature rises. At 1000 °C, the observation reveals a significant transformation in the microstructure. Larger pores, exhibit micro-pores within them, resulting in the formation of a hierarchical and channel-like porous structure (Fig. 3 (f) and (g)). It is suggested that these larger pores may originate from the vascular bundles present in the initial raw material [41]. This overall structural arrangement aligns well with findings reported in previous studies, further substantiating our observations [44,45].

3.4. FTIR analysis

FTIR spectroscopy was employed to investigate the functional groups, chemical bonds, and structural changes of the sample after carbonization at 1000 °C and results are shown in Fig. 4 (a). The peaks located within the 3350-3400 cm⁻¹ range are attributed to stretching vibration of hydroxyl groups of the moisture content of the sample or mineral-based hydroxyl bonded to silicon [47,48]. Peaks at 2920 and 2906 cm⁻¹ are originated from symmetric C–H stretching vibration, suggesting the presence of aliphatic hydrocarbon chains [47,49]. The peak at 1740 cm⁻¹ arises from stretching vibration of C=O, indicating the presence of carbonyl groups, and stretching vibration of C=C related to alkene is appeared at ~1670 cm⁻¹ [49,50]. The peaks appeared in the 1034-1052 cm⁻¹ range are known to be originated from C–N, C–O, C–C, or/and S–O [49,51]. It can be seen that increasing the temperature led to the disappearance of peaks related to C–H, and C=O, which

![Fig. 4. (a) FTIR spectra of raw sawdust and A–CS–1000 and (b) XRD pattern of the synthesized A–CS–1000.](image)

![Fig. 5. CO₂ adsorption uptake of A–CS–1000 (a) carbonization temp. = 700–1100 °C and adsorption temp. = 25 °C, (b) carbonization temp. = 1000 °C, flow rates = 50–150 mL/min, adsorption temp. = 25 °C, (c) carbonization temp. = 1000 °C, flow rate = 50 mL/min adsorption temp. = 0–50 °C, and (d) carbonization temp. = 1000 °C, flow rate = 50 mL/min adsorption temp. = 0, 25 °C, adsorption pressure = 0–20 bar range.](image)
is in agreement with results reported in previous studies [47]. C–R stretching vibration related to alkene compounds or aromatic hydrogen is shown by the peak located at 580 cm\(^{-1}\) [50]. Besides, the intensity of C=O, C–O, C–N, S=O, and C–R peaks increased, which verified that these bonds are stable and may even participate in the formation of new compounds via thermal treatment, including some hydrocarbon-based molecules produced during thermal treatment [47,49]. It is reported that at elevated temperatures, organic functional groups experienced bond cleavage, which results in an increased mass loss and the production of gaseous products [52]. Moreover, the peak located at 881 cm\(^{-1}\) is attributed to phosphate groups in the carbonized sample [53].

### 3.5. XRD analysis

Fig. 4 (b) displays the XRD pattern of A–CS–1000, revealing broad peaks at 24\(^\circ\), 43\(^\circ\), and 80\(^\circ\), attributed to (002), (100), and (110) planes, respectively. It can be observed that the A–CS–1000 XRD spectrum aligns well with the XRD spectrum of activated carbon reported in previous studies, including activated carbon derived from surgical mask waste [54], palm shell [55], fruit waste [56], and a range of nano-porous carbons derived from polypropy (Polypropyylum vulgar) [57]. It has been noted that this structure indicates the presence of amorphous structures, contributing to the generation of adsorbents with more extensively developed pore structures, making them well-suited for gas separation processes [35,58].

### 3.6. CO\(_2\) adsorption performance

To explore the impact of carbonization temperature on CO\(_2\) capture capacities, Fig. 5 (a) depicts the CO\(_2\) uptake of activated carbons synthesized at various carbonization temperatures within the range of 700 \(\degree\)C–1100 \(\degree\)C. It is evident from the data that there is a notable trend in CO\(_2\) uptake corresponding to the variation in carbonization temperature. Specifically, as the carbonization temperature increased from 700 \(\degree\)C to 1000 \(\degree\)C, a substantial enhancement in CO\(_2\) uptake from 3.5 to 9.2 mmol/g was observed after 35 min. However, a further increase in carbonization temperature up to 1100 \(\degree\)C results in a subsequent reduction in CO\(_2\) adsorption amount, which can be related to the structural changes and a decrease in active sites, or decrease in the interaction forces and adsorbate-adsorbent binding [59]. This observed behavior closely aligns with findings from prior studies [46,54]. The initial increase in CO\(_2\) uptake can be attributed to heightened porosity and surface area generated during carbonization at higher temperatures up to 1000 \(\degree\)C (which are reported in Table 1), thus enhancing the adsorption amount. Fig. 5 (b) investigates the influence of flow rate in the 50–150 mL/min range on CO\(_2\) adsorption at 25 \(\degree\)C. It can be seen that the highest CO\(_2\) uptake (9.2 mmol/g) was obtained at the lowest flow rate of 50 mL/min. Subsequently, a gradual decrease in CO\(_2\) uptake can be seen by increasing the flow rate, which are consistent with those reported by Akpasi and Isa et al. [60] and it is reported that reduction in flow rate enhances contact time and, consequently, improves the mass transfer between CO\(_2\) and the adsorbent [60]. Lower flow rates provide increased time for CO\(_2\) molecules to effectively diffuse into the adsorbent’s porous structure, enhancing adsorption uptake. Fig. 5 (c) illustrates the effect of adsorption temperature (0–50 \(\degree\)C), while other parameters, including flow rate, adsorption pressure, and carbonization temperature are kept constant at 50 mL/min, 1 bar, and 1000 \(\degree\)C, respectively. The effect of raising the adsorption temperature from 0 to 50 \(\degree\)C verifies a notable reduction in CO\(_2\) uptake from 9.2 to 2.8 mmol/g, which can be attributed to the exothermic nature of CO\(_2\) adsorption [36]. At higher adsorption temperatures, CO\(_2\) molecules have higher kinetic energy and less tendency for adsorption [61]. In addition, A–CS–1000 was subjected to CO\(_2\) capture at high pressures up to 20 bar and adsorption temperature of 0 and 25 \(\degree\)C, and results are represented in Fig. 5 (d). The results reveal that the adsorption uptake of A–CS–1000 increased up to 17.63 and 16.70 mmol/g at 0 and 25 \(\degree\)C, respectively, as the pressure increase within the 0–20 bar range. This behavior can be attributed to the dynamics of CO\(_2\) adsorption within the adsorbent porous structure. At lower pressures, CO\(_2\) adsorption mainly takes place within the macro-pores of the surface of the adsorbent. However, pressure increase results in the diffusion of CO\(_2\) into the smaller micro and meso-pores of the activated carbon [62].

### 3.7. Selectivity

To evaluate the selectivity performance of A–CS–1000 for CO\(_2\)/N\(_2\) gas mixture (with 85/15 (v/v) composition) to reflect the practical composition of the flue gases [63]), the ideal adsorbed solution theory (IAST) model and adsorption data were used. As depicted in Fig. 6 (a), a notable contrast in adsorption behavior of CO\(_2\) and N\(_2\) can be noticed at both 273 and 25 \(\degree\)C. Furthermore, it becomes apparent that the reduction in adsorption temperature resulted in a more pronounced influence on CO\(_2\) adsorption compared to N\(_2\) adsorption. Notably, the data also reveals that as the temperature decreases from 25 to 0 \(\degree\)C, N\(_2\) adsorption remains nearly constant at a low level of 1.30 mmol/g. Also, it is worth highlighting that the highest N\(_2\) adsorption uptake is 1.30 mmol/g, whereas 10.64 and 9.20 mmol/g are the remarkable CO\(_2\) uptakes at 0 and 25 \(\degree\)C, respectively. These results verify the unique temperature-dependent adsorption of CO\(_2\) and N\(_2\), providing valuable insights into their distinct adsorption properties. Regarding the selectivity analysis, as depicted in Fig. 6 (b), the data indicates that the preference for CO\(_2\) over N\(_2\) in gas adsorption was more pronounced at 0 \(\degree\)C than at 25 \(\degree\)C. Specifically, at 0 \(\degree\)C and 0.1 kPa, the selectivity was ~207.52, while decreasing significantly to 47.31 by increasing the pressure up to 1 bar. Similarly, at 25 \(\degree\)C and 0.1 kPa, the selectivity declined from 189.51 to 40.2 as the pressure increased to 1 bar. The overall pattern of selectivity, enhanced by declining temperature and rising pressure, align with findings documented in previous studies [30,35,63]. Besides, it can be seen that in the low-range pressure (0–1 bar), selectivity decreased drastically while reaching to a relative plateau. This trend signifies a reduction in the affinity for CO\(_2\) and a heightened competitiveness of N\(_2\) by increasing pressure and temperature.
3.8. Recyclability

Assessing the feasibility of CO₂ capture relies significantly on considering how easily materials can be recycled. In this study, recyclability of the synthesized activated porous carbon (A-CS-1000) was conducted through a series of adsorption-desorption cycles (Fig. 7). Each cycle represents the adsorption of CO₂ at 25 °C and 1 bar during 30 min, followed by desorption at 120 °C for 45 min. Findings demonstrate that >98% of the initial adsorption amount is maintained after 10 cycles, highlighting the sustainability and efficiency of the as-prepared activated porous carbon. Minimal decline in the adsorption amount can be attributed to the stable framework of the adsorbent, ensuring that adsorption sites remain stable even after repeated cycles of adsorption and desorption. Furthermore, the relatively moderate desorption temperature of 120 °C minimizes the risk of structural damage or degradation during the recycling process, contributing to the material’s stability.

3.9. Comparative study of activated carbons used for CO₂ adsorption performance

A comparative analysis was conducted to assess the performance of the activated carbon synthesized in the present study and those documented in prior research. Table 2 provides a summary of recent studies employed various activated carbons for CO₂ capture. It becomes evident that not all the previous studies have considered both selectivity and recyclability as the critical parameter. Among them, recyclability has been assessed mostly up to 10 cycles, while selectivity often measured for CO₂/N₂ gas mixture. Furthermore, it is observed that despite the activated carbon synthesized from plastic wood [64] exhibited a higher surface area and larger pore size, it demonstrated a comparatively lower CO₂ uptake compared to A-CS–1000. This can be attributed to the stronger affinity between CO₂ molecules and the adsorbent material in the synthesized A-CS–1000. Regarding Table 2, A-CS–1000 outperformed its counterparts in terms of CO₂ uptake and achieving a well-balanced combination of recyclability, selectivity, and CO₂ uptake, suggesting this activated carbon as a promising candidate for various industrial and environmental applications and further studies.

**4. Conclusions**

This study has successfully developed low-cost and sustainable adsorbents derived from sawdust synthesized through carbonization at temperatures ranging from 700 °C to 1100 °C, followed by activation using CO₂. Reported studies and results of the present study verified that the optimization of both temperature and CO₂ flow rate have been crucial in tailoring the micro-pore characteristics of the final carbon materials, leading to the elevated CO₂ uptake at low pressures. The results highlighted the synthesis of hierarchical porous structure with a surface area, pore volume, and pore size of 1651.34 m²/g, 0.69 cm³/g, and 1.76 nm, respectively, as it exhibited an exceptional CO₂ uptake of 9.2 mmol/g at 1 bar and 25 °C, surpassing other samples carbonized at different temperatures. Furthermore, our findings revealed that increasing the carbonization temperature from 700 °C to 1100 °C led to a consistent enlargement of pore size and pore volume, reaching up to 5.39 nm and 0.86 cm³/g, respectively. However, the surface area exhibited a rising trend, peaking at 1000 °C (1651.34 m²/g) and subsequent reduction at 1100 °C, attributed to pore coalescence. Additionally, the synthesized activated carbon demonstrated a remarkable CO₂/N₂ selectivity of 40.2 at 1 bar and 25 °C using IAST model, further underlining its suitability for CO₂ capture applications. Moreover, the material exhibited promising recyclability, maintaining its adsorption uptake over 10 cycles. Overall, the remarkable CO₂ capture performance observed in porous carbon activated by CO₂ can be attributed to a synergistic combination of high surface area and hierarchical pores <1.75 nm. This extensive porous structure not only provides an available surface for CO₂ adsorption but also facilitates the efficient diffusion and entrainment of CO₂ molecules within the material.

**Table 2**

Comparison of the CO₂ adsorption uptake, selectivity, and recyclability of activated carbons derived from different raw materials.

<table>
<thead>
<tr>
<th>Source</th>
<th>Pore size (nm)</th>
<th>Pore volume (cm³/g)</th>
<th>Surface area (m²/g)</th>
<th>Recyclability</th>
<th>Adsorption uptake (mmol/g)</th>
<th>Selectivity (CO₂/N₂)</th>
<th>T. (°C)</th>
<th>P. (bar)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spent coffee grounds</td>
<td>&lt;1.5</td>
<td>0.61</td>
<td>1476</td>
<td>10</td>
<td>4.54</td>
<td>~12</td>
<td>25</td>
<td>1</td>
<td>[65]</td>
</tr>
<tr>
<td>Date seed</td>
<td>0.6–0.8</td>
<td>0.54</td>
<td>1267</td>
<td>–</td>
<td>5</td>
<td>~9</td>
<td>25</td>
<td>1</td>
<td>[66]</td>
</tr>
<tr>
<td>Plastic waste</td>
<td>2–6</td>
<td>1.15</td>
<td>2155</td>
<td>–</td>
<td>3.19</td>
<td>~10.9</td>
<td>25</td>
<td>1</td>
<td>[64]</td>
</tr>
<tr>
<td>Lotus seed pot</td>
<td>&lt;2</td>
<td>0.59</td>
<td>1592</td>
<td>–</td>
<td>4.02</td>
<td>22</td>
<td>25</td>
<td>1</td>
<td>[67]</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>&lt;2</td>
<td>0.42</td>
<td>938</td>
<td>5</td>
<td>2.8</td>
<td>58</td>
<td>25</td>
<td>1</td>
<td>[68]</td>
</tr>
<tr>
<td>Potassium citrate monohydrate</td>
<td>0.5–10</td>
<td>0.95</td>
<td>1476</td>
<td>10</td>
<td>4.3</td>
<td>~</td>
<td>25</td>
<td>1</td>
<td>[69]</td>
</tr>
<tr>
<td>Walnut shell</td>
<td>2</td>
<td>0.65</td>
<td>1315</td>
<td>5</td>
<td>7.42</td>
<td>12.7</td>
<td>25</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>d-glucose and Pluronic</td>
<td>&lt;10</td>
<td>0.5</td>
<td>1279</td>
<td>–</td>
<td>6.02</td>
<td>~33.14</td>
<td>25</td>
<td>1</td>
<td>[70]</td>
</tr>
<tr>
<td>Chicken manure waste</td>
<td>–</td>
<td>0.22</td>
<td>301.5</td>
<td>10</td>
<td>8.98</td>
<td>60.5</td>
<td>30</td>
<td>1</td>
<td>[38]</td>
</tr>
<tr>
<td>Yellow mombin fruit stones</td>
<td>~1–2</td>
<td>0.63</td>
<td>1384</td>
<td>10</td>
<td>7.3</td>
<td>~</td>
<td>25</td>
<td>1</td>
<td>[71]</td>
</tr>
<tr>
<td>Coal-derived activated carbon</td>
<td>3.56</td>
<td>2.07</td>
<td>4012</td>
<td>10</td>
<td>10.51</td>
<td>25.67</td>
<td>25</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>Sawdust</td>
<td>1.76</td>
<td>0.69</td>
<td>1651.34</td>
<td>10</td>
<td>9.2</td>
<td>40.2</td>
<td>25</td>
<td>1</td>
<td>Present study</td>
</tr>
</tbody>
</table>
carbon, with a modest yield of ~19%, derived from cost-effective and abundant sawdust, showcased promising CO2 uptake, recyclability, and potential for large-scale production, motivating future research to enhance yield through alternative activation methods or temperature treatments.

CRediT authorship contribution statement

S. Foogirnazhad: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. M.M. Zerafat: Writing – review & editing, Supervision, Project administration. M. Asadnia: Validation, Supervision, Project administration. Gh Rezvannasab: Resources, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References


