Research Article

An Experimental and Kinetic Study of the Sorption of Carbon Dioxide onto Amine-Treated Oil Fly Ash

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A new CO₂ adsorbent is produced from waste oil fly ash (OFA). Ammonium hydroxide solution is used to convert OFA to activated carbon. Then, the product is used for the adsorption of CO₂ from a nitrogen/carbon dioxide (N₂/CO₂) gas mixture. The OFA samples are characterized by several techniques. Chemical treatment of OFA considerably changed its surface morphology. In particular, its surface area, as determined by BET measurements, increased from 59 to 318 m²/g. The amine-functionalized ash had a monolayer adsorption capacity of 74.51 mg/g and was obtained at relative pressure, 0.05 < p/pₛ < 0.35. A kinetics study showed that the CO₂ adsorption capacity of OFA increased with increasing CO₂ flow rates and concentrations and decreasing the relative humidity. Unlike physical adsorption, the chemisorption process resulted in increased adsorption capacity with increasing temperatures over the range 0–40°C. We also found that the adsorption process was endothermic (80–173 kJ/mol). The isotherm data for the adsorption process were fitted using different models. The saturation capacity determined from the Sips model, which corresponds to the sum of the saturation capacities of all of the adsorbed layers, was 540.3 mg/g of ash.

1. Introduction

The emission of CO₂ from the combustion of fossil fuels and other sources has recently increased the CO₂ concentration in the atmosphere to an alarming level of 400 ppm [1]. Human activities result in the emission of approximately 29 billion tons of CO₂ into the atmosphere per year, where it acts as a heat-trapping greenhouse gas. Among all greenhouse gases, CO₂ is potentially the highest contributor to the climate change [2]. Stabilizing the CO₂ content of the atmosphere can potentially be achieved by the capture and sequestration of CO₂ from its primary emission sources. CO₂ can be recovered using processes such as membrane separation, liquid solvent absorption using amines, and pressure/temperature swing adsorption or cryogenic techniques [3]. However, the amine-based processes that are currently used in chemical plants to separate CO₂ require large amounts of water and are energy intensive [1]. Additionally, these processes are associated with the generation of byproducts, corrosion of processing equipment, and a high energy of regeneration [4, 5].

Solid adsorbents also have potential to be used in separating CO₂ from gas stream, because they require relatively little energy and can be applied easily over a wide range of temperatures and pressures [5–9]. However, the effectiveness of this technique depends on the development of durable and easily regenerable adsorbents with high selectivity and adsorption capacities [10]. Such materials include activated carbons, carbo-aluminosilicates, zeolites, fly ash, and metal oxides [11]. Promising results are obtained using zeolites to separate CO₂ from gas streams. At low temperatures (20–50°C), these aluminosilicate-based materials are known to exhibit a high adsorption capacity because of their large internal pore volumes, structural features, molecular pore sizes, and wide range of chemical composition [12]. However, the adsorption capacities of these materials decrease rapidly as
the temperature increases [13, 14]. Moreover, the adsorption ability of aluminosilicates is affected by the presence of water due to hydrophilic nature of these materials [15]. Unlike zeolites, activated carbon does not require moisture removal and has a large surface area and an easily modifiable pore structure. However, the use of carbon-based materials as an adsorbent for CO$_2$ separation is limited as a result of the high sensitivity of these materials to the temperatures that are associated with power plant flue gases [1].

Fly ash (FA) is a byproduct of the combustion of fuel oil in power plants that is normally collected using cyclones (mechanical devices) or electrostatic precipitators. It is estimated that worldwide generation of fly ash is 750 million tons where China is the largest producer with amount of 580 million tons in 2015 [16]. FA can be used in a range of applications, including water pollution control [17], agriculture [18], and metal recovery [19, 20]. However, FA is a major waste material and requires proper disposal. Worldwide, approximately 25% of the fly ash that is produced annually is used. In the United States and China, large amounts of fly ash are produced, at utilization levels of 32% and 40%, respectively [21, 22]. Thus, fly ash is an abundant and economical adsorbent precursor that can be used to treat flue gases as well as recover metals from wastewater [23]. Several researchers have used fly ash for these purposes. For instance, Mercedes Maroto-Valer et al. [24] used amine-enriched fly ash to separate CO$_2$ from a gas stream. Panday et al. [25] demonstrated the suitability of using ash from a thermal power plant for the removal of copper from aqueous solutions. The copper adsorption capacity of the solid adsorbent (ash) was dependent on the concentration, temperature, and pH of the solution.

Recently, our group developed a new activated OFA using various oxidizing agents such as sulfuric and nitric acids and the resulting products were used for CO$_2$ capture from CO$_2$/N$_2$ gas stream [26]. The surface area and adsorption capacity were enhanced in comparison with untreated OFA. In the present study, OFA is subjected to an alkaline treatment using ammonium hydroxide solution in an attempt to improve the adsorption capacity of CO$_2$ on the surface through chemisorption in addition to physisorption. The performances of the amine-treated and nontreated OFA are compared. The previous work discussed the synthesis of the adsorbent and in this study the focus is on the kinetics and thermodynamics of CO$_2$ sorption onto the alkaline treated OFA. Further, the CO$_2$ sorption on alkaline-treated OFA is modeled.

2. Methods

2.1. Materials. The OFA used in this study was produced by local electric power generation plants. Ammonium hydroxide solution (30% NH$_3$ in water, Sigma-Aldrich) was used for the chemical treatment and had a density of 0.9 g/mL at 25°C and a purity of ≥99.999%. A portable CO$_2$ meter (from TESTO CO$_2$) and GC-MS (Agilent Technologies) were used to measure the CO$_2$ outlet concentrations and relative humidity was measured by a relative humidity meter at the bed inlet and outlet. Deionized water and soap were used to wash all glassware to remove any adhered impurities.

2.2. Activation of OFA. Ammonium hydroxide solution was used for the activation of OFA. A representative sample of 100 g of the ash was mixed thoroughly with 300 mL of ammonium hydroxide solution at room temperature and then transferred to a 500 mL flask and refluxed at 120°C for 24 h using a temperature ramp of 1°C/min. The mixture was cooled, after which 150 mL of ammonium hydroxide was added and mixed for another 24 h. The resultant mixture was filtered and the filter cake was dried in the oven at 105°C for 4 h and then left to cool at room temperature. The presence of amine functional groups on the OFA surface (as a result of ammonium hydroxide treatment) was confirmed by FTIR analysis of the final product.

2.3. Characterization and Analysis of OFA and Activated OFA. The morphology of OFA was characterized by scanning electron microscopy (SEM) on a JEOL JSM 6400 scanning electron microscope. Prior to analysis at different magnifications, the samples were coated with carbon. The surface area was determined by nitrogen adsorption at 77 K on a Micrometrics 2020 instrument. Prior to analysis, the samples were degassed under vacuum and dried at 150°C for 6 h. A PerkinElmer FTIR spectrophotometer was used to analyze the functional groups of the samples.

2.4. Adsorption Studies

2.4.1. Adsorption Isotherm Study. First the adsorption isotherm of CO$_2$ was measured at different initial pressure values using a magnetic suspension balance (Robotherm). A sample of approximately 0.35 g of OFA was degassed at 100°C for 5 h and subjected to a buoyancy measurement using helium at 25°C. The adsorption isotherm was obtained by measuring the equilibrium weight of the sample at 25°C at various equilibrium pressures of pure carbon dioxide (1–40 bar).

2.4.2. Adsorption Kinetics Study. Next, we measured kinetics parameters including the initial CO$_2$ concentration (363 and 795 ppm), flow rate (0.3, 0.7, and 1.0 mL/min), humidity (20% and 60% RH), and bed temperature (−20 to 40°C) using a jacketed quartz adsorption column (18 cm in length and 1.0 cm in diameter), whereby a glycol/water mixture was circulated through the jacket to maintain isothermal conditions using a PID temperature controller (Figure 1). A representative sample of 1.5 g of activated OFA was placed in the adsorption column. Nitrogen was then introduced into the bed and the concentration of CO$_2$ was measured to ensure that no CO$_2$ was initially present in the ash sample. Subsequently, a CO$_2$/N$_2$ mixture was introduced into the column at different flow rates, concentrations, temperatures, and relative humidities. At the same time, the concentration of CO$_2$ exiting the column was measured at different time intervals. The relative humidity was measured at the inlet and outlet of the column. N$_2$ gas was used in the desorption
3. Results and Discussion

3.1. Characterization of Activated Fly Ash. The SEM images of the untreated and treated OFA samples are shown in Figure 2. As observed, the ash samples mostly consisted of spherical particles. The untreated ash contained large and small pores, with an average pore diameter of 2.3 μm. The particle size ranged from 10 to 100 μm [27]. In contrast, the morphology of the activated OFA exhibited a well-defined porous structure in which the pores were more open than those present in the original OFA.

The FTIR spectrum of the untreated ash is given in Figure 3. The untreated ash exhibited different peaks at 1123, 1623, 2371, 3307, and 3772 cm\(^{-1}\). These broad peaks were associated with C=C, C=O, C=C, H–C=, and O–H functional groups, respectively. The chemically treated ash displayed a broad peak at 3402 cm\(^{-1}\) that indicated the presence of –NH\(_2\)–, while the peak at 3186 cm\(^{-1}\) was attributed to –NH\(_2\) symmetric and –NH\(_2\) asymmetric stretching vibrations [28]. However, after chemical activation, the intensities of the untreated ash peaks at 3772 cm\(^{-1}\) and 3206 cm\(^{-1}\) were reduced to 3402 cm\(^{-1}\) and 3186 cm\(^{-1}\), respectively. At a high alkaline pH, the OH groups attack the surface of OFA during the activation process. Moreover, during the activation process in hot solution, chemical reactions involving carbon oxidation and hydroxide reduction are expected to occur between OFA and ammonium hydroxide. This reaction results in the expansion of the interlayers of adjacent hexagonal network planes in the OFA structure.

Figure 4 shows the N\(_2\) adsorption-desorption isotherms measured at 77 K of the untreated and chemically treated
Table 1: Surface properties of OFA measured by N₂ adsorption analysis at 77 K.

<table>
<thead>
<tr>
<th>Sample</th>
<th>BET surface area (m²/g)</th>
<th>Langmuir surface area (m²/g)</th>
<th>Average pore width (Å)</th>
<th>t-plot micropore volume (cm³/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFA before treatment</td>
<td>59</td>
<td>78</td>
<td>133</td>
<td>0.038</td>
</tr>
<tr>
<td>OFA after treatment</td>
<td>318</td>
<td>391</td>
<td>147</td>
<td>0.678</td>
</tr>
</tbody>
</table>

Table 2: Elemental analysis of fly ash by EDX.

<table>
<thead>
<tr>
<th>Element</th>
<th>Raw OFA</th>
<th>Treated OFA, dried at 105°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spot 1</td>
<td>Spot 2 Spot 3</td>
</tr>
<tr>
<td>C</td>
<td>92.98</td>
<td>92.72 92.43</td>
</tr>
<tr>
<td>O</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S</td>
<td>5.48</td>
<td>5.48 5.41</td>
</tr>
<tr>
<td>Si</td>
<td>—</td>
<td>0.14 0.2</td>
</tr>
<tr>
<td>Na</td>
<td>0.13</td>
<td>0.14 0.15</td>
</tr>
<tr>
<td>Mg</td>
<td>0.23</td>
<td>0.18 0.26</td>
</tr>
<tr>
<td>Ca</td>
<td>0.26</td>
<td>0.2 0.37</td>
</tr>
<tr>
<td>V</td>
<td>0.91</td>
<td>0.88 0.83</td>
</tr>
<tr>
<td>Fe</td>
<td>—</td>
<td>0.28 0.36</td>
</tr>
</tbody>
</table>

Figure 3: FTIR spectra for OFA before and after chemical treatment.

The sodium in the fly ash either leached out upon treatment or was not detectable by EDX.

3.2. Adsorption Isotherm of CO₂ Using Activated OFA.

The CO₂ adsorption-desorption isotherm of activated OFA obtained at different pressures using the Rubotherm instrument is shown in Figure 5. The amount of CO₂ that was adsorbed per gram of OFA was higher than that desorbed at the same equilibrium pressure. A multilayer adsorption process occurred as the equilibrium pressure increased. The difference between the adsorption and desorption curves was related to the amount of CO₂ that was chemisorbed onto the OFA surface. Initially, at low equilibrium pressures, a high amount of CO₂ was chemisorbed, reaching a maximum value of 17.8 mg/g at 16 bar, followed by a decrease in the uptake of CO₂ as the equilibrium pressure was further increased. Increasing the sample pressure increased the concentration of CO₂ molecules on the active sites that resulted in more CO₂–surface interactions. Further increases in the pressure reduced the amount of CO₂ chemisorbed onto the surface, due to consumption of the reactive amine sites and the attainment of the saturation adsorption level in the OFA pores (Figure 6).

The Langmuir, Freundlich, and BET isotherm models were examined to describe the adsorption process and the CO₂ adsorption capacity of treated OFA was estimated accordingly.

The Langmuir model describes monolayer coverage on a solid surface as follows:

\[ q = \frac{Qbp}{1 + bp} \] (1)

where Q (mmol/g) is the maximum amount of CO₂ that is adsorbed per unit mass for a complete monolayer, Cₑ is the equilibrium pressure of CO₂ (bar), and b (L/mmols) is the
Langmuir constant that is related to the affinity of the binding sites of the adsorbent.

The Freundlich model accounts for surface heterogeneity in the energy and is represented by (4):

$$q = k p^b$$  \hspace{1cm} (2)

where both $k$ and $b$ are constants.

The Sips model is a combination of the Langmuir and Freundlich models. The Sips model incorporates both the effect of surface heterogeneity and the saturation capacity of the adsorbent. At low equilibrium concentrations of the adsorbate, the Sips model reduces to the Freundlich model, whereas at high concentrations the amount of adsorbed solutes reaches a plateau at a saturation value, $Q$ (mmol/g) [33]. The Sips model is described by the following expression:

$$q = \frac{Q b p^n}{(1 + b p^n)}.$$  \hspace{1cm} (3)

In the BET model, the formation of multiple layers on the surface of the adsorbent is assumed, thereby achieving a multilayer coverage on the material surface:

$$q = \frac{Q_0 a_1 p}{(p_s - p) [1 + (a_0 - 1) p/p_s]},$$  \hspace{1cm} (4)

where $Q_0$, $a_1$, and $p_s$ represent the saturation capacity, constant account for difference in adsorption energies between the first layer and higher layers, and saturation pressure for CO$_2$ at the studied system temperature. The corresponding isotherm values were fitted using MATLAB (V. 8.3) and the results are presented in Table 3. Among all the studied
Table 3: Isotherm parameters for the Langmuir, Freundlich, and BET models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langmuir</td>
<td>$Q$</td>
<td>652.9</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>$7.322 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.968</td>
</tr>
<tr>
<td></td>
<td>$x^2$</td>
<td>1107</td>
</tr>
<tr>
<td>Freundlich</td>
<td>$k$</td>
<td>10.53</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>$x^2$</td>
<td>1635</td>
</tr>
<tr>
<td>Sips</td>
<td>$Q_s$</td>
<td>540.3</td>
</tr>
<tr>
<td></td>
<td>$k_s$</td>
<td>$6.210 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$n_s$</td>
<td>1.142</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.982</td>
</tr>
<tr>
<td></td>
<td>$x^2$</td>
<td>619</td>
</tr>
<tr>
<td>BET</td>
<td>$Q_0$</td>
<td>74.51</td>
</tr>
<tr>
<td></td>
<td>$a_1$</td>
<td>5.975</td>
</tr>
<tr>
<td></td>
<td>$a_2$</td>
<td>67.05</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td>$x^2$</td>
<td>344</td>
</tr>
</tbody>
</table>

isotherm models, the BET model best fits the adsorption data. The model generated a high regression coefficient of 0.990 and the lowest sum of square errors of 13.44. The saturation adsorption capacity determined from the BET model, which corresponds to a monolayer of adsorption in pressure range $0.05 < p/p_s < 0.35$, was 74.51 mg/g of ash. The saturation capacity determined from the Sips model which corresponds to the sum of the saturation capacities of all of the adsorbed layers was 540.3 mg/g of ash.

3.3. Analysis of the Adsorption Kinetics. The rate of adsorption was determined by passing CO$_2$ through the adsorption column at fixed initial concentrations and relative humidity and monitoring the concentration of CO$_2$ exiting the column as a function of time. Kinetics parameters, namely, the bed temperature, gas flow rate, and concentration and humidity, were investigated. Desorption experiments were performed in the same manner as the adsorption measurements, except that pure and dry N$_2$ gas was used.

Figure 7 shows the breakthrough curves obtained using 1.5 g of treated OFA, an initial CO$_2$ concentration of 350 mg/L, CO$_2$/N$_2$ flow rate of 0.3 L/min, 1.5 g ash, 20% RH, 1 atm, and 22°C.

3.3.1. Effect of Initial CO$_2$ Concentration. Further results on the effect of the initial CO$_2$ concentration are shown in Figures 8 and 9. The OFA adsorption capacity increased with increasing CO$_2$ concentrations [34, 35] because of the increase in driving force between the bulk concentration and the concentration at the particle surface, thereby promoting mass transfer. However, when the ash surface was saturated, further increases in the CO$_2$ concentration did not further improve the adsorption capacity. This activated OFA reached its saturation capacity at higher concentrations quickly. Thus, the saturation time decreased as the adsorbate concentration increased [36, 37].
3.3.2. Effect of Flow Rate. The effect of the gas flow rate was studied at two different CO$_2$ concentrations, 795 ppm and 365 ppm, at both low and high humidities. The effect of the CO$_2$ flow rate was studied using flow rates of 0.3, 0.7, and 1.5 mL/min. Figure 10 shows that increasing the CO$_2$ flow rate reduced the time required to reach the maximum adsorption capacity. Hence, the residence time of the gas in the ash bed decreased [34]. Increasing the gas flow rate increased the diffusion rate of the CO$_2$ molecules to the particle surface. In addition, the rate of mass transfer in the gas film was likely enhanced because of the reduction in the external mass transfer resistance and the saturation time [38, 39]. It has also been reported [39, 40] that the application of CO$_2$ at high pressures increases the strength of the interaction between amine and CO$_2$ molecules, which favors the chemical reaction and increases the extent of chemisorption.

3.3.3. Effect of Humidity. The effect of relative humidity (10% and 80%) on the adsorption of CO$_2$ onto treated fly ash is shown in Figure 11. A decrease in the adsorption capacity at the higher relative humidity was observed. This result can be explained by consideration of the capillary condensation of water vapor in the pores of the ash; at 80% RH, a large portion of the active sites on the surface of these pores are blocked [41, 42]. Increasing the humidity decreases the partial pressure of CO$_2$ in the gas phase and leads to water vapor competing with CO$_2$ molecules to reach the surface. When water condensation dominates over evaporation, there is competition between these two species for adsorption onto the active OFA sites. This was confirmed by measuring the RH at the column’s exit; a 2% decrease in relative humidity was observed. Increasing the adsorption capacity could be achieved by increasing the temperature while reducing the humidity, thus opening up the mesopores [43].

3.3.4. Effect of Temperature. Next, we investigated the effects of bed temperatures of $-20, -10, 0, 10, 20, 30,$ and $40$°C on the rate of CO$_2$ adsorption onto treated OFA. We found that the adsorption rate of CO$_2$ increased up to a break-even point as the bed and inlet gas temperatures increased (Figure 12). This demonstrates the endergonic nature of the interaction between the gas molecules and the ash surface at which both physical and chemical adsorption occurred. Moreover, there was a direct link between increases in the temperature and the pressure drop across the bed [44].

Equations (1) and (2) were used to determine thermodynamic parameters such as the heat of adsorption, standard
Table 4: Thermodynamic parameters for CO$_2$ adsorption onto treated fly ash.

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>Low relative humidity</th>
<th>High relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_c$</td>
<td>$\Delta G_{ads}$ (kJ/mol)</td>
</tr>
<tr>
<td>-10</td>
<td>$3.95 \times 10^{-1}$</td>
<td>$-6.82 \times 10^2$</td>
</tr>
<tr>
<td>-20</td>
<td>$2.89 \times 10^{-1}$</td>
<td>$-2.72 \times 10^2$</td>
</tr>
<tr>
<td>0</td>
<td>$1.00 \times 10^2$</td>
<td>$4.55 \times 10^{-3}$</td>
</tr>
<tr>
<td>10</td>
<td>$8.26 \times 10^2$</td>
<td>$4.98 \times 10^2$</td>
</tr>
<tr>
<td>20</td>
<td>$15.32 \times 10^2$</td>
<td>$6.07 \times 10^2$</td>
</tr>
<tr>
<td>30</td>
<td>$39.92 \times 10^2$</td>
<td>$9.32 \times 10^2$</td>
</tr>
<tr>
<td>40</td>
<td>$48.09 \times 10^2$</td>
<td>$10.11 \times 10^2$</td>
</tr>
</tbody>
</table>

$\Delta G_{ads}$ (kJ/mol) 80 178
$\Delta S_{ads}$ (J/mol·K) 296 597

Figure 12: Effect of bed temperature on adsorption of CO$_2$ onto treated ash. Reaction conditions: initial CO$_2$ concentration of 350 ppm, CO$_2$/N$_2$ flow rate of 0.3 L/min, 1 g ash, and 10% RH.

From the slope and the intercept of the plot, respectively [27, 45–50],

As the temperature increased, both $K_c$ and the adsorption capacity increased, which could be attributed to the increase in the number of active surface sites that were available for adsorption. Additionally, the motion of CO$_2$ molecules on the ash surface increased owing to increases in the temperature [27]. The calculated values of $\Delta H_{ads}$, $\Delta S_{ads}$, and $\Delta G_{ads}$ are listed in Table 4. The positive value of $\Delta H_{ads}$ at a fixed RH indicated that the adsorption process was endothermic [45, 50]. The positive value of $\Delta S_{ads}$ showed the affinity of the chemically treated fly ash for CO$_2$ (adsorption) and the increasing randomness during the adsorption process [51]. The negative values of $\Delta G_{ads}$ at −10 and −20°C indicate the spontaneous nature of the adsorption of CO$_2$ onto the fly ash sample [49]. Positive $\Delta G_{ads}$ values were observed at 0, 10, 20, 30, and 40°C, indicating that spontaneity was not favored at high temperatures where the thermal energy exceeded the adsorption energy. A similar trend was observed for the adsorption/removal of Congo Red from water using activated carbon that was prepared from coir pith [50]. Moreover, $\Delta G_{ads}$ increased with increasing temperatures, further indicating that the reaction was endothermic [52].

4. Conclusions

We suggest that waste OFA, which is primarily composed of unburned carbon, can be used as a low-cost absorbent for the removal of CO$_2$ from a gas stream. Promising results were obtained using chemically treated waste OFA for CO$_2$ adsorption. An ammonium hydroxide solution was used to chemically modify fly ash to improve its CO$_2$ adsorption capacity. The BET surface area of OFA increased from 59 m$^2$/g to 318 m$^2$/g after chemical treatment. Studies of the underlying kinetics showed that the adsorption capacity increases with flow rate, concentration, and temperature. Humidity also strongly influences CO$_2$ adsorption. Thermodynamic studies revealed the heat of adsorption to be 80 and 178 kJ/mol at low (20%) and high (80%) relative humidity, respectively, indicating that the process was endothermic. This indicated that the adsorption of CO$_2$ in alkaline treated OFA is sensitive to humidity and suggests the competitiveness between water vapor and CO$_2$ adsorption on the surface.
A variety of isotherm models were studied to obtain the saturation capacity of the treated OFA and it was found that 540.3 mg/g can be predicted using Sips model, and 652.9 mg/g is achieved by Langmuir model with regression coefficients 0.982 and 0.968, respectively. The activated carbonaceous material presented herein is a promising and economically feasible CO$_2$ adsorbent because of its low cost and high sorption capacity.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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