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Sustainable packaging waste-derived activated carbon for carbon dioxide capture

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ABSTRACT

Global greenhouse gases emissions have increased tremendously since 1950's due to excessive burning of fossil fuel. The objective of this work is to develop and investigate packaging waste-derived activated carbon for carbon capture. Activated carbon was synthesized by carbonization of peanut-shaped packaging waste followed by chemical activation using KOH at a ratio of one to four. The activated carbon was characterized for it is textural properties using N_2 adsorption at 77 K, and carbon dioxide adsorption isotherms at 273, 298 and 323 K. Non-Linear Density Functional Theory (NDLFT) was applied to carbon dioxide isotherm at 273 K to characterize narrow micropores and microporous structure of activated carbon. Field emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM) were used to investigate morphology and microstructure. TEM micrographs confirmed the existence of random micropores. We have also noticed that the textural properties were highly dependent on the concentration of the activating agent. Carbon dioxide adsorption on activated carbon materials has shown dependency on the volume of narrow micropores (less than 0.8 nm). The activated carbon materials have narrow micropore volume in a range of 0.155–0.292 cm^3, and BET surface area of 761–1383 m^2/g. Carbon activated with KOH ratio of three (WDC-03) has shown excellent CO_2 uptake of 5.33 and 4.24 mmol/g at 273 and 298 K respectively. Moreover, it has also shown a high value for the isosteric heat of adsorption (29.8–14.3 KJ/mol) and selectivity of ~16 over nitrogen.

1. Introduction

Among greenhouse gases, carbon dioxide (CO_2) is the major contributor to global warming and climate change. CO_2 comprised about 82% of the total US greenhouse gases (GHG) emissions in 2015 [1]. Its level has increased by 26.5% in the last 60 years. Without mitigation efforts to reduce emissions, the level is expected to increase by 200% by the end of this century; due to excessive burning of fossil fuels for power generation and other industrial processes [2]. Such practices will lead to catastrophic consequences including an increase in the earth's temperature, an increase of sea level and flooding of coastal areas. To counteract the danger of the elevated carbon dioxide level in the atmosphere, several capture and storage technologies were studied as potential methods to reduce the amount released to the environment [3–6].

Several technologies have proven effectiveness for carbon dioxide absorption and adsorption. For instance, the ethanolamines are widely used in industry for selective absorption of CO_2 from flue gases. This process is commonly used in industries which involve extensive use of carbon dioxide such as carbonated beverages industry [7]. However, this technology suffers from lack of sustainability and energy-intensive regeneration performed at temperature range of 100–120 °C. Furthermore, the corrosive nature of ethanolamines reduce the service life of process equipment [8,9]. Adsorption of CO_2 through vacuum swing adsorption process is proposed to be an excellent alternative for conventional ethanolamine absorption technology. The major advantages of adsorption process are sustainability, wide range of available adsorbents and mild regeneration temperature. Various materials such as zeolite, silica, metal organic frameworks (MOF) and activated carbon have been used as adsorbents [10–12]. Recently, the demand for efficient and green materials for water wastewaters treatment has been increasing. This demand resulted in the development of efficient adsorbents from different materials, such as carbon nanotubes, metal oxides nanoparticles, and waste biomass. The adsorbents have shown excellent performance in the removal of pollutants such as hazardous dyes and heavy metals from wastewaters [13–28].

Activated carbon has several advantages over other adsorbents. It has excellent regeneration stability in the humid environment over zeolite and MOF, low cost, wide range available sources and activation processes for its production [29–32]. The most important feature of

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activated carbon is its easily tailorable properties by varying the type and amount activating agent and/ activation condition to produce the desirable textural properties such as surface area, pore volume, pore size, and pores size distribution [33–38]. Moderate KOH to carbon ratio (2–3) produces a high narrow micropore volume, which is responsible for carbon dioxide adsorption. The wheat flour-derived activated carbon using KOH ratio of three showed improved CO_2 adsorption of 5.70 and 3.48 mmol/g at 273 and 298 K, respectively [39]. Sawdust activated carbon synthesized using KOH ratio of two and moderate activation temperature of 600 °C showed high CO_2 adsorption capacity of 4.8 mmol/g at 298 K [32]. Previous studies have correlated the CO_2 adsorption on activated carbon to the volume of ultra or narrow micropores with size less than 0.8 nm and concluded that it is the major contributor to CO_2 uptake [40]. Moreover, studies on utilization of chemicals to produce nitrogen-doped activated carbon concluded that nitrogen content improves carbon dioxide uptake at elevated temperature as well as enhancing cyclic stability [41,42].

Although activated carbon from various waste and biomass sources such as waste coffee ground, pine nutshell, granular bamboo and potato starch-were investigated for carbon capture, there are plenty of potential waste materials to be explored [43–46]. A Recent survey shows that the significant quantities of packaging waste disposed in landfills resulted in increased environmental concerns [47]. Strategies such as recycling, reuse, as well as the conversion of waste to value-added char are currently employed to reduce the large quantities disposed to landfills. One of the well-known methods, of converting waste to value-added char is heating it at elevated temperatures in an inert environment and followed by activation. This method was found to be helpful in minimizing the impacts and reducing the disposed amounts [48,49]. Although produced pyrolytic char is energy-rich, it has poor textural properties in terms of BET surface area and pore volume [50] which limits its utilization; chemical activation can highly improve char properties.

In this work, we explored the packaging waste as a sustainable source for production of activated carbon with excellent CO_2 capture capabilities and CO_2/ N_2 selectivity, using varying amounts of KOH and moderate synthesis temperature. To the best of our knowledge, this is the first report of a study that involves using (BRAN FOAM TOP) peanut shaped packaging waste to produce activated carbon for CO_2 Capture.

2. Materials and methods

2.1. Materials

Peanut shaped loose filler packaging material (BRAN FOAM TOP), made primarily from starch, was procured from ECOLOPACK (Japan). Potassium hydroxide KOH was purchased from Sigma-Aldrich.

2.2. Synthesis

Peanut shaped packaging waste (PSPW) was first washed with distilled water and allowed to dry in an oven overnight at 120 °C. Dried (PSPW) was ground into a fine powder in a ceramic mortar, and then the powder was carbonized in a furnace tube under the flow of nitrogen at a heating rate of 5 °C/min from room temperature to 500 °C. The sample was kept at 500 °C for one hour and then allowed it to cool. The resulting carbonized waste (CW) was mixed with potassium hydroxide KOH at ratios of 1, 2, 3 and 4 by weight. The CW and KOH mixtures were stirred for 3 h at 65 °C and vacuum dried at 120 °C overnight. The dried CW / KOH mixtures were placed in ceramic muffle and heated in a tube furnace at a heating rate of 5 °C/min from room temperature to 700 °C and kept at 700 °C for one hour. After cooling, the products were washed with dilute HCl and distilled water several times until neutral pH is achieved. The synthesized activated carbon was vacuum dried at 120 °C overnight. Samples were labeled based on KOH ratio WDC-0X where X stands for KOH ratio.

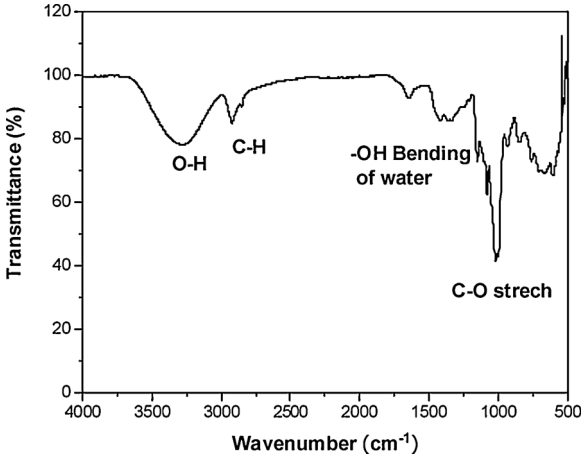

Fig. 1. FTIR spectrum of pristine packaging waste.

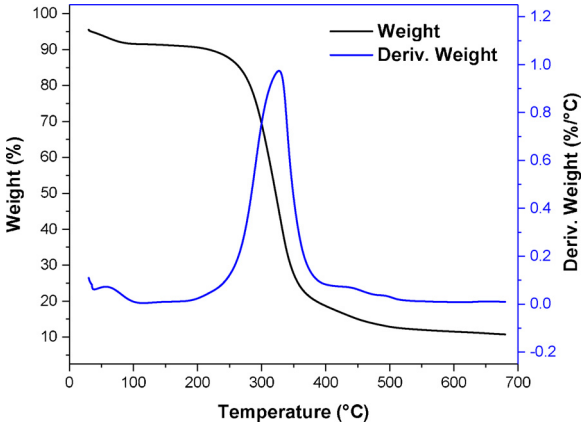

Fig. 2. Pyrolysis of pristine packaging waste under the flow of nitrogen.

3. Characterization

3.1. Pristine packaging waste (PSPW)

3.1.1. Chemical structure

The chemical structure of pristine packaging waste was determined using Fourier-transform infrared spectroscopy (FTIR) Shimadzu FTIR 8400 s machine equipped with MIRacle TM ATR was used to obtain spectrum in the range of 500-4000 cm^{-1}.

3.1.2. Thermal properties

Thermogravimetric analysis (TGA) of pristine packaging waste was carried out in TA Q 500TGA. PSPW (15 mg) samples were heated from room temperature to 700 °C at a heating rate of 5 °C/ min, under nitrogen environment.

3.2. Surface morphology and microstructure

The morphology and microstructure of CW and activated Carbon materials were investigated using FE-SEM (Jeol JSM −7200 F) and Transmission Electron Microscope (TEM-Jeol 2010).

3.3. Nitrogen adsorption

Textural properties were investigated using NOVA2200e (Quantachrome, USA) surface area and pore size analyzer. All samples were vacuum degassed at 150 °C overnight to remove volatiles and used for characterization. Nitrogen adsorption-desorption isotherms were obtained at 77 K and a partial pressure range of (0.005–0.99),