



Research article

Oil removal from water using carbon aerogels derived from pomelo peel

Noppada Srimueang, Thitiya Pung, Thanawan Panich-pat*

Environmental Science and Technology Program, Department of Science and Bioinnovation, Faculty of Liberal Arts and Science, Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom 73140, Thailand

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Abstract

Importance of the work: Agricultural waste material was utilized to make carbon aerogels that can adsorb oils and be reused.

Objectives: To investigate the potential of carbon aerogel made from pomelo peel (CAPP) as a potential sorbent for oils from the surface of water.

Materials & Methods: The CAPPs were prepared from pomelo peel by cutting, freezing at -20°C for 24 hr and freeze-drying at -55°C or -80°C for 24 hr, followed by carbonization or pyrolyzed at 300°C ($5^{\circ}\text{C}/\text{min}$, 1 hr) to obtain CAPP1-1, CAPP1-2, CAPP2-1 and CAPP2-2, followed by investigations based on the contact angle, morphology, sorption, reusability and grease-trap testing.

Results: The average water contact angles of CAPP1-1, CAPP1-2, CAPP2-1 and CAPP2-2 were 124.1° , 79.1° , 99.1° and 84.3° , respectively. Sorption tests were conducted by immersing the CAPPs in 15 mL of oil on water for 30 s, yielding capacities of 4.35–9.04 g/g. Mean $\pm$ SE sorption was highest with diesel oil for CAPP1-1 (6.45 ± 0.35 g/g), with palm oil for CAPP1-2 (8.19 ± 0.56 g/g), with rice bran oil for CAPP2-1 (8.08 ± 0.37 g/g) and with rice bran oil for CAPP2-2 (9.04 ± 0.36 g/g). In household grease-trap testing, CAPP1-2 had the highest palm oil removal (11.71%), followed by CAPP2-2, CAPP2-1 and CAPP1-1. After the second recycle, diesel sorption remained high (73.4–88.6%), decreasing to moderate-to-low levels (36.4–71.4%) after the third recycle.

Main finding: The CAPPs derived from pomelo peels could be fabricated based on freeze-drying and carbonization using a muffle furnace or pyrolysis. Palm oil removal from a grease trap was in the range 7.88–11.71%. Reusability was confirmed through absorption-regeneration tests for diesel oil over three cycles.

* Corresponding author.

E-mail address: faastwp@ku.ac.th (T. Panich-pat)

Introduction

Water pollution caused by oils and organic contaminants is a major environmental challenge, especially in industrial effluents, oil spills and domestic wastewater (Zhao et al., 2017). Oils and hydrocarbons in water bodies pose serious threats, adversely affecting aquatic ecosystems, water quality, human health and public health (Sharma et al., 2024). Traditional methods for oil removal from water, such as skimming, chemical dispersants, physical separation and adsorption, often face limitations related to efficiency, cost and environmental impact, necessitating effective and sustainable remediation techniques. Various methods have been developed for removing oily wastewater and organic solvent in contaminated water, including *in situ* combustion, chemical treatment, biodegradation, flotation, gravity separation, physical sorption (Gupta et al., 2017; Shi et al., 2019). Among these methods, physical sorption has been shown to be effective in the removal of oil and organic pollutants (Gupta et al., 2017).

In recent years, the development of advanced materials for environmental cleanup has gained considerable attention. Among these, innovative materials, such as carbon aerogels (CAPPs), have gained attention due to their high surface area, porosity and tunable properties that enable efficient adsorption of oils and organic pollutants from water, making them suitable candidates for environmental remediation (Maleki, 2016). Therefore, new sorbents are being researched for high sorption capacity of oil and organic solvent, based on their favorable properties of high hydrophobicity, low density, reusability, low cost and environment-friendly applications (Maleki, 2016). Aerogels are porous materials with light weight and low density and can be applied to oil/water separation (Jiang and Hsieh, 2014).

CAPPs are a class of crucial aerogels that are spongy, three-dimension-structured materials with millions of small open pores filled with air (Wan et al., 2016). As CAPPs have multifunctional properties, such as high surface area, abundant porous structure and low mass density, they are considered ideal sorbents for oil-spill treatment (Feng et al., 2015). There has been successful fabrication of light density, three-dimensional carbon-based porous sorbents in the form of aerogel or sponge. Furthermore, carbon materials from agricultural waste have been investigated for the separation of oil and organic pollutants because these carbon materials are abundant, have medium or high efficiency and a low price (Tai et al., 2015).

Utilizing agricultural wastes as a resource for producing such sorbents adds a sustainable dimension to water treatment efforts. Pomelo (*Citrus maxima* (Burm.) Merr. is a type of Southeast Asia fruit, with the pomelo peel (PP) making up about 40% of the total weight of the fruit (Shi et al., 2019). PP is a lignocellulosic agricultural waste material that is abundant and underutilized making it desirable for use as a sorbent because it can be fabricated to be a porous carbon aerogel (Pung et al., 2024). Transforming PP into carbon aerogels not only valorizes this waste but also provides an environment-friendly and cost-effective solution for oil removal. As the surface of PP is a porous structure with macropores (2–20 μm), there might be sufficient space to adsorb oil and organic pollutants. A new family of CAPPs using waste pomelo peels was fabricated using hydrothermal drying at -20°C for 24 hr, then freeze-drying at -80°C for 48 hr and calcining in

a nitrogen-flow tube calciners at $600\text{--}800^{\circ}\text{C}$ for 1 hr, which had excellent sorption capacity for oil and some organic pollutants, with the sorption capacity decreasing slightly with increasing calcination temperature (Zhu et al., 2017). However, some laboratories and commercial applications are unable to provide nitrogen-flow tube calciners, so the process has been modified to carbonization in a conventional calciner at lower temperatures.

The present study investigated the morphology of CAPPs derived from pomelo peel and evaluated their efficiency in oil removal from water. Based on the results, there is potential use of the developed products as effective sorbents, particularly for treating oil-contaminated household wastewater (such as in grease traps). These findings support the development of sustainable, value-added materials for improved wastewater treatment.

Materials and Methods

Materials

Pomelo was obtained from a local garden in Nakhon Pathom Province, Thailand. Sunflower oil, palm oil, soybean oil, rice bran oil, lard oil, sesame oil, diesel oil and crude oil were purchased from local markets in Nakhon Pathom province. Chemical reagents such as *n*-hexane, ethyl acetate and Sudan red III, were purchased from Sigma Aldrich Co. Ltd, Bangkok, Thailand. All analytical grade chemicals were used as received.

Carbon aerogel preparation

Pomelo peels (PPs) were cut off the exocuticle and chopped into small pieces with dimensions of approximately $3\text{ cm} \times 3\text{ cm} \times 1\text{ cm}$ and washed with deionized water several times to remove dirty particles. Then, the PPs were placed in a hot-air oven at 100°C for 10 hr, after which they were washed with hot water (70°C) multiple times to remove any water-soluble materials. The hydrogels were placed in a freezer at -20°C for 24 hr (Pung et al., 2024). Then, they were separated into two groups based on different freeze-drying conditions: 1) at -55°C for 24 hr; and 2) -80°C for 24 hr. These two groups of aerogels were carbonized in a muffle furnace or pyrolyzed in a pyrolysis instrument. The furnace and the pyrolysis instrument were heated to 300°C at $5^{\circ}\text{C}/\text{min}$ and held at this temperature for 1 hr to achieve the carbonization or the pyrolysis, respectively. Then, the PPs were cooled to room temperature to produce black, lightweight PP carbon aerogels. They were named CAPP1-1, CAPP1-2, for freeze-drying at -55°C and carbonization for 24 hr and for freeze-drying at -80°C and carbonization for 24 hr, respectively, and CAPP2-1 and CAPP2-2 for freeze-drying at -55°C and pyrolysis for 24 hr and for freeze-drying at -80°C and for 24 hr, respectively. All samples were kept in a desiccator at room temperature until they were used in experiments.

Characterization of carbon aerogel

The mass of each carbon aerogel was weighed (Shimadzu ATX224R;). The dimensions of the carbon aerogels were measured

Using a Vernier caliper. The water contact angle (WCA) was measured using a static optical contact angle meter (KinoUSA SL 150E; USA). A water droplet (0.4 μL) was deposited on the sample surface using a syringe system of the tester at 25°C.

The porosities as a percentage of CAPP1-1, CAPP1-2, CAPP2-1 and CAPP2-2 were calculated using Equation 1:

$$P = (1 - \rho / \rho_c) \times 100 \quad (1)$$

where P and ρ are the porosity and density of the CAPP sample and ρ_c is the density of amorphous carbon that is defined as the typical value for activated carbon or carbon black of 2 g/cm³ (Li et al., 2014; Wang et al., 2017), with all densities measured in grams per cubic centimeter.

The morphologies of the CAPPs were observed using a field emission-scanning electron microscope (JEOL-JSM-7600F; Japan).

Fourier-transform infrared (FT-IR) spectra were recorded for wave numbers in the range 500–4000 cm⁻¹ to identify surface functional groups.

Sorption experiments

Preliminary sorption test of sunflower oil

At room temperature (28–30°C), a piece of each different CAPP sample was weighed and immersed in 40 mL of sunflower oil using a pair of science forceps. The static sorption process was maintained for 5–60 s. Then, the saturated CAPP was removed from the liquid and weighed immediately. Each experiment was repeated five times. The sorption capacity (Q_e) of CAPP was calculated using Equation 2 (Shi et al., 2019):

$$Q_e = (m_2 - m_1) / m_1 \quad (2)$$

where m_1 and m_2 are the weight of the CAPP samples before and after sorption, respectively, measured in grams.

Preliminary sorption test of sunflower oil floating on the surface of water

The sunflower oil was colored with Sudan red III organic dye (Zhu et al., 2017) using 1% Sudan red III in *n*-hexane. Five drops of 1% Sudan red III were added into 100 mL of sunflower oil and mixed homogeneously. Then, 40 mL of deionized water were poured into beakers to make 5 mL, 10 mL, 15 mL, 20 mL and 25 mL portions of the colored oil. The mixtures formed two separate phases, with the colored oil floating on the surface of the water. A piece of each weighed CAPP was immersed in the oil phase. Then the CAPP was removed from the oil and weighed immediately. Each experiment was repeated five times. The sorption capacity was evaluated using Equation 2.

Sorption testing of several oils floating on the surface of water

Several oils were colored with Sudan Red III. 40 mL of deionized water were poured into a beaker and 15 mL of the colored oil was weighed and added. The mixture formed two separate phases, with the

colored oil floating on the surface of the water. A piece of the weighed CAPP was immersed in the oil phase for 30 s. Then, the CAPP was removed from the oil and weighed immediately. Each experiment was performed 10 times. The sorption capacity of the CAPP was evaluated using Equation 2.

Application of CAPPs for grease trap

The CAPPs were tested for their efficacy in household grease traps. Each type of CAPP was weighed. The deionized water and palm oil were weighed and mixed in a ratio of 1:100. The weighed CAPP sample was arranged on the basket of the grease trap until the surface was fully covered (Fig. 1). The test mixture was poured slowly into the inlet of the grease trap and was allowed to stand for 2 hr. Then, each CAPP was removed and weighed immediately. The sorption capacity of each CAPP was evaluated using Equation 2. The output mixture was determined for the fat and oil content, calculated using Equation 3 (American Public Health Association, 1998). The removal of oil was calculated using Equation 4.

$$\text{Fat and oil (mg/L)} = [(M-E) \times 10^6] / V \quad (3)$$

$$\% \text{ Removal of oil} = [(w_1 - w_2) / w_1] \times 100 \quad (4)$$

where M and E are the weight of evaporating bowl plus oil and of the evaporating bowl, respectively, V is the volume of the mixture and w_1 and w_2 are the weight of the palm oil before and after sorption, respectively, with all weights measured in grams and the volume in milliliters.



Fig. 1 Arrangement of each type of CAPP in grease trap basket.

Reusability

Each CAPP was weighed and immersed in the diesel oil phase for 30 s, then washed in ethyl acetate several times and dried at 100°C for 30 min to obtain the regenerated carbon aerogel (Zhu et al., 2017). Then, each regenerated CAPP was tested for the sorption capacity of diesel oil floating on the surface of water. Each experiment was repeated five times and in three cycles. The sorption capacities of the samples after each cycle were calculated using Equation 2.

Statistical analysis

Statistical analyses were performed using the SPSS software (IBM Corp.; USA). Significant differences among treatments were analyzed using one-way analysis of variance, followed by Duncan's multiple range test at the 95% confidence level ($p < 0.05$).

Results and Discussion

Characterization

The CAPPs had a black, rough and brittle surface morphology, which was typical of carbon aerogels (Fig. 2). Uniform black coloration indicated successful carbonization. Rough and uneven

surface morphology which is characteristic of carbon aerogels, reflects the porous and heterogeneous structure developed during thermal treatment, while a brittle appearance is typical of porous carbon materials. The low density ($< 0.1 \text{ g/cm}^3$) and high porosity ($> 90\%$) indicate a highly porous structure with abundant void spaces (Table 1). These characteristics contributed to the excellent floating behavior of the CAPPs on water and enhanced their oil adsorption capacity due to increased surface area and capillary effects. These results correlated with data from Pung et al. (2024). The observed properties were consistent with other studies that have reported the successful formation of carbon aerogels (Zhu et al., 2017; Phat et al., 2022). However, the brittleness of the material may limit its mechanical stability during repeated use, suggesting that further modification is required to improve durability (Lee and Park, 2020).

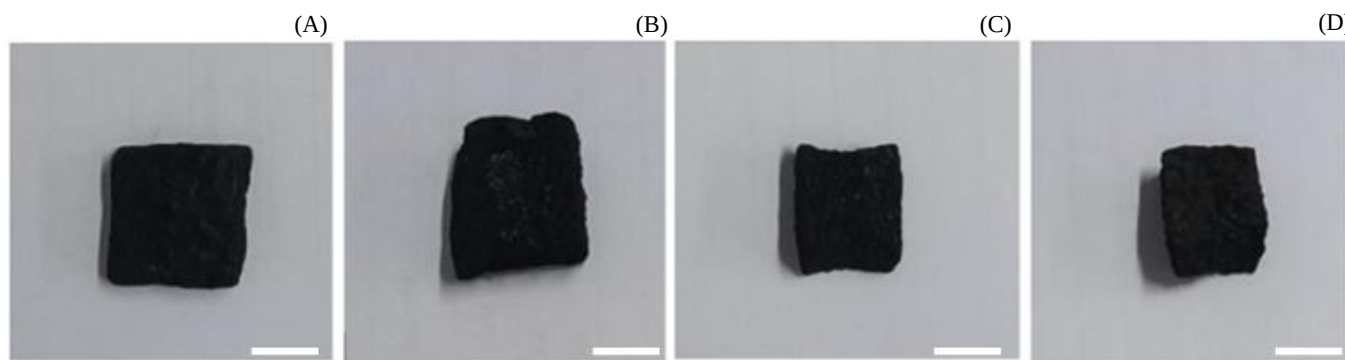


Fig. 2 Photographs from using different processing conditions to make carbon aerogels from pomelo peel (CAPPs): (A) CAPP1-1; (B) CAPP1-2; (C) CAPP2-1; (D) CAPP2-2, where scale bar = 1 cm

Table 1 Density, porosity and hydrophobic values (mean $\pm$ SE) of different carbon aerogels from pomelo peel (CAPPs) made using different processing conditions

Aerogel	Average weight (g)	Average volume (cm ³)	Apparent density (g/cm ³)	Porosity (%)	Hydrophobic property
CAPP1-1	0.396 $\pm$ 0.006	3.79 $\pm$ 0.21	0.095 $\pm$ 0.004	94.7 $\pm$ 0.4	floats on water
CAPP1-2	0.585 $\pm$ 0.014	5.86 $\pm$ 0.34	0.092 $\pm$ 0.008	94.9 $\pm$ 0.4	floats on water
CAPP2-1	0.371 $\pm$ 0.006	4.92 $\pm$ 0.23	0.076 $\pm$ 0.004	96.2 $\pm$ 0.2	floats on water
CAPP2-2	0.345 $\pm$ 0.005	4.84 $\pm$ 0.28	0.072 $\pm$ 0.004	96.4 $\pm$ 0.2	floats on water

Based on the WCA measurements, the wettability of the CAPPs varied significantly depending on preparation conditions (Fig. 3). The WCAs of CAPP1-1 (124.1°) and CAPP2-1 (99.1°) exceeded 90°, indicating strongly hydrophobic surfaces, moderately spherical droplets and reduced hydrophobicity, whereas the lower WCAs of CAPP1-2 (79.1°) and CAPP2-2 (84.3°) suggested that they had increased wettability. This variation in wettability could be attributed primarily to differences in surface chemistry and carbonization conditions. At relatively low carbonization temperatures (300 °C), incomplete decomposition of biomass results in the retention of oxygen-containing functional groups, such as hydroxyl and carboxyl groups, which increase surface polarity and reduce hydrophobicity. The WCAs of the present CAPPs were lower than that reported by Zhu and colleagues of 132.4° (Zhu et al., 2017), likely due to the use of

lower carbonization temperatures compared to high-temperature pyrolysis (600–800°C), which is known to enhance hydrophobicity by eliminating polar functional groups and promoting the formation of more graphitic carbon structures (Law, 2014). Similarly, the WCA values obtained in the present study were comparable but slightly lower than that reported by Pung et al. (2024) of 105.58°, suggesting that differences in processing conditions, such as heating rate, duration and microstructure development, played a critical role in determining surface wettability. In addition to surface chemistry, surface roughness contributes to wettability behavior, as according to the Wenzel and Cassie-Baxter model, increased surface roughness can amplify intrinsic wettability (Wenzel, 1936). In the present study, the rough, porous morphology of the CAPPs likely enhanced hydrophobicity in those samples with inherently hydrophobic surfaces (CAPP1-1 and

CAPP2-1), while samples with higher surface polarity remained less hydrophobic despite their rough structure. The observed wettability has important implications for oil-water separation performance. Hydrophobic and oleophilic materials, such as CAPP1-1 and CAPP2-1, should be more effective for selective oil adsorption, as they repel water while preferentially interacting with oil. In contrast, samples with lower WCAs may exhibit reduced selectivity due to partial water affinity. Therefore, optimizing the carbonization conditions to enhance hydrophobicity is essential for improving the efficiency of CAPPs in practical oil removal applications.

The adsorption performance of porous materials is influenced strongly by both porosity and wettability. Generally, high porosity provides a larger specific surface area and more accessible adsorption sites, thereby enhancing adsorption capacity. Furthermore, favorable wettability facilitates liquid penetration into the pore network, improving contact between the adsorbent and adsorbate and promoting mass transfer within the porous structure (Schlumberger and Thommes, 2021; Kyriakopoulos et al., 2024; Weragoda et al., 2025).

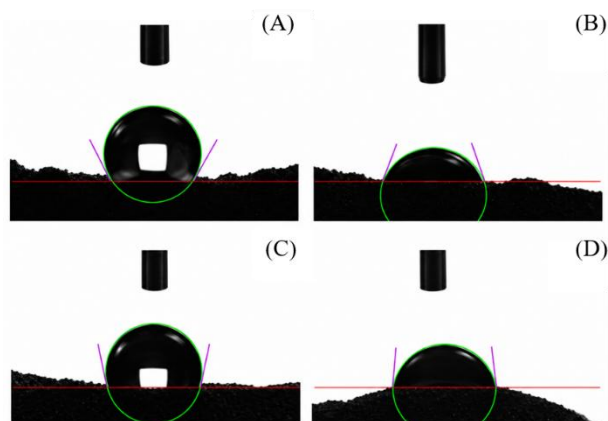


Fig. 3 Water contact angles from using different processing conditions to make carbon aerogels from pomelo peel (CAPPs): (A) CAPP1-1; (B) CAPP1-2; (C) CAPP2-1; (D) CAPP2-2.

The surface morphologies of the CAPPs were examined using scanning electron microscopy (SEM), as shown in Fig. 4. The raw PP has a nest-like architecture composed of irregular flaky plant tissues with limited micropores and mesopores, based on Pung et al. (2024). In the present study, after carbonization, the CAPPs developed a highly irregular and porous surface morphology composed of interconnected sheet-like and fibrous structures. Numerous cavities, channels and void spaces were distributed throughout the material, indicating a well-developed porous network. There was a heterogeneous arrangement of the structural components, including the presence of micro-scale pores and interconnected openings that facilitate mass transfer within the material (Fig. 4). This transformation could be attributed to the thermal decomposition of biomass components, such as cellulose, hemicellulose and lignin, resulting in the release of volatile compounds and the generation of a porous carbon framework (Krylova and Zaichenko, 2018).

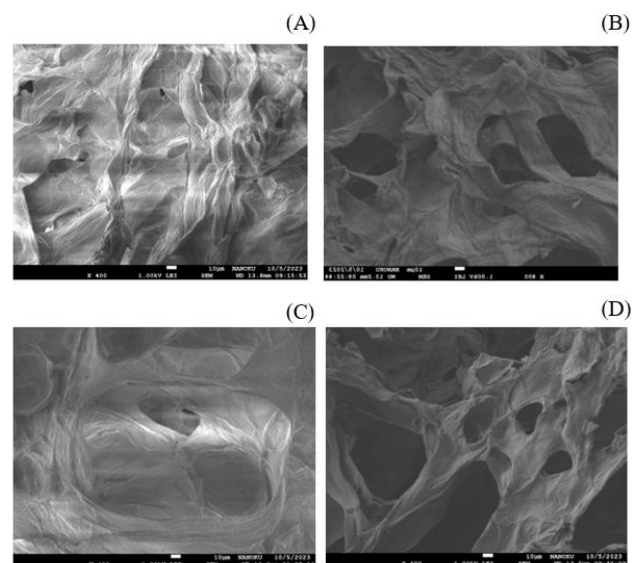


Fig. 4 Scanning electron microscopy images $\times 400$ from using different processing conditions to make carbon aerogels from pomelo peel (CAPPs): (A) CAPP1-1; (B) CAPP1-2; (C) CAPP2-1; and (D) CAPP2-2. Scale bar = 10 μm .

The obtained CAPPs exhibited hierarchical porosity, consisting of abundant micropores and mesopores. Micropores provide a large number of active sites for adsorption, while mesopores facilitate the transport and diffusion of oil molecules into the internal structure. Additionally, the presence of interconnected tunnel-like structures enhances capillary action, allowing oil pollutants to be rapidly absorbed and retained within the porous network. Furthermore, the highly porous morphology suggested a high specific surface area, which is a key factor governing adsorption performance (Zhu et al. 2017). Similar structural features have been reported in other biomass-derived carbon aerogels (Zhang et al., 2016), confirming that the synthesis approach applied in the present study was effective in producing functional porous materials. However, the extensive porosity may have contributed to the observed brittleness of the CAPPs, which could limit their mechanical stability during repeated use. Overall, the SEM analysis demonstrated that the CAPPs had a well-developed porous architecture with interconnected channels and hierarchical pore distribution, playing a crucial role in enhancing their oil adsorption performance.

The morphology of the CAPPs correlated with the findings reported by Pung et al. (2024). According to their Brunauer-Emmett-Teller (BET) analysis of pomelo peel carbon aerogel (PCA), microporosity and mesoporosity may coexist within the PCA sample. Therefore, the BET characteristics of the CAPPs were inferred from the data reported by Pung et al. (2024) and BET analysis was not conducted in the present study.

The FT-IR spectrum of the PP and CAPPs are shown in Fig. 5. The broad peak at 3230–3460 cm^{-1} of PP could be attributed to stretching vibration of the -OH group perhaps in the physically adsorbed water molecules. The peaks at 1738–1742 and 1640 cm^{-1} could be attributed to the stretching vibrations of C=O and -OH,

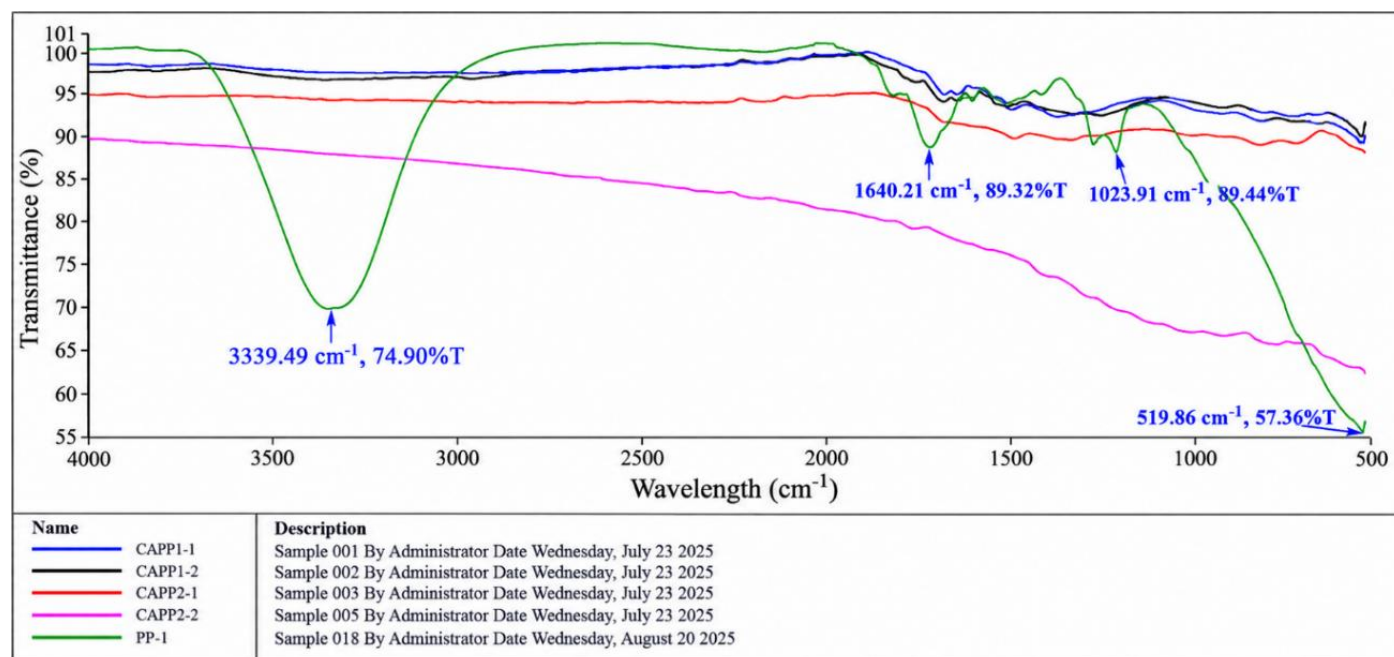


Fig. 5 Fourier-transform infrared spectrum of components of carbon aerogels (CAPPs) containing pomelo peel (PP) made under different processing conditions.

respectively, indicating that the existence of the carbonyl and -OH bending. The peak at 1023 cm⁻¹ could be attributed to C-O-C stretching vibration or C-C framework vibration (Fan et al., 2012).

After freeze-drying followed by carbonization or pyrolysis, the peaks in the CAPPs spectra at 3230–3460 cm⁻¹, 1738–1742, 1640 and 1023 cm⁻¹ became weaker (Fig 5), indicating that these groups had decreased, indicating the surface was less hydrophilic (or more hydrophobic) than PP.

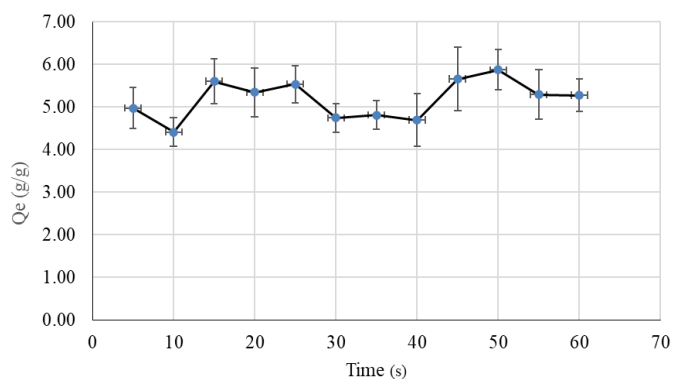


Fig. 6 Sorption capacity (Q_e , mean $\pm$ SE) using carbon aerogel from pomelo peel (CAPP) of CAPP1-1 sample with sunflower oil over time.

Preliminary sorption test of sunflower oil

Due to the presence of abundant microporous and mesoporous structures, the CAPPs were expected to perform well at oil sorption. To evaluate this, the sorption behavior of sunflower oil was investigated using CAPP1-1 over a contact time range of 5–60 s. Based on the results (Fig. 6), the sorption capacities remained nearly

constant across all time intervals ($p = 0.279$), suggesting that equilibrium was reached rapidly within the initial stage of contact. This rapid sorption behavior could be attributed to the highly porous and interconnected structure of the CAPPs, as observed in the SEM analysis. The presence of mesopores facilitated the fast diffusion of oil into the internal structure, while the micropores provided abundant sites for oil retention. In addition, capillary forces within the porous network likely played a dominant role in driving the rapid uptake of oil, allowing the sorbent to achieve near-saturation within a few seconds. Once the pore structure is filled, no substantial increase in sorption capacity could be expected with increasing contact time (Gui et al., 2011). Such fast sorption kinetics are consistent with Zhu et al. 2017 and Wang et al. 2017, who reported on biomass-derived carbon aerogels, where oil adsorption typically reaches equilibrium within seconds to minutes due to the highly accessible pore structure and strong oleophilic interactions. From a practical perspective, this rapid adsorption behavior is highly advantageous for real-world applications, such as grease trap systems, where short contact times are required for efficient oil removal (Gui et al., 2011). Based on these findings, a contact time of 30 s was selected for subsequent experiments, as it was sufficient to ensure equilibrium, while maintaining consistency with other studies (Zhu et al., 2017; Pung et al., 2024). Furthermore, this selection reflected a balance between experimental efficiency and practical applicability.

Preliminary sorption test of sunflower oil floating on water surface

A piece of CAPP1-1 was immersed in different amounts of sunflower oil (5–25 mL) floating on the surface of water for 30 s. Based on the results, sorption capacity increased only slightly

increased with added oil (Fig. 7, $p = 0.928$). Consequently, 15 mL was assigned for the next experiments.

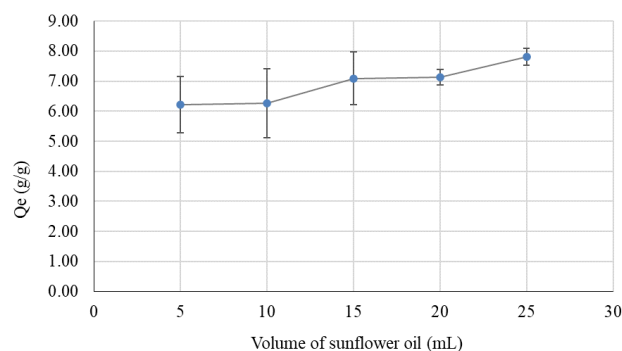


Fig. 7 Sorption capacity (Q_e , mean $\pm$ SE) using carbon aerogel from pomelo peel (CAPP) of CAPP1-1 sample with varying volumes of sunflower oil floating on water surface.

Sorption test of several oils floating on water surface

A piece of each CAPP was immersed in 15 mL of various oils floating on the water surface for 30 s. The sorption capacities were in the range 4.35–9.04 g/g, with the highest mean $\pm$ SE sorption for diesel oil with CAPP1-1 (6.45 ± 0.35 g/g, Fig. 8A), for palm oil with CAPP1-2 (8.19 ± 0.56 g/g, Fig. 8B), for rice bran oil with CAPP2-1 (8.08 ± 0.37 g/g, Fig. 8C) and for rice bran oil with CAPP2-2 (9.04 ± 0.36 g/g, Fig. 8D). For sunflower oil, the sorption capacities were 5.08 ± 0.31 g/g (CAPP1-1), 5.73 ± 0.58 g/g (CAPP1-2), 7.65 ± 0.50 g/g (CAPP2-1) and 7.84 ± 0.42 g/g (CAPP2-2). However, Zhu et al. (2017) reported their carbon aerogel derived from pomelo peel adsorbed 35 g/g of sunflower oil, while Wang et al. (2017) reported their carbon aerogel derived from durian shell adsorbed 19 g/g of sunflower oil. These differences were likely due to the lower carbonization and pyrolysis temperature (300°C for 1 hr) and the use of a muffle furnace without nitrogen flow, which may lead to reduced porosity and hydrophobicity compared to materials produced using high-temperature tubular furnace processes.

Generally, adsorption analysis models are based on the Langmuir and Freundlich isotherms. The Langmuir isotherm assumptions are limited to being monolayer, localized and reversible, where the surface is homogenous and all sites are identical and lateral interaction between adsorbed molecules are absent. The Freundlich isotherm is an empirical model describing how solute molecules distribute between a liquid (or gas) phase and a solid adsorbent at constant temperature. The Freundlich isotherm assumption are a heterogenous surface and non-saturated behavior. Empirical fits have been reported across limited concentration ranges for the adsorption of organics and metals onto soils, activated carbon, and polyresins. (Freundlich, 1906; Langmuir, 1918; Foo and Hameed, 2010).

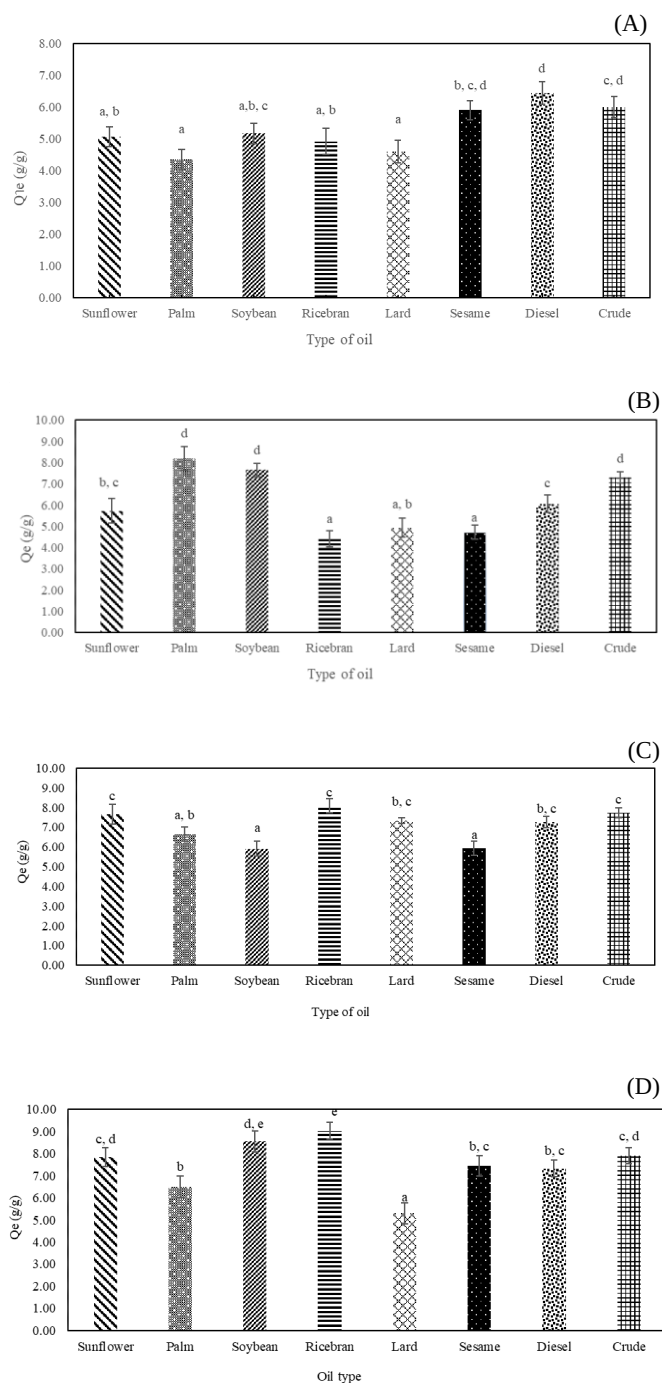


Fig. 8 Sorption capacity (Q_e , mean $\pm$ SE) using different processing conditions to make carbon aerogels from pomelo peel (CAPPs) with different oils floating on water surface: (A) CAPP1-1; (B) CAPP1-2; (C) CAPP2-1; and (D) CAPP2-2. Different lowercase letters above columns indicate significant differences among oil types, according to Duncan's multiple range test ($p < 0.05$).

Application of carbon aerogels made from pomelo peel in grease trap

The application of CAPPs in a household grease trap was evaluated using palm oil, as it is commonly used in domestic settings. This proof-of-concept experiment was designed to explore the feasibility of applying pomelo peel-derived carbon aerogels under practical household grease-trap conditions, thereby bridging the gap between laboratory-scale adsorption studies and real applications. Pung et al. (2022) reported that a pomelo peel sponge aerogel modified with hexadecyltrimethoxysilane achieved a sorption capacity of 3.85 g/g and a removal efficiency of 57.5% for palm oil. For the grease trap without CAPPs (control), the average $\pm$ SE oil weight remaining in the effluent was 12.59 ± 1.80 g, while the amount of oil retained by the grease trap was 71.97 g, corresponding to a removal efficiency of 85.11%. Under the conditions tested in the present study, CAPP1-2 had the highest observed sorption capacity (6.76 g/g), followed by CAPP2-2, CAPP1-1 and CAPP2-1. Likewise, the highest observed oil removal efficiency was with CAPP1-2 (11.71%), followed by CAPP2-2, CAPP2-1 and CAPP1-1 (Table 2). Because this grease-trap application test was conducted as a single proof-of-concept experiment, no statistical comparisons among the CAPP materials were performed. Therefore, these results should be interpreted as preliminary observations demonstrating the feasibility of incorporating CAPPs into household grease traps rather than as definitive evidence of the superiority of any specific material. Although biomass-derived carbon aerogels have been investigated widely for oil-water separation (Zhu et al., 2015; Zhou et al., 2016), their application in household

grease-trap wastewater treatment has received limited attention. The present study has provided preliminary evidence supporting the feasibility of this application and may serve as a basis for future investigations.

Reusability

Reusability is an important property of sorbent materials. In the present study, washing with ethyl acetate followed by heating was used to regenerate the CAPPs (Zhu et al., 2017). The sorption-regeneration process was repeated for three cycles and the regenerated CAPPs were evaluated for diesel oil adsorption (Table 3). Based on the results, the sorption capacities remained relatively high after the second cycle, retaining 73.4–88.6% of the initial uptake. However, after the third cycle, the sorption capacities decreased to moderate levels (36.4–71.4% of the initial values). This decline may be attributed to partial pore blockage, structural damage or residual oil remaining within the porous network after repeated use. Zhu et al. (2017) reported that their carbon aerogels retained high adsorption efficiencies of 98% and 92% for ethanol and acetone, respectively, after five adsorption-regeneration cycles. Similarly, Wang et al. (2017) found that durian shell-derived carbon aerogels maintained 75.31% and 76.18% of their initial sorption capacities for sunflower oil and soybean oil, respectively, after five cycles.

Overall, although the CAPPs performed well initially in the sorption test, their reusability was lower than that reported in those other studies, suggesting that further improvements in structural stability and regeneration methods are needed.

Table 2 Sorption capacity and percentage of oil sorption using different processing conditions to make carbon aerogels from pomelo peel (CAPPs) in grease trap application, where data all from one large-scale application test

Type of CAPP	Weight of CAPP before sorption (g)	Weight of CAPP after sorption (g)	Q _e (g/g)	Weight of oil before sorption (g)	Oil weight sorption by CAPP (g)	Oil sorption by CAPP (%)
CAPP1-1	27.53	175.41	5.37	85.04	6.70	7.88
CAPP1-2	17.96	139.40	6.76	86.10	10.08	11.71
CAPP2-1	23.68	133.14	4.62	85.80	7.68	8.96
CAPP2-2	21.92	160.03	6.30	86.50	7.94	9.18

Table 3 Sorption capacity and percentage values (mean $\pm$ SE) of oil removal by regenerated carbon aerogels made from pomelo peel (CAPPs) using different processing conditions

Type of CAPPs	Q _e after 1 cycle	Q _e after 2 cycles	Q _e after 3 cycles	Amount removed after 2 cycles (%)	Amount removed after 3 cycles (%)
CAPP1-1	5.96 $\pm$ 0.80	5.05 $\pm$ 0.66	3.48 $\pm$ 0.83	84.8	58.5
CAPP1-2	5.90 $\pm$ 0.25	5.23 $\pm$ 0.14	4.21 $\pm$ 0.26	88.6	71.4
CAPP2-1	10.81 $\pm$ 0.67	7.95 $\pm$ 1.06	6.29 $\pm$ 0.53	73.5	58.2
CAPP2-2	5.62 $\pm$ 0.46	4.12 $\pm$ 0.36	2.04 $\pm$ 0.54	73.4	36.4

Conclusion

CAPPs derived from pomelo peels were fabricated by freeze-drying, followed by either carbonization at 300°C for 1 hr or pyrolysis at 300°C for 1 hr. The resultant products were characterized using the WCA and SEM, which indicated that the CAPPs had an interconnected porous morphology. The sorption capacities of the CAPPs with various oils on the surface of water were in the range 4.35–9.04 g/g. The removal rates for the CAPPs of palm oil from a grease trap were in the range 7.88–11.71 %. Furthermore, the reusability of the sorbent was confirmed by absorption-regeneration tests for 3 cycles with diesel oil, with the sorption capacity having medium-to-low values.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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