Effect of particle size on oil adsorption efficiency using untreated lemon peel adsorbents

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Abstract. The disposal of waste cooking oil (WCO) presents significant environmental risks, impacting soil, water, and ecosystems. This study explores the feasibility of lemon peels (LP), an abundant biowaste as a green adsorbent for oil removal from water. LP adsorbents were prepared at three different particle sizes which is 150 µm, 300 µm, and 425 µm, and the properties is analysed using Fourier Transform Infrared Spectroscopy (FTIR) and N_2 adsorption-desorption analysis. Batch adsorption tests were performed to examine the effects of contact time (5–20 min), adsorbent size (150 - 425 µm), adsorbent dosage (0.4 – 1.0 g) and oil-to-water ratio (1:12–1:4) toward the WCO removal efficiency. The FTIR results indicated the consistent presence of key functional group such as hydroxyl, carbonyl, and ester groups across all adsorbents, with no significant changes between different particle sizes. Analysis of surface area showed that LP-150 exhibited the highest surface area (14.69 m^2/g) and pore volume (0.0119 cc/g), contributing to its superior oil adsorption capacity (6.5 g/g). Overall, this study demonstrates that untreated LP is a promising natural adsorbent for WCO removal, and that adjusting particle size significantly enhances its adsorption efficiency.

1 Introduction

Waste Cooking Oils (WCO) consist of all types of oils and fats derived from vegetable or animal sources that have been used during food preparation in households, restaurants, fast food outlets, and the food processing industry [1]. The worldwide annual WCO production is reported to be around 41–52 million tons (Mt), with the European Union producing 1–2.5 Mt per year alone [2]. If WCO is not managed appropriately, it can cause

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serious ecological and public health problems. When improperly disposed of in waterways and aquatic systems, it may lead to unpleasant odours and pollution hazards that affect human and ecological health [3]. This highlights the need for effective and sustainable waste management strategies. Biodegradation, which involves the oxidation of pollutants by living microorganisms, is one promising approach. Nevertheless, the application of this principle on a large scale is hindered by environmental factors such as pH, temperature and oxygen levels [4].

Adsorption has emerged as a promising method for WCO removal. This physical process involves the attachment of pollutants to the surface of solid materials known as adsorbents. It is favoured over other treatment methods due to its simplicity, cost-effectiveness, and high treatment efficiency [5]. Recently, natural adsorbents derived from agricultural, or biomass waste have gained attention for their simplicity, cost-effectiveness, and environmental compatibility in removing oil-based contaminants. Among various types of agricultural waste, lemon peel (LP) which is composed of cellulose, hemicellulose, lignin, and pectin, has become a promising adsorbent. With an annual global production of 7.3 million tons, lemon is the third most significant citrus species that was grown worldwide, following orange and mandarin [6]. Its wide availability, low price, and abundance of functional surface groups make LP an attractive natural material for the removal of WCO from polluted water. In this study, the performance of untreated LP as an adsorbent was explored. LP samples of various particle sizes were prepared and characterized, while the adsorption efficiency was evaluated under different conditions, including contact time, particle size, adsorbent dosage, and oil-to-water ratio.

2 Materials and Method

The lemon peels were collected from the local fruit shop in Selayang, Malaysia. The waste cooking oil (WCO) was obtained from households in Kuala Lumpur area. Distilled water was used throughout the experiment.

2.1 Preparation of Lemon Peel adsorbent

The collected lemon peels (LP) were thoroughly washed with distilled water to remove any surface impurities. After cleaning, the peels were evenly spread on petri dishes and dried in an oven at 110 °C for 24 hours. After this initial drying, each sample was weighed to determine the remaining moisture content. The samples were then returned to the oven for another 24 hours to ensure complete removal of moisture. After 48 hours of drying, the samples were weighed again and compared to the previous measurement. Since there were no further changes in mass, it was confirmed that the peels had reached a constant weight, indicating they were fully dried. If differences had been detected, additional drying would have been carried out in 24-hour intervals until the weight stabilized. Once completely dried, the peels were sieved to obtain particle sizes of 150 μm, 300 μm, and 425 μm for subsequent characterization tests. The samples were denoted as LP-150, LP-300, and LP-425, respectively.

2.2 Characterization of Lemon Peels Adsorbent

The LP adsorbent was analysed using two techniques; (i) Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups, (ii) N_2 adsorption-desorption analysis using Brunauer–Emmett–Teller (BET) method to determine surface properties. For FTIR analysis, 100 mg of LP powder from each particle size was placed into a 13 mm disc mold and pressed at 10 tons for two minutes to form a pellet. The sample was then analysed using a Shimadzu IRTracer-100 (SN A217055) over the wavenumber range of 4000–400 cm^{-1}. The surface area of LPs was measured using Surface Analyzer (NOVAtouch LX2, Quantachrome Instrument, USA; TriStar II 3022, Micromeritics, USA). The samples were degassed at 110°C for 12 hours prior to analysis. The specific surface area was determined using Brunauer-Emmett-Teller (BET) method.

2.3 Adsorption Study

A batch adsorption study was performed to assess the efficiency of lemon peel (LP) as an adsorbent for removing waste cooking oil. The LP-425 adsorbent was selected to examine the effect of contact time. A 0.4 g of LP-425 was placed in a teabag, and its initial weight was measured. The teabag was then immersed in a beaker containing an oil–water mixture with a ratio of 1:12. After immersion periods of 5, 10, 15, and 20 minutes, the teabag was removed and drained in a funnel for 10 minutes to remove excess oil. The final weight of the teabag and adsorbent was recorded. The optimal contact time obtained from this test was then used to evaluate the effect of adsorbent particle size, comparing LP-300 and LP-150 under the same procedure. Following this, the best-performing LP adsorbent was used to investigate the effect of adsorbent dosage (0.4, 0.6, 0.8, and 1.0g). Finally, the optimum adsorbent dosage was applied to study the effect of the oil-to-water ratio. All experiments were conducted in triplicate to ensure data reliability. The amount of oil adsorbed and the adsorption capacity were calculated using Equation 1 and Equation 2.

$$m_{ads} = \frac{m_f - m_i}{m_i} \quad (1)$$

$$q = \frac{x}{m_{ads}} \quad (2)$$

Where, m_{ads} is total mass oil oil adsorbs (g), m_f is final mass of teabag and adsorbent after adsorption (g), m_i is the initial mass of teabag and adsorbent (g), q is adsorption capacity (g/g) and x is adsorbent dosage (g).

3 Results and Discussion

Fig.1 shows the FTIR spectra of the three-lemon peel (LP) samples: LP-150, LP-300, and LP-425. A peak at 1732 cm^{-1} indicates the presence of acetyl ester and carbonyl aldehyde functional groups, which are components of hemicellulose and lignin in the LP cell wall. Peaks around 1600 cm^{-1} are linked to C=C aromatic ring vibrations and C–H deformations from methyl, methylene, and methoxy groups, reflecting the complex

lignin structure [7]. A broad peak at 3320 cm^{-1} was observed, corresponding to the stretching vibration of hydroxyl (–OH) groups from cellulose, pectin, and pigments. Additionally, the peak near 1000 cm^{-1}, which lies in the fingerprint region, represent C–C and C–O–C stretching vibrations of carbohydrate rings, which further confirming the presence of cellulose and hemicellulose components [8].

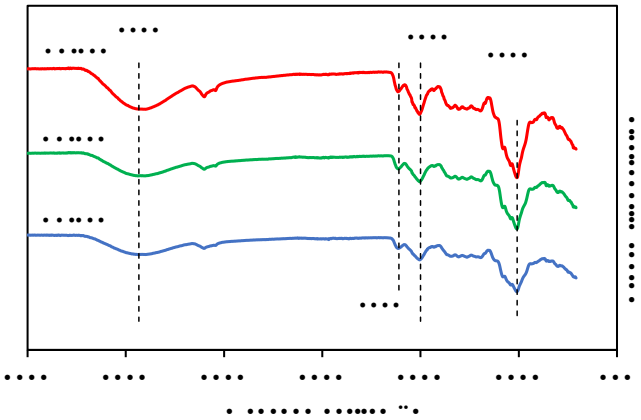

Fig. 1. FTIR Spectra of LP adsorbents.

Notably, no significant changes were seen in the FTIR spectra among the three particle sizes. This indicates that the chemical structure and surface functional groups of the LP remained unchanged, as only the physical particle size was modified during sieving [9]. Since no chemical or thermal treatments were applied, the inherent functional groups were preserved. This consistency confirms that the chemical characteristic of LP remains intact, allowing reliable comparison of adsorption performance across different particle sizes.

Table 1 highlights the N_2 adsorption-desorption results, showing that LP-150 (smallest particle size) had the highest specific surface area (14.69 m^2/g) and pore volume (0.0119 cc/g). This finding is consistent with previous study demonstrating that reducing particle size enhances surface area and exposes internal porosity, thereby enhancing adsorption capacity [10]. LP-300 also had elevated surface area (14.11 m^2/g), while LP-425 had the lowest (8.075 m^2/g). Interestingly, the trend in pore radius did not follow the same pattern. LP-425 showed the largest average pore radius (2.25 nm), while LP-150 had the smallest (1.53 nm). This inverse relationship suggests that as particle size decreases, the material tends to develop more microporous structures with narrower pore channels, leading to a reduction in the average pore diameter [11].

Table 2. Characteristic of LP adsorbents.

Adsorbent	Surface Area (m^2/g)	Pore Volume (cc/g)	Pore Radius (nm)
LP-150	14.69	0.0119	1.53
LP-300	14.11	0.0109	1.78
LP-425	8.075	0.0084	2.25

Fig. 2 illustrates the adsorption performance of LP adsorbents under various experimental conditions, including (A) contact time, (B) adsorbent particle size, (C) adsorbent dosage, and (D) oil-to-water ratio. As shown in Fig. 2A, the adsorption capacity increased with contact time up to 15 minutes, reaching a maximum of approximately 5.7 g/g for LP-425, followed by a slight decline at 20 minutes. The initial increase indicates that more active sites on the LP surface were available for oil adsorption during the early stage, while the subsequent decrease may be attributed to the attainment of equilibrium and partial desorption of weakly bound oil molecules [12]. In Fig. 2B, smaller adsorbent particles (LP-150) exhibited higher adsorption capacity (6.5 g/g) compared to larger ones (LP-425) (5.7 g/g). This enhancement can be attributed to the greater specific surface area associated with smaller particles, as supported by the N_2 adsorption–desorption analysis [13]. The effect of adsorbent dosage, presented in Fig. 2C, shows that the adsorption capacity decreased with increasing dosage. The maximum adsorption capacity (6.5 g/g) was achieved at 0.4 g of LP-150 adsorbent, after which the value gradually declined. This trend is commonly observed due to particle aggregation at higher dosages, which reduces the available surface area and the number of accessible active sites per unit mass of adsorbent [14]. As shown in Fig. 2D, the adsorption capacity decreased as the oil-to-water ratio decreased from 1:12 to 1:4. At higher dilution (1:12), oil droplets were more effectively dispersed in water, promoting greater interaction between oil molecules and the LP surface. In contrast, at lower ratios, the oil phase became more concentrated, limiting mass transfer and reducing adsorption efficiency[15]. Overall, these findings indicate that the optimum adsorption performance (6.5 g/g) was achieved at a contact time of 15 minutes, particle size of 150 μm, dosage of 0.4 g, and oil-to-water ratio of 1:12.

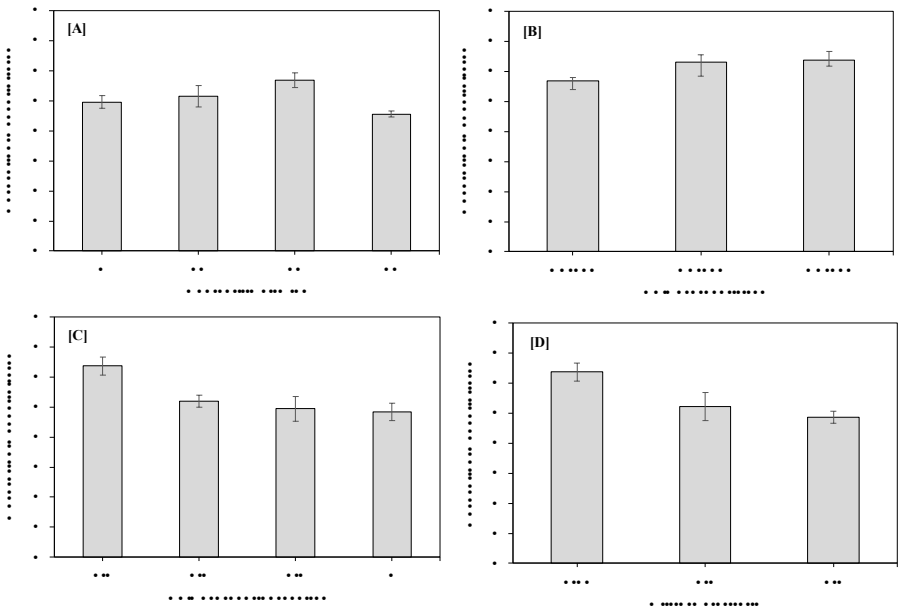

Fig. 2. Adsorption performance of LPs adsorbent [A] Contact time (0.4 g of LP-425, oil-to-water ration of 1:12) [B] Adsorbent size (15 min, 0.4 g of LPs, oil-to-water ration of 1:12) [C] Adsorbent dosage (15 min, LP-150, oil-to-water ration of 1:12) and [D] Oil-to-water ratio (15 min, 0.4 g of LP-150)

4 Conclusion

This study demonstrated that untreated lemon peel (LP) can effectively serve as a natural, low-cost adsorbent for removing waste cooking oil (WCO) from water. The experimental findings confirmed that particle size plays a decisive role in adsorption performance. Among the tested adsorbents, the smallest particle size (LP-150) exhibited the highest specific surface area and pore volume, resulting in the greatest adsorption capacity of 6.5 g/g under optimal conditions of 15 minutes contact time, 0.4 g adsorbent dosage, and a 1:12 oil-to-water ratio. FTIR analysis revealed that all LP samples retained similar surface functional groups, suggesting that the improvement in adsorption efficiency was primarily attributed to physical factors which is enhancement in surface area. Overall, the results highlight the potential of utilizing untreated LP as a sustainable adsorbent for oil removal applications, particularly in small-scale wastewater treatment or resource recovery systems.

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