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Characterization of Palm Oil Mill Fly Ash Based Adsorbent as Bleaching Agent of Crude Palm Oil

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ABSTRACT. The palm oil industry generates significant waste, including fly ash (FA) from palm oil mill boilers, which poses environmental challenges. This study investigated the potential of FA as an alternative adsorbent for the bleaching of crude palm oil (CPO) and compared its performance with commercial bleaching earth (BE). FA was activated thermally at 400°C and chemically using 1.5 M oxalic acid solution to enhance its adsorption capacity. The results showed that chemically activated FA (FA 1.5 M) and thermally activated FA (FA 400°C) reduced the CPO color from 20 Red (R) to 16-17 R, meeting the industrial standard for degummed bleached palm oil (≤ 17 R). The bleaching efficiency of FA 1.5 M was comparable to that of BE under identical conditions (120 °C and 1.5% w/w adsorbent), demonstrating its practical applicability as an alternative bleaching agent. Characterization results showed that FA 1.5 M had a higher silica (SiO_2) content (77.13%) than FA 400°C (72.46%) and BE (52.01%), along with increased surface area and pore size. FTIR analysis confirmed the adsorption of organic components from CPO onto the activated FA surface, while SEM analysis revealed that chemical activation produced a rougher surface morphology with larger pore diameters. Heavy metal concentrations in both activated FA adsorbents were within safe limits for food applications. Furthermore, BET analysis confirmed that FA 1.5 M exhibited a mesoporous structure with improved adsorption isotherms compared to untreated FA. The study showed that FA particularly FA 1.5 M, shows strong potential as an effective, low-cost, and environmentally sustainable alternative adsorbent in the CPO bleaching process.

Keywords: Adsorbent, Bleaching earth, Crude palm oil, Fly ash

INTRODUCTION

The palm oil industry plays a crucial role in the economies of many tropical countries, particularly in Southeast Asia. However, it also generates a significant amount of waste, including fly ash (FA) from palm oil mill boilers. FA is commonly disposed of in landfills, posing environmental and health risks due to its fine particulate nature and potential heavy metal content (Kristanti et al., 2021; Qaim et al., 2020; Uning et al., 2020; Utama et al., 2018). Consequently, the sustainable and economical utilization of FA has become a major focus of recent research (Aigbe et al., 2021; Desniorita et al., 2023; Oktavianty, 2022; Pelita et al., 2023; Shah et al., 2014; Sylvia et al., 2021; Utama et al., 2018). One promising application is the use of FA as an adsorbent material for bleaching of crude palm oil (CPO) (Acquah et al., 2016; Marfitania et al., 2024; Naufa & Azwardi, 2018). Bleaching is a critical step in the CPO refining to produce high-quality palm oil by removing impurities such as pigments, metals, and oxidation products that affect oil quality and stability. Conventional bleaching earth (BE) such as activated clay is commonly used, but its high cost and limited domestic availability necessitate the alternative materials. It has become research important area to develop an alternative adsorbent with cost-effective that can perform efficiently and minimize waste (Abdelbasir et al., 2023; Adiarso et al., 2024; Gunawan et al., 2010; Heryani, 2019; Hidayu et al., 2019; Ifa et al., 2021; Irvan et al., 2020; Placxedes et al., 2024; Soetaredjo et al., 2021; Yuliana et al., 2020).

FA has several characteristics that make a potential candidate as an adsorbent. FA contains a porous structure, high surface area, and various minerals such as silica more than 50%. Silica plays a key role in the adsorption process which can remove impurities (carotenoids, chlorophylls, and other pigments impart a reddish-orange colour) from CPO. Additionally, utilizing FA (industrial byproduct) for valuable resources could be contribute to the circular economy

(Acquah et al., 2016; Desniorita et al., 2023; Naufa & Azwardi, 2018; Pelita et al., 2023; Ram & Mohanty, 2022; Shah et al., 2014). Recent studies have explored the FA feasibility for adsorptive applications, with good results in the context of dyes and heavy metals adsorption (Aigbe et al., 2021; Alouani et al., 2018; Desniorita et al., 2023; Pelita et al., 2023; Shah et al., 2014; Supelano et al., 2019). However, palm oil mill FA application in the bleaching of CPO has not been widely studied. The novelty of FA utilization does not lie solely in the use of FA as a raw material. Most existing works focus only on FA-derived silica utilization or heavy metal/dye adsorption, while limited information is available regarding (i) the effect of different activation methods on FA physicochemical properties, (ii) comparative performance between FA and commercial BE and (iii) the safety of FA for food-related applications. Therefore, a scientific gap remains in understanding how activation mechanisms influence FA surface chemistry, pore structure, and adsorption capability toward CPO impurities such as pigments and free fatty acids (Dogar et al., 2020; Merikhy et al., 2020).

In this study, FA was activated using thermal treatment (400°C) and chemical activation with oxalic acid (1.5 M) to enhance its physicochemical properties. The novelty of this study lies in the comprehensive characterization of activated FA including XRF, FTIR, SEM–EDX, ICP, and BET combined with performance evaluation in the CPO bleaching process under industry-relevant conditions and safety evaluation for food applications. This study provides the first integrated assessment of activated FA as a safe, cost-effective, and environmentally beneficial replacement for commercial BE in palm oil refining, contributing to the development of circular economy in the palm oil industry.

EXPERIMENTAL SECTION

Materials

The main raw materials used in this study were FA (Mutiara Agam Palm Oil Mill, Agam Regency, West Sumatera), CPO and BE (Incasi Raya, Padang, West Sumatera). Additional materials included distilled water, phosphoric acid (H_3PO_4, 85%) and oxalic acid (Novalindo, Padang). H_3PO_4 was used in the degumming process.

FA Activation

Thermal activation: FA was sieved to remove the impurities. Then, FA was washed with distilled water for ± 10 minutes. The sample was dried in an oven at 120°C for 3 hours, followed by calcination in a furnace at temperature of 400°C for 4 hours.

Chemical activation: oxalic acid solution was used at a concentration of 1.5 M. 100 ml of the solution was added to 20 g of FA and mixed at 50°C for 90 minutes at stirring speed of 250 rpm. FA was then separated from the acid solution and washed with distilled water until neutral pH was achieved. Subsequently, the sample was dried in the oven at temperature of 120°C for 3 hours.

Degumming and Bleaching of CPO

Degumming process: 250 ml of CPO and 0.07% (v/v) of phosphoric acid (H_3PO_4, 85%) were mixed at ± 113°C for 30 minutes with stirring speed of 400 rpm.

Bleaching process: degummed palm oil was bleached at temperature of 120°C for 30 minutes (stirring speed 400 rpm). Adsorbents of BE and activated FA were added at an amount of 1.5%. After bleaching, the oil was filtered using filter paper to obtain bleached palm oil.

Analysis and Characterization

The chemical composition of FA, activated FA and BE were analysed by X-ray Fluorescence (XRF; PANalytical Epsilon 3) and Fourier Transform Infrared (FTIR; PerkinElmer Spectrum IR Version 10.6.1). The morphological structure of the adsorbent surface was checked by SEM-EDX (Hitachi S-3400) at an accelerating voltage of 20 kV, working distance of 11 mm and magnification greater than 500x. Pore diameter estimation from SEM images was conducted by measuring visible pore openings using image analysis software integrated with the SEM system. Several representative pores were randomly selected from different regions of each sample, and pore diameters were measured based on the SEM scale bar. The reported values represent the average pore diameter. Furthermore, the contamination of heavy metal test was also carried out to determine the safety of adsorbent in food application. The contamination of heavy metal on adsorbent, CPO and bleached palm oil (BPO) were checked by Inductively Coupled Plasma (ICP; Shimadzu ICPE-9000). Then, the surface area of FA and activated FA was analysed by Brunauer-Emmett-Teller (BET; Quantachrome Instruments NovaWin version 11.03).

RESULTS AND DISCUSSION

The efficiency of FA adsorbent performance compared to commercial BE as the bleaching agent of CPO has been reported in our previous study (Nirmala et al., 2024). The study evaluated the performance of FA, BE and mixed FA-BE adsorbents under various bleaching temperatures and adsorbent dosages. The result showed that activated FA was capable of reducing CPO color, with optimum bleaching conditions obtained at 120°C and adsorbent dosage of 1.5% (w/w). These conditions remain within the typical industrial operating range for BE based bleaching, which generally operates at 100-130 °C using 0.7-1.4% (w/w) adsorbent (Hasibuan, 2018; Heryani, 2019; Irawan et al., 2021; Soetaredjo et al., 2021). Furthermore, the previous study reported that the adsorbents FA 1.5 M and FA 400°C produced the greatest reduction in CPO color from 20 to 16 R. The optimum mixed adsorbent formulation that met the degummed bleached palm oil (DBPO) industrial color

limit (max. 17 R) was BE:FA ratio of 1:3 (Nirmala et al., 2024).

In addition to these findings, preliminary screening experiments conducted in the present study also indicated that other activated FA variants (e.g. FA 0.5 M, FA 1.0 M, and thermally activated FA below 400°C) exhibited lower adsorption performance and less stable surface characteristics compared to FA 1.5 M and FA 400°C. These adsorbents showed reduced color removal efficiency and inferior physicochemical properties (such as surface cleanliness, pore development, and stability), making them less suitable for further analysis (Nirmala et al., 2024). Therefore, FA 1.5 M and FA 400°C were selected for detailed characterization in this work, as they consistently demonstrated the highest bleaching performance among the tested FA adsorbents, based on our previous study.

Chemical Compositions of Adsorbent

The chemical composition of adsorbent was analyzed by XRF and FTIR instruments. The results of XRF characterization of FA 1.5 M, FA 400°C and commercial BE are shown in **Table 1**. The SiO_2 content of the activated FA adsorbents (FA 1.5 M and FA 400°C) increased by 77.13% and 72.46%, respectively. Chemical activation with an oxalic acid solution was able to increase the SiO_2 content higher than physical activation. Naufa and Azwardi (2018) reported that FA activation using oxalic acid can increase the SiO_2 content by ± 27%. From these results, it can be seen that the FA adsorbent has higher SiO_2, but Al_2O_3 content is lower than the BE adsorbent. The SiO_2 and Al_2O_3 content in the adsorbent plays an important role in the adsorbent's adsorption capacity. Silica contributes to surface polarity and provides abundant -OH functional groups that facilitate interactions with polar impurities in CPO, such as carotenoids and free fatty acids, through hydrogen bonding and dipole interactions. Meanwhile, Al_2O_3 improves surface acidity, which promotes chemisorption and enhances pigment removal via acid-base interactions. Higher SiO_2 content is typically associated with increased specific surface area and pore formation, whereas Al_2O_3 contributes to structural stability and surface reactivity. Therefore, variations in SiO_2 and Al_2O_3 content directly influence the overall adsorption mechanism through both physical (surface area/pore size) and chemical (surface functional groups) pathways (Sylvia et al., 2021; Visa et al., 2010).

CaO is the second content of another metal oxide with a high percentage. Nor Shafizah et al. (2022) reported that K_2O and CaO adsorbents were able to reduce FFA in CPO by 63%. This is in line with Syahwandi et al. (2019) who conducted FFA adsorption with ash from an empty fruit bunch of oil palm adsorbent. The highest element contained in empty fruit bunch ash is potassium (K) which can reduce FFA by 24%. Furthermore, the results of FTIR characterization from activated FA (FA 1.5 M and FA 400°C) and BE adsorbent showed in **Figure 1**. BE adsorbent has a sharp peak compared to the other two adsorbents at 981.7 cm^{-1} which detected the presence of the Si-O group. In addition, the peaks appearing at 3544.63 cm^{-1} and 3361.89 cm^{-1} are attributed to the O-H group with a broadening intensity from the H_2O molecule (Pelita et al., 2023; Sastrohamidjojo, 2018; Silverstein et al., 2005). **Table 2** shows that the BE adsorbent contained high water content (10.174%) so that the FTIR analysis detected the O-H group with a fairly sharp peak compared to the FA adsorbent.

Table 1. Chemical composition of FA, activated FA and BE adsorbent

Compound	FA (%)	FA 1.5 M (%)	FA 400°C (%)	BE (%)
SiO_2	32.74	77.13	72.46	52.01
Al_2O_3	0.33	0	0.12	7.88
CaO	20.33	15.63	15.51	14.94
Fe_2O_3	3.68	0.75	1.91	16.88
TiO_2	0.17	0.14	0.14	2.47
K_2O	18.29	1.79	3.87	2.13
P_2O_5	5.52	1.67	3.03	2.48

Tabel 2. pH and water content of activated FA and BE Adsorbent

Adsorbent	pH	Water Content (%)
FA 1.5 M	7	1.639
FA 400°C	10	0.434
BE	7	10.174

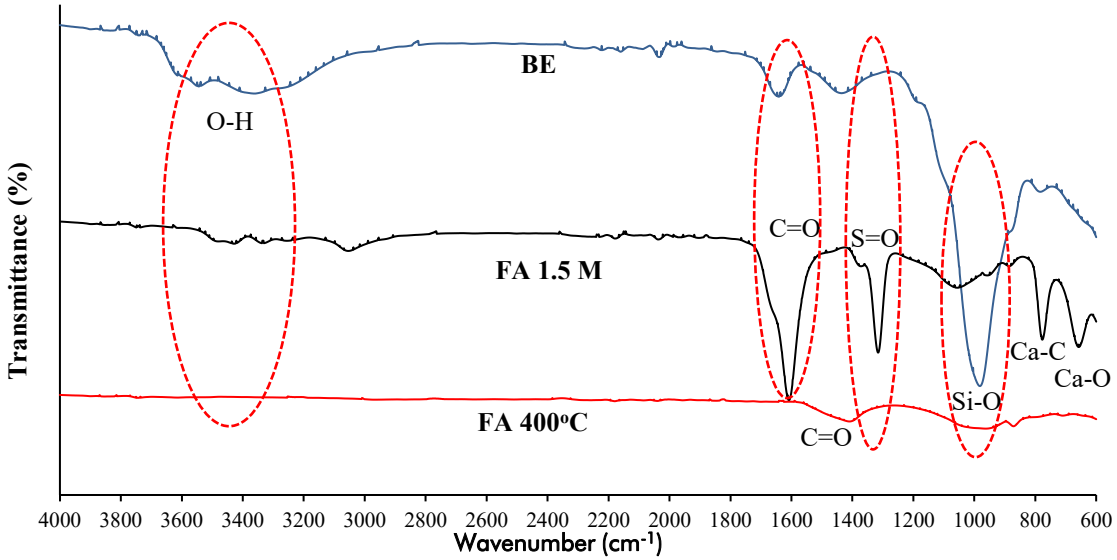

Figure 1. FTIR spectra of activated FA and BE adsorbent

In the FA 1.5 M adsorbent (**Figure 1**), several absorption bands appeared sharper and more intense compared to the FA 400°C and BE adsorbents, indicating differences in surface chemistry induced by chemical activation. The strong band observed at wavenumbers 1608.15 cm^{-1} and 1315.52 cm^{-1} can be attributed to carbonyl (C=O) and sulfonyl-related (S=O) vibrations respectively, which are commonly associated with oxygen-containing functional groups on mineral surfaces or adsorbed organic compounds. The bands at 776.91 cm^{-1} and 657.59 cm^{-1} are assigned to metal-oxygen vibrations, particularly those related to calcium-containing mineral phases based on the spectroscopic data (Farissi et al., 2017; Hidayu et al., 2019; Karanac et al., 2018; Permadani et al., 2018; Silverstein et al., 2005; Syah, 2022; Syahwandi et al., 2019). Meanwhile in the FA 400°C adsorbent, there is a different peak at 1409.70 cm^{-1} which detected the presence of the C=O group. In addition, FTIR analysis before and after bleaching was conducted to evaluate adsorption behavior. The FTIR spectra of FA 1.5 M adsorbent after the adsorption process showed a new peak that was different from the spectra before adsorption (see **Figure 2**). The new peak at wavenumbers 2919.26 cm^{-1} and 2853.34 cm^{-1} which are characteristic of aliphatic C-H stretching, while the band at 1739.61 cm^{-1} is associated with ester or carboxylic carbonyl groups. Additional bands at 1461.26 cm^{-1} and 1165.99 cm^{-1} correspond to C-O-H and C-O groups respectively. These changes indicate the adsorption of carboxylate compounds from CPO onto the FA 1.5 M surface.

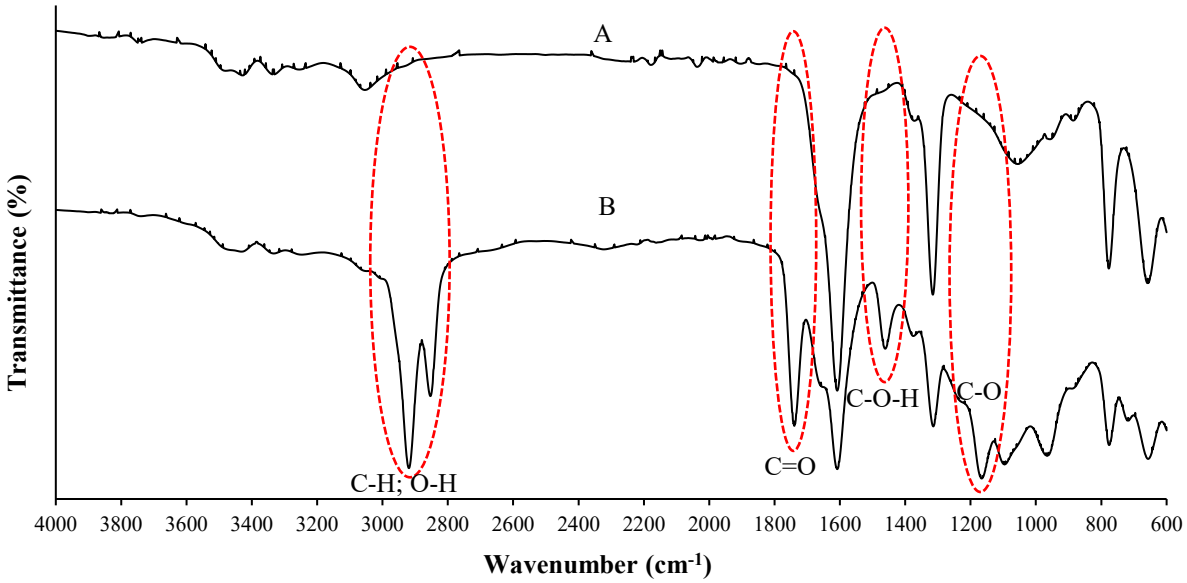

Figure 2. FTIR spectra of FA 1.5 M (A) before and (B) after adsorption

The results of the FTIR analysis of FA 400 °C before and after adsorption showed in **Figure 3**. The peaks appeared at wavenumbers 2918.98 cm^{-1}; 2853.17 cm^{-1}; 1739.90 cm^{-1} and 1167.57 cm^{-1} are typical for the C-H; O-H; C=O and C-O groups respectively. The low wavenumber band at 721.56 cm^{-1} is related to metal-oxygen vibrations, particularly from calcium-containing mineral phases (Farissi et al., 2017; Hidayu et al., 2019; Silverstein et al., 2005; Syah, 2022; Syahwandi et al., 2019). The increased intensity and sharpening of these bands after adsorption indicate the presence of organic compounds from CPO on the FA 400 °C surface, suggesting interactions between fatty acid molecules and surface metal sites through physical adsorption and surface complexation.

The changes observed in the FTIR spectra of FA 1.5 M and FA 400 °C provide qualitative indications of the compositional shifts occurring on the adsorbent surface. The appearance of new peaks corresponding to C-H, C=O, and C-O functional groups after the bleaching process suggests an increased presence of carbon and oxygen containing compounds adsorbed from CPO. Conversely, the characteristic bands associated with the inorganic matrix (such as Si-O, Al-O, and Ca-O) become relatively less dominant, implying partial surface coverage by organic molecules. These spectra changes qualitatively reflect an increase in organic elemental components (C and O) on the adsorbent surface and a reduced exposure of inorganic elements (Ca, Si, Al). The FTIR results provide supportive evidence that shifts in surface composition occurred during adsorption and contributed to the observed adsorption behavior.

In **Figure 4** showed the FTIR analysis of BE adsorbent before and after adsorption. The peaks appeared at wavenumbers 2919.98 cm^{-1}; 2853.74 cm^{-1}; 1740.86 cm^{-1} and 1163.69 cm^{-1}. At this wavenumbers detected the presence of C-H; O-H; C=O and C-O groups respectively. The low wavenumber band at 719.88 cm^{-1} is related to metal-oxygen vibrations, particularly from calcium-containing mineral phases (Farissi et al., 2017; Hidayu et al., 2019; Silverstein et al., 2005; Syah, 2022; Syahwandi et al., 2019). BE adsorbent before the adsorption process detected the presence of O-H groups (H_2O molecules) at 3544.63 cm^{-1} and 3361.89 cm^{-1}. However, after the adsorption process, the peak did not appear caused by heating during the bleaching process (120°C), which reduced the water content in the adsorbent and the oil. So that the O-H group of water molecules did not detect in the FTIR spectrum. The disappearance of these bands, together with the appearance of aliphatic and carbonyl related peaks, indicates the adsorption of organic compounds from CPO onto the BE surface.

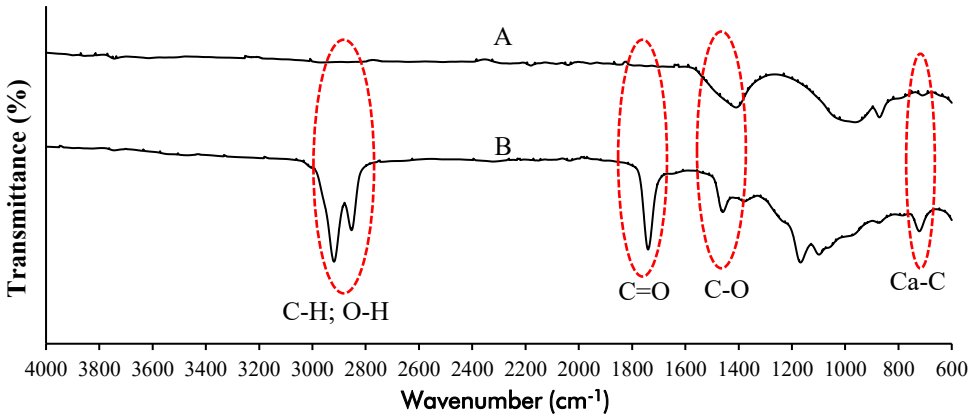

Figure 3. FTIR spectra of FA 400°C (A) before and (B) after adsorption

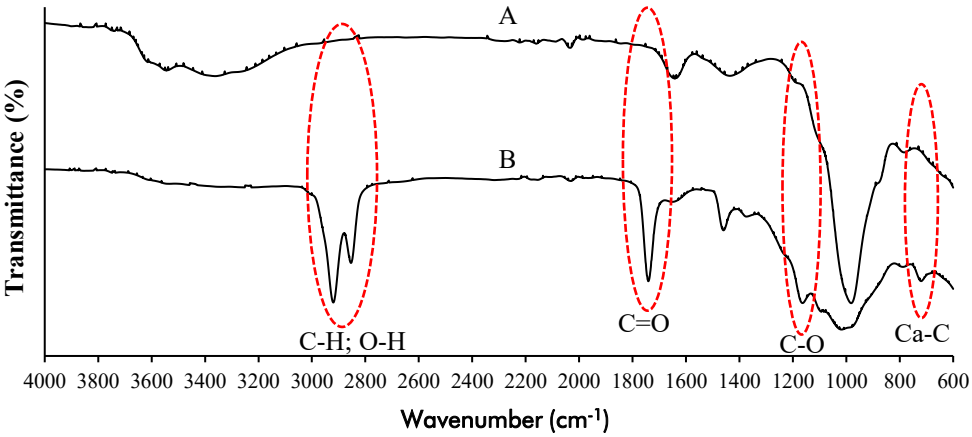

Figure 4. FTIR spectra of BE (A) before and (B) after adsorption

Morphology Characteristic of Adsorbent

The surface morphology of FA before and after activation, along with the commercial BE are shown in **Figure 5.** The surface of untreated FA has varying pore diameters with average diameter of 0.834 µm (**Figure 5.a**). When compared to untreated FA, FA 1.5 M has a rougher surface and larger pore diameter with an average diameter of 1.733 µm (**Figure 5.b**). The surface morphology of FA 400°C is shown in **Figure 5.c**. FA 400°C adsorbent has a rougher surface compared to FA and FA 1.5 M. The particles have an irregular shapes and the surface appears fibrous with an average particle size of 29.67 µm. Based on these results, FA adsorbent has a pore size larger than 50 nm. From this size, the adsorbent can be classified as a macropores type adsorbent. According to pore size classification, adsorbents are categorized into macropores (> 50 nm), mesopores (2-50 nm) and micropores (< 2 nm) (Sylvia et al., 2021).

Figure 5.d showed that the surface morphology of BE adsorbent has an amorphous structure with irregular particle shapes (average particle size of 26.7 µm). It can be seen that the uneven surface structure of BE indicates wide particle size distribution across the surface. Element compositions of adsorbents were analyzed by EDX (**Table 3**). The highest elements in FA were Si, O, and K. Meanwhile after the activation process in FA 1.5 M, several elements such as Al, Fe, S, and Cl were no longer detected, indicating a reduction in the concentrations. The Si content in FA 1.5 M adsorbent decreased while O, Ca and C contents increased. This change may occur due to chemical activation with oxalic acid solution, Si will dissolve and form other compounds.

In FA 400°C, the Si content was lower than FA 1.5 M while the Ca and C contents were higher. Slamet and Imas (2017) reported that fly ash adsorbent (PT Pupuk Kaltim) with demineralized water treatment increased the Ca content in the adsorbent. In this study, FA was also washed with distilled water before calcination at a temperature of 400°C. BE adsorbent has a lower Si content compared to FA 1.5 M. Based on the combined morphological and compositional analyses, FA 1.5 M was identified as the most suitable FA based adsorbent.

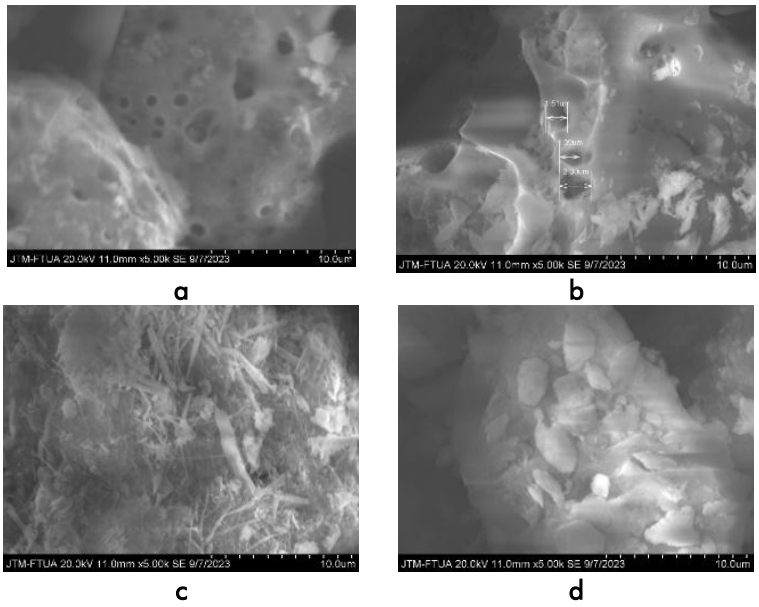

Figure 5. SEM images of (a) FA, (b) FA 1.5 M, (c) FA 400°C and (d) BE at 5000x magnification

Table 3. Element composition of FA, activated FA and BE adsorbent

Element	FA (%)	FA 1.5 M (%)	FA 400°C (%)	BE (%)
O	36.36	37.36	52.98	54.86
Si	34.38	25.97	12.81	20.31
Al	0.24	-	0.40	4.58
Mg	1.91	0.32	0.72	3.12
Ca	4.87	20.71	20.99	1.05
K	12.01	5.47	0.82	0.76
Fe	0.33	-	-	3.65
C	4.32	10.02	10.75	11.68
S	3.67	-	0.39	-
P	1.33	0.15	-	-
Cl	0.59	-	0.14	-

Heavy Metal Contamination on Adsorbent, CPO and BPO

The content of metal contamination in the adsorbent, CPO and BPO was obtained through ICP analysis. Heavy metal content in activated FA adsorbent (FA 1.5 M and FA 400°C) is needed to determine the safety for food application, as the adsorbents are used in the palm oil refining process. The metal contamination test can further ensure the safety of FA because it is waste produced from the palm oil mill itself. The maximum limit of heavy metal contamination in food products were adjusted to SNI 7387:2009 (the maximum limit of heavy metal contamination in food) and SNI 7709:2019 (palm cooking oil). In addition, for standard reference of the heavy metal contamination maximum limit in adsorbents used FEDIOL Brussels, 2017 ref. 16COD137.

Table 4 showed that the heavy metal contamination of FA 1.5 M, FA 400°C and BE has met the standard. Furthermore, to ensure the effect of metal contamination content on palm oil, the test was also conducted on BPO (**Table 5**). CPO before the degumming-bleaching process already contain Cd, Pb, Sn and As metals, although they are still below the maximum limit of heavy metal contamination according to SNI. The presence of these metals may originate from production, storage and transportation process of CPO which is in continuous contact with metal equipment. After bleaching with all adsorbents, BPO contains several heavy metals below the maximum allowable limits according to SNI. The results of analysis also show that the best adsorbent can be used as an alternative adsorbent for the CPO bleaching process is FA 1.5 M.

Brunauer-Emmet-Teller (BET) Surface Area

The specific area of the FA and FA 1.5 M adsorbent were determined by the BET method. As shown in **Table 6**, the surface area of FA 1.5 M increased to 10.351 m^2/g compared to untreated FA. It showed that the acid activation process can increase the surface area of adsorbent. Although this surface area is lower compared to a typical commercial bleaching earths, effective bleaching performance was still achieved. This can be linked to the synergistic effect of surface chemistry, pore accessibility, and active functional groups, rather than surface area alone.

Activated FA contains a high silica content with abundant surface hydroxyl (Si-OH) groups and suitable mesoporous structures, which enhance their strong interactions with polar impurities such as carotenoids and free fatty acids. Moreover, the presence of macropores observed in SEM, facilitates oil diffusion toward the internal mesopores, enhancing adsorption efficiency despite the relatively low surface area. Similar observations have been reported for other mineral-based adsorbents, where adsorption performance is not only determined by surface area but also by surface acidity, pore structure hierarchy, and chemical functionality (Fatimah et al., 2021; Jawad et al., 2021). The pore volume and size also increased after activation process. However, the pore size based on BET method show different results from SEM analysis.

The apparent difference between the pore classifications obtained from SEM and BET analyses arises from the different pore scales and structural features probed by each technique. SEM observations primarily reveal inter-particle pores and surface cavities, which are generally classified as macropores (> 50 nm) formed between aggregated FA particles. These macroporous structures are visible at the micrometer to sub-micrometer scale and mainly influence mass transfer and oil diffusion during the bleaching process (Nadeem et al., 2024).

Table 4. The content of heavy metal contamination on activated FA and BE adsorbent

Metal Contamination	FEDIOL Brussels, 2017 ref. 16COD137	FA 1.5 M	FA 400°C	BE
Cadmium (Cd)	Max 2 mg/kg (ppm)	0.342	0.545	0.109
Lead (Pb)	Max 10 mg/kg (ppm)	0.085	0.097	0.023
Mercury (Hg)	Max 0.1 mg/kg (ppm)	0.064	0.089	0.045
Arsenic (As)	Max 12 mg/kg (ppm)	0.105	0.087	0.076

Table 5. The content of heavy metal contamination on CPO and BPO

Metal Contamination	SNI 7387:2009 SNI 7709:2019	CPO	BPO FA 1.5 M	BPO FA 400°C	BPO BE
Cadmium (Cd)	Max 0.2 mg/kg (ppm)	0.0055	0.0032	0.004	0.0058
Lead (Pb)	Max 0.1 mg/kg (ppm)	0.0057	0.003	0.0021	0.0032
Tin (Sn)	Max 40 mg/kg (ppm)	0.0021	0.0015	0.0013	0.0017
Mercury (Hg)	Max 0.05 mg/kg (ppm)	0	0	0	0
Arsenic (As)	Max 0.1 mg/kg (ppm)	0.102	0.064	0.076	0.110

Table 6. BET analysis results of FA and FA 1.5 M

Material	Surface Area (m^2/g)	Pore Volume (cc/g)	Average Pore Size (Å)
FA	8.375	0.0259	62.075
FA 1.5 M	10.351	0.0534	103.112

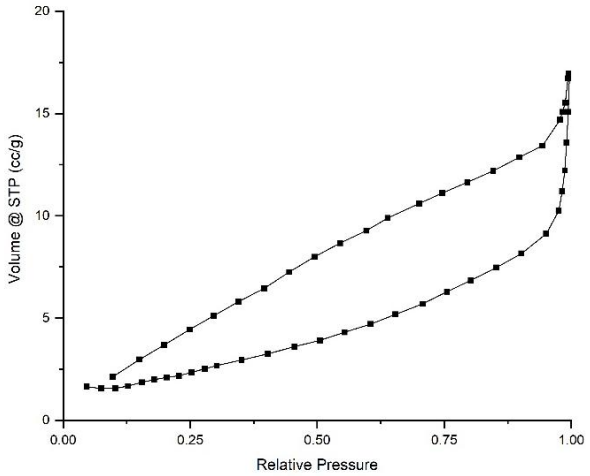

Figure 6. Adsorption and desorption isotherms for FA

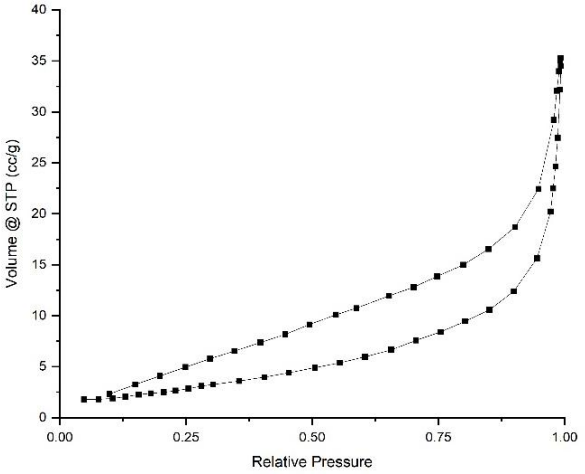

Figure 7. Adsorption and desorption isotherms for FA 1.5 M Adsorbent

In contrast, BET analysis evaluates the intra-particle porosity based on the nitrogen adsorption and desorption isotherms, which is very specific to mesopores (2-50 nm or 20-500 Å) within individual particles. Thus, the BET results indicate that FA 1.5 M has a mesoporous internal structure with a high density of active adsorption sites for pigment and impurity removal (Yi et al., 2020). There is no contradiction between the results of the SEM and BET analysis, because they examine different pore hierarchies. SEM characterizes the macroporous morphology at the particle level, while BET analysis describes the mesoporous network of particles responsible for the adsorption capacity.

The graph of adsorption and desorption isotherms of FA and FA 1.5 M adsorbent showed like a type III isotherm according to the classification of the International Union of Pure and Applied Chemistry (see **Figure 6** and **Figure 7**). A type III isotherm shows the formation of multilayer adsorption. Based on the average pore size obtained, FA 1.5 M adsorbent can be classified as a mesoporous solid with pore size in the range of 20-500 Å (Raja & Barron, 2024; Vargas et al., 2021). The smoother adsorption-desorption curve observed for FA 1.5 M compared to untreated FA further confirms the improved surface properties achieved through chemical activation.

CONCLUSIONS

The potential of palm oil mill fly ash (FA) as a cost-effective alternative adsorbent compared to commercial bleaching earth (BE) for the bleaching of crude palm oil (CPO) has been studied. The results showed that chemically activated FA with oxalic acid (FA 1.5 M) exhibited superior properties compared to thermally activated FA (FA 400°C) and commercial BE.

FA 1.5 M showed higher SiO_2 content, larger surface area, and increased pore volume and size, which enhanced its adsorption capacity. FTIR analysis also proved that the activated FA adsorbent can adsorb component in CPO showed by the different peaks appear before and after bleaching process. SEM analysis revealed that chemical activation significantly improved surface roughness and pore structure. The study also confirmed that heavy metal concebtrations in FA 1.5 M and FA 400°C were within safe limits for food applications. Moreover, BET analysis classified FA 1.5 M adsorbent as a mesoporous material, which is advantageous for adsorption process during the CPO bleaching. Overall, FA 1.5 M proved to be strong potential as a viable alternative adsorbent for bleaching CPO, offering both economic and environmental benefits.

Thus, the implementation of FA as an adsorbent in the palm oil industry could contribute to sustainability and circular economy efforts, enhancing overall efficiency and reducing waste in the palm oil refining process.

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