Selective adsorbent performance in bleaching black soldier fly larvae oil: Effects on physicochemical and sensory quality

Applied Food Research 6 (2026) 102368

Contents lists available at ScienceDirect

Applied Food Research

journal homepage: www.elsevier.com/locate/afres

Selective adsorbent performance in bleaching black soldier fly larvae oil: Effects on physicochemical and sensory quality

Yoga Pratama [a,b,*], Ulil Afidah [a,b], Alif Talitha Zahra [a], Yoel Anggara Saputra [a], Sri Mulyani [a,b], Ahmad Ni'matullah Al-Baarri [a,b], Elena Simone [c]

[a] Department of Food Technology, Faculty of Animal and Agricultural Sciences, Universitas Diponegoro, Semarang, 50275, Indonesia
[b] Food Research for Safety, Security, and Sustainability (FORC3S), Semarang, Indonesia
[c] Department of Applied Science and Technology, Politecnico di Torino, Torino, 10129, Italy

ARTICLE INFO

Keywords:
Black soldier fly larvae oil
Bleaching process
Adsorbent
Oil purification
Sensory characteristics

ABSTRACT

The utilization of Black Soldier Fly Larvae Oil (BSFLO) as a commercial food product is constrained by its undesirable physicochemical and sensory properties, including impurities, dark color, and off-odors, thereby necessitating effective purification strategies. However, the most suitable bleaching agent for BSFLO purification has not yet been clearly established. This study provides a systematic comparative evaluation of selected adsorbents in the bleaching of Black Soldier Fly Larvae Crude Oil (BSFLCO), with a focus on their impact on overall oil quality. Four adsorbents, i.e., synthetic zeolite, bleaching earth, activated carbon, and silica gel, were applied at a concentration of 7.5% (w/v). The effects of adsorbent type were assessed across multiple quality parameters, including chemical composition, oxidative stability, and sensory attributes. Statistical analyses, including both parametric and non-parametric tests, indicated that variations in adsorbent type significantly affected ($p < 0.05$) bleaching yield, peroxide value, free fatty acid content, smoke point, protein content, moisture content, fat content, as well as sensory ranking and hedonic responses. Bleaching earth emerged as the superior adsorbent, significantly outperforming synthetic zeolite and silica gel in reducing protein content and color intensity, which directly correlated with higher consumer color preference. Bleaching earth-treated oil achieved the highest overall hedonic scores and chemical stability, including improved peroxide values and smoke points. These findings highlight the critical role of adsorbent selection in BSFLO purification and provide practical insights for improving the quality and commercial viability of insect-derived edible oils.

Practical applications

The most effective bleaching process using bleaching earth has practical potential for both small-scale and industrial-scale alternative edible oil production. At the small scale, it offers a simple and cost-effective method to improve the color, aroma, and stability of BSFLO, supporting local producers and emerging insect-oil enterprises. At the industrial scale, the selected bleaching process can be integrated into a full oil refining systems (i.e. including degumming, neutralization and deodorization) to enhance the quality of BSFLO and improve its commercial competitiveness.

1. Introduction

Black Soldier Fly Larvae (BSFL, *Hermetia illucens*) have attracted significant global attention due to their efficient waste bioconversion capabilities into sustainable biomass (Pang et al., 2020; Siddiqui et al., 2024). Consequently, BSFL are emerging as promising alternatives for food and industrial uses. The larvae are characterized by rich nutritional composition, predominantly consisting of protein and fat. BSFL fat content reaches 18–33%, while the protein content reaches 32–53% (Wang & Shelomi, 2017). For this reason, most research on BSFL utilization for food applications has primarily focused on these two major components.

Comparative overview to exploration studies on BSFL proteins and lipids shows significant imbalance, where BSFL-protein related works are substantially more prevalent (Huang et al., 2019; Mshayisa et al.,

* Corresponding author.
E-mail address: yogapratama@live.undip.ac.id (Y. Pratama).

https://doi.org/10.1016/j.afres.2026.102368
Received 30 March 2026; Received in revised form 30 June 2026; Accepted 4 July 2026
Available online 4 July 2026

2022; Queiroz et al., 2021; Traksele et al., 2021) compared to investigations on BSFL-derived edible lipids (Mai et al., 2019; Srisuksai et al., 2024). Therefore, further exploration of BSFL edible lipids is both timely and necessary.

BSFL demonstrate considerable potential as a sustainable source of edible lipids, with characteristics comparable to conventional tropical oils such as coconut oil, including high levels of lauric acid and other saturated fatty acids such as palmitic and myristic acids (Vázquez et al., 2024). In addition, BSFL contain micronutrients, including copper, iron, selenium, and vitamins (Salahuddin, 2024). Importantly, BSFL are classified as a non-hazardous species that do not spread specific diseases, making them safe for human health. Purschke et al. (2017) reported that BSFL do not accumulate pesticide or mycotoxin content, further supporting their safety and potential as a food source. Moreover, evidence from safety studies and the ongoing evaluation of *Hermetia illucens* under Regulation (EU) 2015/2283 support its potential as a food ingredient, provided that safety considerations, specifically allergen cross-reactivity with crustaceans and mandatory labeling of the species name, are strictly addressed (Liguori et al., 2022).

However, the direct utilization of BSFL crude oil (BSFLCO) is limited by undesirable physicochemical and sensory properties, including the presence of impurities, pigments, and off-odors. As with conventional edible oils, refining processes such as degumming, neutralization, bleaching, and deodorization are required to improve oil quality (Mai et al., 2019). Among these steps, bleaching plays a critical role in removing pigments, oxidation products, and other impurities that negatively affect both stability and consumer acceptance (Ojewumi et al., 2021). Recent developments in edible oil bleaching have focused on improving both efficiency and sustainability, including microwave-assisted bleaching and the utilization of seashell-based waste materials as bleaching agent (Seçilmiş, 2024; Seçilmiş et al., 2022). In line with these advances, identifying the most effective bleaching agent for sustainable alternative oils such as BSFLO represents an important research direction.

Despite the importance of bleaching in BSFLO production, it remains underexplored. Existing research has largely focused on single adsorbents or general purification approaches, without systematically evaluating the comparative performance of different adsorbent materials. Adsorbents such as bleaching earth, activated carbon, silica gel, and synthetic zeolites are known to exhibit distinct adsorption mechanisms and selectivity toward impurities. Factors such as surface area, pore structure, polarity, surface acidity, hydrophilicity, and ion-exchange properties collectively determine the selectivity and efficiency of these adsorbents towards pigments, oxidation products, soaps, trace metals and other impurities present in oil (Islam et al., 2020; Petrović et al., 2023; Tandewi & Hambali, 2022). More importantly, their relative effectiveness in improving both physicochemical and sensory properties of BSFLO have not been comprehensively investigated. This lack of integrated evaluation limits the ability to design effective purification strategies for BSFLO and hinders its transition toward food-grade applications.

To address the aforementioned gap, the present study provides comparative assessment of selected adsorbents in the bleaching of BSFLCO. To the best of our knowledge, studies systematically comparing the performance of different adsorbents in BSFLO bleaching remain limited. Therefore, this study evaluates their effects on chemical composition, functional properties, oxidative stability, sensory characteristics, and hedonic attributes. By linking adsorbent type to overall oil quality, this study offers new insights into adsorbent selection for the purification of insect-derived lipids and supports the advancement of BSFLO as a sustainable edible oil.

2. Materials and methods

2.1. Materials

BSFL were obtained from a local farm in Semarang (Indonesia). The select adsorbents used in this study included synthetic zeolite (PT Havindo Pakan Optima, Indonesia), bleaching earth (Taiko BD-50, China), activated carbon (Essenli, Indonesia), silica gel (Pingxiang Xinfeng Chemical, China). These four adsorbents were selected due to its commercial availability and their wide spread use in the oil industry. The adsorbents were used without further modification. Commercial coconut oil (PT Barco, Indonesia) was used as a reference sample during evaluation of color intensity and sensorial properties of bleached oil samples. Analytical grade reagents were obtained from local chemical store and were used for all analyses, including NaOH, ethanol (95%), chloroform, glacial acetic acid, potassium iodide, starch solution (1%), sodium thiosulafte, propanol, phenolphthalein indicator, selenium (Supelco Merck KgaA, Germany), sulfuric acid, distilled water, boric acid (4%), mixed indicator (MR-MB), and hydrochloric acid.

2.2. Methods

2.2.1. Adsorbent's particle size distribution

The particle size distribution analysis of the adsorbent was conducted based on the method described by Poullet et al. (2019), with slight modifications. A 50 g sample of each adsorbent was weighed and subjected to mechanical sieving for 5 min using a stacked sieve composed of 10, 20, 40, 50, 60, 70, 80, 100, and 250 mesh. The material retained on each sieve was subsequently collected and weighed to determine the particle size distribution, expressed as percentage of the initial weight.

2.2.2. Adsorbent's bulk density

The bulk density of the adsorbent was determined following the method described by Clementson et al. (2009). A 1 g sample of the adsorbent was placed into a 5 mL graduated cylinder. The cylinder was gently tapped on a flat surface to level the sample, after which the final volume was measured. The bulk density was calculated as the ratio of mass to volume (g/mL).

$$\text{Bulk Density} = \frac{m}{v}\ (g/mL) \tag{1}$$

m: Weight of adsorbent v: Adsorbent volume

2.2.3. Microstructure of adsorbent

Adsorbent microstructural characteristic was performed using scanning electron microscopy following the previously reported method (Singthong et al., 2025). Briefly, samples were secured onto specimen stubs using conductive carbon tape and sputter-coated with gold using an automatic coater (JEOL JEC-3000FC, Tokyo, Japan) under vacuum conditions (<5 Pa) at approximately 20 mA for 120 s. The prepared specimens were then analyzed with a scanning electron microscope (JEOL JSM-6510LA, Tokyo, Japan). Before image acquisition, the chamber was maintained under vacuum for 1 min to ensure stabilization, after which the samples were examined using a predetermined SpotSize setting.

2.2.4. Fourier-transform infrared spectroscopy

Fourier-transform infrared (FTIR) spectroscopy was used to characterize the functional groups of the adsorbents (Neolaka et al., 2018). Spectral analysis was performed using a Thermo Scientific Nicolet iS10 (Thermo Fisher Scientific, USA) equipped with a KBr/Ge mid-infrared beam splitter, a deuterated triglycine sulfate (DTGS) detector, and a Smart iTX attenuated total reflectance (ATR) accessory. Spectra were collected over the wavenumber range of 4000–550 cm^{-1} at a spectral resolution of 4 cm^{-1} with 50 scans per sample. All measurements were conducted under controlled environmental conditions at 25 ± 3 °C and 50 ± 10% relative humidity. The acquired spectra were used to identify the characteristic functional groups and chemical interactions present in the samples.

2.2.5. Pre-treatment of black soldier fly larvae (BSFL)

The pre-treatment process of BSFL was based on the research conducted by

Hurtado-Ribeira et al. (2023), with modifications. Sixteen-day-old larvae were washed thoroughly under running water to remove dirt and debris, then slaughtered by blanching at 90 °C for 20 s. The blanched larvae were drained and subsequently dried in a cabinet dryer at 65 °C for 24 h, using stainless steel trays. The samples were manually stirred at regular intervals to ensure uniform drying until completely dehydrated.

2.2.6. Extraction of black soldier fly larvae crude oil (BSFLCO)

The extraction of BSFLCO was based on the method conducted by Matthäus et al. (2019). Dried BSFL was mechanically extracted using a screw press extractor (Henan Bayern Industrial Co., Ltd) operating at ±50 °C. The extraction resulted in crude oil fraction and pressed-cake BSFL as a by-product. The crude oil fraction was then centrifuged (Hettich Zentrifugen EBA 20 Centrifuge, Germany) at 6000 rpm for 15 min. The oil was separated from the sediment and hereafter referred to as black soldier fly larvae crude oil (BSFLCO). It was then stored in amber bottles at a refrigeration temperature of 4 °C for further analysis.

2.2.7. Purification of black soldier fly larvae crude oil (BSFLCO)

The bleaching process was performed based on the method conducted by Petrović et al. (2023). Centrifuged BSFLCO samples of 30 mL were taken for each adsorbent treatment, namely synthetic zeolite (ZS), bleaching earth (BE), activated carbon (AC), and silica hydrogel (SG). The BSFLCO samples were added with adsorbents at a concentration of 7.5% and then heated to 90 °C on a hot plate (IKA-C MAG HS 7, Germany), with constant stirring using an overhead stirrer (IKA RW 20 Digital, Germany) at 750 rpm for 40 min. The homogenized samples were centrifuged at 6000 rpm for 15 min to separate the oil phase. Hereafter, the separated oil is referred to as black soldier fly larvae crude oil (BSFLO).

2.2.8. Processing yield

The yield was calculated for every step of oil extraction and purification, i.e., drying, mechanical extraction, centrifugation and bleaching. Yield is expressed as the weight of product divided by the weight of feed.

$$\text{Yield} = (\text{mA}/\text{mB}) \times 100\% \tag{2}$$

mA: Weight of product mB: Weight of feed

2.2.9. Protein content

The protein content of BSFLCO and BSFLO was analyzed using the Association of Official Analytical Chemists (AOAC) 945.01 method, based on the Kjeldahl principle. Approximately 0.5 g of sample was digested with 0.5 g of selenium catalyst and 10 mL of H_2SO_4. The digested material was then distilled with 100 mL of distilled water and 40 mL of 45% NaOH. The distillate was collected into 5 mL of 4% H_3BO_3 containing two drops of mixed indicator (MR-MB). The distillate was titrated with 0.1 N HCl until the solution turned purplish blue. The nitrogen content obtained from the titration was converted to protein content using a conversion factor of 6.25. It should be noted that this method determines total nitrogen and may therefore include contributions from non-protein nitrogen compounds.

$$\text{Protein Content}\,(\%) = \frac{(\text{Sample titration} - \text{blank}) \times \text{N HCl} \times 14.008}{\text{Sample weight} \times 1000} \times 100\% \tag{3}$$

2.2.10. Moisture content

Water content analysis was carried out in accordance with the ISO 662: 2016 method. The porcelain cup was preheated in an oven (Memmert, Germany) at 105 °C for one hour, then weighed. A 2 *g* of samples were placed in a petri dish, then dried in an oven at 105 °C for 4 h. After drying, the sample was put into a desiccator for 15 min and weighed to determine the moisture content.

$$\text{Moisture Content } (\%) = \frac{\text{mB} - (\text{mC} - \text{mA})}{\text{mB}} \times 100\% \tag{4}$$

mA: Weight of the porcelain cup mB: Initial sample weight mC: Final sample weight (constant)

2.2.11. Estimated crude fat content

The estimated crude fat content was used to provide further insight into the effect of bleaching on the resulting lipid fraction. Fat content was calculated by subtracting the protein and moisture contents from 100% of the sample, assuming that the oil is essentially 100% lipid and that these two components are the main impurities, while the contribution of other components such as ash and carbohydrates is trace or negligible.

$$\mathit{EstimatedCrudeFatContent}(\%) = 100\% - (\mathit{ProteinContent} + \mathit{MoistureContent}) \tag{5}$$

2.2.12. Peroxide value

The peroxide value of the samples was determined according to the Malaysian Palm Oil Board (MPOB) test method P2.3:2004. Approximately 0.5 g of the BSFLO sample was placed in a 50 mL Erlenmeyer flask, followed by the addition of 3 mL of a glacial acetic acid–chloroform mixture (3:2, v/v). The mixture was shaken until fully homogenized. Subsequently, 0.1 mL of saturated potassium iodide (KI) solution was added, shaken, and allowed to stand for approximately 1 min. Then, 3 mL of distilled water and 1 mL of 1% starch solution were added as an indicator, causing a bluish color to develop. The sample was titrated with 0.005 N sodium thiosulfate ($Na_2S_2O_3$) until the blue coloration disappeared.

$$\text{Peroxide Value} = \frac{(\text{V2} - \text{V1}) \times \text{N} \times 1000}{\text{M}} \text{Meq } O_2/\text{Kg} \tag{6}$$

V2: The amount of $Na_2S_2O_3$ used for the sample (mL)
V1: The amount of $Na_2S_2O_3$ used for blank (mL)
N: Normality $Na_2S_2O_3$
M: Sample weight

2.2.13. Free fatty acid (FFA)

The free fatty acid (FFA) content was determined according to the American Oil Chemists' Society (AOCS) method Ca 5a-40. Approximately 1 g of the BSFLO sample was mixed with 5 mL of 95% ethanol in a 50 mL Erlenmeyer flask and heated to 40 °C. Afterward, 0.15 mL of phenolphthalein indicator was added, and the mixture was titrated with 0.05 N sodium hydroxide (NaOH) until a stable pink coloration persisted for 30 s.

$$\text{FFA} = \frac{\text{V} \times \text{N} \times 20}{\text{m}} \% \tag{7}$$

V: The number of titrants used
N: Normality of NaOH m: Sample weight (g)

2.2.14. Smoke point

The smoke point was determined according to the method described by Mahesar et al. (2017). A total of 10 g of BSFLO was heated until visible smoke appeared, with a sheet of black paper placed behind the sample to enhance clarity and visibility of the smoke formation. The temperature at the onset of smoke was recorded using a digital thermometer (Xueliee GM 320, China) positioned in the testing container.

2.2.15. Color measurement

The color intensity of the oil was determined based on the Association of Official Analytical Chemists (AOAC) (2004) method with modifications. Distilled water and coconut oil were used as blank and reference solutions, respectively. Blank and samples were analyzed using a Spectrophotometer UV–Vis (Biobase BK-UV1900, China) in the arrange of wavelength between 400 and 600 nm. Absorbance was first zeroed on the blank solution, then absorbance readings were started on the comparison solution and the specified BSFLO samples. Color intensity were further analyzed using Origin 2019 software and expressed as the area under curve of the spectrum.

2.2.16. Fatty acid profile

Fatty acid composition testing was conducted according to method of Kritioti et al. (2018) using GC–MS (Shimadzu, Japan), with some modifications. Fatty acids were converted to their corresponding methyl esters (FAMEs) prior to GCMS– analysis. Separation was performed using a Supelco-WAX 10 fused silica capillary column. The oven temperature was initially set at 65 °C and increased at a rate of 4 °C/min to a final temperature of 250 °C, which was held for 15 min. The injection temperature was maintained at 250 °C, operating in split mode with linear velocity flow control. Helium was used as the carrier gas at an inlet pressure of 74.5 kPa, with a column flow of 1.20 mL/min and a linear velocity of 40 cm/s. The purge flow was set at 3.0 mL/min with a split ratio of 10:1. High-pressure injection, carrier gas economizer, and splitter hold functions were disabled.

2.2.17. Ranking and hedonic test

Ranking and hedonic test were carried out based on the method of Pratama et al. (2024) involving 25 untrained panelists (12 males, 13 females, aged 19–25 years) who were screened for being non-smokers and having no known allergies to insects or crustaceans. There were 6 randomly coded samples, namely coconut oil as a reference sample, BSFLCO, and BSFLO samples that have been bleached with 4 different types of adsorbents. Sensory sessions were conducted in individual booths under controlled white lighting to prevent bias. Panelists performed the ranking test by ranking all samples into the attributes of savory or fishy aroma and yellow color, with a scale of (1) highest intensity and (6) lowest intensity. Whereas the hedonic scale was (1) very dislike, (2) dislike, (3) somewhat dislike, (4) average, (5) somewhat like, (6) like, and (7) very like for aroma, color, and overall parameters. Ethical clearance for human participation was obtained from the Health Research Ethics Committee, Faculty of Medicine, Universitas Diponegoro (No. 345/EC/KEPK/FK-UNDIP/XII/2025).

2.2.18. Data analysis

All chemical analyses in this study were performed in triplicate ($n = 3$) to ensure accuracy and reproducibility. Data obtained from yield tests, peroxide value, FFA content, smoke point, protein content, moisture content, and fat content were presented as mean ± standard deviation. Prior to analysis, data normality and homogeneity of variance were assessed using the Shapiro-Wilk test and Levene's test, respectively. Data that met the assumptions were analyzed parametrically using ANOVA and processed using IBM SPSS Statistics 26 software, followed by Duncan's test ($p < 0.05$). Data obtained from fatty acid profile tests were analyzed descriptively and processed using Microsoft Excel 2019 software. Color intensity parameters were analyzed using Origin 2019 software. Data obtained from ranking and hedonic tests were analyzed non-parametrically with the Kruskal-Wallis test and processed using IBM SPSS Statistics 26 software, followed by the Mann-Whitney test ($p < 0.05$).

3. Results and discussion

3.1. Adsorbents' characterization

The physical characteristics of the adsorbents were evaluated through particle size distribution analysis and scanning electron microscopy (SEM). The particle size distribution and bulk density are presented in Table 1, while the SEM micrographs at 5000 × magnification are shown in Fig. 1. The combination of these techniques provides complementary information on the physical attributes of the adsorbents that may influence their adsorption performance.

Synthetic zeolite exhibited a narrow particle size distribution, with >90% of the particles retained between 20 and 40 mesh (850–425 μm). SEM observations revealed a relatively rough surface with no apparent cracks or macropores. In contrast, bleaching earth consisted predominantly of finer particles, with >80% distributed between 60 and 80 mesh (250–180 μm). Its SEM micrograph showed a fractured surface containing numerous cracks, which may facilitate access to the internal adsorption sites and contribute to its adsorption efficiency.

Activated carbon displayed an intermediate particle size distribution, with >80% of the particles evenly distributed among 50, 60, and 70 mesh (300, 250, and 212 μm, respectively). Notably, activated carbon exhibited the lowest bulk density (0.50 g/mL) among all adsorbents. This lower density is most likely attributed to its highly porous carbon network and the inherently lower density of carbonaceous materials compared with mineral-based adsorbents such as zeolite, bleaching earth, and silica gel. Although activated carbon is known to possess an extensive network of micro- and mesopores (Bläker et al., 2019), these features were not visible in the SEM images. Instead, the particles appeared flaky with relatively smooth external surfaces.

Silica gel exhibited the coarsest particle size distribution, with >98% of the particles retained on the 10 mesh sieve (2000 μm). SEM analysis showed a relatively smooth and compact surface with no obvious cracks or surface irregularities. Overall, the observed differences in particle size, surface morphology, and bulk density among the adsorbents are expected to influence their surface accessibility, packing characteristics, and adsorption behavior during the bleaching process.

In addition to the physical characterization, the surface chemical functionalities of the adsorbents were examined by Fourier-transform infrared (FTIR) spectroscopy, and the spectra are presented in Fig. 2. Prominent absorption bands were observed at 1000–1100 cm^{-1} for the three mineral-based adsorbents; synthetic zeolite, bleaching earth, and silica gel. This region is characteristic of the asymmetric stretching vibration of Si-O-Si and Si-O bonds, reflecting the silicate framework that is common to these materials. The abundance of silanol (Si-OH) and siloxane (Si-O-Si) groups contributes to the hydrophilic nature of these adsorbents (Madejová, 2003), facilitating the adsorption of polar

Table 1
Particle size distribution (% w/w) and bulk density of the selected adsorbents.

Mesh Sieve	Nominal Opening (μm)	Adsorbent			
		ZS	BE	AC	SG
10	2000	2.42%	-	0.10%	98.42%
20	850	45.48%	-	0.67%	1.58%
40	425	51.10%	1.24%	10.69%	-
50	300	0.52%	1.60%	28.91%	-
60	250	0.33%	47.41%	27.92%	-
70	212	0.05%	12.16%	29.69%	-
80	180	-	35.48%	0.98%	-
100	150	-	1.28%	0.56%	-
250	60	-	0.83%	0.48%	-
Total		100%	100%	100%	100%
Bulk Density (g/mL)		0.93	0.72	0.50	0.87

Notes: ZS: Synthetic Zeolite; BE: Bleaching Earth; AC: Activated Carbon; SG: Silica Gel, the four adsorbents evaluated in the bleaching process of BSFLO.

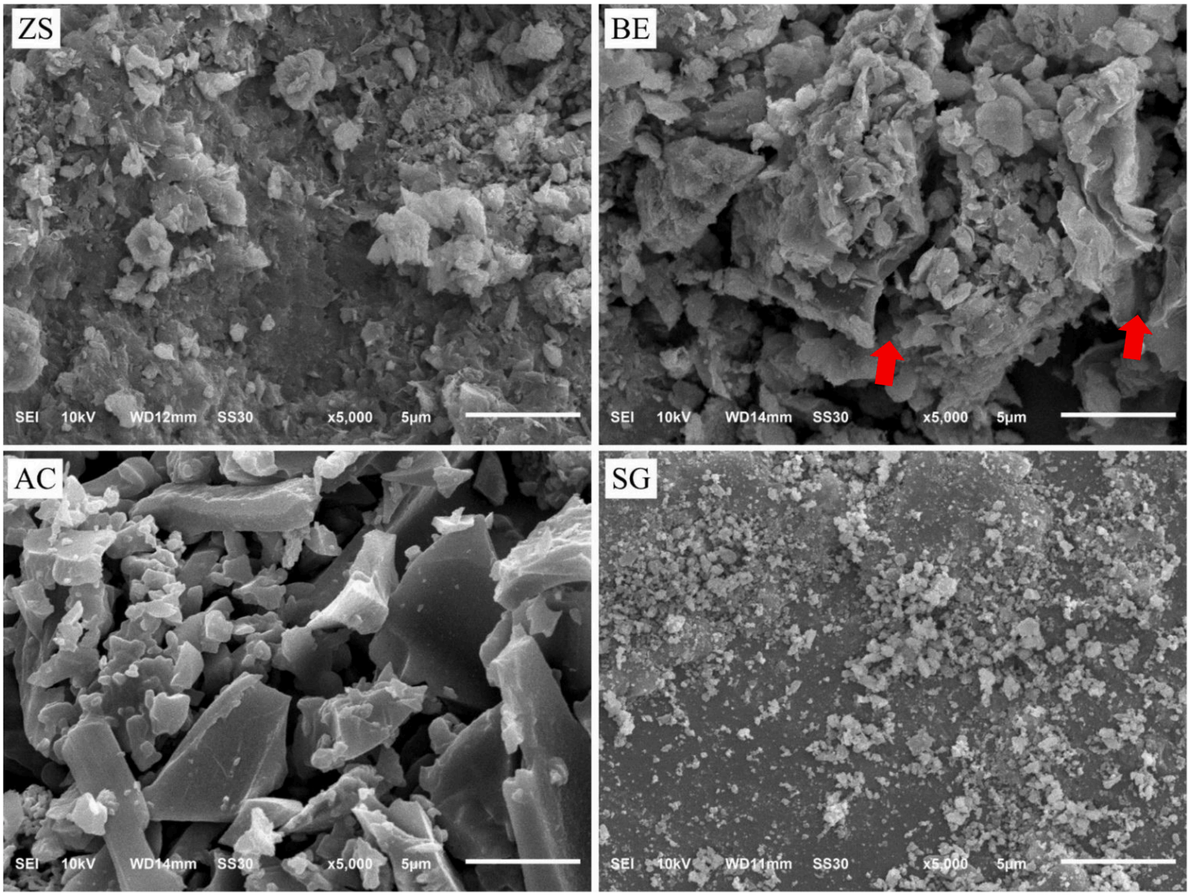

Fig. 1. Scanning electron micrograph of adsorbents (ZS: Synthetic Zeolite; BE: Bleaching Earth; AC: Activated Carbon; SG: Silica Gel) acquired at 5000 × magnification with a 5 μm scale bar. Red arrows indicate cracks of adsorbent.

impurities from edible oils, including moisture, phospholipids (gums), soaps, and other oxygen-containing compounds.

A broad absorption band at 3200–3400 cm^{-1} was also observed for the mineral-based adsorbents, corresponding to the O—H stretching vibration of surface hydroxyl groups and physically adsorbed water molecules (Madejová, 2003). Among the adsorbents, silica gel exhibited a relatively broader and more intense O—H band, suggesting a greater amount of surface-bound water, which is consistent with its highly hydrophilic silica surface. The intensity of this band is influenced by the drying conditions during adsorbent preparation and storage. Although comparing FTIR spectra before and after bleaching would provide direct evidence of moisture and impurity adsorption through changes in surface functional groups, the present study focused only on the spectra of the fresh adsorbents. Therefore, the effectiveness of moisture removal was evaluated indirectly through the moisture content of the bleached oil.

Unlike the mineral-based adsorbents, activated carbon exhibited characteristic absorption bands within 900–1100 cm^{-1} and 1300–1500 cm^{-1}, which are associated with C—O stretching vibrations of phenolic, alcohol, and ether groups, together with vibrations originating from the aromatic carbon framework. These oxygen-containing functional groups are commonly introduced during the activation process and impart polarity to the carbon surface, enhancing its affinity for polar oxidation products, pigments, and other trace impurities present in edible oils (Bläker et al., 2019). Compared with the mineral-based adsorbents, the relatively weak or absent broad O—H stretching band (3200–3400 cm^{-1}) indicates a lower abundance of surface hydroxyl groups and adsorbed water, suggesting that activated carbon is less hydrophilic than silica- and aluminosilicate-based adsorbents.

3.2. Process yield

Black soldier fly larvae crude oil (BSFLCO) was produced from wet larvae through a series of processing steps, including drying, extraction, and centrifugation. The yield data for each processing stage, expressed as the percentage of product weight relative to the initial feed weight, are summarized in Table 2. Drying of wet BSFL to obtain dried biomass resulted in a yield of 32.99%. Subsequent mechanical extraction of the dried biomass produced a crude oil fraction with a recovery yield of 35.41%. However, this crude oil fraction still contained a considerable amount of solid residues and was therefore further purified through centrifugation, resulting in a BSFLCO yield of 67.20%. Overall, the sequential processing steps yielded 7.85% BSFLCO from the initial wet BSFL substrate.

Having obtained the BSFLCO, the bleaching step was subsequently carried out using four selected adsorbents. Table 3 presents the oil yield and chemical properties of the resulting BSFLO after bleaching. The bleaching yields ranged from 69.29 ± 0.22% to 86.82 ± 0.20%. These values represent the ratio between the mass of oil recovered after bleaching (BSFLO) and the initial mass of BSFLCO prior to treatment. Comparable findings were reported by Mai et al. (2019), who observed BSFLO yields of 78–92% after the bleaching process. Statistical analysis indicated that the type of adsorbent used had a significant effect on the bleaching yield ($p < 0.05$), with activated carbon producing the lowest yield and silica gel yielding the highest.

The different yield results among absorbents can be associated with the different adsorption capacities of the adsorbents. High adsorption capacity can typically be achieved with a small particle size and a large pore area and volume (Nweke & Ajemba, 2022). The particle size and bulk density of the adsorbents are presented in Table 1, where lower

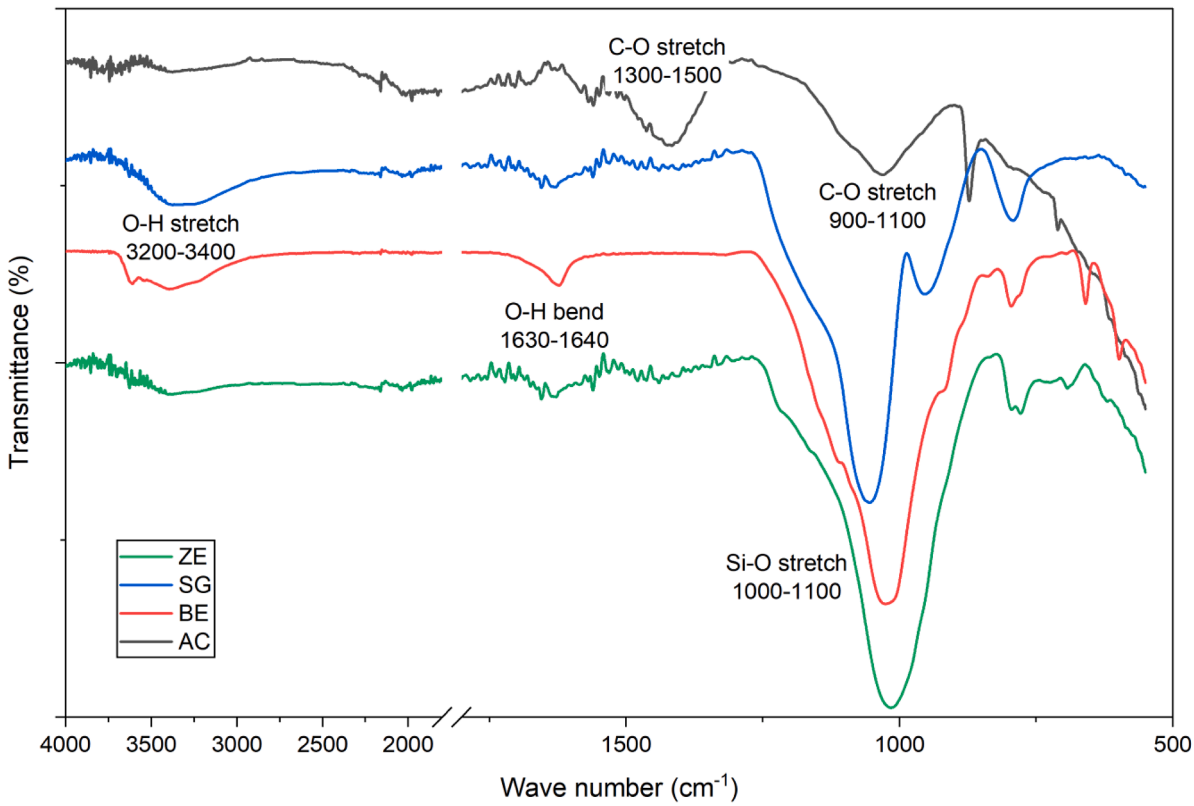

Fig. 2. FTIR spectra (4000–550 cm^{-1}) of the adsorbents: synthetic zeolite (ZS), bleaching earth (BE), activated carbon (AC), and silica gel (SG).

Table 2
Process yield of BSFLCO production.

Processing Stage	Feed	Product	Process Yield (%)
Drying BSFL	Wet BSFL	Dried BSFL	32.99
Mechanical Extraction	Dried BSFL	Oil Fraction	35.41
Centrifugation	Oil fraction	BSFLCO	67.20
Overall BSFLCO production from wet BSFL	Wet BSFL	BSFLCO	7.85

Notes: BSFL: Black Soldier Fly Larvae; BSFLCO: Black Soldier Fly Larvae Crude Oil. Results were expressed as composite data from several extraction processes.

bulk density also indicates higher porosity. Higher adsorption capacity will lead to a greater reduction in impurities, yet result in a lower yield (Rich, 1960). This can be seen in the yield from bleaching earth, which was lower than that of zeolite and silica gel (Table 3), due to bleaching earth having a smaller particle size (60–80 mesh) compared with zeolite (20–40 mesh) and silica gel (10 mesh). Guliyev et al. (2018) also reported the high adsorption capacity of bleaching earth in the oil refining process.

Activated carbon has a larger particle size than bleaching earth (40–70 mesh, shown in Table 1), which generally suggests a smaller surface area and lower adsorption capacity. However, its use resulted in a considerably lower yield of 69.29±0.22%. This lower yield observed during the BSFLO purification process is likely caused by activated carbon's low bulk density of 0.5 g/ml (Table 1). The low density, despite the larger particle size, indicates significantly higher porosity, which consequently required two centrifugation steps rather than one to achieve adequate separation of the adsorbent. After a single centrifugation, a substantial amount of solid material remained unseparated after the activated carbon bleaching process. This finding indicates that the higher porosity of the bleaching agent contributes to more difficult separation by centrifugation. Other separation techniques, such as filter-press separation, may be able to solve this issue.

The higher yield values observed in the silica gel and synthetic zeolite bleaching processes were most likely influenced by their larger particle size and higher density, which facilitated more efficient separation during centrifugation. Petrović et al. (2023) reported that silica gel and synthetic zeolites possess relatively smaller pore volumes and pore diameters than those of bleaching earth, thereby reducing the likelihood of oil becoming trapped within the adsorbent structure. Consistently, Khan et al. (2022) reported limitations in adsorption with

Table 3
Oil yield and chemical properties of black soldier fly larvae oil after bleaching with different absorbent.

Sample*	Oil Yield (%)	Peroxide Value (MeqO$_2$/Kg)	FFA (%)	Smoke Point (°C)	Protein Content (%)	Moisture Content (%)	Estimated Crude Fat Content (%)
BSFLCO	-	2.49±1.02^{a}	0.32±0.04^{a}	180.63±1.44^{a}	0.37±0.13^{a}	0.32±0.11^{a}	99.31%±0.25^{a}
ZS	84.28±0.16^{a}	2.36±0.85^{ab}	0.25±0.05^{b}	183.33±0.45^{b}	0.13±0.04^{b}	0.10±0.05^{b}	99.77%±0.05^{b}
BE	82.83±0.84^{b}	1.44±0.96^{bc}	0.19±0.01^{c}	195.33±1.73^{c}	0.06±0.03^{b}	0.07±0.04^{b}	99.88%±0.03^{b}
AC	69.29±0.22^{c}	2.38±0.87^{ac}	0.28±0.02^{ab}	184.40±0.62^{b}	0.10±0.06^{b}	0.18±0.08^{ab}	99.72%±0.09^{b}
SG	86.82±0.20^{d}	1.91±1.00^{bc}	0.29±0.03^{ab}	183.10±0.53^{b}	0.16±0.03^{b}	0.12±0.06^{b}	99.73%±0.09^{b}

* BSFLCO: Black Soldier Fly Larvae Crude Oil; ZS: Synthetic Zeolite; BE: Bleaching Earth; AC: Activated Carbon; SG: Silica Gel. Data were from triplicate (n = 3) and shown as mean and standard deviation. Different superscript within the same column shows significant statistical difference ($p < 0.05$).

silica gel due to its amorphous structure and compound polarity, while synthetic zeolite has less suitable surface acidity, which may further explain the higher yield values observed.

3.3. Protein content

The protein content of BSFLCO and BSFLO is presented in Table 3. The results indicate a significant difference between BSFLCO and the bleached BSFLO samples, reflecting the effect of the bleaching process and the use of different adsorbents ($p < 0.05$). As the unrefined control, BSFLCO exhibited the highest protein content (0.37±0.13%), likely due to residual impurities remaining from the oil extraction process. Such impurities commonly include proteins and mucilaginous substances, which can adversely affect oil clarity (Abo-Riya et al., 2023). Accordingly, bleaching serves as an important step in reducing protein-related impurities in the oil.

Following bleaching, the protein content of BSFLO ranged from 0.06 to 0.16%, which is comparable to the values reported by Mai et al. (2019) for purified BSFLO (approximately 0.18%). Proteinaceous materials in crude oils are commonly associated with phospholipids, gums, and suspended colloidal materials, which can interact with adsorbents through electrostatic interactions, hydrogen bonding, and physical entrapment within porous structures. Adsorbents with high surface area, suitable pore distribution, and active surface sites therefore exhibit a greater capacity for removing these impurities during the bleaching process (Hussin et al., 2011). Although numerical differences were observed among adsorbents, statistical analysis showed no significant variation in protein content between the different bleaching agents. Among the samples, bleaching earth resulted in the lowest protein content, whereas silica gel produced the highest. As the protein content evaluation showed a trend similar to that of the bleaching yield, these variations were likely associated with differences in overall adsorption caused by physical entrapment resulting from variations in particle size and porosity as indicated in Table 1 and Fig. 1, rather than by specific adsorption of proteinaceous compounds.

3.4. Moisture content

The moisture content of BSFLCO and BSFLO is presented in Table 3. The presence of moisture can accelerate oil quality degradation through hydrolysis, leading to increased free fatty acid formation and rancidity. Significant differences were observed between BSFLCO and several bleached BSFLO samples, indicating the influence of the bleaching process and adsorbent type on moisture removal ($p < 0.05$). After bleaching, the moisture content of BSFLO ranged from 0.07% to 0.18%, which is comparable to the value reported by Mai et al. (2019) for purified BSFLO (0.19%). With the exception of activated carbon, all adsorbents significantly reduced the moisture content relative to BSFLCO, which exhibited a moisture level of 0.32%. The elevated moisture content in crude oil is commonly associated with water bound to impurities present in the oil.

Among the bleached samples, bleaching earth resulted in the lowest moisture content, indicating greater effectiveness in adsorbing water and other polar compounds compared to the other adsorbents. In contrast, the activated carbon sample exhibited a relatively high moisture content after bleaching. Higher residual moisture following the bleaching process indicates lower effectiveness of the adsorbent in removing water and other polar compounds. This is in accordance with the FTIR observation where activated carbon has relatively lower hydrophilicity (Fig. 1). Rojas et al. (2019) reported that activated carbon adsorbents tend to have hydrophobic surfaces, making them more effective in adsorbing non-polar compounds. Consequently, the ability of activated carbon to remove polar compounds such as water appears to be limited, resulting in higher moisture levels compared with the other adsorbents.

3.5. Estimated crude fat content

Table 3 summarizes the estimated crude fat content of BSFLCO and bleached BSFLO samples, which reflecting the proportion of crude fat remaining after the removal of non-lipid components such as proteins and water. Significant differences were observed between BSFLCO and all bleached BSFLO samples, indicating the effectiveness of the bleaching process in reducing impurities ($p < 0.05$). As the control, BSFLCO exhibited the lowest fat content (99.31%), due to the presence of residual impurities that can negatively affect oil quality. Saviane et al. (2021) reported that BSFL extraction typically produces crude oil containing approximately 90% fat and 10% impurities. Thus, the relatively high fat content observed in the BSFLCO of the current study may be attributed to the initial centrifugation step, which removed a substantial portion of solid impurities prior to bleaching. It should also be noted that the definition of “crude oil” in BSFLO processing is not consistently specified in the literature.

Statistical analysis revealed no significant differences in fat content among BSFLO samples treated with different adsorbents. The fat content of the bleached oils ranged from 99.72% to 99.88%, with activated carbon yielding the lowest value and bleaching earth the highest. As the fat content was calculated by difference, it is understandable to get higher fat content with those samples with lower impurities such as protein and moisture. Therefore, adsorbents with better adsorption effects results in higher fat content. The highest fat content observed in the bleaching earth sample indicates its strong effectiveness in impurity removal. Previous studies have reported that bleaching earth exhibits a bleaching efficiency of approximately 30% in impurity adsorption, thereby contributing to improved oil quality (Tandewi & Hambali, 2022). In addition, the selectivity and physicochemical characteristics of each adsorbent influence adsorption performance. Synthetic zeolite and silica gel have been reported to preferentially adsorb polar compounds (Islam et al., 2020), whereas activated carbon is more effective at removing non-polar ones (Rojas et al., 2019).

3.6. Peroxide value

The peroxide values of BSFLCO and bleached BSFLO samples are presented in Table 3. Peroxide value is an important indicator of lipid oxidation, as it reflects the concentration of primary oxidation products, specifically fatty acid hydroperoxides (ROOH), formed along the fatty acid chain Longobardi et al. (2021). Increased lipid oxidation can negatively affect sensory quality, particularly through the development of rancid flavors and off-odors. Statistical analysis showed that peroxide values were significantly influenced by the type of adsorbent used during the bleaching process ($p < 0.05$). The control sample (BSFLCO) exhibited a peroxide value of 2.49 ± 1.02 meqO_2/kg. Comparable peroxide values have been reported for virgin coconut oil (VCO), which has a fatty acid composition similar to BSFLO, ranging from 2.2 to 2.4 meqO_2/kg (Ghani et al., 2018).

Overall, the application of adsorbents resulted in a reduction in peroxide values, which ranged from 1.44 to 2.49 meqO_2/kg. Among the bleached samples, bleaching earth purification resulted in the lowest peroxide value, whereas activated carbon produced the highest. Previous studies have shown that the refining of BSFLO can reduce peroxide values in crude oil by approximately 24–58% (Mai et al., 2019). Statistical comparisons among the adsorbent-treated samples indicated that the bleaching earth and silica gel samples did not differ significantly from each other but both exhibited significantly lower peroxide values than the control ($p < 0.05$). In contrast, the synthetic zeolite and activated carbon samples did not show peroxide values that were significantly different from the control. The greater reduction in peroxide value observed with bleaching earth and silica gel may be attributed to their stronger affinity for toward polar oxidation products (Fig. 1), particularly lipid hydroperoxides. Bleaching earth has a charged clay surface and acidic active sites, whereas the high moisture content trapped within silica gel makes it effective at attracting polar impurities (Hussin et al., 2011; Nock, 2020). The lowest peroxide value observed in the bleaching earth-treated BSFLO is consistent with earlier results for moisture and protein content, further indicating its effectiveness in removing impurities and oxidation products. Vogt and Pacura (2019) reported that bleaching earth can remove peroxide compounds by up to 80%, supporting these findings.

3.7. Free fatty acid content

The free fatty acid (FFA) content of BSFLCO and bleached BSFLO samples is presented in Table 3. Free fatty acids are secondary oxidation products formed through triglyceride hydrolysis and oxidation, and their accumulation can lead to undesirable changes in oil color and aroma (Witasari, Jason et al., 2025, 2025). Statistical analysis showed that FFA content was significantly influenced by the type of adsorbent used during the bleaching process ($p < 0.05$). The control sample (BSFLCO) exhibited an FFA content of 0.32 ± 0.04%, which is lower than the value of 0.98% previously reported for BSFL crude oil (Matthäus et al., 2019). All bleached samples showed a reduction in FFA content, ranging from 0.19% to 0.29%, with the lowest value observed in the bleaching earth sample and the highest in the silica gel sample. Comparable FFA levels in purified BSFLO have been reported by Xiong et al. (2020), who observed values of approximately 0.30%.

FFA adsorption is likely associated with physical entrapment phenomena, as free fatty acids possess smaller molecular sizes compared to triacylglycerols, allowing easier penetration into the pore structure of the adsorbent. Another possible mechanism involves interactions between FFAs and the hydrophilic active sites present on the adsorbent surface (Lestari et al., 2025). Among the adsorbents evaluated, bleaching earth showed significantly lower FFA content than the control and all other bleached samples ($p < 0.05$), indicating its superior effectiveness in FFA removal. This result is consistent with SEM observation (Fig. 1) which shows cracks in bleaching earth surface structure which may facilitate the physical entrapment. The previous reports havealso shown that bleaching earth can adsorb up to 60% of free fatty acids. Its high adsorption efficiency is largely attributed to its bentonite-based structure and acid activation treatment, which enhance the surface area and porosity (Muhammad et al., 2023). Although synthetic zeolite, activated carbon, and silica gel showed some reduction in FFA content compared with the control, their performance was markedly lower than that of bleaching earth. The limited effectiveness of these adsorbents has been associated with structural constraints such as smaller pore size, lower external surface area, or a less favorable surface affinity for FFA molecules (Petrović et al., 2023).

3.8. Smoke point

The smoke point values of BSFLCO and bleached BSFLO samples are presented in Table 3. Smoke point is an important indicator of oil quality, as it reflects the temperature at which thermal degradation and the formation of undesirable flavors and compounds begin to occur. Statistical analysis showed that smoke point values were significantly influenced by the type of adsorbent used during the bleaching process ($p < 0.05$). The control sample (BSFLCO) exhibited a smoke point of 180.63 ± 1.44 °C, which is comparable to that reported for coconut oil at 180.25 °C (Satheeshan et al., 2019). In general, samples treated with adsorbents showed increased smoke points, ranging from 183.10 to 195.33 °C. Among the bleached samples, the lowest smoke point was observed in the silica gel sample, whereas the highest was obtained for the bleaching earth sample. The increase in smoke point following bleaching can be attributed to the removal of impurities such as volatile compounds, free fatty acids, and residual non-lipid components (Mahesar et al., 2017).

Smoke point is closely associated with free fatty acid content, as oils with higher FFA levels tend to exhibit lower smoke points due to the greater volatility of free fatty acids compared to triglycerides (Ujong et al., 2023). This relationship was evident in the present study, where samples with lower FFA content consistently showed higher smoke points. In particular, the bleaching earth sample, which exhibited the lowest FFA content, also produced the highest smoke point. Conversely, the silica gel sample showed the highest FFA content among the bleached samples and, accordingly, exhibited the lowest smoke point. Statistical analysis further confirmed that the bleaching earth–treated sample differed significantly from the control and other adsorbent-treated samples ($p < 0.05$), highlighting its superior effectiveness in improving smoke point through FFA removal. This effectiveness may be related to the suitable particle size and high surface area of bleaching earth, which promote more efficient diffusion and adsorption of FFA molecules (Tandewi & Hambali, 2022). In contrast, the synthetic zeolite, activated carbon, and silica gel samples did not show significant differences in smoke point compared with one another. The relatively lower smoke points observed in these samples indicate limited effectiveness in removing FFA, which may be attributed to constraints in pore volume, surface affinity, or adsorption selectivity compared with bleaching earth.

3.9. Visual appearance and color

Fig. 3 presents the visual appearance and spectrophotometric color profiles of BSFLCO and BSFLO after bleaching with different adsorbents. Coconut oil was used as a reference and appeared as a transparent liquid, whereas BSFL oil samples exhibited yellow to dark yellow coloration with varying intensities. The darkest color was observed in BSFLO bleached with activated carbon, which may be attributed to the adsorbent's low bulk density and the resulting difficulty in complete separation by centrifugation. Consequently, residual fine adsorbent particles contributed to the darker appearance. In contrast, a significant improvement in color was observed in the bleaching earth-treated BSFLO, which appeared bright yellow and closer to the characteristic color of commercially available frying oils.

Quantitative color evaluation was performed using spectrophotometric scanning in the wavelength range of 400–600 nm. As shown in Fig. 3B, higher absorbance was observed in the ranges of 400–450 nm and 450–495 nm, corresponding to yellow and orange complementary color characteristics, respectively (Chiba, 2003). Color intensity was further quantified by calculating the area under the absorbance curve, with results presented in Table 4. As expected, BSFLCO exhibited a higher absorbance area (271.33) compared with coconut oil (4.01), reflecting its lower transparency. Bleaching with adsorbents reduced the absorbance area, with the lowest value observed in the bleaching earth-treated BSFLO (134.92), corresponding to an approximately 50% reduction in color intensity. This is better than what Guliyev et al. (2018) reported, that bleaching processes can reduce yellow color intensity in oil products by up to 30%.

The lower color intensity observed in BSFLO after bleaching demonstrates the ability of bleaching earth to adsorb color-related compounds and associated impurities. This observation is consistent with the protein content analysis (Table 3), which showed the lowest protein level in bleaching earth-treated BSFLO. Although synthetic zeolite and activated carbon have been reported to selectively adsorb organic pigments in oils (Yılmaz & Yücetepe, 2023), their color reduction effects were less pronounced in the present study. It should be noted that visual appearance and spectrophotometric measurements do not always correlate directly, as visual perception is influenced by factors such as light scattering and residual suspended particles.

The high color intensity observed in BSFLCO is likely associated with the presence of impurities such as organic compounds, proteins, and pigments remaining after mechanical extraction. Similar observations were reported by Srisuksai et al. (2024), who found that mechanically extracted BSFLCO exhibited high yellow color intensity due to retained pigments and impurities. The relatively high absorbance areas observed

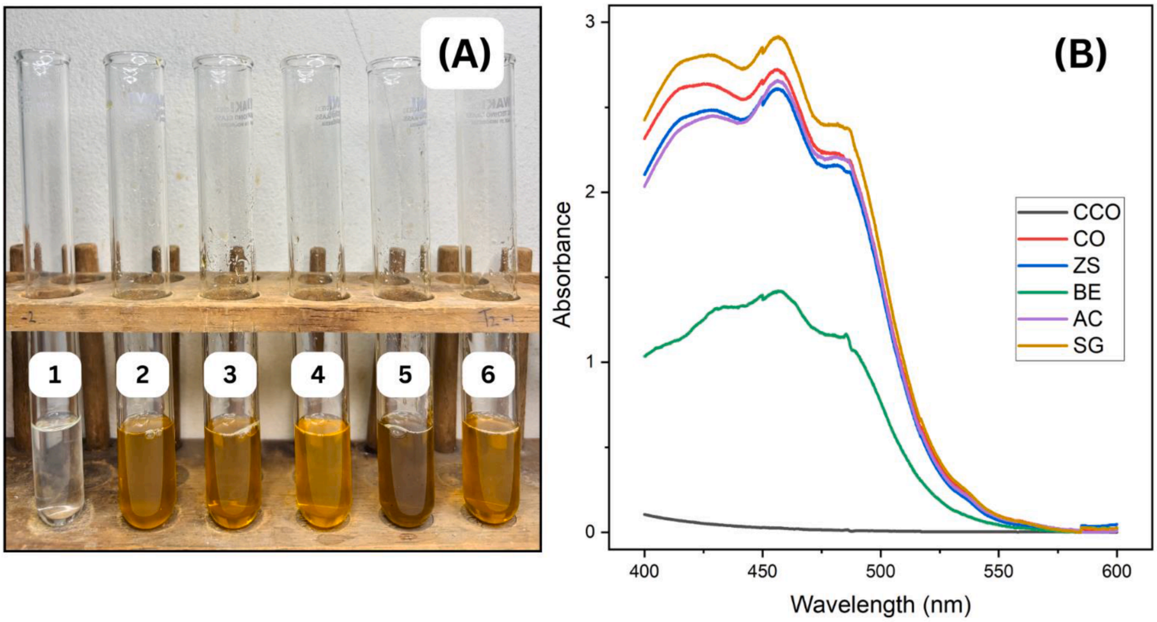

Fig. 3. (A) Visual appearance and (B) Color spectrum of black soldier fly larvae oil (BSFLO). Numbered samples: 1. CCO, 2. BSFLCO, 3. ZS, 4. BE, 5. AC, 6. SG; where CCO: coconut oil, CO: BSFL crude oil, ZS: BSFLO with synthetic zeolite bleaching, BE: BSFLO with bleaching earth bleaching, AC: BSFLO with activated carbon bleaching, SG: BSFLO with silica gel bleaching.

Table 4
Spectrum area under curve of BSFLO.

Sample	CCO	CO	ZS	BE	AC	SG
Area	4.01	271.33	257.06	134.92	258.39	290.08

Note: CCO: coconut oil, CO: BSFL crude oil, ZS: BSFLO with zeolite bleaching, BE: BSFLO with bleaching earth bleaching, AC: BSFLO with activated carbon bleaching, SG: BSFLO with silica gel bleaching.

in BSFLO samples bleached with silica gel and activated carbon may reflect the limited ability of these adsorbents to remove organic color pigments and proteinaceous impurities. Silica gel, as a polar adsorbent, is generally more effective in adsorbing polar compounds than non-polar pigments (Islam et al., 2020). These findings are consistent with the protein content results, as residual proteins and other larval tissue components can contribute to increased color intensity in oil (Abo-Riya et al., 2023). Accordingly, lower adsorption of proteinaceous impurities is associated with higher residual color intensity, and vice versa.

3.10. Fatty acid profile

The fatty acid profile of BSFLCO and bleached BSFLO is presented in Table 5. Analysis was performed using GC–MS on the BSFLCO sample as the control and on the bleaching earth (BE)-treated sample, which exhibited the most favorable overall chemical characteristics among the bleached oils. The BSFLCO sample consisted of 62.85% saturated fatty acids (SFA), 24.70% monounsaturated fatty acids (MUFA), and 12.45% polyunsaturated fatty acids (PUFA). These results are consistent with those reported by Li et al. (2016), who found that BSFLCO was dominated by SFA (59.70%), followed by MUFA (19.80%) and PUFA (19.84%). The bleaching earth-treated sample showed a similar fatty acid distribution, with SFA accounting for 62.09%, MUFA for 25.19%, and PUFA for 12.72%. Comparable findings were reported by Xiong et al. (2020), who observed that BSFLO after bleaching (decolorization) remained dominated by saturated fatty acids (49.6%), followed by monounsaturated (25.3%) and polyunsaturated fatty acids (24%). who observed that BSFLO after bleaching (decolorization) remained dominated by saturated fatty acids (49.6%), followed by mono-unsaturated (25.3%) and polyunsaturated fatty acids (24%).

Table 5
Comparison of fatty acid profile of BSFLCO and BE-treated sample.

Fatty Acid	Concentration (%)	
	BSFLCO	BE
Nonanoic Acid (C9:0)	0.05	-
Decanoic Acid (C10:0)	0.89	0.89
Lauric Acid (C12:0)	26.61	25.85
Tridecynoic Acid (C13:0)	0.14	-
Myristic Acid (C14:0)	9.16	9.18
Pentadecanoic Acid (C15:0)	0.13	0.12
Palmitic Acid (C16:0)	24.79	24.91
Heptadecanoic Acid (C17:0)	0.16	0.30
Stearic Acid (C18:0)	0.67	0.69
Eicosanoic Acid (C20:0)	0.25	0.15
Linoleic Acid (C18:2)	10.91	11.08
Linolenic Acid (C18:3)	1.23	1.30
Arachidonate Acid (C20:4)	0.31	0.34
Oleic Acid (C18:1)	24.43	24.66
Heptadecen-Carboxylic Acid (C17:1)	0.27	0.31
Cholesterol (C27:1)	-	0.14
Total	100	100
Saturated Fatty Acid	62.85	62.09
Monounsaturated Fatty Acid	24.70	25.19
Poly-unsaturated Fatty Acid	12.45	12.72

Notes: BSFLCO: Black soldier Fly Larvae Crude Oil; BE: BSFLO with bleaching earth bleachingOverall, the results indicate that bleaching with bleaching earth caused only minimal changes in the fatty acid composition of BSFLO. Minor variations were observed, including a slight decrease in lauric acid (SFA) and a corresponding increase in oleic and linoleic acids (MUFA and PUFA). Similar trends were reported by Mai et al. (2019), who observed reductions in lauric, palmitic, and stearic acids, accompanied by increases in palmitoleic and oleic acids following purification. These modest changes may be related to limited oxidation of saturated fatty acids during processing, which can slightly alter the relative proportions of unsaturated fatty acids. As the objective of this analysis was to verify that the optimized bleaching treatment preserved the fatty acid profile rather than to evaluate differences among adsorbents, fatty acid composition was determined only for the BE-treated sample without analytical replication. Accordingly, these results should be regarded as confirmatory evidence of fatty acid profile preservation and not as a basis for comparison among treatments.

3.11. Ranking test

The results of the ranking test for fishy aroma and yellow color of BSFLCO and BSFLO samples are presented in Table 6. The ranking test was conducted based on the panelists' objective evaluation of the specified attributes by ordering the samples from the highest to the lowest perceived intensity. For the fishy aroma attribute, the BSFLCO sample showed a significant difference compared to the other samples ($p < 0.05$). Based on the ranking results, BSFLCO received the highest rank, indicating the strongest fishy aroma intensity. This finding is in accordance with Wang dan Shelomi (2017), who reported that crude BSFL oil possesses a pronounced fishy aroma. Samples bleached using synthetic zeolite, activated carbon, and silica gel were ranked second, with no significant differences among them. Previous studies have shown that synthetic zeolite, activated carbon, and silica gel used during the bleaching process are capable of adsorbing various polycyclic aromatic hydrocarbons as well as polar and non-polar compounds, thereby reducing certain aroma-active components in oil (Le-Minh et al., 2018; Wołowiec et al., 2017).

In contrast, the sample bleached using bleaching earth showed a significant difference compared to all other samples ($p < 0.05$) and received the lowest rank, indicating the weakest fishy aroma intensity. This result demonstrates that bleaching earth was more effective in adsorbing aroma-causing compounds, including oxidation products associated with undesirable odors. Meanwhile, coconut oil, used as a comparative sample, showed a significant statistical difference from the BSFL oil samples ($p < 0.05$) and exhibited the lowest fishy aroma intensity overall. Coconut oil typically has a characteristic coconut aroma with only a faint savory note (Satheeshan et al., 2019). Overall, these findings indicate that the bleaching process significantly influenced the aroma profile of BSFLO, with bleaching earth standing out as the most effective adsorbent.

For the yellow color attribute, statistical analysis showed no significant differences among the BSFLCO sample and the samples bleached using synthetic zeolite, activated carbon, and silica gel. The average ranking scores for these samples ranged from 2.64 to 2.68, indicating similarly high yellow color intensity. This observation is consistent with the spectrophotometric evaluation, where the absorbance areas of these four samples did not differ markedly. In contrast, the sample bleached using bleaching earth showed a significant difference compared to the other BSFL oil samples ($p < 0.05$), ranking fourth with lower yellow color intensity and a noticeably brighter appearance. This result aligns with the visual appearance and color spectrum analysis, as well as with findings reported by Yılmaz dan Yücetepe (2023), who showed that oil bleached using bleaching earth exhibits higher brightness compared to oils treated with synthetic zeolite, activated carbon, and silica gel. These results highlight the critical role of adsorbent effectiveness in determining color changes during the bleaching process.

Coconut oil, used as a comparative sample, differed significantly from all BSFL oil samples and ranked last, reflecting the lowest yellow color intensity. This is consistent with its characteristic bright yellow to nearly clear appearance (Satheeshan et al., 2019). Overall, the ranking test results confirm that the bleaching process significantly influenced the color characteristics of BSFLO, with bleaching earth demonstrating superior performance in color reduction.

3.12. Hedonic test

The hedonic evaluation results for aroma, color, and overall preference of the BSFLCO and BSFLO samples are presented in Table 7. These results reflect the panelists' degree of liking for each sensory attribute of the oil samples. For the aroma attribute, no significant differences were observed among all samples ($p > 0.05$). Aroma preference scores ranged from 3.64 to 4.80, corresponding to responses from dislike slightly to neutral. Coconut oil, used as a familiar commercial reference, received the highest aroma score (4.80), indicating a slightly liked response. Similar aroma acceptance levels were observed for BSFLCO and bleached BSFLO samples, with ratings ranging from slightly dislike to neutral. Although BSFLCO and BSFLO are insect-based oils characterized by a mild fishy or umami aroma, their aroma acceptability did not differ significantly from that of the commercial control. This is noteworthy given the significant differences in fishy aroma intensity identified in the ranking test (Table 6), indicating that aroma had a limited influence on the panelists' hedonic response. This finding contrasts with the results of Yin et al. (2020), who reported that the presence of fishy notes reduced consumer acceptance of sesame oil

In contrast to the aroma hedonic evaluation, statistical analysis of the color attribute revealed significant differences among the samples ($p < 0.05$). The BSFLO sample bleached using bleaching earth received the highest color score (5.60), corresponding to a "like" response, while the lowest score was observed for BSFLO bleached with activated carbon. These results are consistent with visual observations (Fig. 1) and the ranking test (Table 6), which showed that activated carbon bleaching produced a darker oil and, consequently, a lower hedonic response. Interestingly, the oil bleached with bleaching earth achieved a higher color preference score than coconut oil, which is nearly colorless. This indicates that a yellowish oil color is more familiar and preferred by the panelists. Ayustaningwarno et al. (2024) similarly reported that consumers tend to favor oils with a bright golden-yellow appearance over clear or colorless oils such. The higher color acceptability observed for the bleaching earth sample is related to its effectiveness in removing pigments and impurities during the bleaching process. Pohndorf et al. (2016) also reported that bleaching earth efficiently adsorbs color

Table 6
Ranking test result of black soldier fly larvae oil after bleaching with different adsorbent.

Sample	Fishy Aroma	Yellow Color
CCO	5.60 ± 1.40^{d}	5.80 ± 1.00^{c}
BSFLCO	1.96 ± 1.50^{a}	2.64 ± 1.00^{a}
ZS	2.88 ± 1.20^{b}	2.64 ± 0.90^{a}
BE	4.40 ± 1.10^{c}	4.68 ± 1.10^{b}
AC	2.88 ± 1.20^{b}	2.56 ± 1.50^{a}
SG	3.28 ± 1.10^{b}	2.68 ± 1.30^{a}

Note: CCO: coconut oil, CO: BSFL crude oil, ZS: BSFLO with zeolite bleaching, BE: BSFLO with bleaching earth bleaching, AC: BSFLO with activated carbon bleaching, SG: BSFLO with silica gel bleaching. The analysis was conducted on a ranking scale from 1 to 6 with 1 being highest intensity and 6 being lowest intensity. Different superscript within the same column indicates statistical significance ($p < 0.05$).

Table 7
Hedonic test result of black soldier fly larvae oil after bleaching with different adsorbent.

Sample	Aroma^{ns}	Color	Overall
CCO	4.80±1.55	4.60 ± 2.00^{bc}	4.48 ± 1.50^{ac}
BSFLCO	3.64±1.93	4.44 ± 1.45^{b}	4.12 ± 1.56^{ab}
ZS	4.08±1.50	4.44 ± 1.19^{b}	4.16 ± 1.03^{b}
BE	4.40±1.50	5.60 ± 0.96^{c}	5.16 ± 1.03^{c}
AC	3.64±1.82	3.20 ± 1.55^{a}	3.36 ± 1.38^{a}
SG	3.92±1.44	4.48 ± 1.76^{b}	4.24 ± 1.30^{b}

Notes: CCO: Coconut Oil; BSFLCO: BSFL crude oil, ZS: BSFLO with zeolite bleaching, BE: BSFLO with bleaching earth bleaching, AC: BSFLO with activated carbon bleaching, SG: BSFLO with silica gel bleaching. The hedonic analysis was conducted on a hedonic scale from 1 to 7 with (1) dislike strongly, (2) dislike, (3) dislike slightly, (4) neutral, (5) like slightly, (6) like, (7) like strongly. Different superscript within the same column indicates statistical significance ($p < 0.05$).

pigments and impurities, thereby enhancing the visual and sensory quality of oil products.

The overall hedonic evaluation showed a significant difference for the bleaching earth-treated sample compared with BSFLCO and the other bleached BSFLO samples ($p < 0.05$). This sample received the highest mean score (5.16), corresponding to a “like slightly” response, indicating the highest overall acceptance among the tested oils. Coconut oil, used as a comparative sample, obtained a neutral score of 4.48 and did not differ significantly from the bleaching earth sample. This outcome reflects the combined influence of aroma and color attributes, for which both bleaching earth-treated oil and coconut oil consistently received higher ratings than the other samples. Overall, these results indicate that bleaching earth treatment improved consumer acceptance of BSFLO relative to the crude oil and other adsorbent-treated samples. In contrast, BSFLCO, synthetic zeolite-, silica gel-treated samples, and coconut oil showed no significant differences in overall hedonic scores, with values ranging from 4.12 to 4.48 (neutral category). The activated carbon-treated sample received the lowest score, corresponding to “dislike slightly”, although it was not statistically different from BSFLCO. The lower overall acceptance of activated carbon sample may be associated with their fishy or umami aroma and darker yellow color. Previous studies have reported that oils with pronounced fishy notes and darker coloration tend to be less preferred by consumers (Ayustaningwarno et al., 2024; Yin et al., 2020). These findings highlight the importance of integrated sensory attributes in shaping panelists’ overall preference for oil products.

3.13. Limitations and future directions

While the present study demonstrated the effectiveness of selected adsorbents in improving the physicochemical and sensory quality of BSFLO at laboratory scale, several aspects remain to be investigated for broader industrial application. First, the evaluation was limited to the selected adsorbent types and commercial brands tested in this study. Although preliminary experiments were conducted to optimize the adsorbent dosage, only the optimum concentration of 7.5% (w/w) was investigated and reported. Therefore, the findings should be interpreted within the context of the selected adsorbents and operating conditions. Practical considerations such as adsorbent regeneration, waste handling, process economics, and industrial-scale refining performance would provide a more comprehensive evaluation of commercial feasibility. The sensory assessment, while valuable for evaluating consumer perception, is inherently subjective and could be complemented by instrumental techniques such as gas chromatography-mass spectrometry (GC–MS) to identify volatile compounds responsible for odor and flavor changes. Finally, long-term storage studies under different environmental conditions are needed to establish oxidation kinetics and develop predictive shelf-life models prior to the commercial application of BSFLO.

4. Conclusions

This study provides a systematic comparison of selected adsorbents for improving the quality of Black Soldier Fly Larvae Oil (BSFLO). This study identifies bleaching earth as the most effective adsorbent for refining BSFLO. Although yields varied between 69.29% and 86.82% across all treatments, bleaching earth consistently produced the highest quality oil with the lowest levels of protein, moisture, peroxide value, and free fatty acids. Furthermore, bleaching earth treatment resulted in a 50% reduction in color intensity and achieved the highest sensory scores for aroma, color preference, and overall acceptance. These improvements were achieved without significantly altering the fatty acid composition, which remained dominated by saturated fatty acids. Compared to activated carbon, synthetic zeolite, and silica gel, bleaching earth offers the optimal balance between chemical stability and sensory quality, making it the superior choice for producing commercially viable, food-grade BSFLO.

Acknowledgement

Ethics statement

This study involving human participants was conducted in accordance with ethical standards. Informed consent was obtained from all participants prior to their inclusion in the study. Ethical clearance for human participation was granted by the Health Research Ethics Committee, Faculty of Medicine, Universitas Diponegoro (No. 345/EC/KEPK/FK-UNDIP/XII/2025).

Generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the author(s) used ChatGPT to assist with improving the English language. The tool was used only for language editing and not for scientific analysis or content generation. The author(s) reviewed and revised the manuscript and take full responsibility for its content.

Fundings

This work was supported by Universitas Diponegoro through the RPIBT scheme (Non-APBN 2025), Assignment Letter Number: 222–659/UN7.D2/PP/IV/2025. YP is grateful for the travel bursary under WCU Staff Exchange 2026 scheme, provided by the Faculty of Animal and Agricultural Sciences, Universitas Diponegoro.

CRediT authorship contribution statement

Yoga Pratama: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Ulil Afidah:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Alif Talitha Zahra:** Writing – original draft, Investigation, Formal analysis. **Yoel Anggara Saputra:** Writing – original draft, Investigation, Formal analysis. **Sri Mulyani:** Writing – review & editing, Supervision. **Ahmad Ni’matullah Al-Baarri:** Writing – review & editing, Software, Resources, Funding acquisition. **Elena Simone:** Writing – review & editing, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abo-Riya, M. A., Zahran, H. A., Hendawy, E. A. A., Tantawy, A. H., & Mohamed, H. I. (2023). Palm kernel oil mucilage as a source of bio-based cationic surfactants for effective control of water surface pollution: Synthesis, surface activity and petroleum capacities. *Journal of Molecular Liquids, 386*, Article 122478. https://doi.org/10.1016/J.MOLLIQ.2023.122478

Ayustaningwarno, F., Afifah, D. N., Anjani, G., Antika, R., Septiarini, D. R., Priciliya, A., Purwanti, R., Wijayanti, H. S., Razaq, A., Ayu, A. M., Katherinatama, A., & Asikin, Y. (2024). Chemical and sensory quality of citrus-flavored vegetable oils. *Discover Food, 4*(1), 1–14. https://doi.org/10.1007/S44187-024-00224-2/FIGURES/6

Bläker, C., Muthmann, J., Pasel, C., & Bathen, D. (2019). Characterization of activated carbon adsorbents – State of the art and novel approaches. *ChemBioEng Reviews, 6*(4), 119–138. https://doi.org/10.1002/CBEN.201900008;PAGE:STRING:ARTICLE/CHAPTER

Chiba, T. (2003). SPECTROSCOPY | visible spectroscopy and colorimetry. In Benjamin Caballero, Paul Finglas, & Luiz Trugo (Eds.), *Encyclopedia of food sciences and nutrition* (2nd, pp. 5454–5459). Academic Press. https://doi.org/10.1016/B0-12-227055-X/01121-4.

Clementson, C. L., Rosentrater, K., & Ileleji, K. E. (2009). A comparison of measurement procedures used to determine the bulk density of distillers dried grains with solubles (DDGS). In *, 53. American Society of Agricultural and Biological Engineers Annual International Meeting 2009* (pp. 485–490). ASABE. https://doi.org/10.13031/2013.29557. *2009*.

Ghani, N. A. A., Channip, A. A., Chok Hwee Hwa, P., Ja'afar, F., Yasin, H. M., & Usman, A. (2018). Physicochemical properties, antioxidant capacities, and metal contents of virgin coconut oil produced by wet and dry processes. *Food Science & Nutrition, 6*(5), 1298–1306. https://doi.org/10.1002/FSN3.671

Guliyev, N. G., Ibrahimov, H. J., Alekperov, J. A., Amirov, F. A., & Ibrahimova, Z. M. (2018). Investigation of activated carbon obtained from the liquid products of pyrolysis in sunflower oil bleaching process. *International Journal of Industrial Chemistry, 9*(3), 277–284. https://doi.org/10.1007/S40090-018-0156-1/FIGURES/4

Huang, C., Feng, W., Xiong, J., Wang, T., Wang, W., Wang, C., & Yang, F. (2019). Impact of drying method on the nutritional value of the edible insect protein from black soldier fly (Hermetia illucens L.) larvae: Amino acid composition, nutritional value evaluation, in vitro digestibility, and thermal properties. *European Food Research and Technology, 245*(1), 11–21. https://doi.org/10.1007/S00217-018-3136-Y/METRICS

Hurtado-Ribeira, R., Villanueva-Bermejo, D., García-Risco, M. R., Hernández, M. D., Sánchez-Muros, M. J., Fornari, T., Vázquez, L., & Martin, D. (2023). Evaluation of the interrelated effects of slaughtering, drying, and defatting methods on the composition and properties of black soldier fly (Hermetia illucens) larvae fat. *Current Research in Food Science, 7*, Article 100633. https://doi.org/10.1016/j.crfs.2023.100633

Hussin, F., Aroua, M. K., & Daud, W. M. A. W. (2011). Textural characteristics, surface chemistry and activation of bleaching earth: A review. *Chemical Engineering Journal, 170*(1), 90–106. https://doi.org/10.1016/J.CEJ.2011.03.065

Islam, M. A., Pal, A., & Saha, B. B. (2020). Experimental study on thermophysical and porous properties of silica gels. *International Journal of Refrigeration, 110*, 277–285. https://doi.org/10.1016/J.IJREFRIG.2019.10.027

Khan, M., Ali, S. W., Shahadat, M., & Sagadevan, S. (2022). Applications of polyaniline-impregnated silica gel-based nanocomposites in wastewater treatment as an efficient adsorbent of some important organic dyes. *Green Processing and Synthesis, 11*(1), 617–630. https://doi.org/10.1515/gps-2022-0063

Kritioti, A., Menexes, G., & Drouza, C. (2018). Chemometric characterization of virgin olive oils of the two major Cypriot cultivars based on their fatty acid composition. *Food Research International, 103*, 426–437. https://doi.org/10.1016/J.FOODRES.2017.10.064

Le-Minh, N., Sivret, E. C., Shammay, A., & Stuetz, R. M. (2018). Factors affecting the adsorption of gaseous environmental odors by activated carbon: A critical review. *Critical Reviews in Environmental Science and Technology, 48*(4), 341–375. https://doi.org/10.1080/10643389.2018.1460984

Lestari, D. P., Usman, T., & Wahyuni, N. (2025). Free fatty acid adsorption of crude palm oil by modified fly ash. *AgriTECH, 45*(4), 375. https://doi.org/10.22146/AGRITECH.100162

Li, S., Ji, H., Zhang, B., Tian, J., Zhou, J., & Yu, H. (2016). Influence of black soldier fly (Hermetia illucens) larvae oil on growth performance, body composition, tissue fatty acid composition and lipid deposition in juvenile Jian carp (Cyprinus carpio var. Jian). *Aquaculture (Amsterdam, Netherlands), 465*, 43–52. https://doi.org/10.1016/J.AQUACULTURE.2016.08.020

Liguori B., Sancho A.I., Poulsen M. Lindholm Bøgh K., 2022. Novel foods: Allergenicity assessment of insect proteins. EFSA Journal 2022; 20(S2):e200910, 9. 10.2903/j.efsa.2022.e200910.

Longobardi, F., Contillo, F., Catucci, L., Tommasi, L., Caponio, F., & Paradiso, V. M. (2021). Analysis of peroxide value in olive oils with an easy and green method. *Food Control, 130*, Article 108295. https://doi.org/10.1016/J.FOODCONT.2021.108295

Madejová, J. (2003). FTIR techniques in clay mineral studies. *Vibrational Spectroscopy, 31*(1), 1–10. https://doi.org/10.1016/S0924-2031(02)00065-6

Mahesar, S. A., Shah, S. N., Shirazi, S. T. H., Nizamani, S. M., & Kandhro, A. A. (2017). Outcome of refining on the physicochemical properties of cottonseed oil. *Pakistan Journal of Analytical & Environmental Chemistry, 18*(2), 105–111. https://doi.org/10.21743/pjaec/2017.12.10

Mai, H. C., Dao, N. D., Lam, T. D., Nguyen, B. V., Nguyen, D. C., & Bach, L. G. (2019). Purification process, physicochemical properties, and fatty acid composition of black soldier fly (Hermetia illucens Linnaeus) larvae oil. *JAOCS. Journal of the American Oil Chemists' Society, 96*(11), 1303–1311. https://doi.org/10.1002/aocs.12263

Matthäus, B., Piofczyk, T., Katz, H., & Pudel, F. (2019). Renewable resources from insects: Exploitation, properties, and refining of fat obtained by cold-pressing from hermetia illucens (Black Soldier Fly) larvae. *European Journal of Lipid Science and Technology, 121*(7). https://doi.org/10.1002/ejlt.201800376

Mshayisa, V. V., Van Wyk, J., & Zozo, B. (2022). Nutritional, techno-functional and structural properties of black soldier fly (Hermetia illucens) larvae flours and protein concentrates. *Foods 2022, 11*(5), 724. https://doi.org/10.3390/FOODS11050724. *Vol. 11, Page 724*.

Muhammad, M., Kamar, I., Chandra, A. R., Shrestha, A., & Pandey, G. P. (2023). Use of bentonite adsorbent from Ujong Pacu for the adsorption free fatty acids from crude palm oil. *Journal of Renewable Energy, Electrical, and Computer Engineering, 3*(2), 76–83. https://doi.org/10.29103/jreece.v3i2.12479

Neolaka, Y. A. B., Supriyanto, G., Darmokoesoemo, H., & Kusuma, H. S. (2018). Characterization, isotherm, and thermodynamic data for selective adsorption of Cr (VI) from aqueous solution by Indonesia (Ende-Flores) natural zeolite Cr(VI)-imprinted-poly(4-VP-co-EGDMA)-ANZ (IIP-ANZ). *Data in Brief, 17*, 1020–1029. https://doi.org/10.1016/J.DIB.2018.01.081

Nock, T. (2020). Silica hydrogel and its use in edible oil processing. *Lipid Library*. https://www.aocs.org/resource/silica-hydrogel-and-its-use-in-edible-oil-processing/.

Nweke, C. N., & Ajemba, R. O. (2022). Clay characterization and bleaching of crude palm oil using acid-activated Nibo Clay. *Bioremediation Science and Technology Research, 10*(1), 14–21. https://doi.org/10.54987/bstr.v10i1.683

Ojewumi, M. E., Ezeocha, C. R., Alagbe, E. E., Obanla, O. R., & Omodara, O. J. (2021). Optimization of bleaching of crude palm oil using activated groundnut hull. *IOP Conference Series: Materials Science and Engineering, 1107*(1), Article 012142. https://doi.org/10.1088/1757-899X/1107/1/012142

Pang, W., Hou, D., Chen, J., Nowar, E. E., Li, Z., Hu, R., Tomberlin, J. K., Yu, Z., Li, Q., & Wang, S. (2020). Reducing greenhouse gas emissions and enhancing carbon and nitrogen conversion in food wastes by the black soldier fly. *Journal of Environmental Management, 260*, Article 110066. https://doi.org/10.1016/j.jenvman.2020.110066

Petrović, Z., Mihajlović, J., Botić, T., Lazić, D., Fazlić, A., & Ćebić, A. (2023). Possibility of bleaching sunflower oil with synthetic zeolite. *Technologica Acta, 15*(2), 25–31. https://doi.org/10.51558/2232-7568.2022.15.2.25

Pohndorf, R. S., Pinheiro, C. P., & Pinto, L. A. A. (2016). Kinetic study of adsorption of pigments and oxidation products in the bleaching of rice bran oil. *International Journal of Food Engineering, 12*(3), 211–219. https://doi.org/10.1515/IJFE-2015-0164/MACHINEREADABLECITATION/RIS

Poullet, P., Muñoz-Perez, J. J., Poortvliet, G., Mera, J., Contreras, A., & Lopez, P. (2019). Influence of different sieving methods on estimation of sand size parameters. *Water (Switzerland), 11*(5), 879. https://doi.org/10.3390/w11050879. NumberMDPI AG.

Pratama, Y., Hardiyanti, F. P., & Hintono, A. (2024). Improving sweet bread properties with diacetyl tartaric acid ester of monoglyceride (DATEM). *Journal of Applied Food Technology, 11*(1), 8–13. https://doi.org/10.17728/JAFT.23112

Purschke, B., Scheibelberger, R., Axmann, S., Adler, A., & Jäger, H. (2017). Impact of substrate contamination with mycotoxins, heavy metals and pesticides on the growth performance and composition of black soldier fly larvae (Hermetia illucens) for use in the feed and food value chain. *Food Addit Contam Part A Chem Anal Control Expo Risk Assess, 34*(8), 1410–1420. https://doi.org/10.1080/19440049.2017.1299946

Queiroz, L. S., Regnard, M., Jessen, F., Mohammadifar, M. A., Sloth, J. J., Petersen, H. O., Ajalloueian, F., Brouzes, C. M. C., Fraihi, W., Fallquist, H., de Carvalho, A. F., & Casanova, F. (2021). Physico-chemical and colloidal properties of protein extracted from black soldier fly (Hermetia illucens) larvae. *International Journal of Biological Macromolecules, 186*, 714–723. https://doi.org/10.1016/J.IJBIOMAC.2021.07.081

Rich, A. D. (1960). Relationship between the apparent bulk density of a bleaching clay and its oil retention. *Journal of the American Oil Chemists Society, 37*(6), 305–307. https://doi.org/10.1007/BF02631774

Rojas, J., Suarez, D., Moreno, A., Silva-Agredo, J., & Torres-Palma, R. A. (2019). Kinetics, isotherms and thermodynamic modeling of liquid phase adsorption of crystal violet dye onto shrimp-waste in its raw, pyrolyzed material and activated charcoals. *Applied Sciences 2019, 9*(24), 5337. https://doi.org/10.3390/APP9245337. *Vol. 9, Page 5337*.

Salahuddin, M., et al. (2024). Flight toward Sustainability in Poultry Nutrition with Black Soldier Fly Larvae. *Animals, 14*(3), 510. https://doi.org/10.3390/ani14030510

Satheeshan, K., Author, C., Seema, B., & Meera Manjusha, A. (2019). Quality analysis of virgin coconut oil processed through different methods. *Journal of Pharmacognosy and Phytochemistry, 8*(3), 2119–2123. https://www.phytojournal.com/archives/2019.v8.i3.10086/quality-analysis-of-virgin-coconut-oil-processed-through-different-methods.

Saviane, A., Tassoni, L., Naviglio, D., Lupi, D., Savoldelli, S., Bianchi, G., Cortellino, G., Bondioli, P., Folegatti, L., Casartelli, M., Orlandi, V. T., Tettamanti, G., & Cappellozza, S. (2021). Mechanical processing of hermetia illucens larvae and bombyx mori pupae produces oils with antimicrobial activity. *Animals, 11*(3), 783. https://doi.org/10.3390/ANI11030783, 2021, Vol. 11, Page 783.

Seçilmiş, Ş. S., Yanık, D. K., Fadıloğlu, S., & Fahrettin, G. (2022). Microwave-assisted bleaching of olive pomace oil: Optimization of bleaching parameters and comparison with conventionally bleached oil. *European Journal of Lipid Science and Technology, 124*(11), Article 2200011. https://doi.org/10.1002/EJLT.202200011;WGROUP:STRING:PUBLICATION

Seçilmiş, Ş. S. (2024). Valorization of waste seashells as bioadsorbent for sunflower oil bleaching. *Journal of Food Process Engineering, 47*(4), Article e14608. https://doi.org/10.1111/JFPE.14608. REQUESTEDJOURNAL:JOURNAL:17454530;WGROUP:STRING:PUBLICATION.

Siddiqui, S. A., Süfer, Ö., Çalışkan Koç, G., Lutuf, H., Rahayu, T., Castro-Muñoz, R., & Fernando, I. (2024). Enhancing the bioconversion rate and end products of black soldier fly (BSF) treatment – A comprehensive review. *Environment, Development and Sustainability, 27*(5), 9673–9741. https://doi.org/10.1007/s10668-023-04306-6. *2024 27:5*.

Singthong, J., Oonmetta-aree, J., & Oonsivilai, R. (2025). Enhancing low-fat meat products: Konjac glucomannan and lotus seed flour as functional ingredients in Moo-Yor. *Food Chemistry Advances, 7*, Article 101022. https://doi.org/10.1016/j.focha.2025.101022

Srisuksai, K., Limudomporn, P., Kovitvadhi, U., Thongsuwan, K., Imaram, W., Lertchaiyongphanit, R., Sareepoch, T., Kovitvadhi, A., & Fungfuang, W. (2024). Physicochemical properties and fatty acid profile of oil extracted from black soldier fly larvae (Hermetia illucens). *Veterinary World, 17*(3), 518–526. https://doi.org/10.14202/vetworld.2024.518-526

Tandewi, S. A. M. S., & Hambali, E. (2022). Refining of fish oil from fish meal processing by-product using Zeolite and bleaching earth. *IOP Conference Series: Earth and Environmental Science, 1034*(1), Article 012050. https://doi.org/10.1088/1755-1315/1034/1/012050

Traksele, L., Speiciene, V., Smicius, R., Alencikiene, G., Salaseviciene, A., Garmiene, G., Zigmantaite, V., Grigaleviciute, R., & Kucinskas, A. (2021). Investigation of in vitro and in vivo digestibility of black soldier fly (Hermetia illucens L.) larvae protein. *Journal of Functional Foods, 79*, Article 104402. https://doi.org/10.1016/J.JFF.2021.104402

Ujong, A. E., Emelike, N. J. T., Owuno, F., & Okiyi, P. N. (2023). Effect of frying cycles on the physical, chemical and antioxidant properties of selected plant oils during deep-fat frying of potato chips. *Food Chemistry Advances, 3*, Article 100338. https://doi.org/10.1016/J.FOCHA.2023.100338

Vogt, E., & Pacura, W. (2019). Hydrophobization of bleaching clay used for purification of waste frying oils. *IOP Conference Series: Earth and Environmental Science, 214*(1), Article 012009. https://doi.org/10.1088/1755-1315/214/1/012009

Wang, Y. S., & Shelomi, M. (2017). Review of black soldier fly (Hermetia illucens) as animal feed and Human food. *Foods (Basel, Switzerland), 6*(10), 91. https://doi.org/10.3390/FOODS6100091. *2017, Vol. 6, Page 91*.

Witasari, L. D., Jason, B., Salim, J. S., Pratama, Y., & Nusantoro, B. P. (2025a). Enzymatic synthesis of zero-trans structured lipids from red palm oil (Elaeis guineensis) and sacha inchi oil (Plukenetia volubilis) blends. *Food Bioscience, 69*, Article 106981. https://doi.org/10.1016/J.FBIO.2025.106981

Witasari, L. D., Salim, J. S., Jason, B., Kurniawan, E. W., Pratama, Y., & Nusantoro, B. P. (2025b). Physicochemical properties of enzymatically interesterified red palm oil. *Journal of Food Composition and Analysis, 146*, Article 107860. https://doi.org/10.1016/J.JFCA.2025.107860

Wołowiec, M., Muir, B., Zieba, K., Bajda, T., Kowalik, M., & Franus, W. (2017). Experimental study on the removal of VOCs and PAHs by zeolites and surfactant-modified zeolites. *Energy and Fuels, 31*(8), 8803–8812. https://doi.org/10.1021/acs.energyfuels.7b01124

Xiong, J., Mao, J., Wang, T., Feng, W., Wang, W., Yang, C., Miao, X., & Wang, C. (2020). Refining and sulfurization of oil from black soldier fly and its application as biodegradable lubricant additive. *JAOCS*. *Journal of the American Oil Chemists' Society, 97*(11), 1243–1251. https://doi.org/10.1002/aocs.12403

Yılmaz, E., & Yücetepe, E. (2023). Screening the alkali-neutralized sunflower seed oil bleaching ability of some natural and acid-activated natural clays, synthetic adsorbents, and metal-organic frameworks. *Gıda, 48*(3), 653–669. https://doi.org/10.15237/GIDA.GD23046

Yin, W., Washington, M., Ma, X., Yang, X., Lu, A., Shi, R., Zhao, R., & Wang, X. (2020). Consumer acceptability and sensory profiling of sesame oils obtained from different processes. *Grain & Oil Science and Technology, 3*(2), 39–48. https://doi.org/10.1016/J.GAOST.2020.04.001