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Comparative study of maggot (*Hermetia illucens*) oil extraction using mechanical pressing and soxhlet methods: Physicochemical characteristics

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ABSTRACT

Larvae of *Hermetia illucens* have been increasingly recognized as a promising renewable lipid feedstock for various industrial, oleochemical, and biotechnological applications. This study compared mechanical pressing and Soxhlet extraction methods to evaluate their effects on the physicochemical properties and lipid composition of maggot oil. Oil extracted by the Soxhlet method resulted in a higher yield (34.60%) than mechanical pressing (22.45%), indicating more efficient lipid recovery. The moisture contents of the oils were 0.643% and 0.468%, respectively. Both extraction methods produced oils with low acid values (1.693 ± 0.127–1.702 ± 0.116 mg KOH/g) and free fatty acid contents (0.603 ± 0.045–0.607 ± 0.042 %), suggesting acceptable oil quality. Saponification values ranged from 157 to 159 mg KOH/g, while peroxide values were 13.56–14.49 meq O_2/kg. The elemental composition results revealed that both oils were predominantly composed of carbon and hydrogen, reflecting their lipid-rich nature. Gas chromatography–mass spectrometry analysis revealed that the extraction method significantly influenced lipid composition. Mechanical pressing preserved a higher proportion of triglycerides, whereas Soxhlet extraction recovered larger amounts of free fatty acids, especially those with medium- and long-chain structures. These findings indicate that extraction techniques not only affect oil yield but also influence the physicochemical characteristics and chemical profile of *H. illucens* oil, which may influence its suitability for different biological and biotechnological applications. The results demonstrate that selecting a suitable extraction method is crucial for producing maggot oil with characteristics tailored to specific downstream applications, including biofuel, oleochemical, and biotechnological products.

Keywords: *Hermetia illucens*, maggot oil, mechanical pressing, physicochemical properties, Soxhlet extraction.

INTRODUCTION

Research on alternative lipid sources derived from biomass has been gaining increasing attention in recent years, in line with the growing demand for sustainable lipid feedstocks for biological, biotechnological, and other value-added applications, including biofuels (Kumar et al., 2025; Spranghers et al., 2017). One type of biomass studied in this context is the larvae of *Hermetia illucens* (Black Soldier Fly), which have a considerable lipid content, generally ranging from 21–42% of the dry biomass weight, depending on the feed type (Lawal et al., 2022; Spranghers et al., 2017). The fatty acids in maggot oil can be saturated or unsaturated, with a predominance of lauric acid ($C_{12:0}$), which is of significant value in oleochemical, biotechnological, and bioenergy applications (Li et al., 2022; Surendra et al., 2016). Another advantage of Black Soldier Fly (BSF) maggots is that their rearing substrate can be derived from organic waste streams, including food-derived residues, animal manure, and agricultural residues (Amrul et al., 2022; Rehman et al., 2023; Wang et al., 2017). Therefore, BSF maggot biomass has attracted growing attention as a sustainable lipid source, underlining the significance of efficient extraction procedures to generate oils with properties appropriate to certain applications.

Maggot oil can be produced using several extraction methods, namely Soxhlet extraction (Ishak et al., 2018), supercritical CO_2 extraction (Muangrata et al., 2024), and mechanical pressing (Nugroho et al., 2022; Rozali et al., 2022). Soxhlet extraction is effective but typically requires substantial quantities of organic solvents and prolonged extraction times, whereas supercritical CO_2 extraction can produce solvent-free extracts but requires specialized high-pressure equipment (Ishak et al., 2018; Muangrat & Pannasai, 2024). Mechanical pressing offers a faster and more straightforward extraction process than Soxhlet extraction and does not require organic solvents. However, its oil yield is generally lower because a portion of the lipids may remain in the residual solid material after pressing (Rozali et al., 2022).

This study employed two extraction methods: mechanical pressing and Soxhlet extraction. Maggot oil extraction by mechanical pressing is a method that does not involve chemical solvents and is a simple, environmentally friendly technique requiring minimal labor (Nugroho et al., 2022; Rozali et al., 2022; Surendra et al., 2016). The basic principle of this method is applying high mechanical pressure to the biomass, whether fresh or dried, thereby damaging the tissue structure and releasing the lipids trapped within larval cells (Caligiani et al., 2018; Chew et al., 2025; Rozali et al., 2022). Meanwhile, Soxhlet extraction is a technique frequently used to achieve high oil yields from biomass, including maggots, and is generally employed when the compounds of interest are not readily soluble in the solvent (Arachchige et al., 2025; Ishak et al., 2018). The basic principle of this method is to dissolve lipids in organic solvents such as n-hexane or ethanol, which are then evaporated and repeatedly condensed (refluxed) until all fats are extracted (Arachchige et al., 2025; Ishak et al., 2018). Comparing the physicochemical characteristics of oil produced by these two extraction methods is important for determining which method yields the highest-quality oil for the intended application.

Maggot oil was characterized by evaluating physical and chemical parameters to determine its quality and potential use as a feedstock for bioenergy, oleochemical, biotechnological, and other bio-based applications (Makkar et al., 2014; Spranghers et al., 2017). The physical and chemical parameters measured included moisture content, acid value, peroxide value, free fatty acid (FFA) content, elemental analysis, density, and viscosity. Moisture content analysis is important because it affects the oil's stability and oxidative resistance during storage, while the acid value and FFA content are used to assess the degree of triglyceride hydrolysis, which can influence oil quality, storage stability, and its suitability for downstream processing, including biodiesel production and other lipid-based applications (Knothe et al., 2005; Lin et al., 2022). The peroxide value is measured to determine the degree of primary oxidation associated with oil rancidity (Ismail et al., 2020). Elemental analysis is performed to characterize the elemental composition of organic samples by determining their C, H, N, S, and O contents using a CHNS/O analyzer, thereby supporting the evaluation of the oil's energy properties as well as its suitability for industrial utilization (ASTM, 2016; Demirbas, 2004). Physicochemical properties, particularly density and viscosity are also important to examine because they significantly influence processing, handling, transport, and end-use performance of lipid-based products, including fuel applications (Tzompa-Sosa et al., 2014).

Gas Chromatography–Mass Spectrometry (GC/MS) was employed to characterize the composition and fatty acid profile of maggot oil, enabling the qualitative and quantitative identification of its major constituents (Forfang et al., 2017; Srisuksai et al., 2024). Fatty acid composition plays a significant role in determining the functional properties of lipids and influences their potential applications in oleochemical products, biotechnology, and bioenergy (Franco et al., 2021; Suryati et al., 2023). Using this characterization method, the quality and potential uses of maggot oil can be assessed to support the selection of appropriate extraction methods and optimize its utilization for specific downstream applications.

This study aimed to compare the physicochemical characteristics of maggot oil produced by mechanical pressing and Soxhlet extraction. The physicochemical parameters measured include moisture content, acid value, peroxide value, free fatty acid content, C, H, N, S, and O content, density, and viscosity. These parameters are commonly used to assess the physicochemical characteristics and quality of oils (Fitria et al., 2025; Mai et al., 2019; Mohamed et al., 2021; Purbaningtias & Sandy, 2024). The fatty acid composition present in maggot oil produced was analyzed using GC/MS. This study is distinguished by its comprehensive evaluation and comparison of the physicochemical characteristics of maggot oil extracted using a solvent-based (Soxhlet) method and a more environmentally friendly, solvent-free method (mechanical pressing). These two methods are evaluated not only on their results but also on their impact on lipid structures, particularly the extent to which improved extraction efficiency reduces or modifies complex lipids.

METHOD

Equipment

The equipment used included a set of glassware, a desiccator, an analytical balance (Joanlab FA2003S 0.0001), a GC/MS QP-2020 NX (Shimadzu, Japan), an MS column SH-Rxi-5Sil (30 m × 0.25 mm i.d., internal diameter), Vortex V-1 Plus, Soxhlet extractor, Eyela OSB-2200 evaporator, RG-307 oil extractor (China), pycnometer, Ostwald viscometer, and FLASHSMART CHNS/O Organic Elemental Analyzer, Shimadzu GCMS-QP2010S (Japan).

Chemicals

The samples used in this study were dried maggots (*Hermetia illucens*) obtained from Protein Indonesia, Depok. The materials used were Whatman 42 filter paper, n-hexane (Merck KGaA), $H_2C_2O_4$ (Merck KGaA), phenolphthalein indicator (Merck KGaA), HCl (Merck KGaA), potassium hydroxide (Merck KGaA), and sodium carbonate (Merck Unilab).

Procedure

Oil extraction by mechanical pressing

Maggot oil extraction from dried maggots was performed using an RG-307 oil extractor (Figure 1). Extraction was performed at an operating temperature of approximately 100–120 °C. A two-kg sample of dried maggots was weighed. The dried maggots were then placed in the oil extractor to extract the maggot oil, and the resulting maggot oil was weighed to determine its total weight. The maggot oil yield was calculated according to the following equation (Eq.1).

Figure 1. Oil extractor RG-307 (China)

Oil extraction using the soxhlet method

The Soxhlet extraction procedure was conducted following the method described by Fitria et al. (2025) using a Soxhlet apparatus (Figure 2). Initially, 2 kg of dried *Hermetia illucens* larvae were pulverized into a fine powder using a blender to achieve a uniform particle size and enhance the efficiency of interaction between the sample and the solvent during the extraction process. The resulting maggot powder was then wrapped in filter paper, and 77–100 g of this powder was weighed out for use in each extraction cycle. The variation in sample mass among extraction cycles resulted solely from the practical loading capacity of the Soxhlet thimble and the amount of powder that could be packed without restricting solvent circulation; therefore, sample mass per cycle was not treated as an experimental variable. The extraction was performed in 22 consecutive cycles until the entire 2 kg batch had been processed. For each cycle, 500–600 mL of n-hexane was added to the round-bottom flask. A Soxhlet apparatus fitted with a condenser was operated at a temperature close to the boiling point of hexane (±60–70 °C). During extraction, the solvent evaporated, condensed in the condenser, dripped into the thimble to dissolve the oil, and was then siphoned back into the flask in a repeating cycle for 4–6 hours until the solvent appeared clear. After that, heating was stopped, and the hexane–oil extract was separated using an Eyela OSB-2200 rotary evaporator to evaporate the solvent. The extraction yield of maggot oil was determined using the following Eq. 1.

$$\text{oil yield (\%)} = \frac{\textbf{maggot oil mass}}{\textbf{mass of dried maggot samples}} \times 100 \quad \text{.....(1)}$$

Figure 2. Soxhlet extractor

Characterization

Moisture content and peroxide value

Moisture content testing was conducted using the gravimetric method (drying oven) until a constant weight was achieved, in accordance with the Association of Official Analytical Chemists (AOAC) standards (Mai et al., 2019), and the peroxide value was analyzed using the iodometric titration method based on American Oil Chemists' Society (AOCS) standards to determine the level of primary oxidation in the oil (Pietri et al., 2021). These tests were performed by the Testing and Calibration Laboratory at the Samarinda Industrial Standards and Services Center.

Acid value and free fatty acid content

Acid value and FFA content were analyzed using the alkalimetric titration method in accordance with SNI 3741:2013 on cooking oil, in which samples were titrated with a KOH solution to determine the free fatty acid content of the oil

- Standardization of KOH Solution

Three drops of phenolphthalein indicator were added to 5 mL of 0.1 N $H_2C_2O_4$ solution, followed by titration with KOH until a persistent pink endpoint was observed. The titration was conducted in triplicate, and the volume of KOH consumed was recorded and used to determine the concentration of the KOH solution. (Purbaningtias & Sandy, 2024).

- FFA Test

A total of 20 mL of 95% ethanol solution was added to an Erlenmeyer flask. The flask was then covered with aluminum foil and heated until the solution boiled. The solution was subsequently cooled to room temperature, after which three drops of phenolphthalein indicator were added and the mixture was thoroughly homogenized. The solution was then titrated with KOH until a magenta endpoint was reached. The volume of titrant consumed was recorded and used to determine the free fatty acid content of the oil (%FFA) and acid value using the following equations (2&3) (ISO 660, 1983; Rusdi et al., 2024):

$$\text{Acidity} = \frac{\boldsymbol{V\ \text{KOH}\ x\ N\ \text{KOH}\ x\ 56{,}11}}{\boldsymbol{m}} \quad \text{.........(2)}$$

$$\text{FFA content} = \frac{\boldsymbol{V\ \text{KOH}\ x\ N\ \text{KOH}\ x\ MW}}{\boldsymbol{10\ x\ m}} \quad \text{.........(3)}$$

Description:
V = volume of the KOH solution (mL)
N = normality of the KOH solution
m = mass of the sample (g)
56.11 = equivalent weight of KOH
MW = molecular weight of the dominant fatty acid (e.g., lauric acid = 200 g/mol)

Saponification value

- Preparation of Blank Solutions

The saponification flask was filled with several boiling stones, then 5 mL of ethanol solution and 22 mL of 0.5 N KOH solution were added. The mixture was refluxed in a boiling water bath for 1 h. Upon completion of the reflux, the solution was allowed to cool to room temperature, after which the reflux condenser was detached. Three drops of phenolphthalein indicator were then added, and the solution was titrated with 0.5 N HCl until the endpoint was reached, as indicated by a color change.

- Sample Analysis

All sample analyses were performed in triplicate. A 4-gram sample was weighed and placed in a saponification flask. Next, 25 mL of 0.5 N KOH solution in alcohol and several pieces of boiling stones were added. The mixture was then carefully brought to a boil using a reflux condenser. After heating was complete, the solution was cooled to room temperature. The reflux condenser was then removed, and 3 drops of phenolphthalein (PP) indicator were added. The solution was then titrated with 0.5 N HCl until the endpoint was indicated by a color change. The saponification number was calculated using the following equation according to ISO 3657 (2020), consistent with procedures reported in previous studies on oil characterization (Purbaningtias & Sandy, 2024).

$$\text{Saponification Number} = \frac{\boldsymbol{56{,}11\ (Vb - Vs)\ x\ N\ \text{HCl}}}{\boldsymbol{m}} \quad \text{...... (4)}$$

Description:
Vb = volume of HCl for the blank (mL)
Vs = volume of HCl for the sample (mL)
N = normality of the HCl solution
56.11 = equivalent weight of KOH (mg/mmol)
m = mass of the sample (g)

Density

The density of maggot oil was determined using a pycnometer according to AOAC Official Method 985.19 (Pycnometer Method). All sample analyses were performed in triplicate. The pycnometer was first cleaned, dried, and weighed while empty to obtain the initial mass. Next, the pycnometer was filled with distilled water to the mark and weighed to determine its volume from the mass of the water, whose density at the measurement temperature was known. After that, the pycnometer was dried, filled with the maggot oil sample to the mark without any air bubbles, and weighed to obtain the mass of the pycnometer containing the sample. The entire weighing process was performed using a high-precision analytical balance, and measurements were taken at a constant temperature, typically around 31 °C. The density of the maggot oil was calculated by comparing the mass of the oil sample in the pycnometer to its previously determined volume (Fitria et al., 2025; Mai et al., 2019).

Viscosity

The viscosity of maggot oil was measured using an Ostwald-type capillary viscometer. Before measurement, the viscometer was cleaned and dried to ensure there were no contaminants that could affect the results. A 5 mL sample of oil was added to the viscometer until it reached the calibration mark. The maggot oil sample was drawn into the viscometer until it reached the predetermined mark. The device was placed in a water bath at a constant temperature, typically around 31 °C, to maintain temperature stability during the measurement process. The maggot oil sample was drawn past the upper mark using a pipette or suction bulb, then allowed to flow by gravity through the capillary. The time required for the sample to flow from the upper mark to the lower mark was recorded using a stopwatch. The same procedure was performed on a standard fluid, usually distilled water, to obtain a reference flow time. The dynamic viscosity of the maggot oil was calculated based on the relationship between flow time, fluid density, and the instrument constant according to Poiseuille's Law as follows (Fitria et al, 2025):

$$\frac{\eta_1}{\eta_2} = \frac{(\rho_1 t_1)}{(\rho_2 t_2)} \quad \text{.............(5)}$$

where 2 is the sample, and 1 is distilled water, η is the absolute viscosity (P), ρ is the density (g/mL), and t is time (s); it is also known that η_1 at 31 °C = 0.00079. Viscosity measurements are expressed in centipoise (cP) or Pa·s and are used to characterize the flow properties of maggot oil as a potential feedstock for energy and oleochemical industry applications.

Elemental analysis

Elemental composition analysis of maggot oil was performed using the CHNS elemental analysis method to determine the content of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) at the Multidisciplinary Research Laboratory of the Faculty of Mathematics and Natural Sciences, University of Indonesia. The testing was performed using a FLASHSMART CHNS/O Organic Elemental Analyzer equipped with an automatic weighing system (balance). The analysis procedure followed the ASTM D5373 standard, which specifies a high-temperature combustion method for determining the carbon, hydrogen, and nitrogen content in organic material or fuel samples.

GC/MS

The chemical constituents of maggot oil were identified using GC/MS by adapting the fatty acid analysis method for *Hermetia illucens* reported by Mohamed et al. (2021) and Srisuksai et al. (2024), with modifications to the instrument's operating conditions to suit the analytical facilities used. The analysis was conducted using a Shimadzu GCMS-QP2010S system equipped with an Agilent DB-5MS UI capillary column (30 m length, 0.25 mm inner diameter, 0.25 μm film thickness). The carrier gas was helium, with linear velocity flow control, a column flow rate of 0.50 mL/min, a pressure of 13.6 kPa, and a total gas flow of 30.4 mL/min. The oil samples were derivatized with BF_3-methanol to convert the fatty acids into more volatile methyl esters, making them easier to vaporize, separate, and identify by GC/MS. The sample was subsequently injected at an injector temperature of 300 °C using split injection mode with a split ratio of 54:1. The oven temperature program was initiated at 70 °C and was held for 5 minutes, then increased at a heating rate of 5 °C/minute until reaching 300 °C and was held for 19 minutes to ensure optimal separation of the components.

The compounds were detected using a mass spectrometer equipped with the electron ionization (EI) method at an ionization energy of 70 eV. The ion source temperature was set to 250 °C and the interface temperature to 305 °C. Data acquisition was performed in scan mode with a mass range (m/z) of 28–600, a scan time (event time) of 0.50 seconds, and a scan rate of 1250 amu/second. The solvent cut time was set to 3 minutes to avoid solvent interference. Data collection began at a retention time of 3.20 minutes and continued until 70 minutes. Compound identification was performed based on the resulting mass spectrum patterns and compared with the mass spectrum library available in the instrument software, allowing the major components in maggot oil to be determined both qualitatively and semi-quantitatively

RESULTS AND DISCUSSION

Based on the findings of this study, the mass of maggot oil obtained using the mechanical pressing method (Figure 3a) was 449 g, yielding a recovery rate of 22.45%, whereas the Soxhlet extraction method (Figure 3b) produced 692 g of oil with a yield of 34.6%, The analysis method used was a descriptive comparative analysis of oil yield (%) obtained from the two extraction methods. The Soxhlet method was considered more effective because it produced a higher oil yield 34.60% than mechanical pressing 22.45%, corresponding to an increase of 12.15 percentage points; this difference was attributed to the ability of n-hexane to dissolve and extract lipids more thoroughly from the *Hermetia illucens* biomass through repeated reflux and siphoning cycles (Azmir et al,. 2013; Srisuksai et al., 2024). This difference in yield indicates that the extraction method significantly affects the effectiveness of lipid separation from *Hermetia illucens* larval biomass (Almeida et al., 2022; Arachchige et al., 2025; Van Huis et al., 2020).

Mechanical pressing extraction methods operate on physical principles to extract oil from biomass tissue; however, their effectiveness is typically suboptimal because some lipids remain trapped within the cellular matrix, proteins, and chitin that form the larval body structure, so not all oil can be fully recovered (Makkar et al., 2014; Sui et al., 2023). In contrast, the Soxhlet extraction method uses organic solvents such as n-hexane, which can dissolve lipid components more effectively through diffusion and mass transfer during repeated reflux cycles between the solvent and the biomass of *Hermetia illucens* larvae (Forfang et al., 2017; Srisuksai et al., 2024). This process allows the solvent to penetrate the biomass cell walls and dissolve triglycerides more efficiently, resulting in a higher oil yield than mechanical pressing methods (Almeida et al., 2022; Kim et al., 2022; Laroche et al., 2019). Therefore, the Soxhlet extraction method is more frequently used to extract lipids in research due to its high extraction efficiency, although it requires longer extraction times and uses organic solvents (Almeida et al., 2022; Kim et al., 2022; Laroche et al., 2019). The characteristic results for maggot oil across various parameters are presented in Table 1.

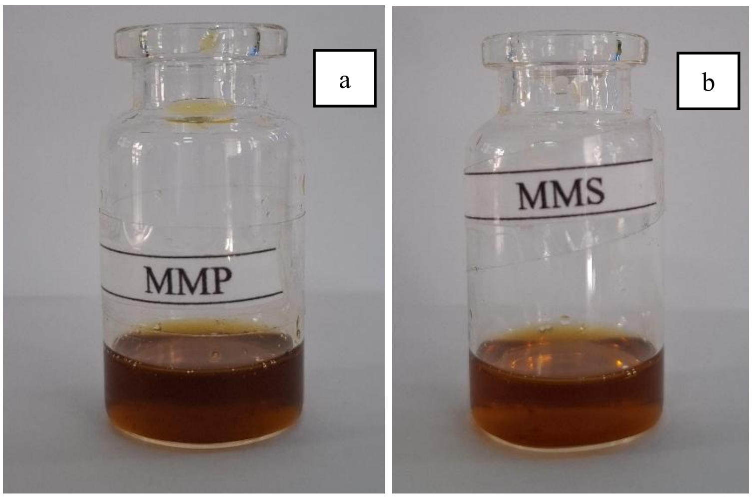

Figure 3. a.) Maggot oil extracted with the mechanical pressing method; b.) Maggot oil extracted with the Soxhlet method.

Table 1 indicates that the moisture content of maggot oil obtained through mechanical pressing was 0.468%, compared with 0.643% for the Soxhlet extraction method. Both values fall within the typical moisture content range reported for *Hermetia illucens* maggot oil. which is approximately 0.1–0.8% (Chia et al., 2018; Fornari et al., 2023; Ismail et al., 2020). These results suggest that the extraction method influences oil properties, as the solvent-based Soxhlet technique enables more efficient recovery of lipid components than mechanical pressing (Azmir et al., 2013; Fitria et al., 2025). The relatively low moisture content in both methods indicates that the maggot oil obtained is stable, as high moisture content can accelerate the hydrolysis of triglycerides into free fatty acids (Gunstone, 2011; Knothe & Razon, 2017; Shahidi & Zhong, 2010). The presence of water can trigger hydrolysis and lipid oxidation reactions that can degrade oil quality (Bao et al., 2023; Fornari et al., 2023).

In this study, the acid value of maggot oil obtained via the mechanical pressing method was 1.693 ± 0.127 mg KOH/g oil, and via the Soxhlet method was 1.702 ± 0.116 mg KOH/g oil, indicating that the processed maggot oil retains good quality because a low acid value reflects a sufficiently minimal degree of hydrolysis (Amaryllis et al., 2024; Knothe & Razon, 2017; Shahidi & Zhong, 2010). These acid values are also consistent with the FFA content obtained in this study: 0.603 ± 0.045 % by mechanical pressing and 0.607 ± 0.042 % by Soxhlet extraction. These relatively low free fatty acid levels indicate that the triglycerides in the maggot oil have not undergone significant hydrolysis, meaning the quality of the maggot oil is still considered good (Amaryllis et al., 2024; Knothe & Razon, 2017).

Table 1. Physicochemical characteristics of maggot oil

Properties	Mechanical pressing	Soxhlet method
Moisture content[a]	0.468 %	0.643 %
Acid Value	1.693 ± 0.127 mg KOH/g oil	1.702 ± 0.116 mg KOH/g oil
Saponification Value	159.626 ± 0.633 mg KOH/g oil	157.556 ± 2.109 mg KOH/g oil
Peroxide Value[a]	13.56 meq O_2/kg oil	14.49 meq O_2/kg oil
Free Fatty Acids (FFA)	0.603 ± 0.045%	0.607 ± 0.042 %
Elemental analysis[a]		
N	0.54 %	0.25 %
C	74.56 %	76.82 %
H	10.56 %	11.23 %
S	0	0
O	11.59 %	11.21 %
Density (ρ)	0.914 ± 0.002 g/mL	0.908 ± 0.0005 g/mL
Viscosity (31 °C)	0.00257 ± 0.00027 Pa·s	0.00139 ± 0.00004 Pa·s

[a] Moisture content, peroxide value, and elemental composition were determined by an external analytical laboratory as single measurements; therefore, standard deviations could not be calculated for these parameters.

In this study, the saponification value of maggot oil obtained via the mechanical pressing method was 159.626 ± 0.633 mg KOH/g oil, and via the Soxhlet method was 157.556 ± 2.109 mg KOH/g oil. These saponification values are comparable to the range documented for maggot oil in previous studies, namely approximately 150 to 200 mg KOH per gram of oil (Chew et al., 2025; Chia et al., 2018), suggesting that medium-chain fatty acids, particularly lauric acid, are important components of maggot oil (Chew et al., 2025; Spranghers et al., 2017; Surendra et al., 2016). The results of the study showed that the peroxide value of maggot oil obtained by mechanical pressing was 13.56 meq O_2/kg of oil, whereas that obtained by the Soxhlet method was 14.49 meq O_2/kg of oil (Chia et al., 2018; Ismail et al., 2020). The higher value observed in the Soxhlet method may be due to heating during extraction, which can accelerate fat oxidation and the formation of hydroperoxides (Shahidi & Zhong, 2010; Zhuang et al., 2022).

Maggot oil produced by the mechanical pressing method had a composition of 0.54% N, 74.56% C, 10.56% H, 0% S, and 11.59% O, whereas maggot oil produced using the Soxhlet method had a nitrogen (N) content of 0.25%, carbon (C) of 76.82%, hydrogen (H) of 11.23%, sulfur (S) of 0%, and oxygen (O) of 11.21%. The high carbon and hydrogen contents indicate that maggot oil is a lipid-rich material with potential for energy-related applications as well as other bio-based products (Atabani et al., 2012; Demirbaş, 2008; Knothe & Razon, 2017). In addition to influencing the calorific value, the elemental composition reflects the chemical characteristics of the extracted oil and may affect its suitability for downstream industrial and biotechnological applications.

From the CHNS/O ratio obtained, the Higher Heating Value (HHV) can be calculated; this is an important parameter for evaluating the suitability of the oil for use as a biofuel source because it reflects the energy produced during optimal combustion (Abbasi, 2025; Sheng & Azevedo, 2005), is primarily influenced by carbon and hydrogen content, while high oxygen levels can reduce this value (Abbasi, 2025; Sheng & Azevedo, 2005). CHNS/O analysis indicates that the HHV of maggot oil obtained by mechanical pressing is 37.26 MJ/kg, whereas the Soxhlet method yields 38.88 MJ/kg.

The higher HHV in the Soxhlet method is associated with higher carbon and hydrogen content. The higher HHV obtained for Soxhlet-extracted oil is associated with its higher carbon and hydrogen contents, suggesting improved energy density. Nevertheless, the comparable elemental compositions of both oils indicate that each extraction method produces lipid-rich oils with potential for different downstream applications depending on the desired physicochemical properties.

The results show that the density of maggot oil obtained by mechanical pressing was 0.914 ± 0.002 g/mL, whereas that obtained by the Soxhlet method was 0.908 ± 0.0005 g/mL. The density of the oil obtained via the Soxhlet method is more comparable to the typical density of vegetable oils, which ranges from 0.90–0.93 g/mL (Knothe & Razon, 2017; Shahidi & Zhong, 2010).

In addition, the viscosity of maggot oil obtained by mechanical pressing was 0.00257 ± 0.00027 Pa·s, whereas that obtained by the Soxhlet method was 0.00139 ± 0.00004 Pa·s. The viscosity of this oil can be influenced by the carbon-chain length and degree of saturation of the fatty acids that compose it. Fatty acids with longer carbon chains and higher saturation levels tend to increase the oil's viscosity (Knothe & Razon, 2017; Maanari et al., 2023). The compound composition of maggot oil from GC/MS analysis using the mechanical pressing and Soxhlet extraction methods is shown in Table 2.

GC/MS analysis of maggot oil obtained via mechanical pressing revealed that the major detected components were a range of saturated and unsaturated fatty acids, along with glyceride derivatives, which are the primary lipid constituents in *Hermetia illucens* larvae (Makkar et al., 2014; Spranghers et al., 2017). The compound with the highest area percentage was glyceryl trilaurate (22.19%), followed by hexadecanoic acid (16.45%), 11-octadecenoic acid (14.22%), and decanoic acid (12.44%), indicating that maggot oil contains triglycerides and medium- to long-chain fatty acids commonly found in insect lipids (Ismail et al., 2020; Van Huis et al., 2013). Additionally, other compounds were detected, such as 9,12-hexadecadienoic acid (6.29%), octadecanoic acid (3.13%), di-oleoyl-glycerol (9.78%), monostearin (3.03%), and monopalmitin (0.78%), which also indicate the presence of glyceride components and free fatty acids that are the main constituents of the oil (Ismail et al., 2020; Surendra et al., 2016). This composition also indicates that maggot oil obtained by mechanical pressing still contains various complex lipid fractions, such as mono- and diglycerides, because the extraction is performed without solvents, thereby enabling the mechanical separation of lipids from the biomass tissue (Van Huis et al., 2013; Van Huis et al., 2020).

As shown in Figure 1, the chemical group composition further supports this observation. Maggot oil extracted by the Soxhlet method (Figure 4a) was dominated by fatty acids, which accounted for approximately 98.99% of the detected compounds. In contrast, maggot oil obtained by mechanical pressing (Figure 4b) showed a more diverse chemical profile, consisting mainly of fatty acids (59.63%) and complex lipids (35.82%), with smaller contributions from sterols, aldehydes, and fatty alcohols. This indicates that Soxhlet extraction tends to favor the recovery or detection of fatty acid compounds, whereas mechanical pressing retains a broader range of lipid fractions, including glyceride derivatives and minor bioactive components.

Table 2. Chemical composition of maggot oil extracted using two different methods.

No	Compounds	% Area		SI
		Mechanical pressing	Soxhlet	
1	Decanoic acid	12.44	1.18	96
2	Dodecanoic acid	1.55	37.64	97
3	Tetradecanoic acid	2.22	5.86	97
4	Arachidonic acid	1.21	-	86
5	9-Hexadecenoic acid	0.77	-	93
6	Hexadecanoic acid	16.45	21.03	96
7	9,12-Hexadecadienoic acid	6.29	-	95
8	11-Octadecenoic acid	14.22	-	95
9	9-Octadecenoic acid (Z)-	0.69	21.40	96
10	Octadecanoic acid	3.13	4.31	96
11	Di-oleoyl-glycerol	9.78	-	93
12	Monopalmitin	0.76	-	85
13	Monostearin	3.09	-	86
14	10-oxo-octadecanoic acid	0.66	-	87
15	13-Octadecenal, (Z)-	0.80	-	88
16	9,12-Octadecadien-1-ol	1.05	-	88
17	Cholesterol	1.47	-	89
18	Glyceryl trilaurate	22.19	-	85
19	Stigmast-5-en-3-ol, (3.beta.,24S)-	1.23	-	90
20	Phenol, 3,5-bis(1,1-dimethylethyl)-	-	1.00	93
21	9,12-Octadecadienoic acid (Z,Z)-	-	7.58	95

GC/MS analysis of larval oil obtained through Soxhlet extraction revealed that free fatty acids constituted the predominant components, primarily dodecanoic acid (37.64%), (Z)-9-octadecenoic acid (21.4%), and hexadecanoic acid (21.03%), which are the major fatty acids commonly found in *Hermetia illucens* maggot oil. Other compounds were also detected, including tetradecanoic acid (5.86%), octadecanoic acid (4.31%), and 9,12-octadecadienoic acid (7.58%); these results indicate that the larval oil is composed of both long-chain saturated and unsaturated fatty acids (Ismail et al., 2020; Srisuksai et al., 2024). This is due to the effectiveness of the solvent, n-hexane, and the high temperature used to extract and simultaneously break down complex lipids in the larval oil (Azmir et al., 2013; Ismail et al., 2020). Therefore, the Soxhlet method tends to yield a simpler lipid profile dominated by fatty acids, as organic solvents can dissolve triglycerides and separate them from the biomass matrix more effectively than mechanical pressing methods (Bligh & Dyer, 1959).

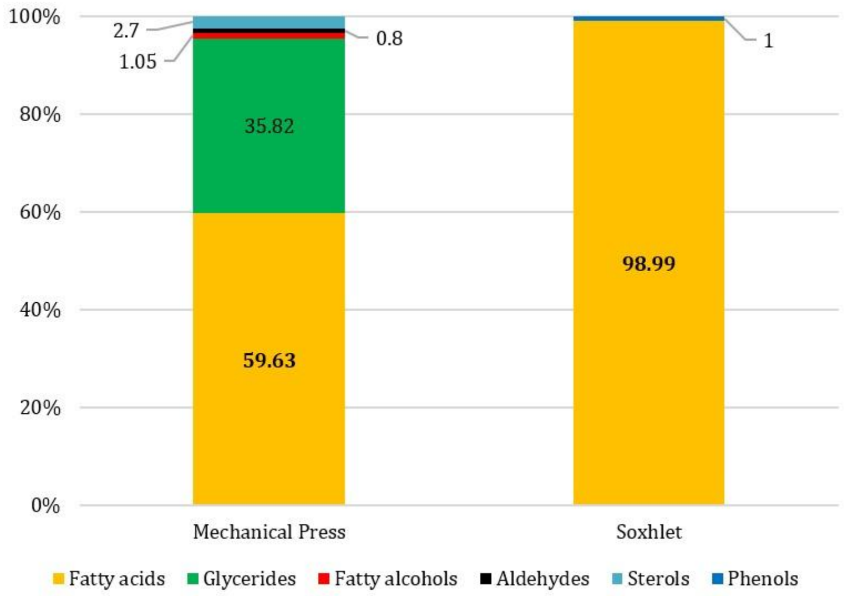

Figure 4. Chemical group composition of maggot oil extracted by (a) the Soxhlet method and (b) mechanical pressing.

Based on the results of maggot oil characterization, maggot oil as a whole shows potential as a potential renewable feedstock for biodiesel production, oleochemical industries, and various biotechnological applications due to its substantial lipid content and abundance of medium-chain saturated fatty acids (Monita et al., 2017). Maggot oil obtained via Soxhlet extraction yields a higher yield due to the superior ability of organic solvents to extract triglycerides more effectively than mechanical pressing, resulting in a fatty acid profile more suitable for conversion into biodiesel (Atabani et al., 2012). The Soxhlet-extracted oil exhibited low moisture content, acid value, and free fatty acid (FFA) levels. These characteristics support the effectiveness of the transesterification process and improve biodiesel quality (Fitria et al., 2025; Meher et al., 2006; Umeh & Okonkwo, 2025). In contrast, mechanical pressing generally results in a lower oil yield while preserves minor compounds and bioactive components, as it does not use chemical solvents or high temperatures (Franco et al.., 2021; Camara-Ruiz et al.., 2023). Therefore, this method is more environmentally friendly and ideal for use in non-energy applications (Azmir et al., 2013; Chia et al; 2018). These minor constituents, including sterols and other bioactive compounds, may have potential applications in oleochemical, cosmetic, and bio-based chemical industries (Shahidi & Zhong, 2010).

Furthermore, differences in lipid composition between mechanically pressed and Soxhlet-extracted oils may also affect their suitability for biotechnological applications. Mechanically pressed oil, which retained a higher proportion of triglycerides and bioactive minor compounds, may be more suitable for the development of nutraceuticals, cosmetics, and lipid-based bioproducts. In contrast, Soxhlet-extracted oil, with its higher free fatty acid content and extraction efficiency, may be advantageous as a feedstock for microbial bioprocesses and enzymatic lipid conversion (Franco et al., 2021; Suryati et al., 2023). Table 3 compares mechanical pressing and Soxhlet extraction in terms of extraction principle, oil yield, processing time, and operating costs, highlighting the main advantages and limitations of each method.

Table 3. Comparison of maggot oil extraction methods.

Aspect	Mechanical pressing	Soxhlet
Extraction principle	Separation of oil using mechanical pressure	Solubilization of lipids using n-hexane through reflux and siphoning
Oil yield	22.45%	34.60%
Time	Relatively short processing time.	Relatively longer processing time due to repeated extraction cycles.
Operating costs	Lower, as only maggots are used as raw material.	Higher, as a solvent must be used

CONCLUSION

The results demonstrated that the Soxhlet method produced a higher maggot oil yield of 34.6%, with a fatty acid profile predominantly composed of dodecanoic acid, 9-octadecenoic acid, and hexadecanoic acid. In addition, its physical properties, particularly density and viscosity, were more comparable to those of conventional oil, suggesting greater suitability for energy-related applications, including biodiesel production, as well as other industrial processes requiring high lipid recovery. In contrast, maggot oil obtained through mechanical pressing yielded a lower oil recovery of 22.45% and was still dominated by triglycerides, including glyceryl trilaurate, hexadecanoic acid, 11-octadecenoic acid, and decanoic acid. This characteristic suggested that it was more suitable for oleochemical, cosmetic, and biotechnological applications or derivative products that require a more environmentally friendly process and the preservation of the natural lipid structure. Overall, the choice of extraction method substantially influenced the yield and lipid composition of *Hermetia illucens* oil, highlighting the importance of selecting an appropriate extraction technique according to the intended downstream application.

REFERENCES

Abbasi, I. (2025). Integrated thermocatalytic and photocatalytic valorization of *Hermetia illucens* biomass for renewable fuel and chemical production. *Cleaner and Circular Bioeconomy, 12,* 100168. https://doi.org/10.1016/j.clcb.2025.100168

Almeida, C., Murta, D., Nunes, R., Baby, A, R., Fernandes, A., Barros, L., Rijo, P., & Rosado, C. (2022). Characterization of lipid extracts from the *Hermetia illucens* larvae and their bioactivities for potential use as pharmaceutical and cosmetic ingredients. *Heliyon, 8*(5), e09455. https://doi.org/10.1016/j.heliyon.2022.e09455

Amrul, N. F., Kabir Ahmad, I., Ahmad Basri, N. E., Suja, F., Abdul Jalil, N. A., & Azman, N. A. (2022). A review of organic waste treatment using Black Soldier Fly (*Hermetia illucens*). *Sustainability*, *14*(8), 4565. https://doi.org/10.3390/su14084565

Amaryllis, A. R., Aflah, A. T., Vera, N., Erwanto, Y., Utama, D. T., & Abidin, M. Z. (2024). Quality and oxidative stability of tallow extracted by dry- and wet-rendering. *Indonesian Food Science and Technology Journal,* *8*(1), 36–42. https://doi.org/10.22437/ifstj.v8i1.32528

AOAC International. (2023). *Official Methods of Analysis of AOAC INTERNATIONAL (22nd ed.). Official Method 985.19: (Apparent) Weight per Unit Volume and Specific Gravity of Fats and Oils: Pycnometer Method.* Oxford University Press. https://doi.org/10.1093/9780197610145.003.3491

Arachchige, A. M. M., Williams, M., Fernando, W. M. A. D. B., Karnpanit, W., Lumanlan, J., & Jayasena, V. (2025). The impact of solvent extraction and enzyme-assisted extraction on the yield and quality of black soldier fly larvae (*Hermetia illucens*) oil. *International*

Journal of Food Science and Technology, *60*(1), 1-10. https://doi.org/10.1093/ijfood/vvaf088

ASTM International. (2016). *ASTM D5291-16: Standard test methods for instrumental determination of carbon, hydrogen, and nitrogen in petroleum products and lubricants.* ASTM International.

Atabani, A. E., Silitonga, A. S., Badruddin, I. A., Mahlia, T. M. I., Masjuki, H. H., & Mekhilef, S. (2012). A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews,* *16*(4), 2070–2093. https://doi.org/10.1016/j.rser.2012.01.003

Azmir, J., Zaidul, I. S. M., Rahman, M. M., Sharif, K. M., Mohamed, A., Sahena, F., Jahurul, M. H. A., Ghafoor, K., Norulaini, N. A. N., & Omar, A. K. M. (2013). Techniques for extraction of bioactive compounds from plant materials: A review*. Journal of Food Engineering*, *117,* 426–436. https://doi.org/10.1016/j.jfoodeng.2013.01.014

Bao, Y., & Pignitter, M. (2023). Mechanisms of lipid oxidation in water-in-oil emulsions and oxidomics-guided discovery of targeted protective approaches. *Comprehensive Reviews in Food Science and Food Safety*, *22*(4), 2678–2705. https://doi.org/10.1111/1541-4337.13158

Bligh, E. G., & Dyer, W. J. (1959). A rapid method of total lipid extraction and purification. *Canadian Journal of Biochemistry and Physiology*, *37*, 911–917. https://doi.org/10.1139/O59-099

Caligiani, A., Marseglia, A., Leni, G., Baldassarre, S., Maistrello, L., & Dossena, A. (2018). Composition of black soldier fly prepupae and systematic approaches for the extraction of lipids, proteins, and chitin. *Food Research International, 109,* 488. https://doi.org/10.1016/j.foodres.2017.12.012

Camara-Ruiz, M., Sánchez-Venegas, A., Blasco-Lavilla, N., Hernández M. D., Sánchez-Liarte, F., Fernández-Gutiérrez, D., & Lara-Guillén A. J., (2023). Comparative assessment of insect processing technologies for sustainable insect protein production. *Sustainability, 15,* 13735. https://doi.org/10.3390/su151813735

Chew, Z. L., Kua, Y. L., Mah, J. K., Ra, N., Lee, T. Z. E., & Yap, S. K. C. (2025). Temperature-controlled mechanical pressing of black soldier fly larvae (BSFL): Yields and qualities of oil and protein meal. *Journal of the American Oil Chemists' Society*, *102*(10), 1501–1512. https://doi.org/10.1002/aocs.70007

Chia, S. Y., Tanga, C. M., Khamis, F. M., Mohamed, S. A., Salifu, D., Sevgan, S., Fiaboe, K. K. M., Niassy, S., van Loon, J. J. A., & Dicke, M. (2018). Threshold temperatures and thermal requirements of black soldier fly (*Hermetia illucens*): Implications for mass production. *PLOS ONE*, *13*(11). https://doi.org/10.1371/journal.pone.0206097

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science, 30*(2), 219–230. https://doi.org/10.1016/j.pecs.2003.10.004

Demirbaş, A. (2008). Progress and recent trends in biofuels. *Progress in Energy and Combustion Science,* *33*(1), 1–18. https://doi.org/10.1016/j.pecs.2006.06.001

Fitria, M., Alvita, L.R., Putra, F.A., Variyana, Y., & Hanifah, W., (2025). Analysis of process variables effecton the efficiency of soxhletation extraction of larvae oil (*Hermetica illucens)* using response surface methodology. *Indonesian Journal of Chemical Analysis.* *8*(1). https://doi.org/10.20885/ijca.vol8.iss1.art7

Forfang, K., Zimmermann, B., Kosa, G., Kohler, A., & Shapaval, V. (2017). FTIR spectroscopy for evaluation and monitoring of lipid extraction efficiency for oleaginous fungi. *PLOS One*, *12*(1). https://doi.org/10.1371/journal.pone.0170611

Fornari, T., Vázquez, L., Villanueva-Bermejo, D., Hurtado-Ribeira, R., Hernández, D. M., & Martin, D. (2023). Effect of moisture and oil content in the supercritical CO_2 defatting of *Hermetia illucens* larvae. *Foods,* *12*(3), 490. https://doi.org/10.3390/foods12030490

Franco, a., Scieuzo, C.,Salvia, R., Petrone, A.M., Tafi, E., Moretta, A., Schmitt, E., & Falabella, P., (2021), Lipids from *Hermetia illucens*, an Innovative and Sustainable Source, *Sustainability, 13,* 10198. https://doi.org/10.3390/su131810198

Gunstone, F. D. (Ed.). (2011). *Vegetable oils in food technology: Composition, properties and uses* (2nd ed.). Wiley-Blackwell. https://doi.org/10.1002/9781444339925

International Organization for Standardization. (1983). *ISO 660:1983 Animal and vegetable fats and oils—Determination of acid value and of acidity.* Geneva, Switzerland: ISO.

International Organization for Standardization. (2020). *ISO 3657:2020 Animal and vegetable fats and oils—Determination of saponification value.* Geneva, Switzerland: ISO.

Ismail, N., Kamal, M. F. M., & Ya, K., (2020), Antioxidant activities of threadfin bream (*Nemipterus japonicus*) hydrolysate and its effect on oxidative stability of frying oil. *Scientific Research Journal*. *17*(2), 129-148. https://doi.org/10.24191/srj.v17i2.7707

Ishak S., Kamari A., Yusoff S., & Halim A. (2018). Optimisation of biodiesel production of Black Soldier Fly larvae rearing on restaurant kitchen waste, *Journal of Physics: Conf. Series, 1097,* 012052. https://doi.org/10.1088/1742-6596/1097/1/012052?utm

Kim, T.-K., Lee, J.-H., Yong, H. I., Kang, M, C., Cha, J. Y., Chun, J. Y., & Choi, Y, S. (2022). Effects of defatting methods on the physicochemical properties of proteins extracted from Hermetia illucens larvae. *Foods*, *11*(10), 1400. https://doi.org/10.3390/foods11101400

Knothe, G. (2005). Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. *Fuel Processing Technology*, *86*(10), 1059–1070. https://doi.org/10.1016/j.fuproc.2004.11.002

Knothe, G., & Steidley, K. R. (2005). Kinematic viscosity of biodiesel fuel components and related compounds. *Fuel, 84*(9), 1059–1065. https://doi.org/10.1016/j.fuel.2005.01.016

Knothe, G., & Razon, L. F. (2017). Biodiesel fuels. *Progress in Energy and Combustion Science*, *58,* 36–59. https://doi.org/10.1016/j.pecs.2016.08.001

Kumar, M., Singh, V. K., Ravi, R., Verma, V., Arora, A., Alam, T., Yadav, A., & Sharma, A. (2024). Biodiesel production from microalgae oils: A critical review. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 240*(2). https://doi.org/10.1177/09544089241251775

Laroche, M., Perreault, V., Marciniak, A., Gravel, A., Chamberland, J., & Doyen, A. (2019). Comparison of conventional and sustainable lipid extraction methods for the production of oil and protein isolate from edible insect meal. *Foods, 8*(11), 572. https://doi.org/10.3390/foods8110572

Lawal, K. G., Kavle, R. R., Akanbi, T. O., Mirosa, M., & Agyei, D. (2022). Lipid nutritional indices, regioisomeric distribution, and thermal properties of Tenebrio molitor and *Hermetia illucens* larvae fat. *Journal of Asia-Pacific Entomology*, *25*(3), 101951. https://doi.org/10.1016/j.aspen.2022.101951

Li, X., Dong, Y., Sun, Q., Tan, X., You, C., Huang, Y., & Zhou, M. (2022). Growth and fatty acid composition of Black Soldier Fly *Hermetia illucens* (Diptera: Stratiomyidae) larvae are influenced by dietary fat sources and levels. *Animals,* *12*(4), 486. https://doi.org/10.3390/ani12040486

Li, Q., Zheng, L., Qiu, N., Cai, H., Tomberlin, J. K., & Yu, Z. (2011). Bioconversion of dairy manure by *Hermetia illucens* larvae: Reduction of waste and biodiesel production. *Waste Management, 31*(6), 1316–1320. https://doi.org/10.1016/j.wasman.2011.01.005

Lin, C, Y., & Ma, L. (2022). Effects of water removal from palm oil reactant by electrolysis on the fuel properties of biodiesel. *Processes*, *10*(1), 115. https://doi.org/10.3390/pr10010115

Maanari, C. P., Gugule, S., Fatimah, F., Utami, A. R. P., Mustapa, M., Rumengan, S. M., Jannah, M., Akbar, J. S., & Rintjap, D. S. (2023). Effect of potassium hydroxide concentration as a catalyst on the yield of coconut oil (*Cocos nucifera*) transesterification. *Indonesian Journal of Pure and Applied Chemistry*, *6*(3), 142–150. https://doi.org/10.26418/indonesian.v6i3.65513

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. *Journal of the American Oil Chemists' Society, 96*(11), 1303–1311. https://doi.org/10.1002/aocs.12263

Makkar, H. P. S., Tran, G., Heuzé, V., & Ankers, P. (2014). State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology*, *197,* 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Meher, L. C., Vidya Sagar, D., & Naik, S. N. (2006). Technical aspects of biodiesel production by transesterification—A review. *Renewable and Sustainable Energy Reviews*, *10*(3), 248–268. https://doi.org/10.1016/j.rser.2004.09.002

Mohamed, H., Marusich, E., Afanasev, Y., & Leonov, S. (2021). Fatty acids-enriched fractions of *Hermetia illucens* (Black soldier fly) larvae fat can combat MDR pathogenic fish bacteria *Aeromonas spp. International Journal of Molecular Sciences,* *22*(16), 8829. https://doi.org/10.3390/ijms22168829

Monita, L., Sutjahjo, S, H., Amin, A, A., Rini, M., & Fahmi. (2017), Urban organic waste processing using black soldier fly larvae (*Hermetia illucens). Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan. 7*(3), 227-234. https://doi.org/10.29244/jpsl.7.3.227-234

Muangrata, R., & Pannasai, S. (2024). Exploring the potential of black soldier fly larvae oil: Supercritical CO_2 extraction, physicochemical analysis, antioxidant properties, shelf life, and keratinocyte growth inhibition. *Journal of Agriculture and Food Research*, *15,* 101008. https://doi.org/10.1016/j.jafr.2024.101008

Nugroho R, A., Aryani R., Manurung H., Sari W., Sanjaya A, S., Suprihanto D., & Rudianto, P, W. (2022). *Maggot dan lalat tentara hitam.* PT Insan Cendekia Mandiri Group.

Pietri, P., Georgiopoulos, G., & Stefanadis, C. (2021). The prognostic role of triglycerides should be revisited. *Journal of the American College of Cardiology, 77(14),* 1840–1841. https://doi.org/10.1016/j.jacc.2020.12.068

Purbaningtias, T. E., & Sandy. (2024). Evaluation of ethanol grade on the robustness of acid number determination in fish oil. *Indonesian Journal of Chemical Analysis,* *7*(2), 237–244. https://doi.org/10.20885/ijca.vol7.iss2.art11

Rehman, K, U., Hollah, C., Wiesotzki, K., Rehman, R, U., Rehman, A, U., Zhang, J., Zheng, L., Nienaber, T., Heinz, V., & Aganovic, K. (2023). Black soldier fly, *Hermetia illucens* as a potential innovative and environmentally friendly tool for organic waste management: A mini-review. *Waste Management & Research*, *41*(1), 81–97. https://doi.org/10.1177/0734242X221105441

Rozali, N, S., Zainuddin, N, A., Yatim, S, R., & Rasdi, W, N. (2022). Study on the extraction of black soldier fly larvae oil. *Journal of Sustainability Science and Management*, *17*(12), 49–66. https://doi.org/10.46754/jssm.2022.12.006

Rusdi, H.O., Kusumaningrum, I. K., Nareswari, T.J., Fauziah, P. N., Maharani, R. N., & Natasya, S. (2024). Separation and determination of free fatty acids in corn oil and palm oil by liquid-liquid extraction and acidi-alkalimetric titration, Walisongo. *Journal of Chemistry*, *7*(1), 098-106. https://doi.org/10.21580/wjc.v7i1.20461

Shahidi, F., & Zhong, Y. (2010). Lipid oxidation and improving the oxidative stability. *Chemical Society Reviews, 39*, 4067–4079. https://doi.org/10.1039/B922183M

Sheng, C., & Azevedo, J. L. T. (2005). Estimating the higher heating value of biomass fuels from basic analysis data. *Biomass and Bioenergy,* *28*(5), 499–507. https://doi.org/10.1016/j.biombioe.2004.11.008

Spranghers, T., Ottoboni, M., Klootwijk, C., Ovyn, A., Deboosere, S., De Meulenaer, B., Michiels, J., Eeckhout, M., De Clercq, P., & De Smet, S. (2017). Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. *Journal of the Science of Food and Agriculture*, *97*(8), 2594–2600. https://doi.org/10.1002/jsfa.8081

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

Sui, H., Shao, J., Agblevor, F. A., Zhang, Y., Wang, X., Yang, H., & Chen, H. (2023). Fractional condensation and aging of pyrolysis oil from cotton stalk. *Biomass and Bioenergy, 174,* 106837. https://doi.org/10.1016/j.biombioe.2023.106837

Surendra, K. C., Olivier, R., Tomberlin, J. K., Jha, R., & Khanal, S. K. (2016). Bioconversion of organic wastes into biodiesel and animal feed via insect farming: A review. *Renewable Energy, 98,* 197–212. https://doi.org/10.1016/j.renene.2016.03.022

Suryati, T., Julaeha, E., Farabi, K., Ambarsari, H., & Hidayat, T. (2023). Lauric acid from the black soldier fly (*Hermetia illucens*) and its potential applications. *Sustainability, 15*(13). https://doi.org/10.3390/su151310383

Tzompa-Sosa, D. A., Yi, L., van Valenberg, H. J. F., van Boekel, M. A. J. S., & Lakemond, C. M. M. (2014). Insect lipid profile: aqueous versus organic solvent-based extraction methods. *Journal of Insect Science*, *62,* 1087-1094. https://doi.org/10.1016/j.foodres.2014.05.052

Umeh, S. I., & Okonkwo, P. A. (2025). The essential properties of oils for biodiesel production. In *Biodiesel plants – fueling the sustainable outlooks*. IntechOpen. https://doi.org/10.5772/intechopen.1008694

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). *Edible insects: future prospects for food and feed security*. FAO Forestry.

Van Huis, A. (2020). Insects as food and feed, a new emerging agricultural sector: A review. *Journal of Insects as Food and Feed, 6*(1), 27–44. https://doi.org/10.3920/JIFF2019.0017

Wang, Y.-S., & Shelomi, M. (2017). Review of black soldier fly (*Hermetia illucens*) as animal feed and human food. *Foods, 6*(10), 91. https://doi.org/10.3390/foods6100091

Zhuang, Y., Dong, J., He, X., Wang, J., Li, C., Dong, L., Zhang Y., Zhou, X., Wang, H., Yi, Y., & Wang, S. (2022). Impact of heating temperature and fatty acid type on the formation of lipid oxidation products during thermal processing. *Frontiers in Nutrition, 9,* 913297. https://doi.org/10.3389/fnut.2022.913297