Exploring Black Soldier Fly Larvae as a Sustainable Biodiesel Source with Base Catalysts: An Analytical and Characterization Study

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Abstract. As the world seeks sustainable alternatives to conventional fuels, biodiesel emerges as a promising renewable energy source. Black Soldier Fly Larvae (BSFL), with a remarkable 30-40% lipid content and waste-reduction capabilities, represents an intriguing prospect for biodiesel production. Importantly, the cultivation of BSFL addresses the critical concern of balancing food production and fuel generation. This research investigates biodiesel synthesis from BSFL oil, utilizing two distinct base catalysts: NaOH and KOH. Biodiesel yields of 92.71% w/w and 90.97% w/w were achieved with KOH and NaOH, respectively. Furthermore, the resulting biodiesel complied with stringent calorific value and quality standards such as density, viscosity, FAME value, and carbon residue outlined in national regulations. These findings underscore the potential of BSFL as a sustainable and viable biodiesel source. Leveraging BSFL for biodiesel production not only contributes to cleaner energy but also addresses waste management challenges, propelling toward a greener and more sustainable future.

Keywords: Biodiesel, Black Soldier Fly Larvae, Base Catalyst, Biofuel Quality, Sustainable Energy Source

1 Introduction

The World Energy Statistics 2019 indicate a substantial 50% surge in global fossil energy consumption over the past two decades. Data from crude oil consumption in 2000 at 8.1 million tons rose to 11.7 million tons in 2018, thereby creating a disparity between energy demand and availability [1]. This heightened demand for fossil energy has led to significant carbon dioxide

RESILIENCE 2023, November 24, Jakarta, Indonesia

DOI 10.4108/eai.24-11-2023.2346539

(CO_2) emissions, posing environmental challenges worldwide. As a mitigation strategy, the International Energy Agency (IEA) has set a target to reduce CO_2 emissions by 70% before 2060 [2]. Notably, approximately 40% of global fossil energy is utilized for transportation, with the transportation sector alone accounting for 96% of national fossil energy consumption [1,3]. To curb this, it is imperative to begin adopting new renewable energy sources with lower emission levels to replace traditional transportation fuels.

Biodiesel has emerged as a promising alternative, boasting high combustion efficiency, minimal CO_2 emissions, and low sulfur content [4]. While 95% of the world's biodiesel supply is derived from vegetable lipids, the high production costs associated with extensive agricultural land use and competition for food resources remain concerning [5]. Recent studies have highlighted varying biodiesel yields from different feedstocks, with used cooking oil using NaOH as a catalyst yielding 98.87% w/w, while the yield from soybean is reported at 86.8% w/w, and that from German caterpillar animal fat stands at 55% w/w [5,6,7,8].

Black soldier fly (BSF) larvae, known scientifically as Hermetia illucens, have emerged as a promising feedstock for biodiesel production, offering a dual function as a potential source of biodiesel and as an effective organic waste reduction technology for organic waste decomposition [9]. The rapid metabolism of BSF larvae enables the conversion of carbohydrates and fat from organic waste into significant lipid deposits within its body [10]. Notably, the lipid content in BSF larvae surpasses that of soybean and palm oil, with its fat content ranging between 30% and 40%, compared to 18% and 36% in soybean and palm oil, respectively [11].

In the context of biodiesel production, this research employs the indirect transesterification method, involving extraction, esterification with sulfuric acid catalyst (H_2SO_4), and the use of potassium hydroxide (KOH) and sodium hydroxide (NaOH) as base catalysts in transesterification. The choice of the indirect transesterification method is driven by its ability to yield higher content and its minimal potential for saponification reactions, in contrast to the direct transesterification method, which yields only 30% and is prone to saponification reactions [12]. This study delves into an in-depth exploration of the impact of KOH and NaOH catalysts on yield, the characteristics of biodiesel based on FAME values, and the quality of biodiesel derived from BSF larvae oil, all in accordance with the quality standards outlined in the Directorate General of EBTKE Decree No. 189/2019.

2 Materials and Methods

2.1 Extraction

The process of extracting oil and fat from the BSFL was carried out under optimized conditions as stated by (Park, et al, 2022) The BSFL samples were initially oven-dried for 48 hours at 105°C to remove any residual water content. Subsequently, the oil extraction from BSFL was achieved using the soxhlet extraction method with the use of n-hexane solvent. The ratio between the n-hexane and BSFL powder was maintained at 5:1 (ml/g). A notable indicator of the completion of the extraction process was the complete clarity of the solvent observed in the siphon tube.

2.2 Esterification

The extracted BSFL oil was subjected to pre-treatment to reduce the percentage of Free Fatty Acids (FFA). This pre-treatment step was essential to prevent any saponification reactions during the subsequent transesterification process. The esterification process was optimized using methanol as the solvent and H2SO4 as the acid catalyst. The specific weight ratio, in grams, of methanol to BSFL oil and the acid catalyst was denoted as X:Y:Z. The mixture was heated in a round-bottom flask at 50 °C for 60 minutes under a stirring speed of 300 rpm. The resulting esterified oil was promptly separated from the methoxide solution using a centrifuge for the subsequent process.

2.3 Transesterification

The esterified oil was subsequently converted into fatty acid methyl ester (FAME). The oil was mixed with methanol in a 1:6 ratio, utilizing a base catalyst of 0.5% w/w of the esterified oil. Two different types of commercial base catalysts, KOH and NaOH, were employed in the process. The mixtures were heated at 60°C for 60 minutes under stirring at 400 rpm. The final step in the biodiesel synthesis process involved purifying the biodiesel through a washing procedure with distilled water at 50°C, maintaining a 2:1 v/v ratio [15].

The obtained biodiesel was characterized, analyzed, and compared with the Indonesian biodiesel quality standard specified by the Directorate General of EBTKE Decree No. 189/2019. The yield measured by equation 1 is standardized to Standar EN 14103:2020 – Fatty Acid Methyl Ester:

$$\textit{Crude}\ \text{biodiesel}\ (\%) = \frac{W_A}{W_B} \times 100 \tag{1}$$

Description:

W_A : Weight of crude biodiesel after reaction (mg)

W_B : Weight of crude biodiesel before reaction (mg)

W : Weight of crude biodiesel (mg)

The density value, which is one of the quality standard parameters of biodiesel according to SNI 04-7182-2015, was determined using a picnometer at a biodiesel temperature of 40°C.

$$\rho_{\text{bio}} = \frac{\text{mass}_{\text{pycno+bio}} - \text{mass}_{\text{pycno}}}{\text{volume pycno}} \tag{2}$$

Description:

$\text{Mass}_{\text{pycno+bio}}$ = Pycnometer mass + biodiesel mass (g)

$\text{Mass}_{\text{pycno}}$ = Mass of pycnometer before biodiesel filling (g)

$\text{Volume}_{\text{pycno}}$ = Pycnometer volume (mL)

Viscosity, a key quality parameter for biodiesel, was analyzed according to SNI 04-7182-2015 using an Oswalt viscometer at a temperature of 40°C. The equation used to determine the viscosity value is as follows:

$$\eta_{Biodiesel} = \frac{\rho_{biodiesel} \times t_{Average\ Biodiesel}}{\rho_{water} \times t_{Average\ water}} \times \eta_{Water} \quad (3)$$

Description:

$\eta_{biodiesel}$ = Viscosity of biodiesel (cP)

$\rho_{biodiesel}$ = Density of biodiesel (g/mL)

ρ_{water} = Density of water (g/mL)

$t_{Average\ biodiesel}$ = Average time biodiesel flows (s)

$t_{Average\ water}$ = Average time water flows (s)

η_{water} = Viscosity of water (cP)

3 Results and Discussions

3.1 BSF Larvae's Dual Role: Lipid Source and Organic Waste Reduction

Black soldier fly (BSF) larvae serve a dual purpose, acting as a source of lipids for biodiesel production and effectively reducing organic waste by up to 80%. In this study, 4.60 kg of BSF larvae were processed, resulting in a dry weight of 1.43 kg, which in turn produced 319.5 g of biodiesel. Figure 1 illustrates the capability of BSF larvae in reducing organic waste by 80%. Considering the organic waste generation of 31.6 kg, BSF larvae can effectively reduce it by 80%, indicating that 4.60 kg of BSF larvae can potentially degrade 25.3 kg of organic waste. The mass balance of organic waste to biodiesel by BSFL is provided in **Figure 1**.

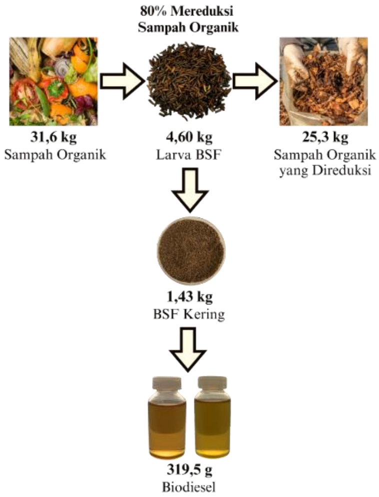


Fig. 1. Estimation of Mass Balance of Organic Waste to Biodiesel Derived from BSFL

3.2 Extraction Process

Before the oil extraction process, BSFL was dried and subsequently pulverized into powder to enhance the extraction efficiency. **Figure 2** illustrates the various stages, depicting BSFL larvae before drying (a), BSFL after drying (b), and BSFL powder (c).

(a) **(b)** **(c)**

Fig. 2. Black Soldier Fly Larvae

(a) BSFL before drying (raw), (b) BSFL after drying, (c) BSFL powder

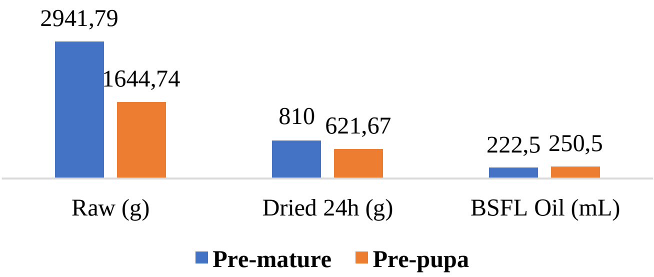


Fig. 3. The Extraction Chart of BSFL Oil

During the premature phase, BSFL underwent a 72.46% shrinkage from raw weight to dry weight, whereas the pre-pupa phase experienced a mass shrinkage of 62.20%. Subsequently, both BSFL phases yielded a combined total of 473 mL of extracted oil. As depicted in **Figure 3**, the pre-pupa phase exhibited a higher lipid content, ranging from 28% to 35%, compared to the premature phase, which displayed a lipid content of 9.4% from raw material BSFL [17].

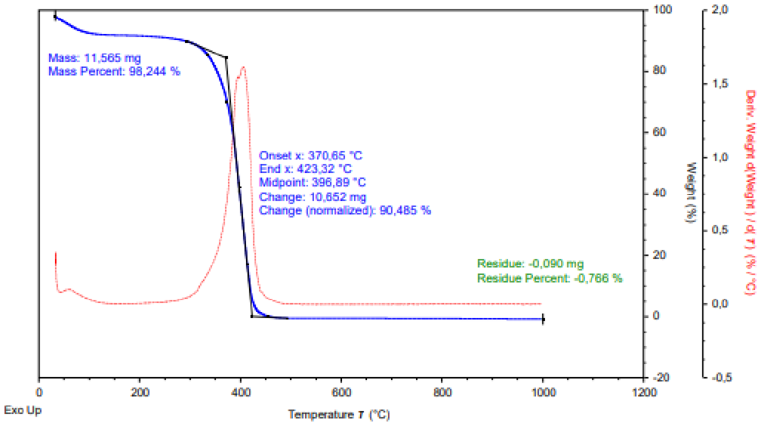


Fig. 4. The TGA Curve of Extracted BSFL Oil

The extracted BSFL oil was analyzed using the Thermogravimetric Analysis (TGA) method with the Mettler Toledo Thermal Analysis DSC (Fisher Scientific, Pennsylvania of United State), operating within a temperature range of 25°C to 1000°C. The TGA curve of BSFL oil is depicted in **Figure 4**. A minor water loss of approximately 2% was observed around 100°C, while significant degradation of over 90% occurred between 370°C and 450°C. At temperatures exceeding 450°C, all organic substances decomposed until reaching the final temperature, resulting in zero remaining mass.

3.3 Esterification Process

Biodiesel derived from BSFL oil undergoes a series of processes and must meet specific qualification requirements before it can be utilized as biodiesel. Oil with an FFA content of less than 2% does not require esterification with an acid catalyst. However, previous research has indicated that the BSFL oil has an FFA value of 3.7%, necessitating an esterification process. This process is implemented to prevent saponification during the transesterification process using a base catalyst.

(a) **(b)** **(c)** **(d)**

Fig. 5. The Product Obtained during the Esterification Process of BSFL Oil

(a) BSFL Oil, (b) Esterified Oil, (c) Esterified Glycerol, (d) Esterified Residue

Figure 5 illustrates the by-products generated during the acid pre-treatment process, including glycerol and esterification residue. During the separation process, three distinct layers were formed: the uppermost layer consisting of esterified oil, the second layer comprising blackbrown liquid glycerol, and the bottom layer comprising black-brown solid esterified residue.

Table 1. Esterified BSFL Oil Yield

Run.	BSFL Oil (g)	H_2SO_4 (g) 3% w/w	Esterified Oil (g)	Yield (%)	Average Yield (%)
1	60	1.8	49.32	82.20	
2	60	1.8	53.42	89.00	86.38 ± 3.66
3	60	1.8	52.75	87.92	

The average yield of esterified BSFL oil was 86.38%, with the remaining by-products consisting of glycerol and esterification residue.

3.4 Transesterification Process

The yield of the transesterification process is influenced by several factors, particularly the catalyst concentration, temperature, reaction time, and stirring speed. This study compares the biodiesel production from BSFL oil using two base catalysts, namely KOH and NaOH.

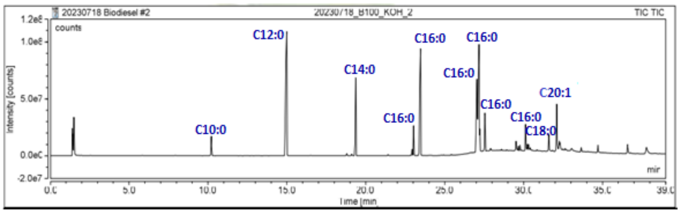
Table 2. Biodiesel Yield Using. KOH and NaOH catalysts

The Catalyst Type	Ratio of Oil : Methanol (w/w)	Esterified Oil (g)	Amount of Catalyst (0.5% w/w)	Transesterified Oil (g)	Yield (%)	Average Yield (%)
		60	0.3	57.18	95.30	
KOH	1:6	10	0.05	9.02	90.20	92.71 ± 2.55
		12.02	0.06	11.13	92.63	
		60	0.3	57.31	95.52	
NaOH	1:6	10	0.05	8.68	93.20	90.97 ± 2.46
		10	0.05	9.06	90.60	

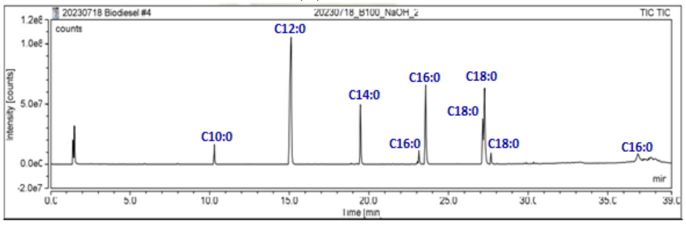
The transesterification employs base catalysts with 0.5% w/w of esterified oil. The biodiesel yield obtained from both NaOH and KOH catalysts is relatively similar, ranging from 90% to 92%, as depicted in the table above.

3.5 Biodiesel Gas Chromatography-Mass Spectrometry (GC-MS) Analysis

The identification of Fatty Acid Methyl Esters (FAME) was conducted using GC-MS (Thermo Fisher Scientific, USA). The GC-MS chromatogram of FAME derived from NaOH and KOH catalysts is presented in **Figure 6**.



(a)



(b)

Fig. 6. GC-MS Chromatograms

(a) KOH based Biodiesel, (b) NaOH based Biodiesel

The analysis revealed a FAME content of 97.89% for KOH-catalyzed FAME, consisting of palmitic acid (47.14%), lauric acid (22.45%), and stearic acid (7.86%). Similarly, NaOHbased FAME exhibited a content of 99.16%, dominated by lauric acid (34.67%), stearic acid (23.40%), and palmitic acid (23.05%). The total FAME content quality standard, as specified in Director General of EBTKE Decree No.189/2019, stipulates a minimum FAME value of 96.5%. Consequently, the GC-MS analysis indicates that both KOH-catalyzed and NaOHcatalyzed biodiesel meet the required standards.

3.6 Biodiesel Density

The density is one of the essential parameters for determining biodiesel standards. The results of the density values for biodiesel derived from BSFL oil using KOH and NaOH catalysts are as follows:

Table 3. Density of Biodiesel with KOH Catalyst and NaOH Catalyst (40°C)

The Catalyst Type	Empty Pycnometer Mass (g)	Filled Pycnometer Mass (g)	Density (kg/m^3)	Average Density (kg/m^3)	Standard Decree of Director General of EBTKE No. 189/2019 (kg/m^3)	Description
KOH	48.86	58.64	851.06	851.69 ± 0.55	850 - 890	Qualified
	48.87	58.67	851.90			
	48.54	58.34	852.11			
NaOH	48.55	58.73	885.17	885.71 ±0.46		Qualified
	48.55	58.73	885.91			
	48.55	58.74	886.04			

The density tests were conducted in accordance with the SNI 04-7182-2015 Biodiesel standard, with measurements taken at 40°C. The average density values obtained with KOH and NaOH catalysts were 851.69 kg/m^3 and 885.71 kg/m^3, respectively. The biodiesel density standard, as outlined in Director General of EBTKE Decree No. 189/2019, ranges from 850 to 890 kg/m^3. Thus, it can be concluded that biodiesel produced with both KOH and NaOH catalysts meets the specified biodiesel quality standards.

3.7 Viscosity of Biodiesel

Viscosity plays a critical role in engine performance, as high viscosity can hinder fuel flow, resulting in increased strain on the diesel engine. Viscosity also influences the flash point blackout and the emission levels of the engine. The viscosity values of biodiesel derived from BSFL oil using KOH and NaOH catalysts are as follows:

Table 4. Viscosity of Biodiesel with KOH Catalyst and NaOH Catalyst (40°C)

Name of Sample	**Flow Time (s)**	**Viscosity (cSt)**	**Average Viscosity (cSt)**	**Standard Decree of Director General of EBTKE No.189/2019 (cSt)**	**Description**
BSFL Oil	2,312.21 2,418.05 2,358.54	19.83 20.74 20.23	20.26 ± 0.45	-	-
KOH Catalyzed Biodiesel	376.80 380.05 374.40	3.32 3.26 3.21	3.23 ± 0.02	2.3 – 6.0	Qualified
NaOH Catalyzed Biodiesel	395.55 395.49 398.67	3.39 3.39 3.42	3.40 ± 0.01	2.3 – 6.0	Qualified

The biodiesel viscosity test was conducted using an Ostwald Viscometer based on the SNI 047182-2015 Biodiesel testing standard. The viscosity value of biodiesel from used cooking oil with the NaOH catalyst ranged from 3.16 to 3.07 cSt. BSFL oil exhibited a viscosity value of 20.26 cSt, while KOH and NaOH catalyzed biodiesel demonstrated viscosity values of 3.23 cSt and 3.40 cSt, respectively. The viscosity standard for biodiesel ranges from 2.3 to 6.0 cSt. Therefore, it can be concluded that biodiesel produced with both KOH and NaOH catalysts adheres to the specified quality standards.

3.8 TGA Analysis of Biodiesel

The following are comparative results from TGA testing conducted on biodiesel with KOH and NaOH catalysts:

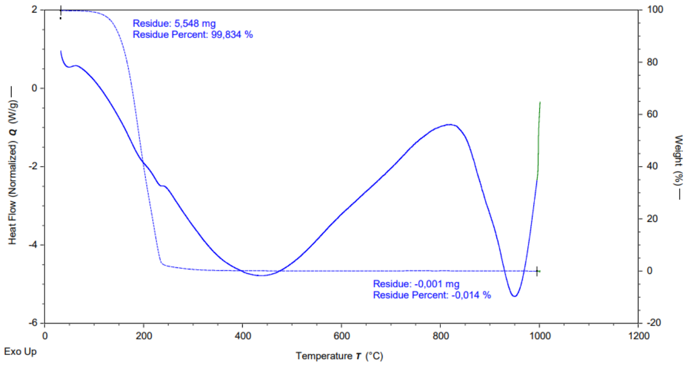


Fig. 8. The TGA curve of biodiesel with KOH catalyst.

Both TGA curves exhibit similar patterns, demonstrating relative stability up to 100℃ and showing zero remaining residue. These results indicate that the biodiesel meets the standard for residue content, where the maximum limit is 0.3%.

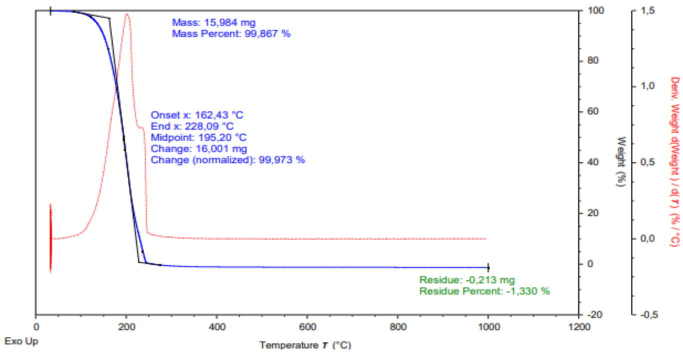


Fig. 9. The TGA curve of NaOH-catalyzed biodiesel

3.9 Calorific Value of Biodiesel

Calorific value testing was conducted based on ASTM D-240 test standards using a Parr Bomb Calorimeter 6400. The following are the calorific values of biodiesel from BSFL oil with KOH and NaOH catalysts:

Table 5. Calorific Value of Biodiesel with KOH Catalyst and NaOH Catalyst

The Catalyst Type	Analyzed Value (Cal/g)	Analyzed Value (kJ/kg)	Solar Calorific Value (kJ/kg)[26]	Commercial B100 Calorific Value (kJ/kg)[27]
KOH	9,245.16	38,681.74	41,200	36,153.944
The Catalyst Type	**Analyzed Value (Cal/g)**	**Analyzed Value (kJ/kg)**	**Solar Calorific Value (kJ/kg)[26]**	**Commercial B100 Calorific Value (kJ/kg)[27]**

NaOH	9,235.98	38,643.34	41,200	36,153.944

The calorific value serves as a parameter for comparing the quality of biodiesel and fossil diesel. In the case of biodiesel derived from used frying oil, the reported calorific value is 37,200 kJ/kg, which is lower than that of fossil diesel at 41,200 kJ/kg. According to Pertamina Corporation, Indonesia, the biodiesel standard (B100) is 36,153.944 kJ/kg. Table 5 shows the calorific value of biodiesel from BSFL oil with KOH and NaOH catalysts, which are 38,681.74 kJ/kg and 38,643.34 kJ/kg, respectively. Referring to the standard (B100) by PT Pertamina Corporation, Indonesia, the calorific value of biodiesel from BSFL oil meets the requirements for use as diesel engine fuel. Additionally, the obtained biodiesel still exhibits a higher calorific value than the reported frying oil.

4. Conclusion

The successful extraction of BSFL oil and its subsequent conversion into biodiesel were achieved. The experiment, varying catalysts using KOH and NaOH, resulted in yields of 92.71% and 93.11%, respectively. GC-MS testing to determine the FAME content revealed that KOH and NaOH-catalyzed biodiesel exhibited FAME contents of 97.89% and 99.16%. The quality analysis of biodiesel with KOH and NaOH catalysts demonstrated an average density value of 851.69 kg/m^3 and 885.71 kg/m^3, while the viscosity values were 3.23 cSt and 3.40 cSt, respectively. The carbon residue parameter of biodiesel with both catalysts was nearly zero. Furthermore, the calorific values for each biodiesel were determined to be 38,681.74 kJ/kg and 38,643.34 kJ/kg, fulfilling the requirements for use as diesel engine fuel. All parameters tested for both types of biodiesel met the quality standards outlined in Director General of EBTKE Decree No. 189/2019.

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