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New Approach to Improving Fuel and Combustion Characteristics of Black Soldier Fly Oil

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This study proposes a new approach to improve the fuel properties of Black Soldier Fly crude oil (BSFO) by blending it with diethyl ether (DEE). DEE was chosen due to its ideal characteristics such as its low viscosity and high Derived Cetane Number (DCN = 139). Additionally, its low boiling point also improves the fuel spray and evaporation of the blend. At a constant temperature of 40 ℃, comparing pure BSFO to a 40 % DEE to BSFO blend, the kinematic viscosity reduced from 29.76 mm^2/s to 3.14 mm^2/s and the DCN increased from 59.6 to 99.3. The basic fuel properties of Black Soldier Fly (BSF) biodiesel blended with US No. 2 diesel, B5, B15, B25, and B50 (FAME volume percentage) were also compared with BSFODEE mixtures. BSFODEE40 % has the potential to meet the fuel standards specified by the American Society for Testing and Materials (ASTM) standards D6751.

1. Introduction

Recently, there has been an increased interest in biomass conversion derived from insects, especially the widely spread Black Soldier Fly or Hermetia Illucens. The BSF is an ideal candidate because it contains an abundant amount of oil, 15.5% - 34.8 wt. % (Manzano-Agugliaro et al., 2012). Another advantage of the BSF is that on top of being used for biofuel production, they can also be used for waste management during their larval growth cycle (Craig Sheppard et al., 1994; Leong et al., 2016; Li et al., 2011; Newton et al., 2005; Surendra et al., 2016; Zheng et al., 2012). The Life Cycle Assessment of BSFO production indicates great potential for the reduction of greenhouse gas emissions (Salomone et al., 2017).

BSFO contains a relatively high concentration, 67 % of total fatty acids, of medium chain saturated fatty acids (C12:0 – C16:0) (Ramos et al., 2009). Due to its high viscosity and free fatty acid (FFA) content, recent studies have focused on improving the fuel quality of BSFO by transesterification coupled with both acid-catalysed esterification and lipase-catalysed transesterification (Leung et al., 2009; Nguyen et al., 2017). Varying the BSF's food sources alter the characteristics of the BSFO and its resultant biodiesel (Fatty Acid Methyl Ester, FAME) profile, which meets the European biodiesel standard, EN14214 (Li et al., 2011; Zheng et al., 2012).

Blending FAME with conventional diesel neutralizes carbon dioxide emissions, improves lubricity, increases nitrogen oxide, and reduces the formation of carbon monoxide, noxious unburned hydrocarbons, and particulate matters. Two-step esterification has been widely accepted in the industry but biodiesel production issues with crude oil pre-treatment, water consumption during biodiesel washing, and catalysis recycling have proven to be a concern. Lipase-catalysed transesterification can not only solve catalysis recycling problems but also reduce water usage whereas expensive lipase catalysis hinders its industry applications (Meher et al., 2006). As a result, recent studies have considered fuel blending as an alternative strategy to obtain cleaner-burning fuels with satisfactory properties (Ribeiro et al., 2007).

BSFO has ideal burning properties like other animal fats and fish oil (Bardone et al., 2014). However, due to its high viscosity, the direct use of BSF crude oil in an engine can inflict long-term durability problems such as soot deposition on and inside the injectors, piston ring sticking, and lubricant oil contamination (Ma and Hanna, 1999). Blending less viscous fuels with the crude oil, such as alcohol, carbonate ester, and ether was conducted in an effort to solve the aforementioned problems. These blends' key properties such as energy content, ignition quality and blend stability were analysed to determine their affects (Hansen et al., 2004). This

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was done because the addition of DEE to crude vegetable oil was found to not only improve its ignition quality and viscosity but to also lower its NOx and total hydrocarbon formation in a Compression Ignition engine, analogous to the fuel quality modification by transesterification process (Vedharaj et al., 2016). No study has yet explored the potential of various blends of BSFO with other solvents.

In this paper, the blending effects on various fuel properties such as ignition quality and kinematic viscosity at 40 °C were highlighted. Initially, BSFO was converted to FAME by acid-catalysed esterification and base-catalysed transesterification and its FAME chemical composition profile was analysed in a gas chromatography–mass spectroscopy (GC–MS) coupled with a flame ionization detector (FID). As per ASTM standards, important fuel properties, such as density, flash point, boiling points, ignition quality and kinematic viscosity at 40 ℃ were determined. Various biodiesel binary mixtures in conventional diesel were compared with BSFO-DEE blends. Both biodiesel mixtures and BSFO-DEE blends were prepared at different volume percentages. The mixtures prepared were B5, B15, B25 and B50, whereas the DEE blends prepared were BSFODEE10, BSFODEE20, and BSFODEE40.

2. Methodology

2.1 Fuel blend preparation

The Black Soldier Flies were grown and sourced from Agriprotein, located in South Africa. The new-born BSF larvae were fed with pre-consumer waste consisting of expired fruits, vegetables, and various types of organic foods. They were collected as they turned into prepupae after rearing for approximately 7 to 14 days. The BSF prepupae were preliminarily dried and the crude fat was extracted using petroleum as a solvent. At room temperature (25℃), the extracted BSF crude oil appears as a greasy viscous solid yellow fat.

To produce BSF biodiesel, melting the solid BSF crude fat at approximately 30℃ ensured a homogeneous solution for the reactions carried out in following steps. The BSF free fatty acid content was determined by titration with a 0.1 % NaOH solution as biomasses with a high acid value (more than 3 %) require pretreatment for FFA conversion by acid-catalyzed esterification (M. P. Dorado et al., 2002). With a 4:1 methanol to fat ratio, a 1 % by weight sulfuric acid in methanol solution was used for the esterification process. The reaction was conducted at 75 ℃ with 1-hour reaction time. The bottom layer, consisting of the remaining tri-, di-, and mono-glycerides were transferred into a new reactor for alkaline-catalyzed transesterification. For the transesterification process, a 1.5 % NaOH (w/w) in methanol solution was added at a 5:1 ratio of methanol to fat. The reaction was conducted at 75 ℃ with 30-minute reaction time. After draining the resultant glycerol layer and washing the FAME in a separatory funnel, the FAME was moved to a heating plate and distilled at 80 ℃ to remove any residual methanol.

As the goal of this study was to evaluate the feasibility of blending DEE with BSF crude oil, the blends' various fuel properties were compared with a mixture of BSF FAME and US No. 2 diesel at 5 %, 15 %, 25 %, and 50 % (vol./vol.). The 5 % DEE-BSFO blend proportion was determined as the volume required to match the viscosity requirement of US No. 2 diesel. Note that the blending fuels were all research grade, including the diesel fuel provided from Coryton Advanced Fuels and the DEE procured from Sigma-Aldrich of 98 % purity. Blending DEE at 10 % with BSFO was found to be the adequate ratio to create a homogeneous mixture at room temperature. Various proportions, 10 %, 20 %, and 40 % (vol./vol.) of DEE blends in BSFO were prepared. Although the physical properties of fuel blending by mass can remain constant regardless of temperature variation, industry usually carries out fuel mixing at a commercial plant on a volume basis at ambient temperature, 25 °C. For this reason, blending rules as a function of volumetric fractions is favoured in this study.

2.2 Characterization of the fatty acid methyl ester (FAME) derived from BSF

Fatty acid methyl ester (FAME) analysis was performed using Agilent 7890A gas chromatography–Agilent 5975C mass spectroscopy (GC–MS) coupled with a flame ionization detector (FID) and equipped with HP-5MS (19091S-433, Agilent) column (30 m× 250 μm i.d.; 0.25 μm film thicknesses). The oven temperature was set at 115 ℃, raised to 220 ℃ at rate of 5 ℃/min, held for 5 min, and finally raised to 250 ℃ at rate of 10 ℃/min where it was held for another 1 min. The injection volume was 1 μL using helium as the carrier gas at rate of 0.9235 mL/min with split ratio 25:1 at the inlet. Identification of the methyl esters was made by matching the database in NIST MS Search 2.0 and comparing the retention time with the standard FAME mixture.

2.3 Fuel properties characterization

Gross heating values were measured using a Parr 6400 automated bomb calorimeter following the procedures as recommended by ASTM D240. Flashpoints were determined using a MINIFLASH FLP from

Grabner Instruments according to ASTM D6450. Fuel was distilled using a MINDIS ADXpert from Grabner Instruments following the procedure established by ASTM D86. The density and kinematic viscosity of various blends at 40°C were determined using an Anton-Paar Stabinger viscometer SVM 3000 and following standard ASTM D7042-04. The ignition quality of the blends was evaluated by determining the time between the fuel injection and the sudden needle pressure rise marking the start of fuel ignition as per ASTM D6890. A detailed explanation on the measurement principle and other associated components of Ignition Quality Tester (IQT) can be found in (Yang et al., 2015). Before starting fuel tests, the IQT was calibrated with a reference fuel, heptane, with 15 preliminary cycles to ensure steady operation. 40 ml of each blended fuel was run 32 times to have an average number of Ignition Delay Time (IDT). For IDT (τ_{id}) values inside the range of 3.1 to 6.5 ms, the DCN was calculated using Eq(1), and for values outside of this range, the DCN was calculated using Eq(2):

$$\mathrm{DCN} = 4.46 + \left(\frac{186.6}{\tau_{\mathrm{id}}[\mathrm{ms}]}\right) \tag{1}$$

$$\mathrm{DCN} = 83.99[(\tau_{\mathrm{id}}[\mathrm{ms}] - 1.512)^{-0.658}] + 3.547 \tag{2}$$

3. Results and discussion

3.1 BSF FAME profile determined by GC-MS-FID and its fuel properties

GC-MS-FID analysis of BSF FAME results are shown in Figure 1. The first peak representing capric acid methyl ester (C10:0) appeared after 7 minutes while the other major peaks, representing lauric acid methyl ester (C12:0) (27.8 %) appeared at 11.336 minutes, palmitic acid methyl ester (C16:0) (20.4 %) at 19.491 minutes, oleinic acid methyl ester (C18:1) (13.2 %) at 22.644 minutes, and linoleic acid methyl ester (C18:2) (24.8 %) at 22.796 minutes. These four middle-long carbon chain methyl esters, ranging from 12 to 18 carbons, are considered to significantly affect the fuel properties of BSF biodiesel

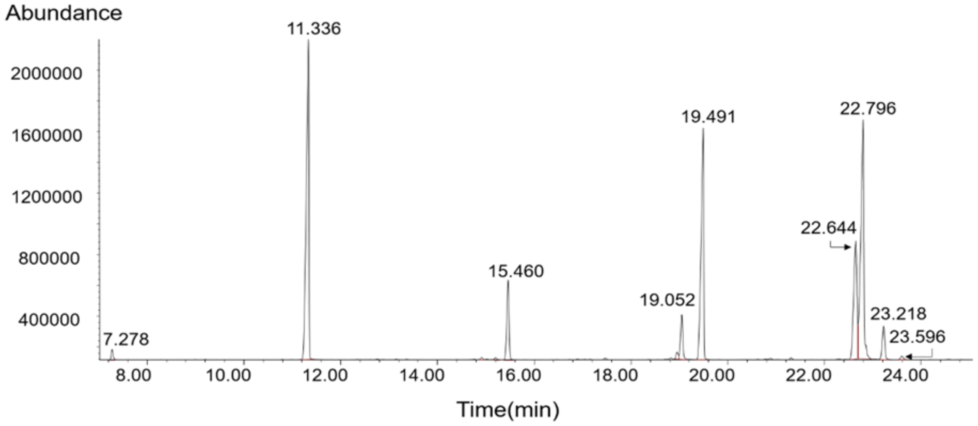

Figure 1: GC-MS-FID analysis results of BSF FAME

Table 1: FAME composition derived from BSF fed with pre-consumer waste (PCW) and BSF fed with manure

FAME composition (mass percent, %)	BSF biodiesel (fed PCW)	BSF biodiesel (fed manure)^{a}
Capric acid methyl ester (C10:0)	0.6	3.1
Lauric acid methyl ester (C12:0)	27.8	35.6
Myristic acid methyl ester (C14:1)	nil	7.6
Tetradecanoic acid methyl ester (C14:0)	5.9	nil
Palmitoleic acid methyl ester (C16:1)	4.0	3.8
Palmitic acid methyl ester (C16:0)	20.4	14.8
Linoleic acid methyl ester (C18:2)	13.2	5.8
Oleinic acid methyl ester (C18:1)	24.8	23.6
Stearic acid methyl ester (C18:0)	3.0	3.6
Nonadecanoic acid methyl ester (C19:1)	0.3	1.4
Saturated FAME	57.7	57.1
Unsaturated FAME	42.3	42.9

a Sourced from (Zheng et al., 2012)

In Table 1, the BSF FAME profiles derived from pre-consumer waste and manure are compared. BSF FAME derived from two-step esterification was found to contain 57.7 % saturated FAME and 42.3 % unsaturated FAME. Compared to the BSF FAME profile fed with manure from Zheng et al., 2012, little variation of the chemical composition was observed.

3.2 Basic fuel properties

Table 2 indicates that fuel properties were improved as the crude oil was converted to FAME. BSF biodiesel conversion treatment not only increased BSFO DCN from 59.6 to 63.5 but also significantly reduced kinematic viscosity at 40 °C from 29.76 mm^2/s to 3.77 mm^2/s. Noting that BSFO contains mostly triglycerides with a minor amount of free fatty acids while BSF biodiesel contains saturated and unsaturated long straight-chain FAME, both BSFO and its derived biodiesel have higher DCN and viscosity than US No. 2 diesel.

The flash point of BSF biodiesel was measured to be 140 °C, however, the high boiling point of BSF biodiesel compared to conventional diesel could actually decrease fuel spray and vaporization quality during fuel injection thus causing engine knockings. Overall, all properties can meet the requirements as specified by the ASTM D6731 biodiesel standard. Gross heating value is an important indicator of fuel consumption; the greater it is, the lower the fuel consumption and vice versa. Although the gross heating value is not specified in the ASTM D6751 biodiesel standard, the information presented in the Table 2 is useful in demonstrating that BSF biodiesel can meet the minimum gross heating value, 35 MJ/kg, as specified by the European standard EN 14213.

Table 2: fuel properties characterization of BSF biodiesel

Properties	ASTM standard	US No. 2 Diesel	BSFO	BSF Biodiesel	ASTM D6751
Density at 40°C (kg/m^3)	D7042	835	885	861	nil
Gross heating value (MJ/kg)	D240	45.97	39.47	39.52	nil
Flash point (°C)	D6450	55	>200	140	≥93
Kinematic viscosity at 40°C (mm^2/s)	D7042	2.64	29.76	3.77	1.9-6.0
Derived Cetane Number	D6890	55.8	59.6	63.5	≥47
Initial boiling point (IBP) (°C)	D86	174.6	172.2	279.0	nil
Temperature at 50% recovered (°C)	D86	259.8	309.0	318.1	nil
Temperature at 90% recovered (°C)	D86	*n.d.*	*n.d.*	*n.d.*	≤360
Final boiling point (FBP) (°C)	D86	343.7	354.8	369.3	nil

n.d. is not determined

3.3 Fuel blending effects

Ignition quality and kinematic viscosity at 40 ℃ of various blends were studied in the IQT and viscometer. Given the data from Table 3, good ignition quality of BSFO and its derived biodiesel were displayed. According to the ASTM D6890 method, an IDT of 3.36 ms and a DCN of 59.6 of BSFO was estimated by IQT. Crude oil ignition quality was improved after conversion to FAME as a shorter IDT, 3.18 ms, and a higher DCN, 63.5, were observed. Mixing 5 %, 15 %, 25 %, and 50 % BSF biodiesel in conventional diesel was found to proportionally increase DCN from 55.8 to 58.7. On the other hand, blending 40 % DEE in BSFO was found to raise the DCN from 59.6 to 99.3. Note that the fluctuation of the chamber skin temperature during the IQT as well as the volatility of blending solvents used resulted in a variation of the ignition quality estimations. The standard deviation of IDT in BSFODEE blends was found to be around 1.5 ms, which gave ±4 DCN variation under a 95 % of confidence interval.

Table 3 Fuel properties comparison between BSFODEE solvent blends and BSF biodiesel blends

Solvent Blends[a]	DCN	IDT (ms)	Viscosity (mm^2/s)	Biodiesel Blends[b]	DCN	IDT (ms)	Viscosity (mm^2/s)
BSFODEE0	59.6	3.36	29.76	B0	55.8	3.63	2.64
BSFODEE10	67.7	3.02	16.41	B5	56.0	3.62	2.70
BSFODEE20	72.8	2.85	8.05	B15	56.6	3.58	2.78
BSFODEE40	99.3	2.33	3.14	B25	57.1	3.55	2.87
BSFODEE100	138.7	2.03	0.23	B50	58.7	3.44	3.15
				B100	63.5	3.18	3.77

Table 3 shows that the DCN proportionally increased with DEE blending volume in BSFO at a rate of approximately 10 % with every 10 % DEE blended in. Also, standard deviation of the IDT in each biodiesel blend test was noted to be below 0.09 ms (DCN variation ±1, under a 95 % confidence interval), thus a good estimation of ignition quality improvement was also deduced from BSF biodiesel blending in US No. 2 diesel mixtures. Blending DEE in BSFO greatly dropped the kinematic viscosity at 40 °C from 29.76 mm^2/s to 3.14 mm^2/s while in the B5, B15, B25, and B50 biodiesel mixtures, kinematic viscosity at 40 °C was observed to slightly rise from 2.62 mm^2/s to 3.15 mm^2/s. The Anton-Paar Stabinger viscometer SVM 3000 averaged three values of kinematic viscosity at 40 °C per ASTM D7042 standards with less than 2.5 % variation.

a. BSFODEE0, BSFODEE10, BSFODEE20, BSFODEE40, BSFODEE100 respectively correspond to 0 %, 10 %, 20 %, 40 %, and 100 % (vol./vol.) DEE mixing with BSFO.

b. B0, B5, B15, B25, B50, and B100 respectively correspond to 0 %, 5 %, 15 %, 25 %, 50 %, and 100 % (vol./vol.) blending in US No. 2 diesel.

As seen in Figure 2a, two proportional increasing trends on DCNs were observed by blending DEE in BSFO as well as BSF biodiesel mixtures. Note that DCNs of BSFODEE blends were significantly greater than those of mixtures of BSF FAME and US No. 2 diesel. Thus, BSFODEE blends demonstrated greater ignition quality than biodiesel blending in conventional diesel. Blending DEE in BSFO also greatly improved the BSFO flow properties as a parabolic-like descending curve was observed in Figure 2b. A positive linear relationship in viscosity was observed when blending BSF biodiesel in conventional diesel while the flow properties did not vary markedly with US No. 2 diesel.

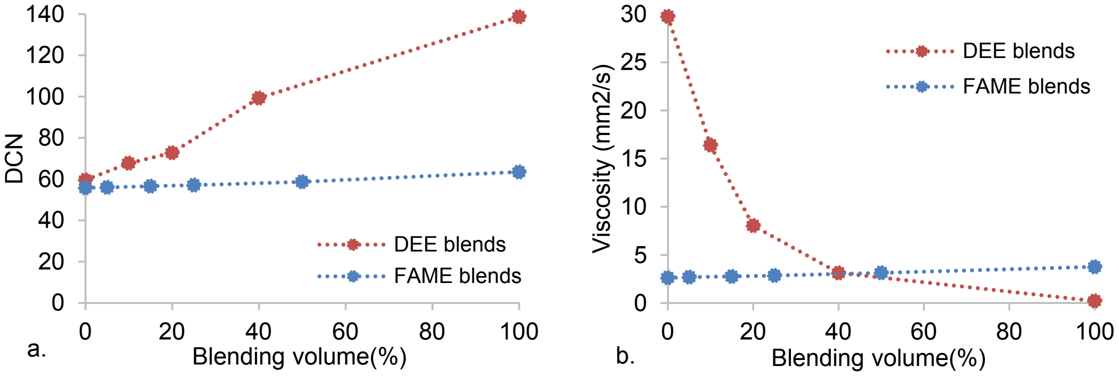

Figure 2: Comparison of blending effects of BSF FAME in US No. 2 Diesel and DEE in BSFO

4. Conclusions

In this study, the combustion properties of BSF crude oil were improved by a two-step treatment consisting of esterification and transesterification, as well as by blending it with a less viscous solvent, DEE. Based on this study, BSF biodiesel blending with conventional diesel was found to be ready for application in industry as specified by ASTM standards. Blending DEE in BSFO made the direct use of BSFO feasible as two important combustion properties, viscosity and DCN, both satisfied the US ASTM D6751 biodiesel standard. The ignition quality of the 40% BSFO-DEE blend was estimated to be DCN 99.3 with a kinematic viscosity of 3.14 mm^2/s at 40°C. Therefore, the newly proposed solvent blending methodology with DEE can not only significantly save cost, time, and energy compared to fuel refineries but can also have created fuel properties better than traditional biodiesel-diesel blends. On the other hand, bio-derived fuel, BSFO and DEE blends are ideal, sustainable, and clean fuels when compared to conventional petroleum. DEE is synthesized from ethanol, which can be produced from a fermentation process using glucose derived from sugars, starch, or cellulose. Using BSF larvae can also be taken as an approach to efficiently upcycle organic waste to useful raw materials, including compost, crude fat and protein. Considering these two advantages, the environmental impact can be greatly reduced by combining the use of BSFO and DEE.

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