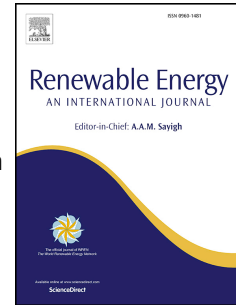


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Production of biofuel from AD digestate waste and their combustion characteristics in a low-speed diesel engine

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1 **Production of biofuel from AD digestate waste and their** 2 **combustion characteristics in a low-speed diesel engine**

3
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15 16 **Abstract**

17 Anaerobic digestion biogas plants generate large amounts of digestate that cannot always be
18 valorised as fertilizer. This study proposes an alternative use through pyrolysis of the digestate
19 for the production of liquid fuels for compression ignition engines. The digestate pyrolysis oil
20 (DPO) and two types of biodiesel were produced and mixed with different alcohols. A total of
21 five blends of DPO, biodiesel and alcohol were prepared and characterized, showing that their
22 acidity and viscosity were higher than for pure diesel, and their heating value was lower. Blends
23 containing 60% biodiesel, 20% DPO, and 20% butanol were then tested in an engine, showing
24 that the maximum in-cylinder pressure and heat release rate were 4.6% and 3% lower,
25 respectively, compared to diesel, and the engine thermal efficiency at full load was 6-8% lower.

26 The nitric oxide and smoke emissions were 7% and 40% lower, respectively, but the carbon
 27 dioxide emissions were 7-10% higher than with diesel. The blends showed retarded start of
 28 combustion by 1.5° crank angle, which delays the ignition by about 6.4%. This study concludes
 29 that blends can be used as a fuel for agriculture and marine diesel engines, although their
 30 viscosity should be reduced by improving the pyrolysis conditions.

31 **Keywords:** Biodiesel; Combustion; Digestate; Emission; Engine; Pyrolysis;

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33 Abbreviations

AD	Anaerobic digestion
BT	Butanol
BD	Burn duration
DPO	Digestate pyrolysis oil
DEE	Diethyl ether
HHV	Higher heating value
HC	Hydrocarbons
HRR max	Maximum heat released rate
FLP	Fuel line pressure
CHRR	Cumulative heat release rate
ID	Ignition delay
LFB	Lamb fat biodiesel
Me	Methanol
NO	Nitric oxide
PT	Pentanol
Pmax	Maximum cylinder pressure
SoC	Start of combustion
WCOB	Waste cooking oil biodiesel
DPO20+PT20+WCOB60	20% DPO + 20% Pentanol + 60% WCOB
DPO10+DEE20+WCOB70	10% DPO + 20% Diethyl ether + 70% WCOB
DPO20+BT20+WCOB60	20% DPO+ 20% 1-butanol + 60% WCOB
DPO20+BT20+LFB60	20% DPO+ 20% 1-butanol + 60% LFB
DPO20+Me20+WCOB60	20% DPO+ 20% Methanol + 60% WCOB

34 1. Introduction

35 Worldwide, about 1.3 billion tonnes per year of food waste is generated by industries,
 36 households, and associated supply chains [1], and 20% of human-related methane emissions
 37 comes from the waste sector [2].

38 In general, the disposal of biodegradable waste from industry, forestry, farming and agriculture
39 has always been through landfilling, releasing methane that contributes to the rise in
40 greenhouse gas emissions (GHG). To mitigate that, landfilling is banned in many European
41 countries, and today we are already able to convert a high variety of biodegradable waste into
42 different chemicals and products [3]. Anaerobic digestion of the more moist bio-waste and
43 thermal treatment of the drier fractions are common waste-treatment solutions. Liquid biofuels
44 are already widely used and provided some 3% of transport energy globally in 2017 [4]. While
45 electric vehicles are gradually replacing light-duty vehicles, long-distance and heavy-duty
46 transport are harder to electrify, and biofuels are expected to be primarily used in aviation,
47 shipping and trucks after 2030 [3]. About half of the technologies that will decarbonise our
48 energy system are not yet fully developed [5]. While ethanol, biodiesel, hydrogenated
49 vegetable oils and biomethane are well established biofuels, pathways for pyrolysis oils,
50 methanol, butanol, dimethyl ether (DME) and other ethers are still under development.

51 Every year, several million tonnes of digestate are produced worldwide as a co-product of the
52 anaerobic digestion [6]. Although it is excellent as organic fertilizer and for soil improvement
53 and amendment, the environmental risk that intense digestate land application pose [7] [8] has
54 led to restrictive regulations in many countries. To maximize its utilization and minimize its
55 adverse effects, the thermo-chemical valorization has been widely explored, mainly via
56 pyrolysis of the digestate to produce pyrolysis oils, biochar and pyrolysis gases [10], [11], [12],
57 [13], [14], [15], [16].

58 Pyrolysis oils are renewable biofuels that typically exhibit a high viscosity, high acidity, low
59 energy density, and a complex chemical composition that includes various hydrocarbons and
60 oxygen-containing compounds [17, 18]. While they offer the potential to mitigate waste
61 disposal issues, they need necessitate blending in order to enhance their stability, energy
62 content, and combustion efficiency in engines.

63 For example, the engine performance of blends of diesel with pyrolysis oil derived from waste
64 cooking oil was investigated by Gad et al., revealing a 29% drop in the engine thermal
65 efficiency when compared to pure diesel [19]. Similar results were found for blends of diesel
66 with 30% tyre pyrolysis liquid and 20% Karanja biodiesel [20].

67 This blending approach with diesel facilitates the integration renewable fuel sources into
68 existing infrastructure, but high decarbonisation targets can be achieved only with neat biofuel
69 applications. To explore more sustainable fuel blends, Hossain et al. [21] combined waste
70 cooking oil and digestate pyrolysis oil (up to 30%) with butanol (20%). The introduction of
71 butanol into the mixture led to the formation of stable blends, and resulted in a viscosity
72 reduction of over 90%. Moreover, while the blends exhibited a decrease in the engine brake
73 thermal efficiency of up to 7% compared to diesel, they demonstrated a significant reduction
74 in smoke and CO emissions [21]. As part of the study, they also assessed the miscibility and
75 stability of digestate pyrolysis oil with various fuels, over a 30-day period at room temperature.
76 While the pyrolysis oil could form stable mixtures with waste cooking oil and soybean oil, it
77 was incompatible with biodiesel or fossil diesel, unless a cosolvent was added.

78 Building on these findings, the current study evaluates the characteristics of blends comprising
79 digestate pyrolysis oil, biodiesel, and various cosolvents. Although the cosolvents were not
80 obtained from renewable sources here, they could be produced through fermentation of
81 lignocellulosic materials, thus making the blends 100% renewable [4].

82 This study aims to (i) convert digestate into liquid biofuel through pyrolysis, (ii) produce
83 biodiesel from two different waste streams, (iii) formulate and characterize various blends, and
84 (iv) evaluate their engine performance against conventional fuels.

85

86

87 2. Materials and methods

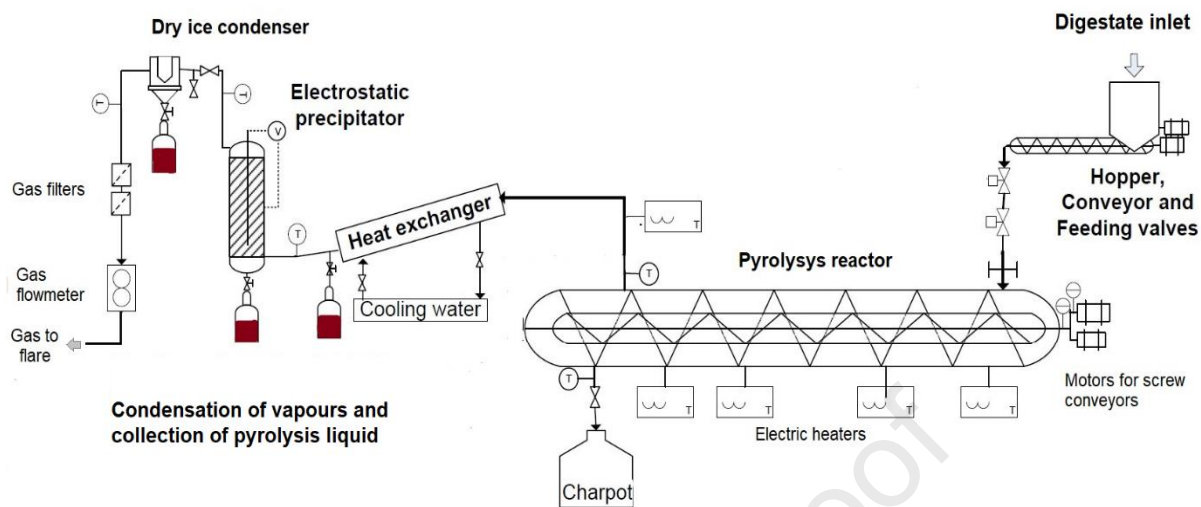
88 2.1. Production of digestate pyrolysis oil

89 Digestate from the anaerobic digestion of maize stover and green rye was obtained from a
90 company called MeMon BV (Dorset Group, The Netherlands). The digestate pellets have a
91 composition of 11.5% moisture, 47.8% of volatile matter, 9.1% fixed carbon and 31.6% ash,
92 and a HHV of 13.3 MJ/kg (all based on a 11.5% moisture content).

93 As part of this work, the pyrolysis oil was produced in a pyrolysis pilot plant, using a feeding
94 rate of 5 kg/h of digestate pellets. The plant, shown in figure 1, consists of a pyrolysis reactor
95 and an oil condensing train [21]. The pyrolysis reactor (Pyroformer[®]) is a horizontal cylindrical
96 reactor made of carbon steel (1800 mm long, 200 mm diameter) with two screw conveyors
97 inside for the movement and recirculation of the solid material within. Each run starts by
98 purging the reactor with nitrogen to eliminate any oxygen, and setting the electrical heating
99 jackets of the reactor at 500°C. Once steady state is reached, the vapours produced in the reactor
100 have a temperature of 390°C. Condensation of these vapours takes place in a shell and tube
101 heat exchanger, an electrostatic precipitator for aerosols removal (20 kV) and a dry ice
102 condenser. The pyrolysis liquid is collected in three glass containers connected to each of these
103 three units. Once mixed and poured into separating funnels, the liquid separates into an organic
104 phase (pyrolysis oil) and an aqueous phase (with 50% of light organics). The non-condensable
105 vapours are filtered, measured, and flared off. The biochar is collected in a sealed carbon steel
106 pot for further analysis. Overall, the products yields on weight basis were: 20% pyrolysis oil,
107 20% aqueous phase, 50% biochar and 10% of gas. The ash content of biochar was 60%, and
108 its higher heating value 10 MJ/kg. The water content shows that 50% of this liquid is aqueous
109 phase and 50% is organic phase (pyrolysis oil).

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Figure 1. Pyrolysis pilot plant

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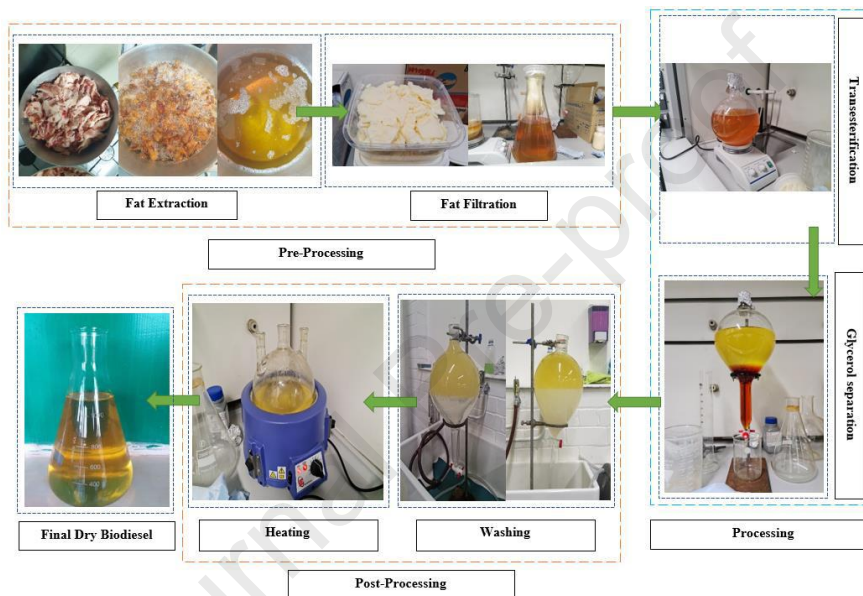
116 2.2. Production of biodiesel

117 Waste cooking oil (WCO) and waste animal fat (Lamb Fat – LF) were chosen as viable
 118 feedstock for biodiesel production. The free fatty acids content (FFA) was about 2.1 mgKOH/g
 119 for waste cooking oil and 1.6 mgKOH/g for lamb fat. These values are obtained after titration
 120 and using Equations 1 and 2 [22]. The FFA content shows that biodiesels can be produced
 121 from these feedstock without esterification. Extraction of LF and LF biodiesel production is
 122 shown in Fig. 2. WCO and LF was transformed into biodiesel via transesterification process,
 123 using potassium hydroxide (KOH) as catalyst. Two different types of biodiesel were thus
 124 produced using animal fat and vegetable oil, respectively, with a methanol to oil molar ratio of
 125 4:1 and 1 wt.% KOH [23]. Using a 5L glass reactor and a stirring hot plate (65°C and 600 rpm
 126 at 90 minutes), several batches were produced to obtain biodiesel from lamb fat (LFB) and
 127 biodiesel from waste cooking oil (WCOB). In total about sixteen litres of WCOB and LFB

128 were produced. Each batch was transferred into a decantation funnel and allowed to settle
 129 overnight to separate the glycerol (bottom layer) from the biodiesel (top layer). The biodiesel
 130 was separated, washed, analysed, and stored for subsequent blending.

$$131 \quad \text{Acid value (mgKOH/g)} = \frac{V \times 0.1N \times Mw}{m} \quad (1)$$

$$132 \quad \text{FFA \%} = \frac{\text{Acid value}}{2} \quad (2)$$



133

134 Figure 2. Lamb fat biodiesel production

135 **2.3. Preparation of blends**

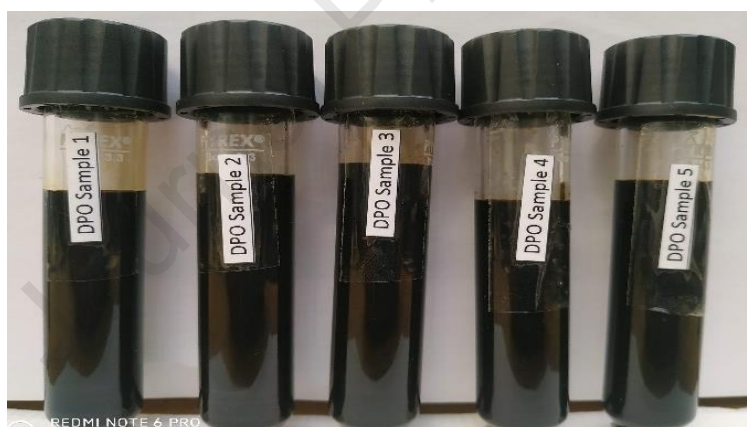
136 Using 60-70% of biodiesel and 10-20 % of digestate pyrolysis oil (DPO), the five blends shown
 137 in Table 1 were prepared for characterization and stability analysis. Since biodiesel and the
 138 pyrolysis oil are immiscible, 20% of solvent was used for each blend, which also reduced its
 139 viscosity. By using pentanol, 1-butanol, methanol, or diethyl ether as cosolvents;
 140 homogeneously stable blends were achieved in all cases (Fig. 3). Initially, these cosolvents
 141 were selected due to their high energy content and low viscosity values. Four different types
 142 of cosolvents were used to assess the miscibility performance with DPO and biodiesel. The

143 proportion of the cosolvents were kept in the range of between 10-20% in all blends. For
 144 miscibility analysis, the quantity of each blend prepared was 100 ml. The blends samples were
 145 stored at room temperature for 30 days. No phase separation was observed, and mixture was
 146 found to be homogeneous after 30 days.

147 Table 1. Blend samples and composition

Blend	Acronym	Composition	Homogeneous mixture (Yes/No)
Sample 1	DPO20+PT20+WCOB60	20% DPO + 20% Pentanol + 60% WCOB	Yes
Sample 2	DPO10+DEE20+WCOB70	10% DPO + 20% Diethyl ether + 70% WCOB	Yes
Sample 3	DPO20+BT20+WCOB60	20% DPO+ 20% 1-butanol + 60% WCOB	Yes
Sample 4	DPO20+BT20+LFB60	20% DPO+ 20% 1-butanol + 60% LFB	Yes
Sample 5	DPO20+Me20+WCOB60	20% DPO+ 20% Methanol + 60% WCOB	Yes

148



149

150 Figure 3. Blend samples 1, 2, 3, 4, and 5

151 2.4. Materials characterization

152 The acid value, density, viscosity, flash point and higher heating value of biodiesel, pyrolysis
 153 oil, alcohols and their blends were analysed and compared with those for fossil diesel, biodiesel
 154 (EN14214) and marine diesel oil standards (ISO 8217). Fossil diesel was purchased from a
 155 local filling station, and properties of fossil diesel were measured in the lab. The results are
 156 shown in Table 2. The ester content profile of biodiesel samples and DPO blends was also

157 obtained using a GC-MS (Table 3). The calculation of the saturated fatty acids (SFA %),
 158 monounsaturated fatty acids (MUSFA %) and polyunsaturated fatty acids (PUSFA %) were
 159 derived from Eq. 3, 4 and 5 [24]. Canon Fenski u-tube viscometers (with measurement
 160 uncertainty of 0.16–0.22 %) and a thermostatic water bath (0.1° C) were used to measure the
 161 kinematic viscosity of the samples. Density was measured using an ASTM-D7544 hydrometer
 162 and the higher heating value (HHV) was measured using a Parr 6100 bomb calorimeter (0.1%
 163 accuracy). The flashpoint was determined using an ASTM121 D1655-compliant Setaflash
 164 Series 3 plus closed cup flash point tester (model 33000-0, accuracy 0.5%). The acid number
 165 was determined using a Mettler Toledo G20 compact titrator following ASTM-664-04. It was
 166 found out that none of the blends meet the biodiesel standard, but they are mostly within the
 167 limit of the marine fuel one, meaning they are suitable for marine applications but not as road
 168 transportation fuels. Fuel samples 3 and 4 shows slightly lower viscosity values than other
 169 blends, hence these two blends were chosen for an experimental investigation to determine
 170 engine performance, combustion, and emissions characteristics.

$$171 \text{ SFA \%} = \sum C - C \text{ single bond FAs} \quad (3)$$

$$172 \text{ MUSFA \%} = \sum \text{More than one } (-C - C -) \text{ double bond FA s} \quad (4)$$

$$173 \text{ PUSFA \%} = \sum \text{More than one } (-C = C -) \text{ double bond FA s} \quad (5)$$

174

175 Table 2. Properties of the different fuels and materials

Properties	Acid Value (mgKOH/g)	Density (kg/m ³)	Higher Heating Value (MJ/kg)	Viscosity (mm ² /s) at 40°C	Flash Point (°C)	Latent heat of vaporization (kJ/kg) [25]
DPO (Hossain et al., 2016)	8.4	1077.14	26.77	473	120	-
WCOB	0.5	882	38.821	4.16	165	-
LFB	0.23	887	39.62	3.23	135	-
Fossil Diesel	0.02	835	45.3	3.01	65	375
Methanol	-	792	22.79	0.397	12	1162.64

1-butanol	-	809.6	35.45	0.259	35	585.40
1-Pentanol	-	814.9	36.5	0.402	33	308.05
Sample 1	2.987	857	38.983	42.35	140	-
Sample 2	3.062	856	37.775	40.86	155	-
Sample 3	4.343	866	37.446	35.86	160	-
Sample 4	4.712	882	37.701	33.35	145	-
Sample 5	2.876	976	38.792	40.28	148	-
Biodiesel EN14214	0.5	860-900	>37.5	3.5-5	>120	-
Marine diesel oil ISO 8217	2.0-5	975-1010	-	<700/50°C	>60	-

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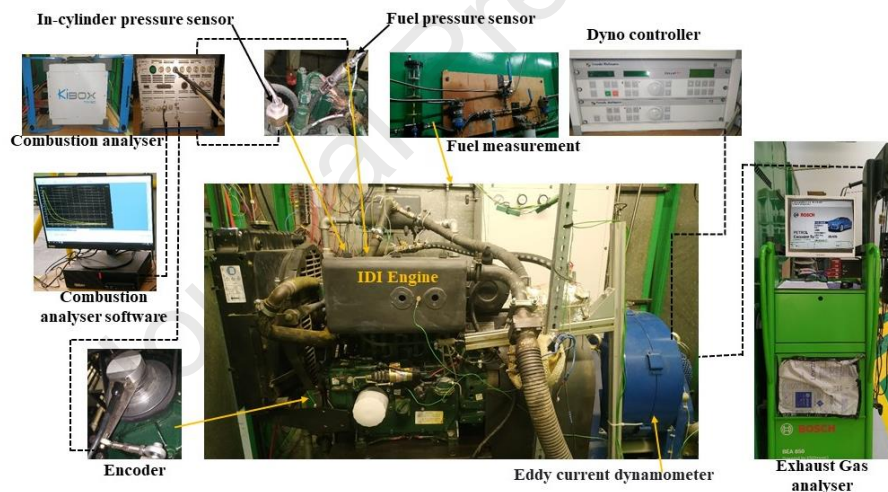
Table 3. Ester content profile of WCOB, LFB and their blends (wt.%)

Formula	Fatty acid methyl ester	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	WCOB	LFB
C ₉ H ₁₆ O ₄	Dimethyl pimelate	-	-	-	0.3	-	-	-
C ₁₅ H ₃₀ O ₂	Myristic acid (C15:0)	-	0.1	-	1.7	-	-	2
C ₁₃ H ₂₆ O ₂	Undecanoic acid (C13:0)	-	-	-	-	-	-	0.2
C ₁₆ H ₃₂ O ₂	Pentadecanoic acid (C16:0)	-	-	-	-	-	-	0.4
C ₁₅ H ₃₀ O ₂	Tetradecanoic acid (C16:0;OH)	-	-	-	-	-	-	0.3
C ₁₇ H ₃₄ O ₂	Palmitic acid (C17:0)	14	14.7	14.1	20.5	14	12.5	24.5
C ₁₇ H ₃₂ O ₂	Hexadecenoic acid (C17:0;OH)	-	-	-	-	-	1.7	0.9
C ₁₈ H ₃₄ O ₂	Heptadecenoic acid (C17:1)	-	-	-	-	-	-	0.4
C ₁₈ H ₃₆ O ₂	Methyl isoheptadecanoate (C18:0)	-	-	-	1.1	-	-	1.4
C ₁₈ H ₃₆ O ₂	(C18:0;OH)	-	-	-	0.7	-	-	0.9
C ₁₉ H ₃₈ O ₂	Stearic acid (C19:0)	3.9	4.3	3.7	27.3	3.8	3.6	27.7
C ₁₉ H ₃₆ O ₂	Methyl petroselinate (C19:1)	1.7	-	-	-	-	-	-
C ₁₉ H ₃₆ O ₂	Elaidic acid (C19:1)	-	-	1.6	5.6	-	-	-
C ₁₉ H ₃₆ O ₂	Oleic acid (C19:1)	-	-	-	0.3	-	-	-
C ₁₉ H ₃₆ O ₂	(C19:1)	32.6	-	-	-	-	-	-
C ₁₉ H ₃₆ O ₂	(C19:1 cis)	-	25.5	31.7	37.5	33.2	33.6	32.7
C ₁₉ H ₃₆ O ₂	(C19:1trans)	-	-	-	-	-	-	6.4
C ₁₉ H ₃₄ O ₂	(C19:2cis,trans)	-	54.1	-	-	49	-	-
C ₁₉ H ₃₄ O ₂	Linolelaidic acid, (C19:2trans)	-	-	-	1.2	-	48.2	1.2
C ₁₉ H ₃₄ O ₂	(C19:2)	47.8	-	47.9	-	-	-	-
C ₁₉ H ₃₄ O ₂	Methyl linolate (C19:2cis)	-	-	-	0.7	-	-	0.9
C ₁₉ H ₃₂ O ₂	Linolenic acid C19:3	-	0.5	-	-	-	-	-
C ₂₀ H ₄₀ O ₂	Palmitic acid, butyl ester (C20:0)	-	-	-	1.1	-	-	-
C ₂₁ H ₄₂ O ₂	Nonadecanoic acid C21:0	-	0.2	-	-	-	-	-
C ₂₁ H ₄₀ O ₂	(C21:1)	-	0.1	-	1.2	-	-	-
C ₂₁ H ₃₈ O ₂	(C21:2)	-	-	1	-	-	-	-
C ₂₂ H ₄₄ O ₂	(C22:0)	-	-	-	0.8	-	-	-
C ₂₃ H ₄₆ O ₂	(C23:0)	-	0.3	-	-	-	-	-
C ₂₅ H ₅₀ O ₂	Methyl lignocerate C25:0	-	0.1	-	-	-	-	-
Saturated fatty acids (SFA) (%)		17.9	19.7	17.8	52.4	17.8	17.8	58.3
Monounsaturated fatty acids (MUSFA) (%)		34.3	25.6	33.3	44.6	33.2	33.6	39.5
Poly-Unsaturated fatty acids (PUSFA) (%)		47.8	54.6	47.9	1.9	49	48.2	2.1

178

179 2.5. Engine test rig

180 The engine was a 3-cylinder, naturally aspirated, Lister-Petter Alpha series, water-cooled,
 181 indirect injection diesel engine (Fig. 4). The test engine's parameters are stated in Table 4. The
 182 speed was kept constant at 1500 rpm to better emulate agricultural engines, which often run at
 183 a constant speed and variable torque. A Froude Hofmann AG80HS eddy current dynamometer
 184 was used to load the engine. Six engine loads were chosen for this study: 20 percent (1.9 kW),
 185 40 percent (3.8 kW), 60 percent (5.7 kW), 70 percent (6.65 kW), 80 percent (7.6 kW), and 100
 186 percent (9.75 kW). A Kistler cylinder pressure sensor (6.2 mm, installed near the fuel injector)
 187 and KiBox data acquisition system were used for the combustion analysis. Engine exhaust gas
 188 emissions were analysed with a Bosch BEA 850 gas analyser, specification shown in Table 4.



189

190 Figure 4. Experimental engine test rig and measurements devices

191 Table 4. Engine performance analysis instruments

Test engine specification	
Parameter	
Engine model & manufacture	LPWS Bio3 & Lister Petter, UK
Number of cylinders	3
Bore/stroke	86x88 mm
Cylinder volume	1.395 litres
Rated speed	1500 rpm
Engine power	9.9 kW
Fuel injection timing	20 deg. bTDC

Compression ratio	22	
Bosch BEA 850 emission gas analyser		
Parameter	Measuring range	Resolution
Carbon monoxide (CO)	0-100 % vol.	0.001 % vol.
Carbon dioxide (CO ₂)	0-18 % vol.	0.01 % vol.
Hydrocarbon (HC)	0-9999 ppm vol.	1.0 ppm vol.
Oxygen (O ₂)	0-22 % vol.	0.01% vol.
Nitric oxide (NO)	0-5000 ppm vol.	1.0 ppm vol.
Smoke (opacity)	0-100 %	1 %

192

193 3. Results and discussions

194 3.1. Properties of the blends

195 The properties of the different fuels and materials used in the study are shown in Tables 2 and
 196 Table 3. In general, the heating value of DPO is lower than the WCOB, LFB and fossil diesel
 197 due to higher oxygen content in DPO. Higher the fuel bound oxygen lower the heating value.
 198 On the other hand, the viscosity of DPO is much higher than neat biodiesels and fossil diesel
 199 viscosity values. This is due to polar nature of the DPO fuel molecules which produce strong
 200 interparticle force. This force tighten the molecules very closely resulting higher viscosity. The
 201 GC-MS analysis shows that DPO have long hydrocarbon chain (Table 3). Long carbon chain
 202 is another reason for higher viscosity of DPO. The density is an important property, since high
 203 density fuels require higher injection pressures and lead to increased ignition delays [26]. The
 204 density of neat DPO is quite high, 22% higher than fossil diesel, due to dipol-dipol attraction
 205 of the molecules and longer hydrocarbon chain. The density was decreased when biodiesel and
 206 cosolvent was added to DPO. Some of the blends comply with the density requirements for
 207 biodiesel (samples 3 and 4), and one of them (sample 5) complies with that for marine diesel
 208 (Table 2).

209 DPO, biodiesel and the solvents are all oxygenated, and therefore the heating value of their
 210 blends is lower than that for fossil diesel (Table 2). They all comply though with the minimum
 211 heating value required in the biodiesel standard (EN 14214). Higher acid value promotes

212 corrosion in the fuel line and can damage the fuel injector. Apart from acidity, the parameter
213 that is more negatively affected is the viscosity of the fuel. During engine combustion, high
214 viscosities lead to poor atomization and longer ignition delay [23]. Since the viscosity of DPO
215 is 100 times higher than that for biodiesel, DPO and its blends can only be used as marine
216 diesel oil, for which standard ISO 8217 sets a maximum of 700 mm²/s. The higher the flash
217 point of a fuel, the safer it is to store, handle and transport. DPO has a flash point comparable
218 to that of biodiesel, only slightly lower, but still 45% higher than the flash point of diesel fuel.
219 This makes the flash point of the DPO blends about 55% higher than diesel fuel, and thus safe
220 to store and transport. The ester content profile of the blends and the individual biodiesels are
221 provided in Table 3. The chemical properties of the fuel such as saturated fatty acids (SFA)
222 and unsaturated fatty acids (USFA) affects the ignition quality of the fuels. Table 3 shows that
223 LFB contains of higher amount of SFA, about 58.3%. When LFB was mixed with DPO, the
224 SFA level of the blend (sample 4) was improved. This would help to improve the ignition
225 quality of the fuel blends.

226

227 **3.2. Combustion behaviour in the engine**

228 Considering their fuel properties, samples 3 (DPO20+BT20+WCOB60) and sample 4
229 (DPO20+BT20+LFB60) closely align with the marine diesel fuel standard. Consequently,
230 these two blends were chosen for the subsequent engine tests. The research encompassed an
231 examination of combustion characteristics, performance metrics, and emissions at 1500 rpm
232 across varying engine loads for five distinct fuels: conventional diesel, WCOB, LFB,
233 DPO20+BT20+WCOB60, and DPO20+BT20+LFB60. The results of the engine combustion
234 characteristics were meticulously recorded and are presented graphically in Figure 5 and 6,
235 illustrating in-cylinder pressure, heat release rate, fuel line pressure, ignition commencement

236 and termination, ignition delay, combustion duration, P_{max} , HHR_{max} , and the cumulative heat
237 release rate.

238 **3.2.1. In-cylinder pressure**

239 Figure 5 shows the in-cylinder pressure at three different engine loads: (a) 20%, (b) 60%, (c)
240 and 100%. The DPO blends present a lower in-cylinder pressure than diesel, WCOB and LFB.
241 The maximum in-cylinder pressure (Figure 6b) for DPO blends DPO20+BT20+WCOB60 and
242 DPO20+BT20+LFB60 were reduced by 1.7% and 0.5% at 20% load, 0.5% at 60% load, and
243 3% and 4.6% at 100% load, respectively. The higher viscosity of the DPO blends reduces the
244 rate of fuel atomization, evaporation, and fuel/air mixing rate [21]. Therefore, the start of
245 combustion and ignition delay increase, reducing the in-cylinder pressure of DPO blends
246 (Figure 5). Moreover, a higher latent heat of vaporization of 1-butanol (585.40 kJ/kg) results
247 in higher heat absorption during combustion and reduces the cylinder pressure and temperature
248 [25]. The start of combustion of the DPO blends was retarded compared to diesel, WCOB and
249 LFB (Fig. 6a). The start of combustion at 20% load of DPO20+BT20+WCOB60 and
250 DPO20+BT20+LFB60 was retarded by 1.2° and 0.5° CA, respectively, and 1.5° and 1° CA at
251 100% load, compared to diesel. It is due to the higher viscosity of DPO blends which results
252 in poor atomization and air/fuel mixing [21]. Another reason for the late SoC was because of
253 the cooling effect of 1-butanols latent heat of vaporisation. The lower cetane number and higher
254 heat of vaporization of 1-butanol increase the auto-ignition temperature [27].

255 **3.2.2. Ignition delay**

256 As shown in Fig. 6a, the ignition delay (ID) period for the blends were longer than those for
257 diesel fuel and biodiesel. Compared to diesel fuel, the ID for DPO20+BT20+WCOB60 and
258 DPO20+BT20+LFB60 were longer by 5% and 2.3% at 20% load, 4.6% and 0.6% at 60% load,
259 and 6.4% and 4.4% at 100% load. The longer ID period of the DPO blend samples is due to

260 the higher viscosity and butanol cooling effect. The higher viscosity affects the fuel spray
261 characteristics such as fuel droplet sizes, atomization, vaporization and fuel/air mixing rate
262 [28]. This fuel spray characteristic phenomena strongly affected by the viscosity of the fuel which
263 results longer ID. Moreover, higher latent heat of vaporization of butanol consume heat from
264 the compressed air and take time to reach to the ignition stage. This reduced the cylinder
265 temperature (due to the cooling effect) resulting longer ID periods [25].

266 Compared with biodiesel, blend DPO20+BT20+WCOB60 shows longer ID periods by 2.5%
267 and 3% at 20% load, 6.7% and 6.8% at 60% load, and 5% at 100% load than WCOB and LFB,
268 respectively. Neat WCOB and LFB have lower viscosity and higher ignition quality and hence
269 shows better combustion efficiency. On the other hand, blend DPO20+BT20+LFB60 shows
270 lower ID by 0.9% at 20% load than WCOB due to higher cetane number and lower viscosity
271 of LFB [23]. Moreover, the ID for DPO20+BT20+LFB60 was increased by 1-3% at 60% and
272 100% load than WCOB (Fig. 6a). The ID of DPO20+BT20+LFB60 blend was found to be 1-
273 3% lower than LFB at all engine loads (Fig. 6a). The higher ignition quality and lower viscosity
274 of LFB improved combustion efficiency, which increases in-cylinder temperature and reduces
275 the ID periods. It has also been observed that DPO20+BT20+LFB60 resulted in 1.66% shorter
276 ID than DPO20+BT20+WCOB60. It is due to a higher SFA% of LFB (Table 3) than WCOB,
277 which results in better ignition quality [23]. The delay can also be observed from the fuel line
278 pressure (FLP) profile (Fig. 6b) due to high viscosity. It was observed that blend
279 DPO20+BT20+WCOB60 shows higher FLP about 4-16% than diesel fuel (Fig. 6b) due to
280 higher viscosity. The conventional fuel pump governor could apply more force to inject fuel
281 into the cylinder [21, 29].

282

283

284 3.2.3. Combustion duration

285 The end of combustion (EoC) and burn duration (BD) are shown in Fig. 6a. Both blends show
286 shorter EoC and BD as compared to diesel. Blend DPO20+BT20+WCOB60 shows 1-2.5°C
287 shorter EoC at 20% and 60% load but increased by 1.2°C at 100% load as compared to diesel
288 fuel. Whereas, blend DPO20+BT20+LFB60, shows 0.2-1.9°C shorter BD than diesel fuel
289 when the engine was operated at low (20%) and full (100%) load condition (Fig. 6a).
290 Oxygenated fuels improves the combustion efficiency. Neat DPO, butanol and biodiesels all
291 are oxygenated fuels and hence DPO blends gave shorter BD.

292 3.2.4. Heat release rate

293 The heat release rate increases with increased engine load (Fig.s 5 and 6b) due to the higher
294 amount of fuel injected per stroke [30]. Compared to diesel, DPO blends show a slightly higher
295 heat release rate (Fig. 5a-c). The HRR_{max} for DPO20+BT20+WCOB60 and
296 DPO20+BT20+LFB60 at low load (20%) was 28.49 J and 26.91 J, respectively, which are 11%
297 and 4%, higher than diesel fuel, 7% and 0.3% higher than WCOB and LFB (Fig.s 5a and 6b).
298 At 60% load, HRR_{max} for DPO20+BT20+WCOB60 fuel was found to be 1.3% and 5% higher
299 than diesel and WCOB, respectively. Whereas DPO20+BT20+LFB60 shows 3% and 2.6%
300 lower HRR_{max} when compared to diesel fuel and LFB, respectively (Fig.s 5b and 6b). The
301 higher HRR for DPO20+BT20+WCOB60 at low and medium load could be due to late start of
302 combustion, longer ID period and leaner fuel mixture. The longer ID allows more fuel to burn
303 in premixed combustion phase, and as a result of that increases the HRR [27]. Moreover,
304 DPO20+BT20+LFB60 shows lower HRR at 60% load (Fig. 5b & 6b). This is probably due to
305 the higher cetane number and lower viscosity of LFB as compared to WCOB. A comparative
306 study of WCOB and chicken fat biodiesel (CFB) was carried out by Sharma et al.,[23]. They
307 reported that, compared to vegetable derived biodiesel, animal fat-based biodiesel gave lower

308 HRR; due to the higher percentage of short chain saturated fatty acids and higher cetane
309 number. LFB also shows shorter ignition delay period due to higher cetane number [23].

310 At 100% load, HRR_{max} for DPO blends DPO20+BT20+WCOB60 and
311 DPO20+BT20+LFB60 were found lower by 6% and 3% than diesel fuel (Fig. 5c & 6b). The
312 low HRR_{max} at full load is mainly due to the rich fuel/air mixture and cooling effect of 1-
313 butanol through latent heat of vaporisation. Even though ID was longer at full load due to
314 higher viscosity, the BD was smaller to complete the combustion. Moreover, higher heat of
315 vaporization of 1-butanol absorbed heat during the combustion and reduced the cylinder
316 temperature, which resulted lower heat released rate[25].

317

318 **3.2.5. Cumulative heat release rate**

319 Figure 5 (d-f) compares the cumulative heat release rate at engine loads for the blends, diesel,
320 and biodiesel samples, providing more detail about the overall energy released during
321 combustion. The CHRR for the blends was lower than for diesel fuel at low and medium engine
322 load, not much changes was observed at full load. At 20% and 60% loads (Fig. 6d), the in-
323 cylinder temperature was lower, which reduced the fuel combustion efficiency rate due to
324 higher latent heat of vaporisation of butanol, which slows down the combustion efficiency [31].
325 Moreover, higher viscosity of the blends affects fuel spray characteristics which affects
326 combustion efficiency.

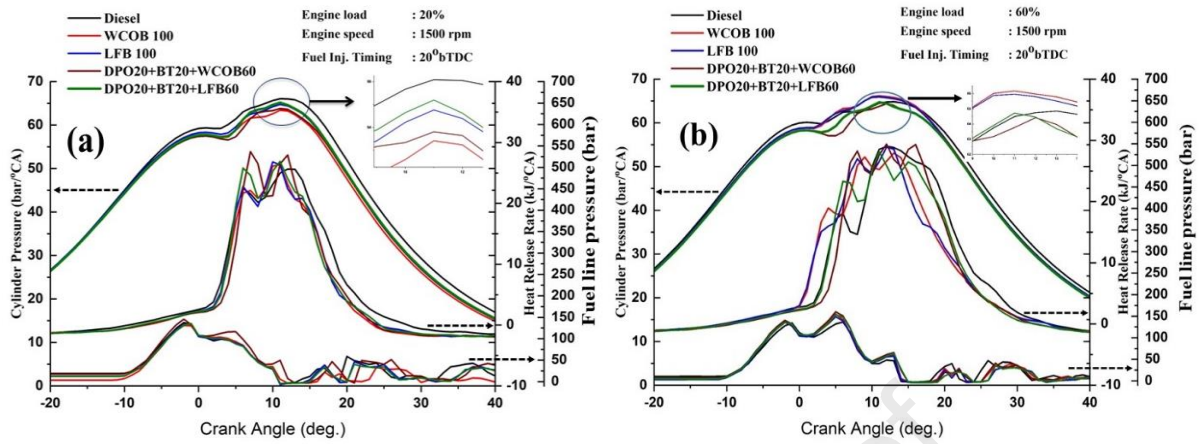
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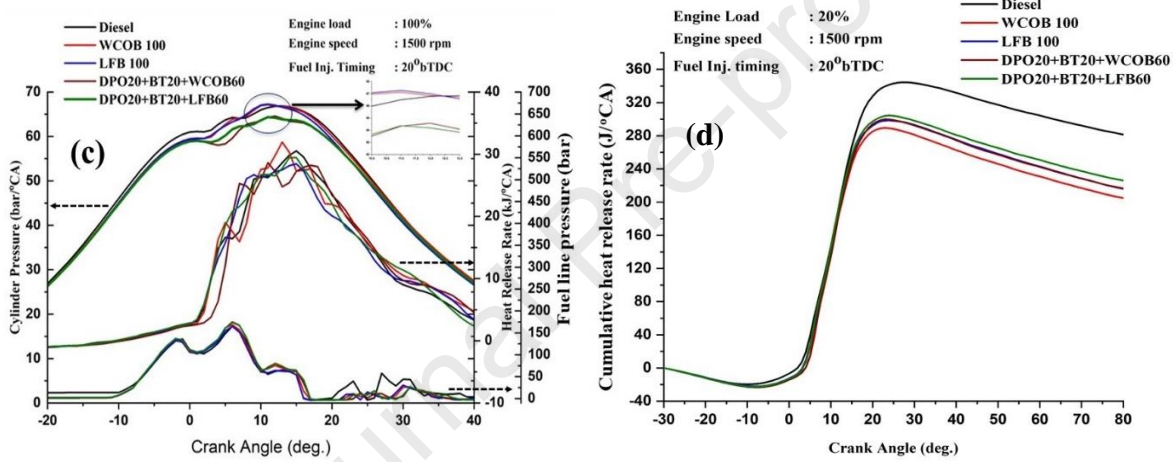
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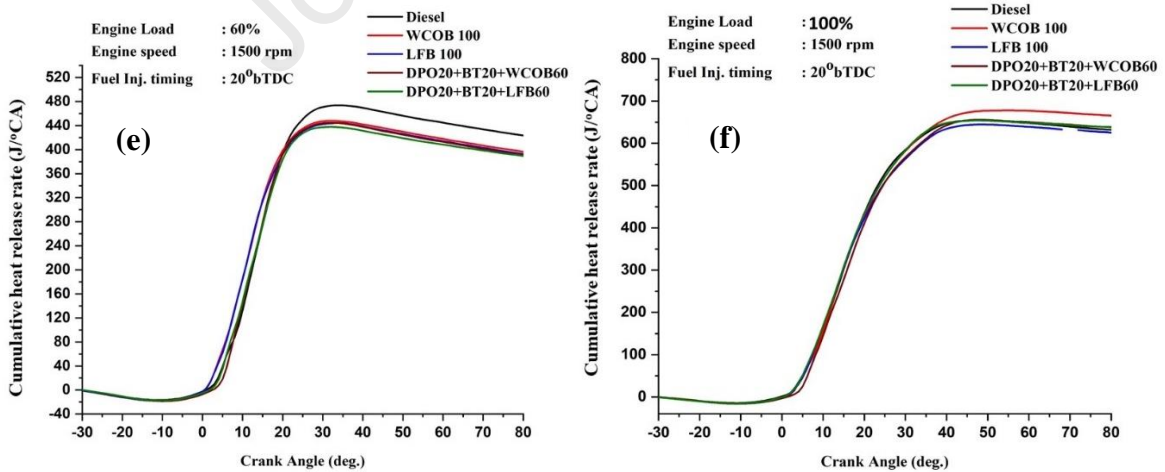
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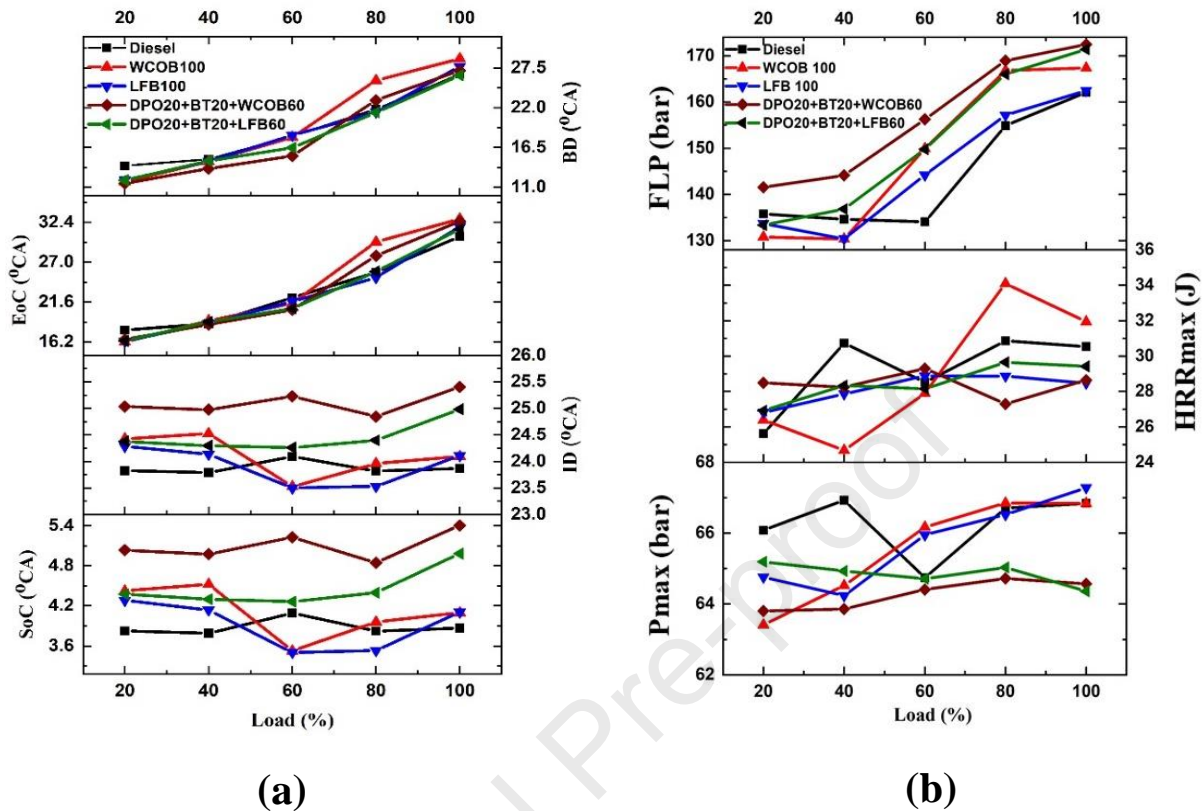


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335 Figure 5. Cylinder pressure, heat release rate, fuel line pressure and cumulative heat release

336 rate of diesel, biodiesel and DPO blends at low, medium and high loads

337



338

339

340 Figure 6. Combustion behaviour of diesel, biodiesel and DPO blends at different engine loads

341

342 - (a) SoC, EoC, ID and BD (b) Pmax, HRRmax and FLP.

343

344 **3.3. Engine performane**

345 Figure 7 shows the variations in brake thermal efficiency (BTE) and brake specific fuel

346

347 consumption (BSFC) with respect to brake power.

348

349 **3.3.1. Brake thermal efficiency**

350 At low load, in-cylinder temperature was lower, which reduced the fuel combustion rate due

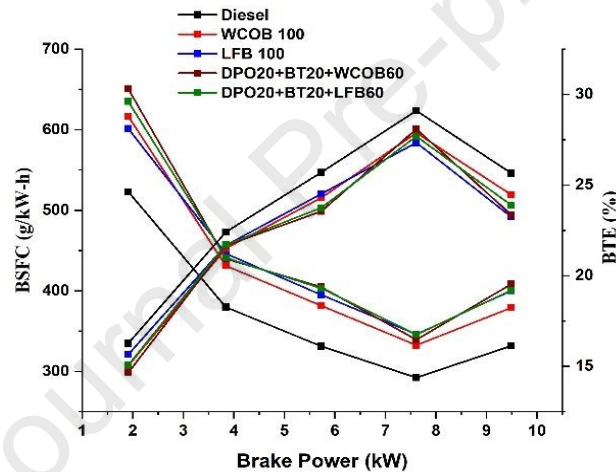
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352 to lean air/fuel mixture [27]. Therefore, the BTE was observed lower at low load. As the engine

353

354 load increases, fuel consumption also increases to attain a constant speed of 1500 rpm (Fig. 7).

350 This increases the combustion efficiency and raises the in-cylinder temperature due to the rich
 351 fuel/air mixture [31]. It was observed that the BTE of biodiesel and DPO blends were lower
 352 compared to diesel fuel. Lower heating values of neat biodiesels and DPO caused this. of the
 353 later. Blends DPO20+BT20+WCOB60 and DPO20+BT20+LFB60 show lower BTE as
 354 compared to WCOB and LFB, by 8% and 6% respectively. This can be explained because of
 355 the higher viscosity, lower heating value and addition of the 1-butanol [32, 33]. As higher
 356 viscosity affects the fuel spray characteristics, fuel combustion efficiency was reduced due to
 357 incomplete combustion of the fuels. Another factor of lower BTE for DPO blends is the higher
 358 latent heat of vaporization of 1-butanol [32, 33].



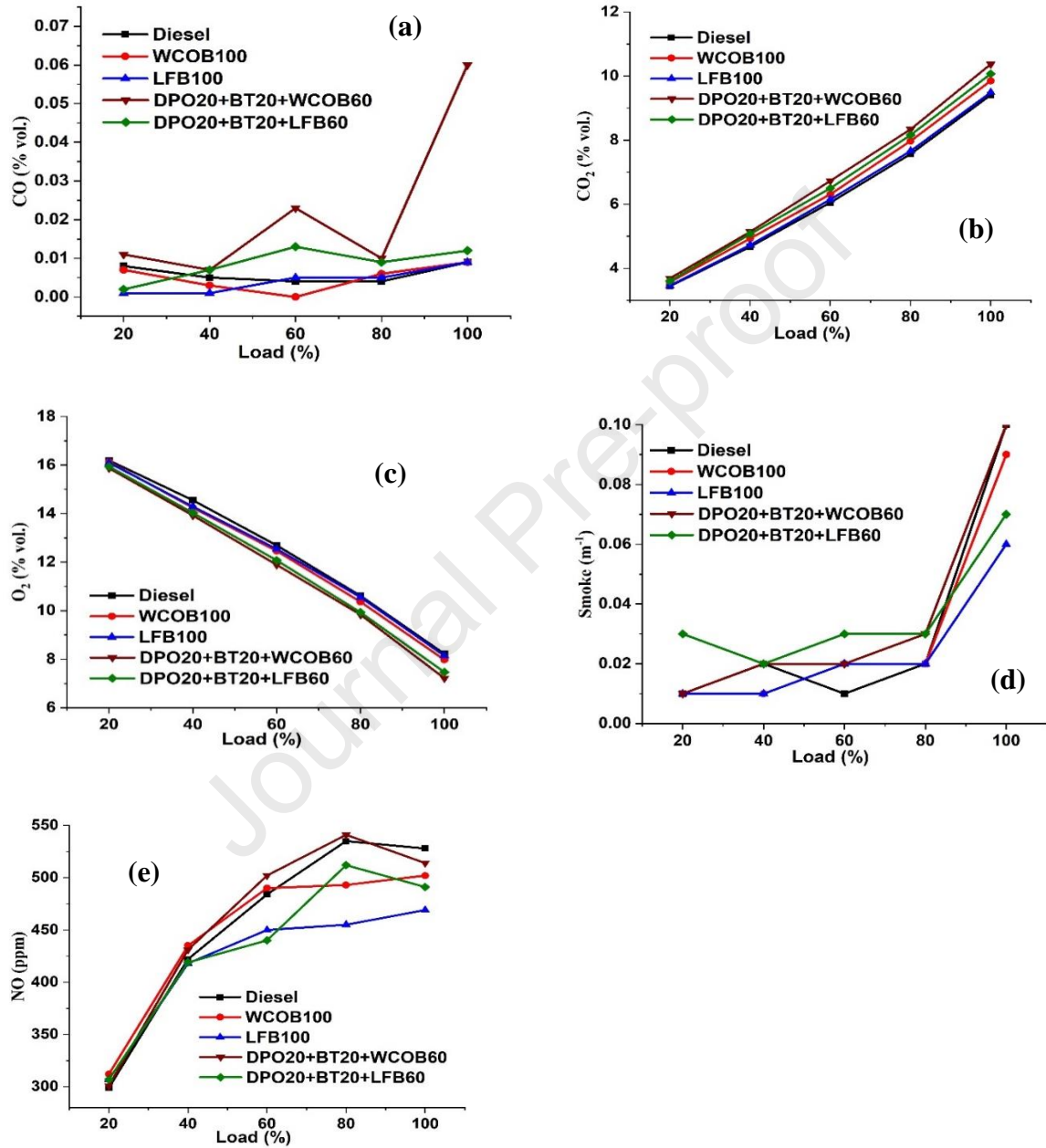
359
 360 Figure 7. DPO blends engine performance

361 3.3.2. Brake specific fuel consumption

362 The brake specific fuel consumption (BSFC) for biodiesel and the blends was higher than that
 363 for diesel fuel (Fig. 7), due to the lower heating value and higher viscosity of the biodiesel and
 364 the blends. Results show that the BSFC of blends DPO20+BT20+WCOB60 and
 365 DPO20+BT20+LFB60 are 23% and 20%, higher than for diesel fuel at full load, respectively.
 366 At 100% load, DPO20+BT20+WCOB60 shows 7% higher BSFC than neat WCOB, and for
 367 DPO20+BT20+LFB60 it is 0.5% higher than neat LFB. It is a well-known fact that biodiesel

368 has higher BSFC due to lower calorific value, but the addition of 1-butanol increases the auto-
 369 ignition temperature, which further increases the fuel consumption [27].

370 3.4. Engine emission characteristics



371 Figure 8. Engine emission (a-e) characteristics at different engine loads

372 3.4.1. Carbon monoxide

373 The formation of carbon monoxide (CO) is a sign of incomplete combustion, which decreases
374 with the increase of the engine load [19]. This is due to increase in the in-cylinder temperature,
375 resulting in the rapid oxidation of CO to CO₂ [23]. This rate is higher with oxygenated fuel
376 such as biofuel and biodiesels. DPO blends show higher CO emissions than biodiesel and diesel
377 fuel (Fig. 8a). The CO emissions for blends DPO20+BT20+WCOB60 and
378 DPO20+BT20+LFB60 were increased by around 86% and 25% with respect to diesel fuel at
379 100% load. At the same time, it was 40% and 44% higher with respect to neat WCOB and LFB
380 (Fig. 8a) at 100% load, respectively. Higher CO emission of DPO blends are due to higher
381 viscosity, leading to poor atomization, resulting in incomplete combustion. The cooling effect
382 of butanol's latent heat of vaporisation reduced in-cylinder temperature, which reduced the
383 oxidation rate of CO to CO₂ [31]. Furthermore, DPO blends consists of longer hydrocarbon
384 chain (Table 3), these longer chains also responsible for higher carbon emission; higher the
385 carbon, higher is the carbon emissions.

386 **3.4.2. Carbon dioxide**

387 The formation of CO₂ emissions gradually increases with increased engine load due to
388 increased fuel consumption [34]. Compared to diesel fuel, DPO20+BT20+WCOB60 and
389 DPO20+BT20+LFB60 show 7% and 4% higher CO₂ at 20% load and 10% and 7% at 100%
390 load (Fig. 8b). The formation of higher CO₂ with the DPO blends is due to their higher oxygen
391 content. This fuel bound oxygen increased the CO₂ gases during diffusion combustion by
392 increasing CO to CO₂ formation [27]. The longer hydrocarbon chain present in DPO fuel also
393 responsible for higher CO₂ emissions.

394 **3.4.3. Oxygen and smoke emission**

395 Figure 8c shows how oxygen decreases with higher engine loads. It is because of the rich
396 fuel/air mixture. The DPO blends show approximately 10% less oxygen at full load. It

397 decreased due to increases the quantity of the fuel/strokes. Smoke formation increases with
398 increased engine load, as shown in Fig. 8d. Smoke emissions for all the biodiesels and DPO
399 blends were lower than the diesel fuel at 100% load (refer to Fig. 8d). Due to incomplete
400 combustion, DPO20+BT20+WCOB60 and DPO20+BT20+LFB60 blends show 2% and 60%
401 higher smoke than diesel at 20% load. The cylinder temperature is lower under low load than
402 at full load, higher viscosity of blends reduces fuel evaporation rate, lowering combustion
403 efficiency [35]. The presence of butanol in the blend reduces in-cylinder temperature due to
404 cooling effect through latent heat of vaporisation of butanol, which resulted in incomplete
405 combustion and increases the smoke emission. Furthermore, because of the high in-cylinder
406 temperature at full load, this effect is reduced [31]. As the engine load is increased, the cylinder
407 temperatures are increased. Therefore, at full load, DPO blends DPO20+BT20+WCOB60 and
408 DPO20+BT20+LFB60 show 1% and 40% lower smoke than diesel (refer to Fig. 8d). The fuel
409 bound oxygen present in the blends and high in-cylinder temperatures at high loads played an
410 important role on producing reduced levels of smoke emissions.

411 **3.4.4. Nitric oxide**

412 Figure 8e shows the formation of NO emissions for all tested fuels. The NO gas emission
413 increases due to formation of thermal-NO_x caused by higher in-cylinder temperatures.
414 Compared to diesel fuel, blends DPO20+BT20+WCOB60 and DPO20+BT20+LFB60 show
415 0.6% and 2% higher NO emissions at low load. Fuel bound oxygen of the DPO blends caused
416 this behaviour. At 100% load, DPO20+BT20+WCOB60 and DPO20+BT20+LFB60 blends
417 show 2% and 7% lower NO emissions than diesel (Fig. 5f). The formation of reduced NO with
418 DPO blends is due to the addition of 1-butanol wherein more heat was absorbed due to higher
419 heat of vaporization, which reduces the flame temperature during combustion [35]. Presence
420 of butanol in the blend helped in reducing the NO gas emission at full load condition [31].

421

422 **4. Challenges and Limitations**

423 The adoption of any sustainable biofuels is greatly influenced by the producing cost. Non edible
 424 oil has higher acid values than edible oils. Hence, a two stage process known as esterification
 425 is required to produce biodiesels from non edible oils. Table 5 shows estimated cost parameters
 426 for biodiesels and DPO blends. At laboratory scale, estimated cost of producing LFB at
 427 laboratory is £6.53/litre. In contrast, estimated cost of a blend sample produced at laboratory
 428 scale is £6.02 per litre. Even though this cost is high, large scale production of biodiesel and
 429 pyrolysis oil would lower the overall cost of both biodiesel and DPO blends.

430

431

Table 5. Economic analysis of LFB and DPO blend sample

Material	Price/quantity	Required quantity	Price in GBP
Lamb fat biodiesel (LFB) production cost:			
Waste lamb fat	£0.35/kg	1100g	£0.38
Methanol	£5/ litre	245ml	£1.25
Potassium hydroxide (KOH)	£75/kg	9.5g	£0.72
Distilled water	£0.7/litre	3-5 litre	£3.5
Power (unit)	£0.34p/kWh	2-3	£0.68
Unit cost of LFB			£6.53/litre
Price of DPO blend sample:			
Unit cost DPO/ pyrolysis oil	5.5/litre	200ml	£1.1
Butanol	£5/ litre	200ml	£1.00
LFB	6.53/litre	600ml	£3.918
Total cost of blend sample (20%DPO + 20% butanol + 60LFB)			£6.02/litre

432

433 Current study shows that digestate oil can be blended successfully with biodiesels and used in
 434 low speed diesel engines. However, there are still challenges associated with the storage and
 435 use of the DPO blends. One of the big challenges is to meet the fuel standards, although the
 436 blends are not far from standards, further research is needed to meet the standard so that the

437 engine manufacturers allow to use the blends in the engines. Another challenge is the long-
438 term stability of the pyrolysis oils, as pyrolysis oils composition changes with time. In some
439 cases, digestate oils may contain high water content, dewatering the pyrolysis oil could be
440 expensive as high-water content fuels would corrode and erode the engine components. Proper
441 training is needed to prepare the blends and utilise them in the engines. Some pyrolysis oils
442 may contain trace metals, so careful analysis of oils and engine emission is important. Engine
443 maintenance frequency may increase due to the solids content present in the blends. The DPO
444 blends could be suitable for using in marine engines for shipping application. These oils can
445 also be used in stationary engines for power generation, and to power construction and
446 agricultural machineries. These oils may also be suitable for using in small trucks for
447 transportation of goods in rural areas.

448

449 **5. Conclusions and recommendations**

450 The present study aims to see how blends of digestate pyrolysis oil, biodiesel and alcohol
451 perform in a multi-cylinder indirect injection CI engine. In the present investigation, an
452 analysis was made to assess the combustion, performance and emissions characteristics of
453 pyrolysis oil produced from anaerobic digestion. Digestate pyrolysis oil and biodiesel were
454 produced and blended with WCOB and LFB using different cosolvents to reduce the blend
455 viscosity and improve miscibility. A total of five samples were prepared and characterized by
456 using DPO, waste cooking oil biodiesel (WCOB), lamb fat biodiesel (LFB) and alcohols.. Out
457 of these, blends DPO20+BT20+WCOB60 and DPO20+BT20+LFB60 were chosen for the
458 engine tests due to better stability and fuel properties. The important findings and novelty of
459 the study are summarised below:

- 460 (i) The fuel physical and chemical properties of neat fuel and blends directly influenced
461 the engine performance, combustion efficiency and emissions. Fuel properties such as
462 viscosity and heating value directly effects the fuel spray characteristics, and
463 combustion efficiency. The chemical properties such as molecular structure, short and
464 long charbon chain, higher % of long carbon chain increases the viscosity; whereas
465 saturation and unsaturation level effect the heating and ignition quality of the fuels.
466 Hence, it is important to match the fuel properties with the fuel standards.
- 467 (ii) Two stable blends were obtained by mixing 20% DPO and 20% 1-butanol with 60%
468 WCOB and LFB, respectively. The DPO blends show a reduction in acid value, density,
469 viscosity, and heating value about 60%, 18%, 90% and 18% compared to pure DPO,
470 but they are all still higher than those for diesel fuels.
- 471 (iii) The start of combustion for DPO blends were observed to be retarded by 1-1.5° CA
472 and ignition delay was increased by 6% compared to diesel fuel at full engine load.
- 473 (iv) The maximum in-cylinder pressure for blends DPO20+BT20+WCOB60 and
474 DPO20+BT20+LFB60 were observed to be 3% and 4.6% lower with diesel fuel at full
475 engine load, respectively, whereas DPO20+BT20+LFB60 shows 3% lower HRR_{max}
476 than diesel at full load. This could be due to the addition of butanol which reduced the
477 overall in-cylinder combustion temperature. Due to higher latent heat of vaporization,
478 butanol consume heat from the fuel combustion to reach the combustible stage.
- 479 (v) DPO blends emit 7% more CO₂ than diesel fuel at full load. This increase in CO₂
480 emissions is due to the addition of oxygenated butanol, and its cooling effect due its
481 higher latent heat of vaporization. The NO_x emissions for DPO blends was 7% lower
482 than with diesel fuel at full load, again due to the butanol.

483 In summary, this study affirms that DPO blends hold promise as a viable alternative fuel for
484 both power generation, agricultural and construction machineries, and marine engine

485 applications. Future research avenues include exploring the utilization of higher proportions of
486 DPO blends in engines and conducting a durability study to assess the long-term performance
487 of engines using these blends.

488

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493

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Declaration of interests

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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