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Emissions of Polycyclic Aromatic Hydrocarbons and Particle-Bound Metals from a Diesel Engine Generator Fueled with Waste Cooking Oil-Based Biodiesel Blends

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ABSTRACT

This study investigates the emission of a heavy-duty diesel engine generator fueled with waste cooking oil (WCO)-based biodiesel blends (W) and operated at 1.5 and 3.0 kW loads. A brand of pure fossil diesel was adopted as the base fuel, with 20% and 40% WCO-based biodiesel added into the based fuel to form W20 and W40 blends, respectively. The emission characteristics of PM, metals and PAHs were analyzed. Experimental results indicate that alternative WCO-based fuels had slightly higher fuel consumption rates (FCR) and brake specific fuel consumptions (BSFC) than conventional diesel (0.6–4.1% for FCR and 1.0–7.6% for BSFC), and similar engine thermal efficiency. The PM emissions reductions when using W20 and W40 were 19% and 6.5%, respectively, at 1.5 kW, and 27% and 19%, respectively, at 3.0 kW. The emissions of particle-bound metals were 13.6–13.8% lower when using W20 than using conventional diesel, but 12.0–12.3% higher when using W40. The metal contents of PM rose with the addition of WCO-based biodiesel. The metal elements of PM were dominated (> 90% mass) by Na, Mg, Al, K, Ca, Fe and Zn, while the major trace metals were Mn, Cu, Sr and Pb. The use of WCO-based biodiesel blends reduced the emissions of total-PAHs (44.0% in average) and total-BaP_{eq} (80.2% in average). The mass reductions of MMW- and HMW-PAHs using W20 and W40 were more significant at 3.0 kW than at 1.5 kW, while the reduction of LMW-PAHs was greater at 1.5 kW than at 3.0 kW. Thus, the reduction in total-BaP_{eq} was greater at the higher engine load. Accordingly, we conclude that the WCO-based biodiesel is a potential candidate of cleaner alternative energy sources.

Keywords: Polycyclic aromatic hydrocarbons; Particle bound metals; Waste cooking oil; Biodiesel; Diesel engine generator.

INTRODUCTION

Diesel engines are widely adopted in large-scale equipment, ships and buses due to their greater dependability, higher torque output and lower fuel costs than gasoline engines. However, diesel engine emissions (e.g., particulate matter (PM), nitrogen oxides (NO_x), hydrocarbon (HC), carbon monoxide (CO), and toxic air pollutants) cause serious environmental pollution, and are harmful to human health. Diesel particulate matter (DPM) is a component of diesel exhaust produced mainly by incomplete combustion of carbon particles (Alves *et al.*, 2015; Cheng *et al.*, 2015), soot, trace metals (Lin *et al.*, 2005; Haseeb *et al.*, 2011) and toxic organic pollutants (Tsai *et al.*, 2016), such as polycyclic aromatic hydrocarbons (PAHs) (Jin *et al.*, 2014), polychlorinated dibenzo-*p*-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs) (Mwangi *et al.*, 2015a), polychlorinated biphenyls (PCBs), polybrominated dibenzo-*p*-dioxins (PBDDs), polybrominated dibenzofurans (PBDDs) and polybrominated diphenyl ethers (PBDEs) (Chang *et al.*, 2014). Studies have shown that exposure to diesel exhaust endanger human health by increasing the risk of cardiovascular and respiratory conditions, as well as lung cancer (Benbrahim-Tallaa *et al.*, 2012; Tang *et al.*, 2016). Diesel engines are commonly known as a major source of ambient PAH emissions in some urban areas and cities (Lin *et al.*, 2008; Shi *et al.*, 2009; Cheruiyot *et al.*, 2015). Therefore, reducing diesel engine pollution emissions is an important issue for study, and is of concern in many countries. The use of biodiesel as fuel can easily reduce diesel engine emissions.

Biodiesel is one of the most promising and clean alternative fuels that are generated from renewable resources, and can be employed directly in diesel engines without any

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modification owing to its biodegradability, high oxygen content (~10 wt%) and high cetane number (Kameda *et al.*, 2007; Refaat, 2009). Many studies have confirmed that the use of an appropriate proportion (~20 vol%) of biodiesel can lower the diesel engine emissions of PM, gas pollutants (HC, CO and CO_2), PAHs and other pollutants (McCormick, 2007; Wu *et al.*, 2009; Lin *et al.*, 2010; Tsai *et al.*, 2010; Lin *et al.*, 2012). The conflict between food and bioenergy can be avoided by converting non-edible greases (e.g., waste cooking oil, WCO) into biofuels, and is presently feasible. However, some poor-quality aluminum, copper or stainless cooking utensils with may result in the presence of toxic metallic elements (Ni, Cr, Fe) (Kamerud *et al.*, 2013; Bassioni *et al.*, 2015) in the recycled WCO. According to Health Canada, cooking a meal in an aluminium pan can add about 1–2 mg aluminium (the WHO acceptable daily intake is 50 mg day^{-1}) to food (Diamond, 2005). Bassioni *et al.* (2012) concluded that aluminium foil is not appropriate for cooking, especially with acidic food. Excessive consumption of food baked with aluminium foil may carry a serious health risk. Therefore, the emission of particulate toxic metals from the combustion of WCO-biodiesels needs to be investigated.

Several recent studies have found that as well as PAHs, diesel engines may produce other toxic organic compounds (e.g., PCDD/Fs, PCBs and PBDEs) that are harmful to humans in the fuel oil combustion process (precursor or *de novo* reaction) (Laroo *et al.*, 2011; Pekarek *et al.*, 2001; Chang *et al.*, 2014; Tsai *et al.*, 2016). Investigations on the use of biodiesels as alternative fuels of diesel engines generally focus on the emission reductions of traditional gaseous pollutants, total PM, carbon species and PAHs (Dorado *et al.*, 2003; Agarwal and Agarwal, 2007; Cheng *et al.*, 2015; Mwangi *et al.*, 2015a). The emission of particulate toxic metals from non-road diesel generators fuelled with WCO-biodiesel blends has seldom been explored. This work investigated the emissions of 21 particle-bound metals (Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Sr, Mo, Cd, Sn, Sb, Ba and Pb) and 16 US-EPA PAH (particle- and gas-phase) compounds from a small generator fuelled with WCO-biodiesel blends under 1.5 and 3.0 kW loads. Additionally, fuel consumption and energy efficiency using different WCO-biodiesel blends were also examined at various generator bearing power loads.

MATERIALS AND METHODS

Sampling Methods

This study adopted three biodiesel-diesel blends with different mixing ratios of WCO-biodiesel to premium diesel: premium diesel fuel (D100), W20 (20 vol% WCO-biodiesel + 80 vol% D100) and W40. Different blended fuels were tested in a generator at a stable energy output (110 V/60 Hz, 1800 rpm) under loads of 1.5 and 3.0 kW. The diesel-engine generator was a four-stroke, water-cooled, single fuel-injection cylinder (bore: 88.0mm, stroke: 96.0 mm), manufactured by YANMAR Ltd., Japan (Model: TF110E &YSG-5SEN). The generator had one phase/two wires, an output frequency of 50/60 Hz and a maximum output power of 4 kW.

An auto-detector flow sampling system, equipped with a quartz fiber filter (2500 QAT-UP, 47 mm; Pall Corporation, New York, USA), was installed downstream of the diesel generator exhaust to measure the emitted concentrations of particle-bound PAH samples. Gas-phase PAHs emissions were accumulated using two connected glass cartridges filled with XAD-2 resin. Additionally, the particle-bound metal samples were collected by a Teflon filter (47 mm; 2.0 μm; Pall Corporation) under the same operating parameters. The experiments were performed three times (each sampling time = 30 min) for each combination of parameters. The premium diesel fuel was obtained from the Chinese Petroleum Corporation, Taiwan, and the pure WCO-biodiesel was manufactured by Chant Oil Co. Ltd., Taiwan. Further details of the fuel compositions and sampling programs can be found elsewhere (Tsai *et al.*, 2015b, 2016).

PAH Analysis

The gas-/particle-phase PAH samples accumulated from the diesel-generator exhausts were extracted using 1:1 (v/v) *n*-hexane/dichloromethane for 24 hr. The extracts were then concentrated, cleaned by a silica column of ~27 cm silica gel particles (size range = 0.04–0.063 mm) under a layer of anhydrous Na_2SO_4 (~1 cm high) and above a support of glass fibers, and reconcentrated by purging with ultra-pure nitrogen to exactly 1.0 mL for the subsequent identification of 16 PAHs by a gas chromatograph/mass selective detector (GC/MSD; model: GC 6890N/HP 5973). The limits of detection (LODs) for the 16 PAH compounds were 0.023–0.106 ng, and the recovery efficiencies were 83.9–92.6% (average = 86.4%). Additional analysis parameters and procedures of GC/MSD can be found elsewhere (Lin *et al.*, 2012; Chang *et al.*, 2013).

According to the molecular weights of 16 PAH compounds, the PAHs were divided into three categories: low molecular weight (LMW)-, medium molecular weight (MMW)-, and high molecular weight (HMW)-PAHs. The LMW-PAHs included naphthalene (Nap), acenaphthylene (AcPy), acenaphthene (Acp), fluorine (Flu), phenanthrene (PA), and anthracene (Ant) while the MMW-PAHs were fluoranthene (FL), pyrene (Pyr), benzo[a]anthracene (BaA), and chrysene (CHR). The HMW-PAHs were the group of benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo(a)pyrene (BaP), dibenzo[a,h]anthracene (DBA), indeno[1,2,3,-cd]pyrene (IND), and benzo[ghi]perylene (Bghip). The carcinogenic factors of the identified PAHs were calculated in terms of BaP_{eq}, from the toxic equivalence factors (TEFs) of these compounds (PAH concentration × TEF). In this study, the TEFs that were specified by Nisbet and LaGoy (1992) were used. The carcinogenic potency of Total-PAHs (Total-BaP_{eq}) was evaluated by summing the BaP_{eq} concentrations of individual PAH compounds.

Metal Analysis

In this study, the particle-bound metal samples gathered from Teflon filter paper were extracted by nitric acid solution, and analyzed with inductively coupled plasma mass spectrometry (ICP-MS). The extraction and analysis steps were as follows. Each Teflon filter paper was carefully

cut into small pieces. Each piece was then placed in a screw-cap 50mL graphite digestive tube. A 20 mL 10% HNO_3 solution was then added into each tube, and the screw cap was tightened. The locked graphite digestive tubes were extracted for 120 minutes with an ultrasonic bath, and then heated in a block heater at 80–85°C for 30 minutes. After cooling, each digested solution was filtered by a cellulose acetate filter (pore size 0.45 μm) and diluted to a volume of 25 mL using 10% HNO_3 for the analysis of 21 metals (Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Sr, Mo, Cd, Sn, Sb, Ba and Pb) using inductively coupled plasma-mass spectrometry (ICP-MS) (Agilent 7500a ICP-MS; Agilent Technologies Inc.). The calibration was performed using multi-element (metal) standards (certified reference materials (CRMs); Spex, Metuchen, USA) in a 1% (v/v) HNO_3 solution. Every tenth sample was spiked using the liquid standards that contained known amounts of the metal elements that were analyzed. The CRMs were also used as quality control standards.

For the analyses of elements using ICP-MS measurements, the method detection limits (MDL) for Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Sr, Mo, Cd, Sn, Sb, Ba and Pb were 6.12, 5.22, 3.16, 19.3, 24.3, 0.36, 0.04, 0.14, 0.03, 2.22, 0.03, 0.31, 5.27, 0.31, 0.20, 0.99, 0.02, 3.15, 0.12, 0.51 and 0.06 μg L^{-1}, respectively. The recovery efficiencies of 21 metals were 95.2–113.8% (average = 106.2%). Both field and laboratory blank samples were prepared and analyzed for each sampling and analysis. All data were corrected according to blanks.

RESULTS AND DISCUSSION

Engine Performance

The engine performance is the first consideration when developing new alternative fuels, because conventional engines and their related apparatus are generally only run with conventional diesel fuel. Therefore, this work reports the fuel consumption rate (FCR), brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). The FCRs were measured by a scaled cylinder, and evaluated as described in the experimental section. The FCRs using D100, W20, and W40 were 1.07 ± 0.02, 1.08 ± 0.01, and 1.11 ± 0.013 L hr^{-1}, respectively (Table 1). The FCR levels using W20 and W40 were 0.60–1.69% and 3.95–4.13% higher than that of D100, respectively. To eliminate the effect of unstable electricity generation among the tests of various fuel blends, the BSFCs (L kWh^{-1}) were then determined by Eq. (1) as follows.

$$BSFC\left(\text{L kWh}^{-1}\right)=\frac{FCR}{P_e} \tag{1}$$

where FCR denotes the fuel consumption rate (L h^{-1}), and P_e represents the averaging electricity power output (kW) during each sampling period.

The BSFCs using D100 were 0.714 ± 0.012 L kWh^{-1} and 0.495 ± 0.019 L kWh^{-1} at 1.5 and 3.0 kW engine load, respectively, and rose by 1.01–2.38% and 3.64–7.56% when using W20 and W40, respectively (Table 1). The higher additive ratio of WCO-based biodiesel might further reduce the heating value of the fuel blend, increasing the BSFC. However, either FCR or BSFC could directly measure the combustion efficiency or emission potential, since they had different input energies (LHVs of fuels). Therefore, this study represents the overall energy transfer efficiencies for using different fuel blends by the BTE (Eq. (2)).

$$BTE\left(\%\right)=\frac{3.6}{BSFC\times d_F\times LHV_F}\times 100\% \tag{2}$$

where d_F and LHV_F represent the density (kg L^{-1}) and lower heating value (MJ kg^{-1}) of each fuel blend, respectively.

The BTEs fell when D100 (14.1% ± 0.2%) was replaced by W20 (13.9% ± 0.1%) and W40 (13.5% ± 0.1%), representing 1.42% and 4.26% reduction, respectively, at 1.5 kW engine load. Additionally, the differences of BTEs among the three diesel blends were all below 0.01%, while more fuel were injected during each stroke at 3.0 kW engine load. Notably, the reductions in BTE when replacing D100 with W40 were smaller than the increases in BSFC, revealing that the oxygen and non-aromatic compounds in WCO-based biodiesel blends partially balance the lower heating value of biodiesel blends. Some previous studies even indicate that the oxygenated additives in diesel could improve the thermal efficiency of engines and reduce the BSFC (Yoshimoto *et al.*, 1999; Lin *et al.*, 2006; Lin *et al.*, 2010; Mwangi *et al.*, 2015a; Tsai *et al.*, 2015a). However, the higher viscosity was the second drawback of WCO-based biofuel for energy performance, since the more viscos fuel pray would lower the break down and vaporization processes before the combustion and eventually leaded to more incompletely combustion and consume fore fuels. Fortunately, both W20 had W40 had a similar overall energy performance to the original diesel fuel. The emissions of regulated and toxic pollutants thus became the major consideration of the alternatives.

Table 1. Fuel consumption and engine performance using WCO-based biodiesel blends at various loads.

Fuel Performances	Loads	D100	W20	Increases, %	W40	Increases, %
FCR (L hr^{-1})	1.5 kW	1.07 ± 0.02	1.08 ± 0.01	+1.69%	1.11 ± 0.01	+4.13%
(n = 3)	3.0 kW	1.49 ± 0.04	1.50 ± 0.02	+0.60%	1.55 ± 0.01	+3.95%
BSFC (L kWh^{-1})	1.5 kW	0.714 ± 0.012	0.731 ± 0.005	+2.38%	0.768 ± 0.007	+7.56%
(n = 3)	3.0 kW	0.495 ± 0.019	0.500 ± 0.009	+1.01%	0.513 ± 0.006	+3.64%
BTE (%)	1.5 kW	14.1% ± 0.2%	13.9% ± 0.1%	–1.42%	13.5% ± 0.1%	–4.26%
(n = 3)	3.0 kW	20.3% ± 0.8%	20.3% ± 0.4%	between ± 0.01%	20.2% ± 0.2%	between ± 0.01%

D: diesel; W: waste cooking oil-based biodiesel.

PM Emissions

The PM concentrations in engine exhaust ranged from 60.2–69.1 mg Nm^{-3}, 49.5–54.8 mg Nm^{-3}, and 58.4–62.7 mg Nm^{-3}, and averaged 64.9 ± 4.47 mg Nm^{-3}, 52.3 ± 2.66 mg Nm^{-3}, and 60.7 ± 2.21 mg Nm^{-3} using D100, W20 and W40, respectively, at 1.5 kW (as shown in Fig. 1). Additionally, the high PM levels were found to be 124–133 mg Nm^{-3} (average: 129 ± 4.52 mg Nm^{-3}), 85.3–104 mg Nm^{-3} (average: 94.7 ± 9.17 mg Nm^{-3}) and 98.0–111 mg Nm^{-3} (average: 104 ± 6.40 mg Nm^{-3}) using D100, W20 and W40, respectively, at 3.0 kW. The above results show significant PM emission reductions of 19% and 6.5% at 1.5 kW, and 27% and 19% at 3.0 kW, using W20 and W40, respectively. These emission improvements could result from the higher fuel-oxygen content for WCO-based biodiesel (11.8%) compared to D100 (< 0.2%), leading to more complete combustion (Lin *et al.*, 2006; Lin *et al.*, 2010; Chang *et al.*, 2014; Tsai *et al.*, 2015a, 2016). The nano particle emission concentration and their total area were also reported to be reduced by oxygenated fuel additives (Saxena and Maurya, 2016). Yang *et al.* (2016) further indicated that the use of oxygenated diesel blends could affect the nanostructure and pyrolysis of PM, which was easier to oxidize and advantageous for diesel particulate filter regeneration. Additionally, as biodiesel has a higher cetane index than fossil diesel, it shortens the ignition delay, leading to an earlier start of combustion reaction (Musculus, 2002; Lin and Lin, 2011). However, biodiesel had a higher viscosity than D100, inhibiting the nebulization of fuel spray. Therefore, the use of biodiesel reduces the PM emission, with W20 achieving the lowest value and increased again with W40, which has higher viscosity and worse spray combustion than W20 in this investigation. Conversely, a higher engine operation load increased the PM emission concentration, which could be attributed to more fuel mass being injected into the cylinder, and then combusted to produce more products (PM). These rises could be partially inhibited by using W20 and W40, as shown in Fig. 1.

Particle-Bound Metals

The concentrations of total particle-bound metals with D100 were 616 ± 43.2 μg Nm^{-3} to 2,104 ± 54.5 μg Nm^{-3} in the engine exhaust, and 13.6–13.8% lower at 531 ± 27.8 μg Nm^{-3} to 1,817 ± 45.0 μg Nm^{-3} when using W20 (Table 2). This reduction of metal emission could be attributed to the PM emission reductions, since W20 had a higher fuel oxygen content, while its viscosity was not significantly increased to inhibit the vaporization of fuel spray. However, the metal emission concentrations increased (by 12.0–12.3%) (692 ± 50.7 to 2356 ± 385 μg Nm^{-3}) when the generator was fuelled with W40, probably because the crude waste cooking oils had a higher metal content than the regular diesel (leading to 7.36–17.7% and 20.0–39.0% higher metal content in PM by using W20 and W40 (Table 2), respectively, than using D100). Therefore, W40 had higher overall particle-bound metal emissions than D100, but higher PM emission concentration.

The metal elements in the PM sample were dominated (over 90% mass of total metals) by Na, Mg, Al, K, Ca, Fe, and Zn. The major contents of the remaining trace metals were Mn, Cu, Sr and Pb (Fig. 2). Several previous studies support our findings. Kerminen *et al.* (1997) collected the particles emitted from a lab-diesel engine, and found similar results to this study (dominant metals: Na, Mg, Al, K, Ca,

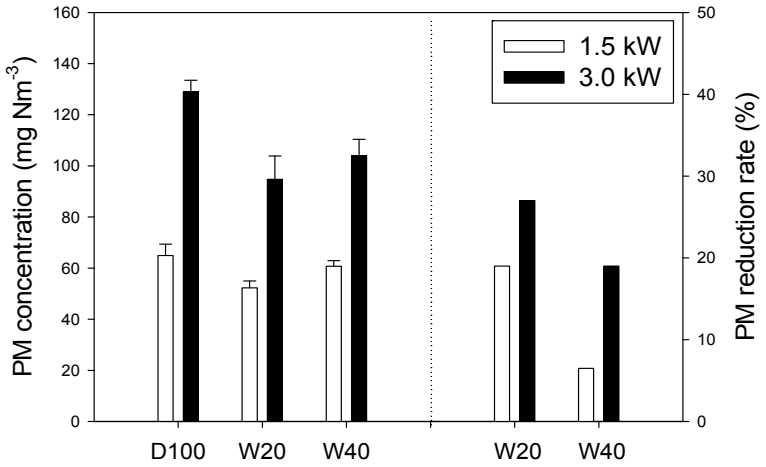

Fig. 1. PM concentrations and reductions using various diesel blends at two engine loads.

Table 2. Particle-bound metal emissions using WCO-based biodiesel blends at various loads.

Load	Metal Concentrations (μg Nm^{-3}) (n = 3)					Metal Content (%) in PM (n = 3)				
	D100	W20	Increases (%)	W40	Increases (%)	D100	W20	Increases (%)	W40	Increases (%)
1.5 kW	616 ± 43.2	531 ± 27.8	*–13.8%*	692 ± 50.7	*+12.3%*	0.95 ± 0.12	1.02 ± 0.10	*+7.36%*	1.14 ± 0.05	*+20.0%*
3.0 kW	2104 ± 54.5	1817 ± 45.0	*–13.6%*	2356 ± 385	*+12.0%*	1.64 ± 0.03	1.93 ± 0.17	*+17.7%*	2.28 ± 0.50	*+39.0%*

D: Diesel; W: WCO-biodiesel.

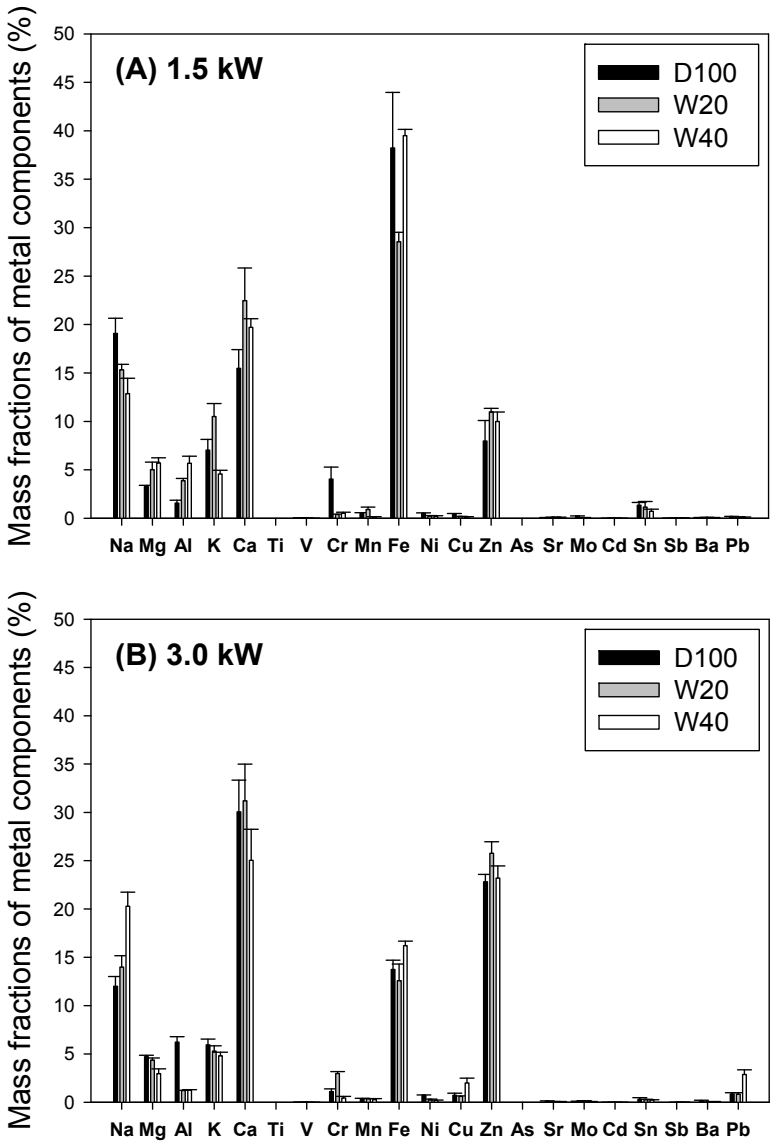

Fig. 2. Mass fractions of metal components by using various diesel blends at (A) 1.5 kW and (B) 3.0 kW engine loads.

Fe and Zn). Norbeck *et al.* (1998) also concluded that the major metals on diesel-PM were Zn, Fe, Ca, Pb and Ba, contributing 0.3% of the total PM mass. Yang *et al.* (1998) also reported that the major metals in PM from diesel exhaust were Fe, Al, Ca, Na, Cr, Ba, Ni, Mg and K, while the Fe and Al contributed 77 mg g^{-1} and 48 mg g^{-1} in PM. The trace metals Mn, Zn, Cu, Pb, Cd, V and Sr were mainly contributed by Mn (5.2 mg g^{-1}), Zn (3.7 mg g^{-1}), Cu (2.4 mg g^{-1}) and Pb (1.8 mg g^{-1}). Additionally, Valavanidis *et al.* (2006) found that diesel vehicles emitted much greater Cu, Pb, V, Cr, and Zn content than gas engines.

The above metal compositions in the fine particle from diesel engine emissions could be associated with the lubricant contents (Zn, Ca and Mg), additives of catalyst and the friction products of engine units (Fe, Ni, Cu, Cr and Sd) (Pacyna, 1996; Sappok *et al.*, 2012). Specifically, Fe emission could be from the friction of cylinder liners, piston rings, valves and crank shafts (Haseeb *et al.*, 2011). Cr was emitted from the wear of compression rings, gears and cam bearings (Agarwal and Dhar, 2010). Pb, Al and Cu, could be from the coating material (Agarwal and Dhar, 2010), wear of pistons (Wander *et al.*, 2011) and wear of bearings (Haseeb *et al.*, 2011), respectively. Hu *et al.* (2009) and Liati *et al.* (2015) indicated that the vehicle lubricant contents could cause Ca, Zn, Mg, P and B emissions.

The atmospheric metal pollutants were emitted from natural and anthropogenic sources, transported by air movement and deposited by gravity, or washed out by rainfall to the near-ground environment. Wang *et al.* (2003) found that the overall annual emissions of crustal metallic elements (Al, Ca, Fe, Mg and Si) and non-natural elements (Ag, Ba, Cd, Cr, Cu, Mn, Mo, Ni, Pb, Sr, Ti, V, Zn, As and Hg) from diesel vehicles were 269 ton yr^{-1} and 58.7 ton yr^{-1}, respectively. These annual emissions were significantly higher than those from coal power plants (90.1 ton yr^{-1} and 1.66 ton yr^{-1}), coke production plants (60.5 ton yr^{-1} and 3.74 ton yr^{-1}) and electric arc furnaces (2.06 ton yr^{-1} and 0.173 ton yr^{-1}).

PAH Emissions and Toxicities in the Exhaust of Diesel Engine

Figs. 3(A) and 3(B) show the total-PAHs and BaP toxicity equivalent (BaP_{eq}) concentrations of WCO-based biodiesel blends. The total-PAH mass concentrations for using W20 and W40 were 152–221 μg Nm^{-3} and 167–228 μg Nm^{-3}, respectively, at two engine loads, representing about 45.6–46.0% and 40.6–43.8% reductions (as shown in Fig. 4(A)), respectively, in comparison to those for using D100. At the two engine loads, the total-BaP_{eq} concentrations for using W20 and W40 were 0.418–0.451 μg BaP_{eq} Nm^{-3} and 0.462–0.534 μg-BaP_{eq} Nm^{-3}, respectively (about 74.9–88.5% and 70.3–87.3% reductions when compared with using D100) (Fig. 4(B)). This phenomenon was also likely associated with more complete combustion provided by fuel oxygen in W20 and W40, and the fair viscosity of W20 to the fuel injection system. The above findings are supported by some researches (Chang *et al.*, 2014; Mwangi *et al.*, 2015a; Tsai *et al.*, 2015a, 2016). The emissions of total-PAHs and total-BaP_{eq} were higher at the higher load (3.0 kW) than the lower one (1.5 kW) by using all fuel blends, because the PAH contents in fuels were positively correlated with the FCR and BSFC. Since, the reduction of total-PAH concentrations was more significant at 1.5 kW (40.6–46.0%), while the total-BaP_{eq} levels decreased more obviously at 3.0 kW (87.3–88.5%). This opposite trend contributes to the different compositions of PAH congeners. However, compared with W20, W40 had more PAH emission from the generator was observed at two loads. This phenomenon is possibly associated with W40 had a higher viscosity than W20, reducing the nebulization of fuel spray, which adversely affects fuel combustion and also could result in resynthesis of PAHs during combustion (Lin *et al.*, 2006; Tsai *et al.*, 2010).

Figs. 5 and 6 illustrate the mass and BaP_{eq} concentration of PAH congeners at 1.5 and 3.0 kW loads, respectively. The congener mass and BaP_{eq} fractions (profiles) were computed from the mass and BaP_{eq} of individual PAH congener divided by total-PAH and total-BaP_{eq}, respectively (Figs. 7 and 8 in percentages). The mass fractions of LMW-PAHs (Nap, AcPy, Acp, Flu, PA, and Ant) were 86–94% at two loads and dominated by 2-ring Nap (62.7–72.9%; average: 67.1%), 3-ring PA (5.9–8.9%; average: 7.7%), and AcP (3.9–7.5%; average: 5.5%); while the mass contribution of 5-ring BaP, which has much higher toxicity, was only 0.2% on average. The BaP_{eq} had different congener profiles from the mass. The most contributive congener in toxicity was BaP (16.9–70.9%; average: 36.1%), followed by Nap (7.3–40.3%; average: 22.8%) and BbF (9.4–13.1%; average: 11.4%).

For the congener reductions by using WCO-based biodiesel blends, the greatest mass reductions occurred in Nap (24–30%; average: 27%), while the most toxic BaP was reduced slightly (0.3–0.6%; average: 0.5%). Among the investigated PAH species, BaP exhibited the greatest BaP_{eq} reduction, ranging 49–69% (average 59%), while Nap only reduced the BaP_{eq} level by 2.7–4.7% (3.7% in average). To further clarify the reason of BaP_{eq} reduction by using W20 and W40, the mass and BaP_{eq} concentrations of congeners with similar ring numbers and molecular weights were assigned to three groups, namely low-molecular-weight PAHs (LMW-PAHs), medium-molecular-weight PAHs (MMW-PAHs) and high-molecular-weight-PAHs (HMW-PAHs). The order of mass contribution in term of different molecular weight-PAHs was LMW-PAHs > MMW-PAHs > HMW-PAHs, while the order of BaP_{eq} contribution was HMW- > LMW- > MMW-PAHs. Furthermore, the mass reductions of MMW- and HMW-PAHs by using W20 and W40 were more significant at 3.0 kW than at 1.5 kW, while the reduction of LMW-PAHs was greater at 1.5 kW than at 3.0 kW. Since the MMW- and HMW-PAHs had much higher toxicities than LMW-PAHs, the total-BaP_{eq} reductions were then along with the tendencies of MMW- and HMW-PAHs and leaded to the aforementioned opposite trends to mass reduction in term of engine loads. Previous studies indicated that the use of biodiesels not only dilutes the aromatic compounds released from the fossil fuel and oxidizes the PAH precursor (C_2H_2), but also provides more rapid and complete combustion to degrade the levels of MMW- and HMW-PAHs to LMW-PAHs, further reducing the total-BaP_{eq} in the diesel engine exhaust (Agarwal, 2007;

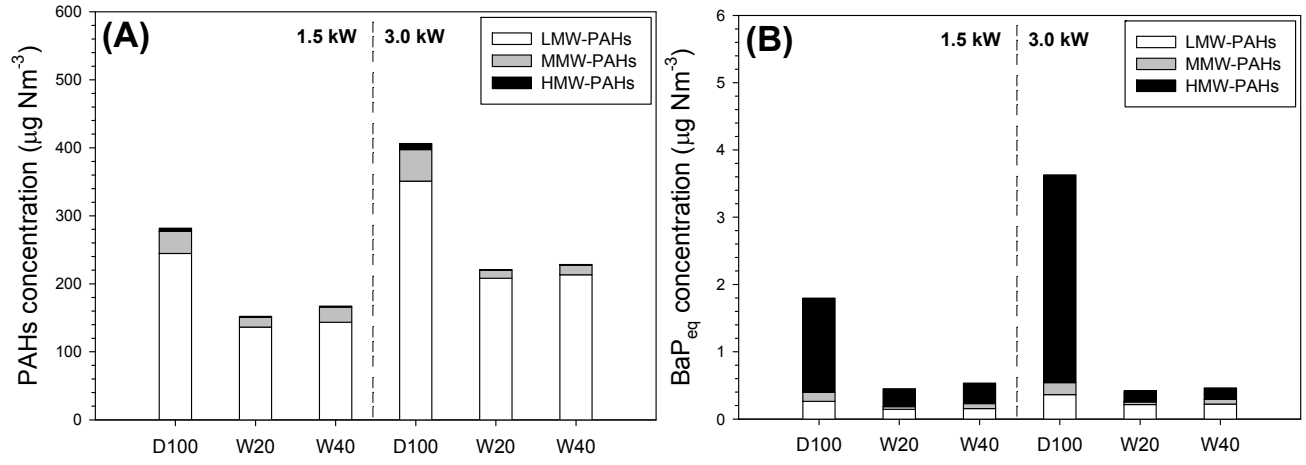

Fig. 3. (A) Mass and (B) BaP_{eq} concentrations of LMW-, MMW-, and HMW-PAHs by using diesel blends at two engine loads.

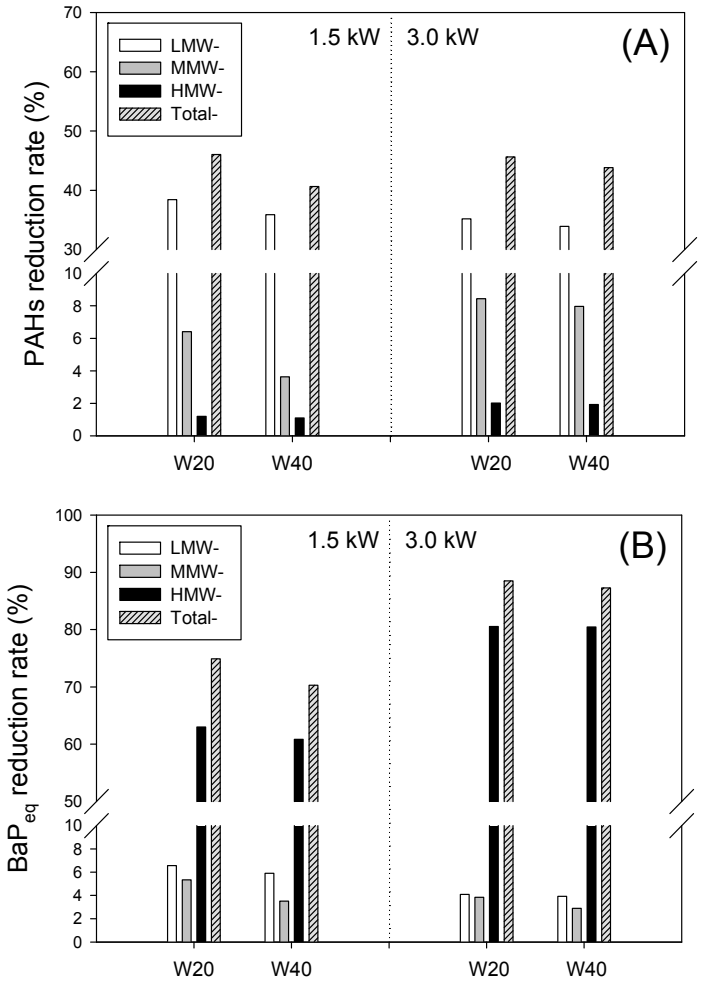

Fig. 4. Reduction rates of LMW-, MMW-, and HMW-PAHs in terms of (A) mass and (B) BaP_{eq} concentrations using WCO-based biodiesel blends at two engine loads.

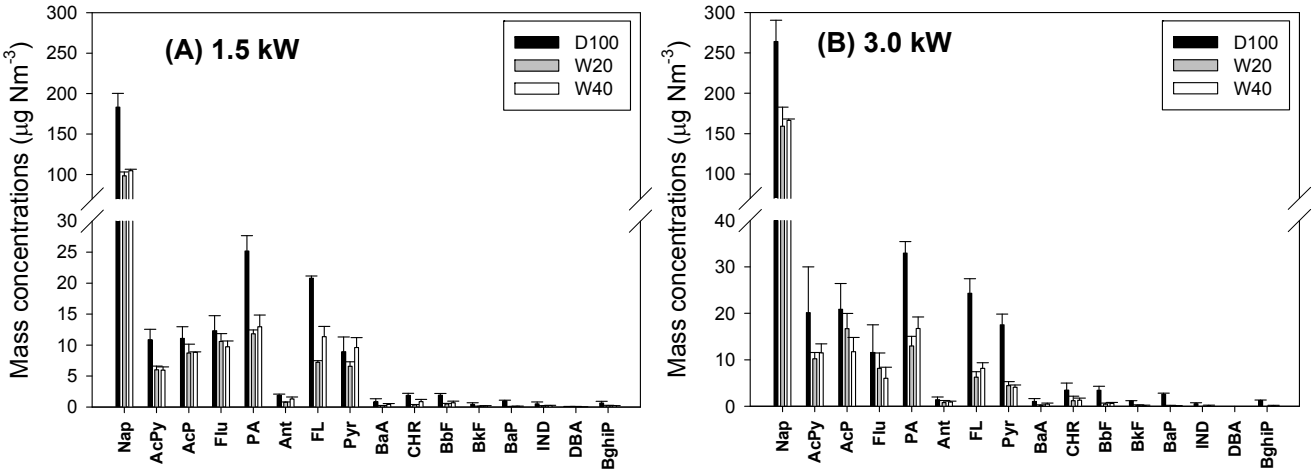

Fig. 5. Mass concentrations of PAH congeners using various diesel blends at (A) 1.5 kW and (B) 3.0 kW engine loads.

Mwangi *et al.*, 2015a). The WCO-based biodiesel blends were also been reported as an greener fuel for POP reduction in both internal combustion engine and incinerators since they could enhance the oxidation of hydrocarbons and further inhibit the reformation of POPs from C_2H_2 precursor (Tsai *et al.*, 2015b, 2016; Chen *et al.*, 2017).

Emission Factors of PAHs

Table 3 shows the emission factors (EFs) of BaP_{eq} in term of unit fuel consumption and power generation by

using D100, W20 and W40 at the two engine loads. The EFs of D100, W20 and W40 were 1.30 μg-BaP_{eq} L^{-1}, 0.290 μg-BaP_{eq} L^{-1}, and 0.335 μg-BaP_{eq} L^{-1}, (corresponding to 0.931 μg-BaP_{eq} kWh^{-1}, 0.212 μg-BaP_{eq} kWh^{-1}, and 0.257 μg-BaP_{eq} kWh^{-1}), respectively, at 1.5 kW load. The EF reductions were 77.7% and 74.2% in term of fuel

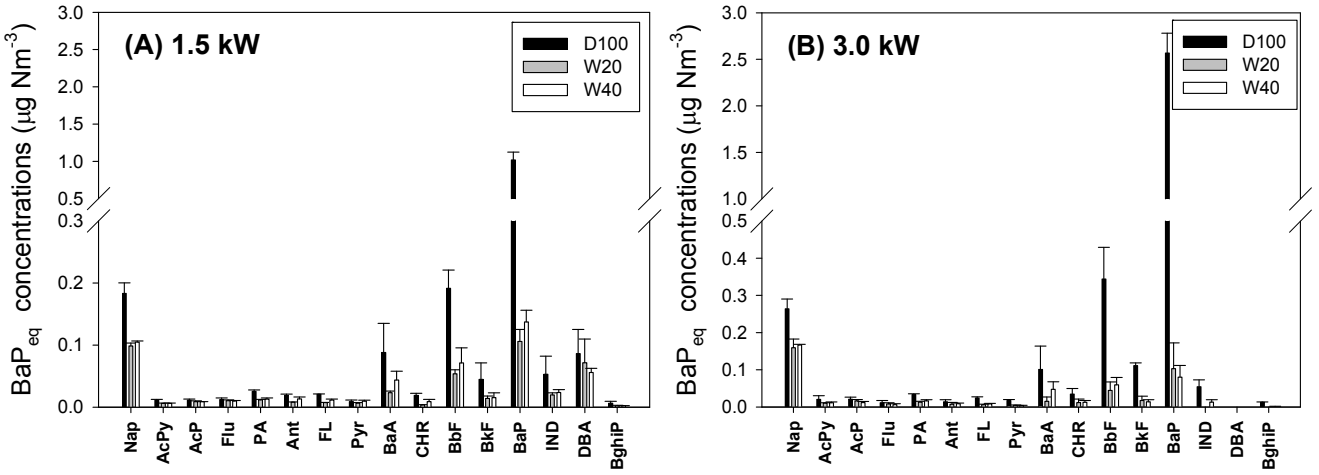

Fig. 6. BaP_{eq} concentrations of PAH congeners using various diesel blends at (A) 1.5 kW and (B) 3.0 kW engine loads.

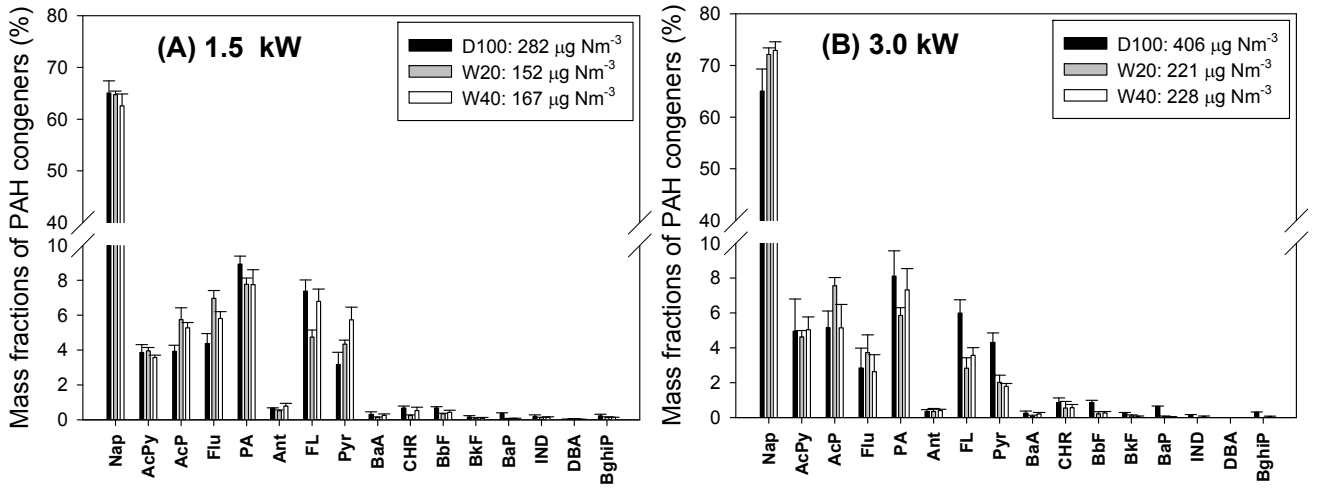

Fig. 7. Mass fractions of PAH congeners using various diesel blends at (A) 1.5 kW and (B) 3.0 kW engine loads.

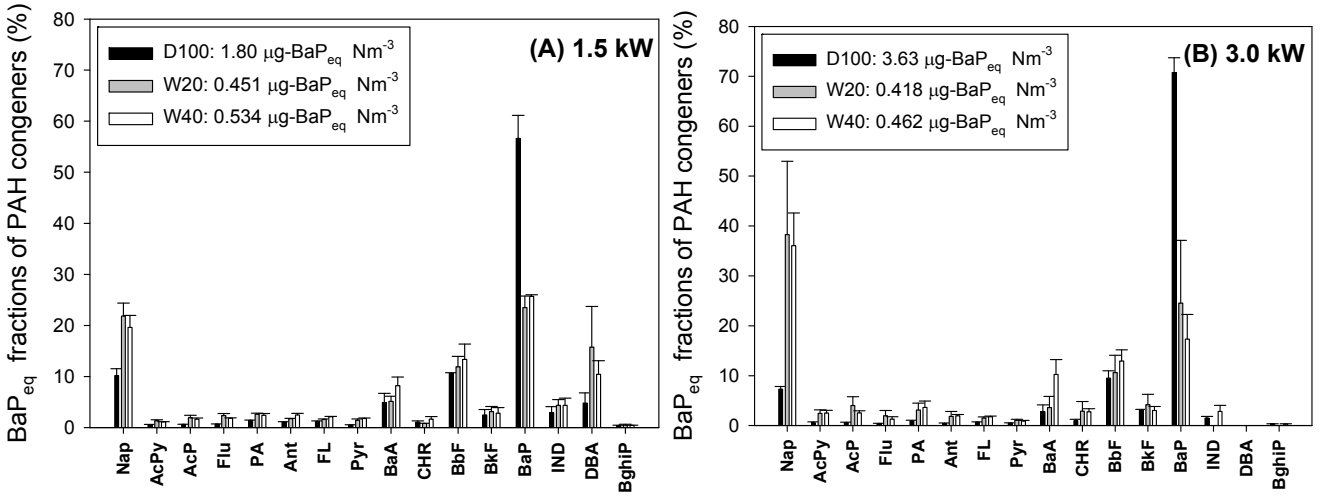

Fig. 8. BaP_{eq} fractions of PAH congeners using various diesel blends at (A) 1.5 kW and (B) 3.0 kW engine loads.

Table 3. PAH emission factors in terms of fuel consumption and power generation.

Fuel	PAH Emission Factors	Activities	Increases (%)
D100			
1.5 kW	1.30 μg-BaP_{eq} L^{-1}	*Fuel consumption*	Based fuel
	0.931 μg-BaP_{eq} kWh^{-1}	*Power generation*	Based fuel
3.0 kW	1.53 μg-BaP_{eq} L^{-1}	*Fuel consumption*	Based fuel
	0.755 μg-BaP_{eq} kWh^{-1}	*Power generation*	Based fuel
W20			
1.5 kW	0.290 μg-BaP_{eq} L^{-1}	*Fuel consumption*	–77.7
	0.212 μg-BaP_{eq} kWh^{-1}	*Power generation*	–77.2
3.0 kW	0.173 μg-BaP_{eq} L^{-1}	*Fuel consumption*	–88.7
	0.087 μg-BaP_{eq} kWh^{-1}	*Power generation*	–88.5
W40			
1.5 kW	0.335 μg-BaP_{eq} L^{-1}	*Fuel consumption*	–74.2
	0.257 μg-BaP_{eq} kWh^{-1}	*Power generation*	–72.4
3.0 kW	0.187 μg-BaP_{eq} L^{-1}	*Fuel consumption*	–87.8
	0.096 μg-BaP_{eq} kWh^{-1}	*Power generation*	–87.3

consumption, and 77.2% and 72.4% for the EF per power generation using W20 and W40, respectively. At 3.0 kW engine load, the EFs of D100, W20 and W40 were 1.53 μg-BaP_{eq} L^{-1}, 0.173 μg-BaP_{eq} L^{-1}, and 0.187 μg-BaP_{eq} L^{-1} (or 0.755 μg-BaP_{eq} kWh^{-1}, 0.087 μg-BaP_{eq} kWh^{-1}, and 0.096 μg-BaP_{eq} kWh^{-1}), respectively. The EF reductions corresponded to 88.7% and 87.8% in terms of fuel consumption, and 88.5% and 87.3% by power generation by W20 and W40, respectively. Nevertheless, the reductions in EFs using WCO-based biodiesel blends were greater at the higher engine load, which again reflected a better combustion condition of oxygenated fuel additives.

CONCLUSIONS

This study focuses on the use of WCO-based biodiesel blends in a HDDE with operation loads of 1.5 and 3.0 kW. The energy performance, PM, particle-bound metals and PAHs in the exhaust gas were investigated. The fuel consumption rate and BSFC were slightly higher (0.6–4.1% for FCR and 1.0–7.6% for BSFC) using alternative WCO-based fuels than using conventional diesel, but their engine thermal efficiencies were similar. The use of W20 and W40 achieved PM emission reductions of 19% and 6.5%, respectively, at 1.5 kW and 27% and 19%, respectively, at 3.0 kW. The higher engine load resulted in a higher PM emission. The emission concentrations of particle-bound metals were reduced by 13.6–13.8% when using W20, but increased by 12.0–12.3% when using W40. The metal contents of PM rose with the addition of WCO-based biodiesel to the petroleum diesel. The metal elements in PM were dominated (> 90% mass) by Na, Mg, Al, K, Ca, Fe and Zn. The major trace metals were Mn, Cu, Sr and Pb. The uses of W20 and W40 could effectively reduce the emissions of total-PAHs (average 44.0%) and total-BaP_{eq} (average 80.2%). The mass reductions of MMW- and HMW-PAHs by using W20 and W40 were more significant at 3.0 kW than at 1.5 kW, while the reduction of LMW-PAHs at 1.5 kW was more than that at 3.0 kW. Thus, the total-BaP_{eq} were more reduced at the higher engine load. Nevertheless, the annual consumption of diesel fuel in Taiwan was reported by 16.7 ML, meaning the annual emissions of PAH toxicity were around 2.17–2.56 g BaP_{eq}. Those annual emissions could be further reduced by 1.69–2.27 g BaP_{eq} if we replace the diesel fuel by W20. This result provides a more healthy and sustainable fuel usage in both academic and practical aspects. In conclusion, the WCO-based biodiesel blends are good candidates of cleaner alternative fuels for diesel engine generators.

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REFERENCE

Agarwal, A.K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Prog. Energy Combust. Sci.* 33: 233–271.

Agarwal, A.K. and Dhar, A. (2010). Karanja oil utilization in a direct-injection engine by preheating. Part 2: Experimental investigations of engine durability and lubricating oil properties. *Proc. Inst. Mech. Eng. Part D* 224: 85–97.

Agarwal, D. and Agarwal, A.K. (2007). Performance and emissions characteristics of Jatropha oil (preheated and blends) in a direct injection compression ignition engine. *Appl. Therm. Eng.* 27: 2314–2323.

Alves, C.A., Lopes, D.J., Calvo, A.I., Evtyugina, M., Rocha, S. and Nunes, T. (2015). Emissions from light-duty diesel and gasoline in-use vehicles measured on chassis dynamometer test cycles. *Aerosol Air Qual. Res.* 15: 99–116.

Bassioni, G., Mohammed, F.S., Al Zubaidy, E. and Kobrsi, I. (2012). Risk assessment of using aluminum foil in food preparation. *Int. J. Electrochem. Sci.* 7: 4498–4509.

Bassioni, G., Korin, A. and Salama, A.E.D. (2015). Stainless steel as a source of potential hazard due to metal leaching

into beverages. *Int. J. Electrochem. Sci.* 10: 3792–3802.

Benbrahim-Tallaa, L., Baan, R.A., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., Guha, N., Loomis, D., Straif, K. and Workin, I.A.R.C.M. (2012). Carcinogenicity of diesel-engine and gasoline-engine exhausts and some nitroarenes. *Lancet Oncol.* 13: 663–664.

Chang, Y.C., Lee, W.J., Lin, S.L. and Wang, L.C. (2013). Green energy: Water-containing acetone-butanol-ethanol diesel blends fueled in diesel engines. *Appl. Energy* 109: 182–191.

Chang, Y.C., Lee, W.J., Wang, L.C., Yang, H.H., Cheng, M.T., Lu, J.H., Tsai, Y.I. and Young, L.H. (2014). Effects of waste cooking oil-based biodiesel on the toxic organic pollutant emissions from a diesel engine. *Appl. Energy* 113: 631–638.

Chen, C.Y., Lee, W.J., Mwangi, J.K., Wang, L.C., Wu, J.L. and Lin, S.L. (2017). Reduction of persistent organic pollutant emissions during incinerator start-up by using crude waste cooking oil as an alternative fuel. *Aerosol Air Qual. Res.* 17: 899–912.

Cheng, M.T., Chen, H.J., Young, L.H., Yang, H.H., Tsai, Y.I., Wang, L.C., Lu, J.H. and Chen, C.B. (2015). Carbonaceous composition changes of heavy-duty diesel engine particles in relation to biodiesels, aftertreatments and engine loads. *J. Hazard. Mater.* 297: 234–240.

Cheruiyot, N.K., Lee, W.J., Mwangi, J.K., Wang, L.C., Lin, N.H., Lin, Y.C., Cao, J., Zhang, R. and Chang-Chien, G.P. (2015). An overview: Polycyclic aromatic hydrocarbon emissions from the stationary and mobile sources and in the ambient air. *Aerosol Air Qual. Res.* 15: 2730–2762.

Diamond, J. (2005). A report on alzheimer's disease and current research. Alzheimer Society of Canada, http://brainxchange.ca/Public/Files/Events/National/ADandCurrentResearch_DrJackDiamond.aspx.

Dorado, M.P., Ballesteros, E., Arnal, J.M., Gomez, J. and Lopez, F.J. (2003). Exhaust emissions from a diesel engine fueled with transesterified waste olive oil. *Fuel* 82: 1311–1315.

Haseeb, A.S.M.A., Fazal, M.A., Jahirul, M.I. and Masjuki, H.H. (2011). Compatibility of automotive materials in biodiesel: A review. *Fuel* 90: 922–931.

Hu, S.H., Herner, J.D., Shafer, M., Robertson, W., Schauer, J.J., Dwyer, H., Collins, J., Huai, T. and Ayala, A. (2009). Metals emitted from heavy-duty diesel vehicles equipped with advanced PM and NO_x emission controls. *Atmos. Environ.* 43: 2950–2959.

Jin, T.S., Qu, L., Liu, S.X., Gao, J.J., Wang, J., Wang, F., Zhang, P.F., Bai, Z.P. and Xu, X.H. (2014). Chemical characteristics of particulate matter emitted from a heavy duty diesel engine and correlation among inorganic and PAH components. *Fuel* 116: 655–661.

Kameda, T., Nakao, T., Stavarache, C., Maeda, Y., Hien, T.T., Takenaka, N., Okitsu, K. and Bandow, H. (2007). Determination of polycyclic aromatic hydrocarbons and nitrated polycyclic aromatic compounds in diesel-engine exhaust particles from combustion process of biodiesel fuel. *Bunseki Kagaku* 56: 241–248.

Kamerud, K.L., Hobbie, K.A. and Anderson, K.A. (2013). Stainless steel leaches nickel and chromium into foods during cooking. *J. Agric. Food Chem.* 61: 9495–9501.

Kerminen, V.M., Makela, T.E., Ojanen, C.H., Hillamo, R.E., Vilhunen, J.K., Rantanen, L., Havers, N., VonBohlen, A. and Klockow, D. (1997). Characterization of the particulate phase in the exhaust from a diesel car. *Environ. Sci. Technol.* 31: 1883–1889.

Laroo, C.A., Schenk, C.R., Sanchez, L.J. and McDonald, J. (2011). Emissions of PCDD/Fs, PCBs, and PAHs from a modern diesel engine equipped with catalyzed emission control systems. *Environ. Sci. Technol.* 45: 6420–6428.

Liati, A., Pandurangi, S.S., Boulouchos, K., Schreiber, D. and Dasilva, Y.A.R. (2015). Metal nanoparticles in diesel exhaust derived by in-cylinder melting of detached engine fragments. *Atmos. Environ.* 101: 34–40.

Lin, C.C., Chen, S.J., Huang, K.L., Hwang, W.I., Chang-Chien, G.P. and Lin, W.Y. (2005). Characteristics of metals in nano/ultrafine/fine/coarse particles collected beside a heavily trafficked road. *Environ. Sci. Technol.* 39: 8113–8122.

Lin, C.C., Chen, S.J., Huang, K.L., Lee, W.J., Lin, W.Y., Tsai, J.H. and Chaung, H.C. (2008). PAHs, PAH-induced carcinogenic potency, and particle-extract-induced cytotoxicity of traffic-related nano/ultrafine particles. *Environ. Sci. Technol.* 42: 4229–4235.

Lin, S.L., Lee, W.J., Lee, C.F. and Chen, S.J. (2010). Energy savings and emission reduction of nitrogen oxides, particulate matter, and polycyclic aromatic hydrocarbons by adding water-containing acetone and neat soybean oil to a diesel-fueled engine generator. *Energy Fuels* 24: 4522–4533.

Lin, S.L., Lee, W.J., Lee, C.F. and Wu, Y.P. (2012). Reduction in emissions of nitrogen oxides, particulate matter, and polycyclic aromatic hydrocarbon by adding water-containing butanol into a diesel-fueled engine generator. *Fuel* 93: 364-372.

Lin, Y.C., Lee, W.J. and Hou, H.C. (2006). PAH emissions and energy efficiency of palm-biodiesel blends fueled on diesel generator. *Atmos. Environ.* 40: 3930–3940.

Lin, Y.S. and Lin, H.P. (2011). Spray characteristics of emulsified castor biodiesel on engine emissions and deposit formation. *Renew. Energy* 36: 3507–3516.

McCormick, R.L. (2007). The impact of biodiesel on pollutant emissions and public health. *Inhalation Toxicol.* 19: 1033–1039.

Musculus, M., Dec., J., Tree, D., Daly, D., Langer, D., Ryam, T.W. and Matheaus, A.C. (2002). Effects of water-fuel emulsions on spray and combustion processes in a heavy-duty DI diesel engine. *SAE Technical Paper* 2002-01-2892.

Mwangi, J.K., Lee, W.J., Chang, Y.C., Chen, C.Y. and Wang, L.C. (2015a). An overview: Energy saving and pollution reduction by using green fuel blends in diesel engines. *Appl. Energy* 159: 214–236.

Mwangi, J.K., Lee, W.J., Whang, L.M., Wu, T.S., Chen, W.H., Chang, J.S., Chen, C.Y. and Chen, C.L. (2015b). Microalgae oil: Algae cultivation and harvest, algae residue torrefaction and diesel engine emissions tests.

Aerosol Air Qual. Res. 15: 81–98.

Nisbet, I.C.T. and LaGoy, P.K. (1992). Toxic equivalency factors (TEFs) for polycyclic aromatic hydrocarbons (PAHs). *Regul. Toxicol. Pharm.* 16: 290–300.

Norbeck, J.M., Durbin, T.D. and Truex, T.J. (1998). *Measurement of primary particulate matter emissions from light-duty motor vehicles*. Prepared for Coordinating Research Council, Inc., and South Coast Air Quality Management District, by Center for Environmental Research and Technology, College of Engineering, University of California, Riverside, CA.

Pacyna, J.M. (1996). *Atmospheric Trace Elements from Natural and Anthropogenic Sources*. Toxic Metals in the Atmosphere, John Wiley and Sons, New York.

Pekarek, V., Grabic, R., Marklund, S., Puncochar, M. and Ullrich, J. (2001). Effects of oxygen on formation of PCB and PCDD/F on extracted fly ash in the presence of carbon and cupric salt. *Chemosphere* 43: 777–782.

Refaat, A.A. (2009). Correlation between the chemical structure of biodiesel and its physical properties. *Int. J. Environ. Sci. Technol.* 6: 677–694.

Sappok, A., Kamp, C. and Wong, V. (2012). Sensitivity analysis of ash packing and distribution in diesel particulate filters to transient changes in exhaust conditions. *SAE Int. J. Fuels Lubr.* 5: 733–750.

Saxena, M.R. and Maurya, R.K. (2016). Effect of butanol blends on nano particle emissions from a stationary conventional diesel engine. *Aerosol Air Qual. Res.* 16: 2255–2266.

Shi, G.L., Feng, Y.C., Wu, J.H., Li, X., Wang, Y.Q., Xue, Y.H. and Zhu, T. (2009). Source identification of polycyclic aromatic hydrocarbons in urban particulate matter of Tangshan, China. *Aerosol Air Qual. Res.* 9: 309–315.

Tang, S.D., LaDuke, G., Chien, W. and Frank, B.P. (2016). Impacts of biodiesel blends on $PM_{2.5}$, particle number and size distribution, and elemental/organic carbon from nonroad diesel generators. *Fuel* 172: 11–19.

Tsai, J.H., Chen, S.J., Huang, K.L., Lin, Y.C., Lee, W.J., Lin, C.C. and Lin, W.Y. (2010). PM, carbon, and PAH emissions from a diesel generator fuelled with soy-biodiesel blends. *J. Hazard. Mater.* 179: 237–243.

Tsai, J.H., Lin, S.L., Mwangi, J.K., Chen, C.Y. and Wu, T.S. (2015a). Energy saving and pollution reduction by adding water containing *iso*-butanol and *iso*-propyl alcohol in a diesel engine. *Aerosol Air Qual. Res.* 15: 2115–2128.

Tsai, J.H., Chen, S.J., Huang, K.L., Lin, W.Y., Lin, C.C., Ding, J.Y., Yang, C.H., Chiu, J.Y. and Chiu, C.H. (2015b). Characteristics of exhaust emissions of a diesel generator fueled with water-containing butanol and waste-edible-oil-biodiesel blends. *Aerosol Air Qual. Res.* 15: 2129–2139.

Tsai, J.H., Chen, S.J., Huang, K.L., Chang-Chien, G.P., Lin, W.Y., Feng, C.W., Syu, J.Y. and Huang, H.T. (2016). Characteristics of persistent organic pollutant emissions from a diesel-engine generator fueled using blends of waste cooking oil-based biodiesel and fossil diesel. *Aerosol Air Qual. Res.* 16: 2048–2058.

Valavanidis, A., Fiotakis, K., Vlahogianni, T., Bakeas, E.B., Triantafillaki, S., Paraskevopoulou, V. and Dassenakis, M. (2006). Characterization of atmospheric particulates, particle-bound transition metals and polycyclic aromatic hydrocarbons of urban air in the centre of Athens (Greece). *Chemosphere* 65: 760–768.

Wander, P.R., Altafini, C.R., Colombo, A.L. and Perera, S.C. (2011). Durability studies of mono-cylinder compression ignition engines operating with diesel, soy and castor oil methyl esters. *Energy* 36: 3917–3923.

Wang, Y.F., Huang, K.L., Li, C.T., Mi, H.H., Luo, J.H. and Tsai, P.J. (2003). Emissions of fuel metals content from a diesel vehicle engine. *Atmos. Environ.* 37: 4637–4643.

Wu, F.J., Wang, J.X., Chen, W.M. and Shuai, S.J. (2009). A study on emission performance of a diesel engine fueled with five typical methyl ester biodiesels. *Atmos. Environ.* 43: 1481–1485.

Yang, H., Li, X.H., Wang, Y., Mu, M.F., Li, X.H. and Kou, G.Y. (2016). Pyrolysis characteristic analysis of particulate matter from diesel engine run on diesel/polyoxymethylene dimethyl ethers blends based on nanostructure and thermogravimetry. *Aerosol Air Qual. Res.* 16: 2560–2569.

Yang, H.H., Lee, W.J., Mi, H.H., Wong, C.H. and Chen, C.B. (1998). PAH emissions influenced by Mn-based additive and turbocharging from a heavy-duty diesel engine. *Environ. Int.* 24: 389–403.

Yoshimoto, Y., Masayuki, O. and Hiroya, T. (1999). Reduction of NO_x, smoke and BSFC in a diesel engine fueled by biodiesel emulsion with used frying oil. *SAE Technical Paper* 1999-01-3598.

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