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Utilization of waste cooking oil in a light-duty DI diesel engine for cleaner emissions using bio-derived propanol

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ABSTRACT

Waste cooking oil from restaurants could be efficiently reused in diesel engines by adding alcohols to make it less dense and viscous instead of preheating or trans-esterification to biodiesel. This study aims to replace diesel with waste cooking oil (WCO) as a reuse fuel and n-propanol as a renewable fuel by up to 50 %vol. Three blends D50-WCO45-PR5, D50-WCO40-PR10 and D50-WCO30-PR20 were prepared with this objective. n-propanol addition was expected to reduce the viscosity of WCO, the carcinogenic smoke emission (via its inbound oxygen) and the greenhouse gas NOx (via its higher vaporization latent heat). Fuel property tests by standard methods indicated that n-propanol reduced viscosity of WCO by 4.5 times along with densities comparable to diesel. Engine testing at the entire load spectrum revealed that, addition of n-propanol reduced NOx, smoke, CO and CO_2 emissions with respect to diesel. However, addition of *n*-propanol to D50-WCO50 caused an increase in BSFC for all blends. BTE improved with n-propanol addition to D50-WCO50 at all loads but remained lower than diesel. Smoke emissions gradually decreased with increase in *n*-propanol fraction for all blends. HC emissions increased for all blends and CO emissions lowered with *n*-propanol addition. Both the greenhouse gas emissions of CO_2 and NOx reduced with n-propanol addition. Thus WCO could be efficiently reused to reduce harmful emissions and reduce fossil fuel dependence with n-propanol addition instead of being an environmental hazard contaminating land and water resources.

1. Introduction

With the dwindling fossil reserves, researchers are in relentless pursuit for sustainable energy sources to fuel diesel engines that have been integral powertrains for heavy machinery, power generation, transportation, industrial and agro machines across several nations [1]. Nonetheless diesel exhaust contain toxic, carcinogenic suspended particulate matter and greenhouse gases like NOx and CO_2 that causes global warming and climate change [2]. Hence there is necessity for a two-pronged approach to replace the dependency on fossil diesel and to reduce the environmental impact of diesel exhaust. Reusing waste cooking oil (WCO) discarded by restaurants and households as a fuel extender in diesel engines could address one more environmental concern i.e., its disposal which has been a challenge faced by government organizations across the world [3]. EU generates about 1 million tonnes of WCO annually [4]. In case of US, almost 3 billion gallons of waste frying oil was produced every year [5]. Canada produces an estimated 0.135 million tonnes of waste cooking oil every year [6]. India generates 4 million tonnes every year with no proper disposal system in place [7]. WCO was banned from draining into sewers or dumping into landfills or diverting into an animal feed in several countries [8,9].

Hence re-routing WCO as a fuel in diesel engines would be a sustainable move to complement diesel independency. However, direct use of vegetable oils in diesel engines could clog fuel filters, increase coking of injectors, carbon buildup in engine parts, sticking of piston-rings to cylinder walls, gelling of lubrication oil and increase engine wear [3,8,10,11]. To avoid these problems, WCO was usually preheated which prevented fuel-filter clogging [10] and increased engine performance [12] but caused thermal stresses in closely-fitted engine parts and decreased the overall thermal efficiency of the engine [13,14]. Another method to re-use WCO is to trans-esterify it into biodiesel which is an expensive and time-consuming process. Free fatty acids in WCO have a negative influence on the economics of biodiesel

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production by increasing the overhead on alcohol requirement for trans-esterification into biodiesel [15]. Glycerol disposal is another issue to be dealt during trans-esterification. To add to the woes, diesel engines fueled with biodiesel were known to emit high volumes of NOx when compared to fossil diesel [16].

However, a majority of investigations available in the literature usually involves converting WCO to biodiesel before using in diesel engines. Dogan [17] evaluated the cooking conditions on the key physical properties of biodiesel derived from WCO and reported that properties like viscosity, density, flash point, pour point and calorific value deteriorated with increase in salt content, water content, cooking time and cooking temperature. Post combustion, there is evidence that biodiesel derived from WCO increases emissions of aldehydes (formaldehyde and acetaldehyde) and aromatic alkenes (benzene, toluene and xylene) in diesel engines [18]. Karavalakis et al [19] studied the effect of biodiesel origin on carbonyl, PAH, nitro-PAH and oxy-PAH emissions in a EURO 4 compliant diesel engine fueled with four biodiesels derived from soybean oil, olive oil, animal fat oil and used frying oil as blends with diesel and concluded that the presence of polymerization and cyclic acids in used frying oil increased carbonyl and PAH emissions of the engine. Cheung et al. [20] reported that a blend of biodiesel derived from WCO and methanol increased the aldehyde emissions and had less influence on aromatic alkene emissions.

Meanwhile blending raw WCO directly with diesel and alcohol has recently gained momentum because it is cheap, quick and need no alterations to the engine. But WCO/ethanol blends were found to be unstable and required surfactants to maintain its long term stability [10,21,22]. Sharon et al. [23] added n-butanol to WCO/diesel blends up to 15%vol. and tested them in a light-duty DI compression-ignition engine and reported enhancement of physical properties of the fuel. The engine showed lower BTE with increase in n-butanol content in the blends. Smoke, CO, and NOx emissions of the engine decreased with n-butanol addition to WCO/diesel. This study utilized only upto 15%vol. of butanol for this purpose. Later Dhanasekaran et al [24] attempted another high carbon alcohol (n-pentanol) addition by up to 20%vol. in WCO/diesel and found that NOx emissions increased when n-pentanol content increased beyond 20%vol. BTE decreased and BSFC increased with n-pentanol addition. Smoke decreased while HC, CO increased with increase in n-pentanol fraction in WCO/diesel.

The oxygen content of a fuel plays an importance role in reducing the smoke emissions [25]. Methanol has 49.93% by wt. oxygen but its addition to WCO/diesel increased PAH emissions [19]. Methanol and ethanol also required surfactants to maintain their phase stability with diesel because of their hydrophilic nature [10]. Butanol has only 21.59% by wt. of oxygen in its molecule while for pentanol it is 18.15% by wt. which is still low. Propanol has an oxygen content of 26.6% by wt. which could be exploited to obtain better smoke reduction in an engine [2].

From the existing literature, the effects n-propanol addition in conjunction with WCO/diesel blends on engine characteristics were not reported yet. The carbon in waste cooking oil and n-propanol is renewable unlike the carbon in fossil fuels and hence would provide a sustainable solution to the on-going environmental crisis. This study attempt to replace 50%vol. of diesel with a reuse fuel (WCO – 45%vol.) and a renewable fuel (*n*-propanol – 15%vol.) by preparing three blends of diesel/*n*-propanol/WCO. The consequences on performance and emissions of a DI diesel engine on using these three blends (D50-WCO45-PR5, D50-WCO40-PR10 and D50-WCO30-PR20) were investigated.

2. Materials and methods

2.1. Test fuels

Waste cooking oil was obtained from the nearby outlet of Kentucky Fried Chicken, India. This oil was mainly used for frying chips at a

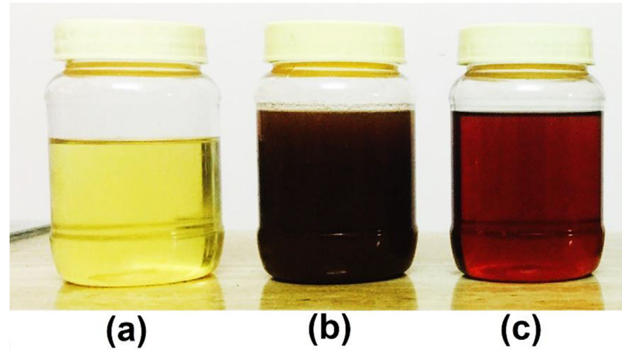

Fig. 1. Physical appearance of (a) Diesel, (b) WCO and (c) D50-WCO30-PR20.

temperature range between 140 °C and 175 °C. Before use, WCO is filtered through a 4 μm strainer to remove any suspended food particles. No other thermal/chemical treatments were done to the oil. Analytical grade *n*-propanol of purity 98% was obtained from Merck Millipore, India. Diesel was procured from the retail outlet of Hindustan Petroleum, Chennai. The cost of diesel at the time of experimentation in India is INR 60 per litre and N-propanol was procured at a price of INR 600 per litre. WCO was collected without any cost. The ternary blend D50-WCO30-PR20 worked out to a cost of INR 150. Research is underway to increase the yield of n-propanol via biosynthesis which could eventually bring down the price of n-propanol in the near future [2]. Three blends were prepared according to the objective so as to replace 50%vol. of diesel by a combined 50%vol. of a reuse component (WCO) and a renewable component (n-propanol). They are prepared and designated as follows: (1) D50-WCO45-PR5 (50%vol. diesel, 45%vol. WCO and 5%vol. n-propanol) (b) D50-WCO45-PR10 (50%vol. diesel, 40%vol. WCO and 10%vol. n-propanol) and (c) D50-WCO30-PR20 (50%vol. diesel, 30%vol. WCO and 20%vol. n-propanol). The blends were kept without disturbance and were observed to be stable without phase separation after almost 2 months at room temperature (25 °C). Fig. 1 presents a comparison between the appearances of diesel, WCO and used and D50-WCO30-PR20 after kept for 8 weeks in isolation. The cloudy and viscous nature of WCO was observed to be to be light and clear for the blend D50-WCO30-PR20, after the addition of n-propanol and diesel.

A comparative analysis was carried out between the performance and emissions behavior of these blends with respect to diesel and D50-WCO50 (50%vol. diesel and 50%vol. WCO) for improvements. The properties estimated using standard methods were presented in Table 1. A reduction of up to 4.5 to 7.5 times the viscosity of WCO was obtained by mixing diesel and n-propanol.

Table 1
Properties of test fuels.

Properties	Low heating value (MJ kg^{-1})	Kinematic viscosity at 40 °C ($mm^2 s^{-1}$)	Density ($kg\,m^{-3}$)	Flash point (°C)
Test Standard	ASTM D 240	ASTM D 445	ASTM D 4052	ASTM D 93
D100	43.356	3.52	850.0	70
PR100	31.248	1.82	804.7	11
WCO100	37.680	52.00	900.0	271
D50-WCO50	40.518	13.53	875.0	71
D50-WCO45-PR5	40.197	11.44	870.2	–
D50-WCO40-PR10	39.875	9.68	865.4	–
D50-WCO30-PR20	39.231	6.92	856.2	–