Performance and Emission Studies of Waste Vegetable Oil as Blends with Diesel and Kerosene—An Economic Route for Valorizing Liquid Waste

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Abstract Rise and instability in fuel prices and growing environmental concerns have promoted the scope for alternate to diesel fuel. Vegetable oils or their transesterified forms are used in the diesel engine after blending with various petroleum fuels. Waste vegetable oil (WVO), a known problematic liquid waste, holds potential in this regard. However, WVO is associated with the problem of higher viscosity and lower calorific value. The present work proposes to overcome such limitations by blending with diesel and kerosene. Three blends with varying volumes of WVO in diesel as well as kerosene were prepared. Physical properties of the blends showed similarity with that of diesel fuel and conformed to diesel standards. The various WVO blends showed acceptable engine performance and emission. WVO-kerosene blends recorded lower BSFC and higher BTE than diesel-kerosene blends. WVO-kerosene blends resulted in lower CO and HC emissions than diesel. A rise in the NO_x emission with the addition of WVO in the fossil fuels was recorded. Blending WVO with fossil fuels reduced the overall fuel price. WVO-kerosene blends can cause 22–40% reduction in overall price as compared to similar WVO-diesel blends.

Keywords Waste vegetable oil · Fuel blends · Emissions · BFSC · BTE

1 Introduction

Diesel is the fuel of choice for agricultural, transportation, industrial, logistics, and power generation sectors because of the capability to produce more energy and cleaner emissions characteristics in diesel engines [1]. The increment in demand for diesel associated with the demerits of price instability, depleting reserve, and rising environmental concerns pressed an emphasis toward an alternative to diesel fuel [2]. Vegetable oils hold a great potential in this regard as they are linked with renewable

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origin, lower sulfur content, superior storage, handling, and transportation capabilities [3]. As alternative engine fuels, vegetable oils have been successfully demonstrated as an effective substitute in diesel engines [4]. But, owing to the growing food versus fuel dispute, it has become imperative to search for oils from other sources [5, 6]. Waste vegetable oil (WVO) or waste cooking oil holds great promise in this regard. WVO is a problematic liquid waste, which is generated in huge quantities throughout the globe [7, 8]. WVO is often linked with economic losses and environmental disposal issue [9, 10]. Hence, re-utilization of WVO is the need of the hour.

1.1 Various Utilization Routes of WVO

The utilization of WVO as alternate blends in CI engines usually requires their derivatization into methyl esters, more commonly known as biodiesel. This process of derivatization is known as transesterification. But, the derivatization of WVO into biodiesel forfeits the economic gain, which is linked with direct utilization of WVO [11]. The reason is higher cost of biodiesel production, which brings the overall cost of their blends close to diesel [8]. Several reports on the engine performance, combustion, and emission studies using WVO-biodiesel are available [10]. In general, it has been reported that with the increase in the biodiesel fraction in the blend, the brake specific fuel consumption (BSFC) increases, while the brake thermal efficiency (BTE) decreases with respect to diesel. In terms of emissions, carbon monoxide (CO) tends to decrease, while unburnt hydrocarbon (HC) shows increasing trend. However, the oxides of nitrogen (NO_x) emission were reported to behave differently. Only a handful of reports are available on utilization of WVO as diesel blends. But, in all these studies, WVO was used either after preheating or with additives [5]. The literature on direct utilization of WVO (with preheating or additives) as alternative blend fraction for diesel is summarized in Table 1.

The literature survey suggested that WVO has been used as diesel blend, either upon preheating or with an additive. Thus, it is pertinent to study the impact of the direct blending of WVO with diesel on fuel properties, engine performance, and emission characteristics. Also, kerosene has been reported to lower the density and viscosity of vegetable oil blends and assists in improving engine performance [18–20]. Thus, engine performance and emissions of WVO blends containing kerosene need to be looked into.

Table 1 Literature (2000 onward) on WVO utilization in CI engine as fraction in diesel blends

WVO blend type	Engine operating parameters	Changes in engine performance and emissions*	References
Neat sunflower WFO Neat palm WFO	33 kW, 3.11 L, 4-s, 1-cyl, direct injection at 210 bar IP, 23ºbTDC IT, 17.5:1 CR, 1500 RPM	Sunflower WFO: 9.8% ↑ in BSEC, 3.2% ↓ in CO, 28.1% ↑ in NOx Palm WFO: 11.8% ↑ in BSEC, 6.5% ↓ in CO, 22.4% ↑ in NOx	[3]
0.50 fraction WCO-diesel blend	4.4 kW, 0.661 L, 4-s, 1-cyl, direct injection at 210 bar IP, 23ºbTDC IT, 17.5:1 CR, 1500 RPM	5% ↑ in BSEC, 5% ↓ in BTE, 50% ↑ in CO, 41.2% ↑ in HC, 7.2% ↓ in NOx	[11]
0.50 fraction WVO-diesel blend	3.8 kW, 0.553 L, 4-s, 1-cyl, direct injection at 210 bar IP, 23ºbTDC IT, 16.5:1 CR, 1500 RPM	4.2% ↑ in BSEC, 10.7% ↓ in BTE, 40% ↑ in CO, 18.2% ↑ in HC, 10.4% ↓ in NOx	[8]
0.50 fraction WCO-diesel blend	4.4 kW, 0.661 L, 4-s, 1-cyl, direct injection at 210 bar IP, 23ºbTDC IT, 16.5:1 CR, 1500 RPM	7.1% ↑ in BSEC, 3.8% ↓ in BTE, 50% ↑ in CO, 41.2% ↑ in HC, 6.7% ↓ in NOx	[12]
Neat WCO	3.7 kW, 0.630 L, 4-s, 1-cyl, direct injection at 200 bar IP, 27ºbTDC IT, 16:1 CR, 1500 RPM	14.1% ↓ in BTE, 60% ↑ in CO, 25% ↑ in HC, and 24.4% ↓ in NOx	[13]
0.05 fraction palm WCO-diesel blend and 0.05 fraction coconut WCO-diesel blend	53.6 kW, 2.4 L, 4-s, 4-cyl, indirect injection CI at 22.3:1 CR, 3000 RPM	Palm WCO-diesel blend: 1.2% ↓ in BP, 27.3% ↓ in HC, and 2.1% ↑ in NOx Coconut WCO-diesel blend: 0.7% ↓ in BP, 36.4% ↓ in HC, and 0.8% ↓ in NOx	[14]
0.50 and 0.75 fraction WCO-diesel blend	40 kW, 1.590 L, 4-s, 4-cyl, indirect injection at 190 bar IP, 27ºbTDC IT, 23.5:1 CR, 1500 RPM	No change in CO, 13.6% ↑ in HC and 125% ↑ in NOx for 0.50 WCO blend 175% ↑ in CO, 36.4% ↑ in HC and 300% ↑ in NOx 0.75 WCO blend	[15]
WFO heated above 75 ºC	3.7 kW, 4-s, 1-cyl, direct injection at 190 bar IP, 27º bTDC IT, 1500 RPM	20% ↑ in BSEC, 10.7% ↓ in BTE, 163.6% ↑ in CO, and 19.6% ↑ in NOx	[16]
WCO heated above 55 ºC	4.0 kW, 4-s, 1-cyl, direct injection at 3600 RPM	4.5% ↑ in BSFC, 8.8% ↓ in BP, 2% ↓ in BTE, 8.7% ↑ in CO, and 13.5% ↑ in NOx	[17]

WCO—waste cooking oil; WFO—waste frying oil; l—liter; s—stroke; cyl—cylinder; CR—compression ignition; RPM—rotations per minute; IP—injection pressure; IT—injection timing; bTDC = before top dead center; EGR—exhaust gas recirculation; BSFC—brake specific fuel consumption; BSEC—brake specific energy consumption; BP—brake power; BTE—brake thermal efficiency; CO—carbon monoxide; HC—hydrocarbon; NO_x—oxides of nitrogen; NR—not reported; ↑—increase; ↓—decrease; *- relative to neat diesel fuel

Table 2 Properties of diesel, kerosene, and WVO

Fuel samples	Density at 15 °C (g/cc)	Viscosity at 40 °C (mm^2/s)	Flash point (°C)	Cetane index	Higher heating value (MJ/kg)
Diesel	0.823	3.12	48	52.25	46.47
Kerosene	0.797	1.67	46	49.16	46.79
WVO	0.881	32.03	189	44.28	39.99
Diesel standard (IS 1460:2017)	0.810–0.845	2.0–4.5	35 (min.)	46 (min.)	–
Test method	ASTM D 1217	ASTM D2983	ASTM D93	ASTM D976	ASTM D240
Instruments	Pycnometer	Digital rotational viscometer	Pensky Martens Closed-cup apparatus	Atmospheric distillation apparatus	Digital bomb calorimeter

2 Materials and Methods

2.1 Formulation of D-WVO and K-WVO Fuels

The WVO, collected from local restaurants and hostels, was precisely blended with diesel and kerosene in fixed volumetric proportions. The WVO fraction was precisely maintained at 0 (only fossil fuel), 0.20 (20% WVO and 80% fossil fuel), 0.35 (35% WVO and 65% fossil fuel), and 0.50 (50% of both WVO and fossil). As it is known that a stationary research engine with a conventional fuel injection system would find it difficult to handle fuels with viscosities several times higher than diesel [1]. WVO fractions greater than 0.50 were not considered while preparing WVO blend fuels. The properties of the diesel, kerosene, and WVO were characterized as per ASTM standard protocol and are presented in Table 2. The viscosity of kerosene was found to be very lower than diesel, whereas WVO showed more than 10 times higher viscosity than diesel. Also, the higher heating value of WVO was very lower than both diesel and kerosene. Thus, blending kerosene with WVO would likely to lower the viscosity of the blended fuels.

2.2 Experimental Setup

The experimental engine setup comprised of a stationary 0.553 L, four-stroke, single-cylinder, compression ignition (CI) diesel engine (Make: Kirloskar; Model: AV-1) paired with a custom-built meter for measurement of volumetric fuel consumption

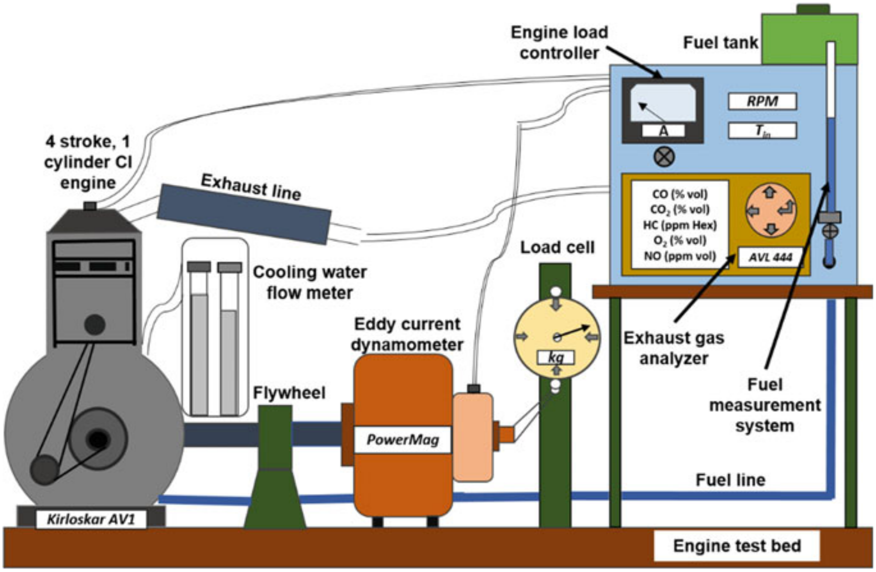

Fig. 1 Schematics of the experimental setup

rate, an eddy-current dynamometer, and a five-gas analyzer (Make: AVL; Model: Digas 444). The schematics of the experimental test setup is shown in Fig. 1. The engine was operated at 1500 RPM and at fixed operating conditions of 16.5:1 compression ratio, 210 bar injection pressure, and an injection timing of 23º before the top dead center. The engine load was varied from 0 to 60% of the full load, with increments of 20% at each step. Appropriate engine cool-off and lubrication were ensured for each experimental run with test fuels to maintain good engine health.

3 Results and Discussions

3.1 Properties of Various Fuels

The dissolution of WVO in both diesel and kerosene helped in preparing blends of the desired variations in WVO fractions. Various blends of WVO with diesel and kerosene were found to be quite stable with no phase separation occurring after 14 days. The six blends (3 D-WVO and 3 K-WVO) were analyzed for their fuel properties using ASTM standard test methods.

The density of the fuel determines the evaporation characteristics of fuel which affect its combustion and fuel economy. A denser fuel will cause higher mass flow for the same volume of fuel injected, thereby elevating the fuel consumption [19]. The denser WVO increased the densities of its blends with the increase in its fraction in the blend (Fig. 1a). However, the lower densities of K-WVO blends than D-WVO blends were obtained. The various K-WVO blends conformed to the IS 1460:2017 standard (0.820–0.845 g/cc), whereas only D-WVO_0.20 and D-WVO_0.35 blends were within the standard limits. Thus, K-WVO blends were expected to show better fuel injection characteristics and lower fuel consumption than D-WVO blends. A minimum of 35 ºC flash point is required to be considered for fueling a CI engine, as per IS 1460:2017 standards. But, vegetable oil blends were known to have high flash points. Yet, they were reported to satisfactorily power a diesel engine [4]. Moreover, higher flash point is desired for safer handling and transportation of fuel. The flash points of the blended fuels increased with linearly with WVO addition (Fig. 2b). However, superior volatility of kerosene than diesel lowered the flash points of its blends than D-WVO blends.

Viscosity plays a pivotal role in the atomization and spray behaviors of a fuel. Higher viscosity minimizes jet penetration and causes poor atomization of fuel droplets, but also reduces fuel loss by enhancing lubricity [20]. The viscosity of diesel and kerosene blends was seen to increase with the addition of WVO fractions (Fig. 1b). The standard range for diesel, as per IS 1460:2017, is 2.0–4.5 mm^2/s at 40 ºC. Two K-WVO blends (K-WVO_0.20 and K-WVO_0.35) and only one diesel blend (D-WVO_0.20) conformed to the standard range. So, a better engine performance characteristics are expected of these particular blends. Calorific value is the measure of the energy obtainable form a fuel from its combustion and determines the thermal efficiency of an engine. A fuel should possess calorific value above 43.0 MJ/kg to be able to provide enough power to run an engine [5]. With the addition of WVO, the calorific value showed a steep decrease. However, the calorific values of all the WVO blends were above 43.0 kJ/kg (Fig. 2b). Thus, it can be confirmed that the blended fuels hold the ability to provide power to the CI engine similar, if not more, to neat diesel.

3.2 Engine Performance Analysis

The engine performance was evaluated at 60% engine load condition in terms of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE). BSFC is the rate of fuel consumption by an engine for producing a specific brake power. With a rise in the WVO fraction in blend, the BSFC of the various blends was found to increase, as presented in Fig. 3a. This trend is due to the higher density and viscosity of most of the blended fuels than diesel. Higher density of fuel affects the fuel atomization and fuel-jet penetration inside the cylinder. Conversely, the inherent lubricity of vegetable oils reduces fuel losses [21]. There exists a critical balance between the two phenomena and governs the rate of fuel consumption [8]. However, better fuel properties of K-WVO_0.20 blend resulted in 2.5% reduction in BSFC. As compared to the diesel blends, K-WVO blends caused only 3.3% increment in BSFC relative to diesel. Similar result is reported elsewhere [19].

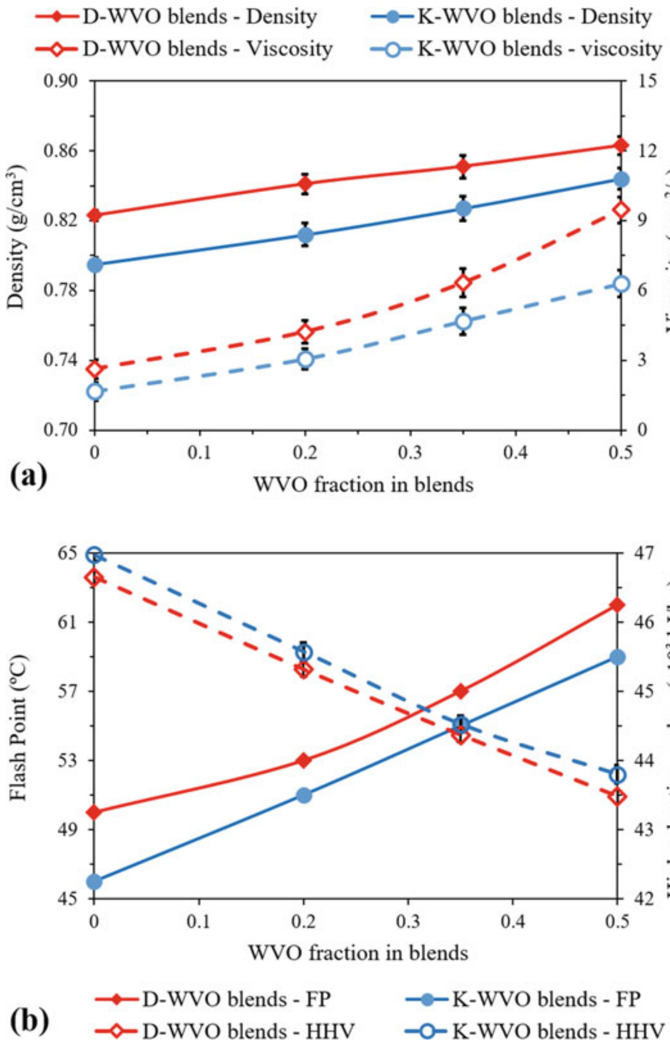

Fig. 2 Variations in different fuel properties for D-WVO and K-WVO blends

BTE is dependent on the rate of fuel consumption and the calorific value of the fuel [8]. The BTE of the blend fuel was found to drop with the rise in the WVO fraction. Lower calorific value and increased fuel consumption are the probable reasons. The K-WVO blends showed 3.3–4.8% higher BTE than neat diesel. Although the calorific values of theses blends were lower than diesel, their densities and viscosities were very much similar to diesel. Also, owing to the reduction in fuel loss [8] and superior volatility of kerosene caused faster air-fuel mixing, assisted the combustion process,

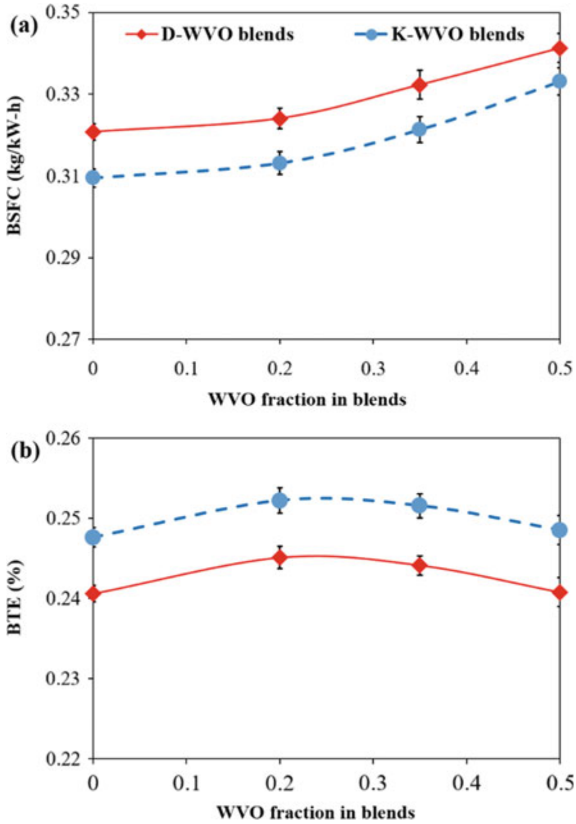

Fig. 3 Variations in engine performance—**a** BSFC and **b** BTE for D-WVO and K-WVO blends at the highest load condition

and increased the BTE [20]. The highest increase in BTE was recorded for the K-WV_0.20 blend. Thus, it can be inferred that K-WVO blends demonstrated superior engine performance over their diesel counterparts.

3.3 Engine Emission Analysis

Brake specific emissions were investigated for the various blended fuels in terms of carbon monoxide (CO), unburnt hydrocarbon (HC), and oxides of nitrogen (NO_x). The emission profile of various WVO blends at 60% engine load is presented and discussed in the subsequent paragraphs.

CO emission is the result of incomplete combustion of fuel inside the cylinder. CO emission decreases with an increase in engine load. This is because higher temperature inside the cylinder due to a rise in engine load improves the combustion efficiency of the engine [22]. It has been reported that CO emission reduces with the elevated oxygen content in the fuel. The reason is oxygenated fuel enhances combustion of fuel and converts CO into CO_2 more efficiently [6]. Since WVO contains 10–12% oxygen, with the increment in the WVO fraction in the blended fuel, specific CO emission was found to decrease, as shown in Fig. 4a. In between the two types of blend fuels, the D-WVO blends recoded a slightly higher brake specific CO emission than their analogous kerosene blends. With respect to pure diesel, D-WVO blends caused 13.4–18.1% CO reduction, whereas for K-WVO blends, it reduced 26.7–30.7% relative to diesel.

HC is also produced due to incomplete combustion of fuel. Literature suggests that more HC emission occurs at lower loads due to low in-cylinder temperatures

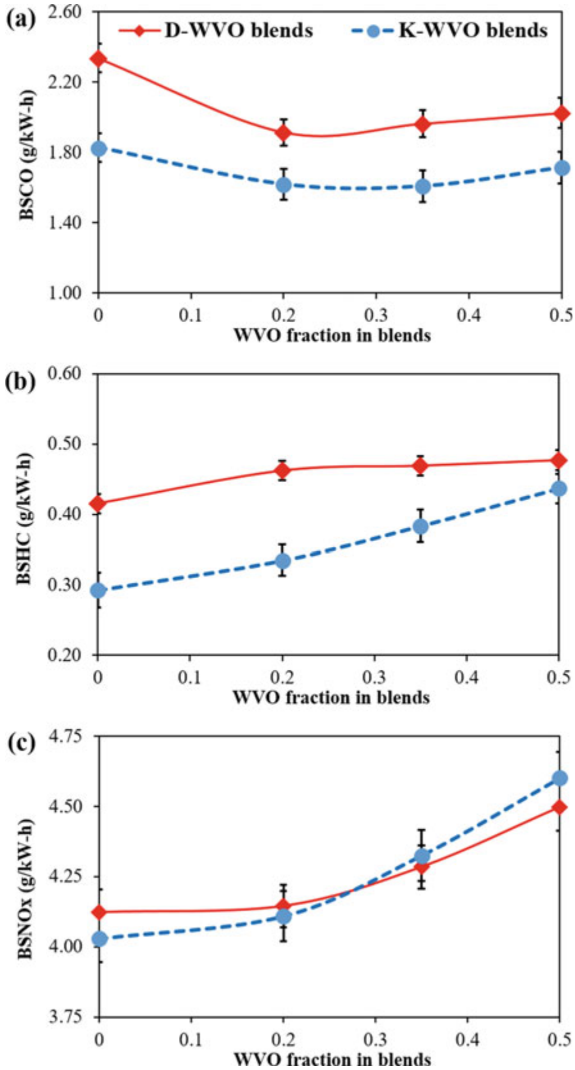

Fig. 4 Variations in **a** CO, **b** HC, and **c** NO_x emissions for D-WVO and K-WVO blends at the highest load condition

than at high loads [23]. The brake specific HC emissions for various WVO blends are shown in Fig. 4b. With the addition of WVO fraction in diesel, specific HC emission increased, but it remained somewhat steady (11–12% increase) for the varying WVO fractions in the blend. However, for the K-WVO blends, HC emission showed an increasing trend with the increment in WVO fraction. A probable reason would be higher volatility of kerosene and over-leaning effect at the power stroke which resulted in accumulation of fuel particles at the far corners of the engine cylinder. These fuel particles avoid complete combustion and are emitted as unburnt HC in the subsequent exhaust stroke [20]. However, an HC reduction of 5.3–19.3% was achieved with K-WVO blends when compared to diesel fuel. A reduction in the emissions for kerosene-biodiesel as opposed to diesel-biodiesel blend is reported in the literature [19].

Higher NO_x emission takes place at high engine load conditions. It is known that NO_x formation takes place at an elevated engine temperature and pressure, which occurs only at higher engine loads [18]. Figure 4c presents the brake specific NO_x emission at the highest engine load condition. It can be observed that for both D-WVO and K-WVO blends, the NO_x emission amplified with a rise in the portion of WVO. A significant increment in the fuel-bound oxygen is the probable reason behind this trend. At higher in-cylinder temperatures, enhanced oxidation of air-bound nitrogen takes place resulting in elevated NO_x emissions [7, 24]. As a result, higher WVO fractions caused more elevated NO_x emission. Only K-WVO_0.20 blend showed NO_x emission somewhat comparable to neat diesel. The D-WVO_0.50 and K-WVO_0.50 blends have caused 9.1–11.6% rise in NO_x emission relative to diesel. Similar trend was reported elsewhere [10, 18].

3.4 Economic Aspects of Utilizing WVO Blends

Since WVO is essentially a waste, its addition in fossil fuels should reduce the overall fuel cost [11]. A recent article has concluded that WVO-diesel blends are way cheaper than biodiesel-diesel blends [8]. A lower price of unmodified WVO makes it a promising alternative fuel fraction. Such an economic comparison between the diesel and kerosene blends of WVO should be an integral part of the study. The costs of various WVO blends were calculated from the fuel prices presented in the recent literature [10, 18]. The cost of different WVO blends is presented in Table 3. In order to identify the most economic WVO blend, such an economic analysis is pertinent. Blending 0.50 fraction of WVO with the fossil fuels, substantial reduction in the overall fuel cost can be achieved. Among the fossil fuels, a 61% reduction in overall fuel cost was recorded for K-WVO_0.50 blend, as opposed to 39% for D-WVO_0.50 blend. Lower cost of kerosene has made the K-WVO blends more economical than their respective diesel counterparts. The kerosene blends are recorded to lower the overall fuel cost by 22–40% when compared to the diesel blends containing similar fractions of WVO. Thus, WVO when blended in kerosene at equal proportions has the

Table 3 Economic comparison of various WVO blends against diesel

Fuel fraction in blend	Cost of diesel blends	Cost of kerosene blends	% reduction in cost for diesel blends	% reduction in cost for kerosene blends
WVO_0.00	$ 0.89	$ 0.49	–	–
WVO_0.20	$ 0.75	$ 0.44	10.77%	50.88%
WVO_0.35	$ 0.65	$ 0.39	27.23%	55.95%
WVO_0.50	$ 0.54	$ 0.35	38.94%	61.03%

Note Prices of various fuels were obtained from [10, 18]

potential to provide an economic equivalent of the diesel fuel with a great possibility in various industrial sectors.

4 Conclusions

A common and abundant liquid waste was valorized as alternate fuel fraction in this study. The effect of blending WVO with diesel and kerosene was investigated in this study. Three blends comprising of 0.20, 0.35, and 0.50 fraction WVO were separately formulated with diesel and kerosene. The fuel properties of such blends were determined and were found to be within the standards for diesel, except for the viscosity of D-WVO_0.50 blend. With replacement in diesel with kerosene, the WVO blends demonstrated fuel properties close to hose for diesel. K-WVO_0.20 blend showed better engine performance, with a reduced BSFC and elevated BTE relative to diesel. Lower density and viscosity and higher calorific value and superior volatility of kerosene should be the probable reason. K-WVO blends resulted in lower CO and HC emissions than diesel. However, with the addition of WVO in the blend, a rise in the NO_x emission was observed. Only K-WVO_0.20 blend recorded NO_x emission similar to diesel. Blending WVO with fossil fuels reduced the overall price. K-WVO blends can cause 22–40% reduction in overall fuel cost, relative to similar diesel counterparts.

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