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Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine

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ABSTRACT

An experimental investigation has been carried out to analyze the performance and emission characteristics of a compression ignition engine fuelled with Karanja oil and its blends (10%, 20%, 50% and 75%) vis-a-vis mineral diesel. The effect of temperature on the viscosity of Karanja oil has also been investigated. Fuel preheating in the experiments – for reducing viscosity of Karanja oil and blends has been done by a specially designed heat exchanger, which utilizes waste heat from exhaust gases. A series of engine tests, with and without preheating/pre-conditioning have been conducted using each of the above fuel blends for comparative performance evaluation. The performance parameters evaluated include thermal efficiency, brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC), and exhaust gas temperature whereas exhaust emissions include mass emissions of CO, HC, NO and smoke opacity. These parameters were evaluated in a single cylinder compression ignition engine typically used in agriculture sector of developing countries. The results of the experiment in each case were compared with baseline data of mineral diesel. Significant improvements have been observed in the performance parameters of the engine as well as exhaust emissions, when lower blends of Karanja oil were used with preheating and also without preheating. The gaseous emission of oxide of nitrogen from all blends with and with out preheating are lower than mineral diesel at all engine loads. Karanja oil blends with diesel (up to 50% v/v) without preheating as well as with preheating can replace diesel for operating the CI engines giving lower emissions and improved engine performance.

1. Introduction

Using straight vegetable oils in diesel engines is not a new idea. Rudolf Diesel first used peanut oil as a fuel for demonstration of his newly developed compression ignition (CI) engine in year 1910. Later with the availability of cheap petroleum, crude oil fractions were refined to serve as 'diesel', a fuel for CI engines. During the period of World War-II, vegetable oils were again used as fuel in emergency situations when fuel availability became scarce. Nowadays, due to limited resources of fossil fuels, rising crude oil prices and the increasing concerns for environment, there has been renewed focus on vegetable oils and animal fats as an alternative to petroleum fuels.

Vegetable oil is easily available worldwide. It is a renewable fuel with short carbon cycle period (1–2 years compared to millions of year for petroleum fuels) and is environment friendly. These are the triggering factors for research all over the world to consider vegetable oils and their derivatives as alternative to petroleum diesel. However major disadvantage of vegetable oil is its viscosity, which is order of magnitude higher than that of mineral diesel. The fuel injection system of new technology engines is sensitive to fuel viscosity changes. High viscosity of the vegetable oil leads to poor fuel atomization, which in turn may lead to poor combustion, ring sticking, injector cocking, injector deposits, injector pump failure and lubricating oil dilution by crank-case polymerization [1,2]. Viscosity of the vegetable oils must be reduced in order to improve its engine performance. Heating, blending with diesel and transesterification are some of the methods used to reduce viscosity of vegetable oils. Transesterification process is a relatively expensive chemical process since it involves use of chemicals, catalysts and process heat.

Silvico et al. [3] used heated palm oil as fuel in a diesel generator. This study revealed that exhaust gas temperature and specific fuel consumption increased with an increase in charge percentage. CO emissions increased at higher loads. This was due to lack of oxygen at higher equivalence ratios. Palm oil NO_x emissions were however lower than mineral diesel. Masjuki et al. [4] used preheated palm oil to run a CI engine. Better spray and atomization characteristics were obtained due to reduction in the viscosity of fuel while preheating it. Torque, brake-power, specific fuel consumption, exhausts emissions and brake thermal efficiency were found to be comparable to those of mineral diesel. Abbas et al. [5] experimented with pure sunflower oil and reported a higher

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emission of CO, NO_x, HC and PM as compared to that of mineral diesel due to a shorter ignition delay and higher diffusive burning. Ghormade and Despande [6] used soybean oil to run a CI engine. They found that there were only slight variations in part load efficiency and there was no improvement in brake specific fuel consumption by blending. Wang et al. [7] conducted experiment on blended vegetable oil with diesel. They reported higher exhaust gas temperature with very small changes in CO and lower NO_x as compared to diesel. Dhinagar and Nagalingam [8] studied neem oil, rice-bran oil and Karanja oil on a low heat rejection engine. An electric heater was used to preheat the oil. Without heating, 1–4% lower efficiency was reported compared to that of mineral diesel. However, it improved with preheating of vegetable oils. Senthil Kumar et al. [9] used Jatropha oil–diesel blend and found that exhaust gas temperature, smoke, HC and CO are higher compared to mineral diesel. Several investigators [10–21] conducted experiment on different vegetable oil blends with mineral diesel however very few of them conducted experiments using 100% straight vegetable oils and there is very limited literature available on utilizing 100% vegetable oil. Literature suggests that vegetable oils can substitute for mineral diesel if reduction in viscosity is achieved by blending it with diesel or by preheating. In India, Karanja oil is readily available which is essentially non-edible in nature and finds no significant use. It can be used to fuel single cylinder CI engines, which are widely used in agriculture sector and for stand-by power generation applications.

2. Karanja oil and its properties

Karanja (*Pongamia Pinnata)* is one of the forest-based tree-borne non-edible oil with a production potential of 135,000 metric tons per year in India. It is one of the few nitrogen fixing trees (NFTs), which produce seeds containing 30–40% oil. The Karanja tree is cultivated for two purposes: (1) as an ornamental tree in gardens and along avenues and roadsides, for its fragrant Wisteria-like flowers and (2) as a host plant for lace insects. This species is commonly called pongam, Karanja, Pongamia, or a derivation of these names [12,23–24]. Karanja is a medium sized fast-growing evergreen tree (Fig. 1), which reaches 40 feet in height and spread, forming a broad, spreading canopy casting moderate shade [25]. Flowers are pink, light purple, or white. Pods are elliptical, 3–6 cm long and 2–3 cm wide, thick walled, and usually contain a single seed (Fig. 2). Seeds are 10–20 mm long, fig oblong and light brown in color. Native to humid and subtropical environments, Karanja thrives in areas having an annual rainfall ranging from 500 to 2500 mm. In its natural habitat, the maximum temperature ranges of maximum from 27 to 38 °C and minimum 1–16 °C. Mature trees can withstand water logging and slight frost. This species grows up to elevations of 1200 m. It can grow on most soil types ranging from stony to sandy to clayey, including Verticals. It does not do well on dry sands. It is highly tolerant of salinity. It is commonly found along waterways or seashores, with its roots in fresh or salt water. Highest growth rates are observed on well-drained soils with assured moisture.

Air-dried Karanja kernels have typically 19.0% moisture, 27.5% fatty oil, 17.4% protein, 6.6% starch, 7.3% crude fiber, and 2.4% ash. Fatty acid composition and structure of Karanja oil is given in Table 1. A single tree is said to yield 9–90 kg seed per year, indicating a yield potential of 900–9000 kg seed/ha. A thick yellow–orange to brown, bitter, non-drying, non-edible oil is extracted from seeds. Yields of 25% (v/v) are possible using a mechanical expeller. It is typically used for tanning leather, soap, and as illuminating oil. The oil has a high content of triglycerides, and its disagreeable taste and odor are due to bitter falconoid constituents such as pongamiin and karanjin. The oil is also used as a lubricant, water-paint

Fig. 2. Karanja seed [26].

Table 1
Fatty acid composition of Karanja oil [22]

Fatty acid	Structure[a]	Formula	Percentage (%)
Palmitic acid	16:0	$C_{16}H_{32}O_2$	3.7–7.9
Stearic acid	18:0	$C_{18}H_{36}O_2$	2.4–8.9
Oleic acid	18:1	$C_{18}H_{34}O_2$	44.5–71.3
Linoleic acid	18:2	$C_{18}H_{32}O_2$	10.8–18.3
Lignoceric	24:0	$C_{24}H_{48}O_2$	1.1–3.5
Archidic	–	–	2.2–4.7
Behenic	–	–	4.2–5.3
Eicosenoic	–	–	9.5–12.4

[a] XX:Y:: No. of carbon atoms: Number of double bonds.

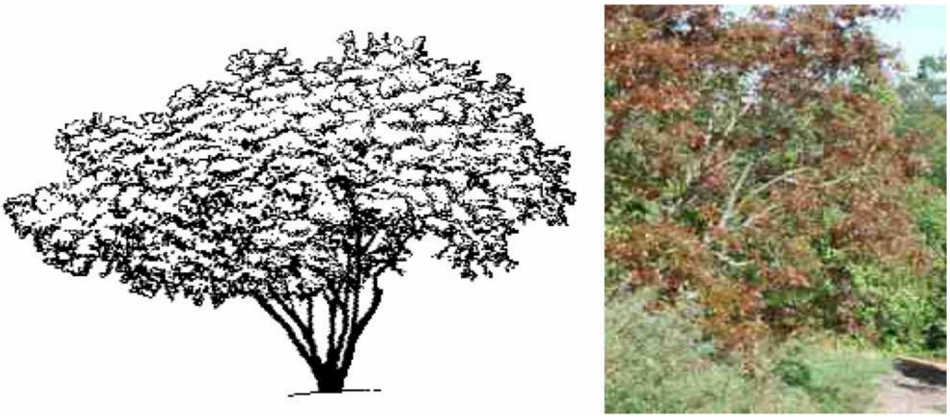

Fig. 1. Karanja tree.

binder, and pesticide. The oil has also been tried as fuel in diesel engines, showing a good thermal efficiency [12].

The objective of this paper is to investigate the performance and exhaust emission characteristics of a single cylinder diesel engine fuelled with Karanja oil (K100) and its blends K10, K20, K50 and K75 with and without preheating using a novel exhaust gas heat exchanger specially designed for this purpose.

3. Experimental setup

The experiment of performance and emission characteristics were conducted on a typical four-stroke, single cylinder, constant-speed, water-cooled, direct-injection diesel engine, typically used in the agricultural sector. The engine is coupled with an AC alternator. The detailed specifications of the engine and alternator are given in Table 2. The alternator was used for loading the engine. Before conducting the experiments, the alternator was calibrated for its efficiency at different loads. For this purpose, various losses in the alternator such as copper loss, armature loss, friction and windage loss were measured and a calibration curve for the efficiency of generator was prepared (Fig. 3). This curve was used while analysis of the engine data generated. The inlet valve opens 4.5° before TDC and closes 35.5° after BDC. The exhaust valve opens 35.5° before BDC and closes 4.5° after TDC.

Tests were conducted at no-load, 20, 40, 50, 60, 80, and 100% of rated load for all fuels. Engine speed was maintained at 1500 rpm (rated speed) during all experiment. Fuel consumption, inlet airflow rate and exhaust temperatures were also measured. The smoke opacity of the exhaust gases was measured by smoke opacimeter (Make: AVL Austria; Model: 437). Exhaust gas composition was measured using NDIR based exhaust gas analyzer (Make: AVL Austria; Model: 444 Digas). This analyzer measures CO_2, CO, HC, NO and O_2 in the exhaust gas. The measurement range and accuracy of the exhaust analyzer are given in the Table 3.

Table 2
Technical specification of the engine and the alternator

Engine specification	
Manufacturer	Kirloskar Oil Engine Ltd., India
Model	AV-1
Engine Type	Vertical, 4-stroke, single cylinder, Constant-speed, direct-injection, Compression Ignition engine
Rated power	3.67 kW at 1500 rpm
Bore/stroke	80 mm/110 mm
Displacement volume	552.92 cc
Compression ratio	17.5
Nozzle opening pressure	180–200 bar
Cooling	Water-cooled
Alternator specification	
Manufacturer	Kirloskar Electric Co. Ltd., India
Alternator Type	Single phase, 50 Hz, AC alternator
Rated output	5 KVA @ 1500 rpm
Rated voltage	230 V
Rated current	32.6 A

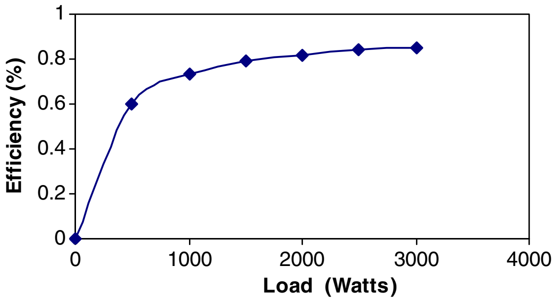

Fig. 3. Calibration curve for alternator.

The schematic diagram of experimental setup is shown in Fig. 4. The vegetable oil tank is connected to two sets of fuel filters. One filter is used at a time and in the event of filter clogging, the fuel supply is shifted to second filter and the clogging filter can be changed without stopping/interrupting the engine operation. Then filtered oil is passed through a heat exchanger, which utilizes waste heat of exhaust to preheat the oil. The length of the heat exchanger is designed in such a manner that the oil is preheated to a predetermined temperature, thus avoiding the possibility of overheating the oil. The preheated oil is then supplied to fuel pump and injector. The engine is first started with mineral diesel and switched on to vegetable oil, when the vegetable oil is heated to sufficient level by the exhaust gases. Similarly while switching the engine off, it is shifted back to mineral diesel 15 min before stopping so that the fuel line, fuel filter, etc. is flushed off of vegetable oil blends. By doing this, cold starting problems of the engine can be avoided to a large extent. Flow control valves, fuel measurement devices and thermocouples, etc. are provided at different places as shown in Fig. 3 to make operation possible.

4. Results and discussion

Various physical and thermal properties of Karanja oil (K100) and its blends (K10, K20, K50 and K75) were evaluated vs. mineral diesel. These properties include density, viscosity, flash point, fire point and calorific values. The results are shown in Table 4. The experiment were conducted using each fuel sample thrice and performance of the engine was evaluated using several parameters such as thermal efficiency, brake specific fuel consumption, brake specific energy consumption, and exhaust gas temperature. The data for all fuels is shown in one figure for comparison. Two sets of performance and emission curves are shown in Figs. 5 and 6. The first set is for unheated fuel samples and the second set is for preheated fuel samples. No visible problem was observed during the experiment for any fuel sample.

It can be observed from Fig. 5a that the thermal efficiency of all fuel blends except K100 is higher than mineral diesel however on preheating the fuel samples (Fig. 5b), all blends and K100 show visibly higher thermal efficiency compared to mineral diesel. Preheating the fuel samples, which have higher viscosity than mineral diesel at room temperature, reduces the viscosity and increases the volatility. This enhances the fuel atomization leading to improved fuel air mixing. Oxygenated fuel gives a better fuel combustion delivering improved thermal efficiency. The unheated fuel samples show comparatively lower thermal efficiency possibly due to larger droplet size in the fuel spray. From Fig. 5b, it can also be observed that the thermal efficiency generally increases with increase in blend concentration.

Table 3
Exhaust gas analyzer specifications

Exhaust gas	Measurement range	Resolution	Accuracy
CO	0–10 vol.%	0.01 vol.%	<0.6% vol.: ±0.03% vol. ⩾0.6% vol.: ±5% of ind. val.
HC	0–20,000 ppm	⩽2000: 1 ppm vol. >2000: 10 ppm	<200 ppm vol.: ±10 ppm vol. ⩾200 ppm vol.: ±5% of ind. val.
CO_2	0–20 vol.%	0.1 vol.%	<10% vol.: ±0.5% vol. ⩾10% vol.: ±5% of val. M.
O_2	0–22 vol.%	0.01 vol.%	<2% vol.: ±0.1% vol. ⩾2% vol.: ±5% of val. M.
NO	0–5000 ppm	1 ppm vol.	<500 ppm vol.: ±50 ppm vol. ⩾500 ppm vol.: ±10% of ind. val.

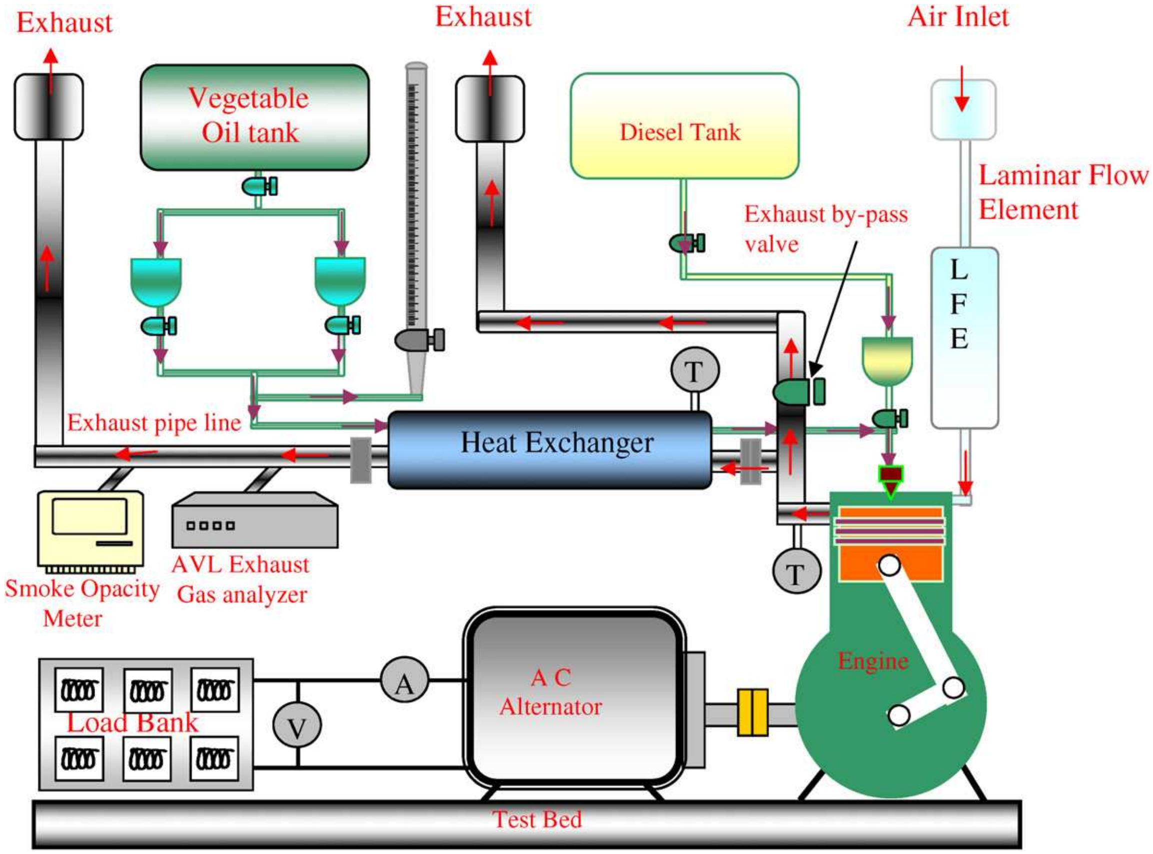

Fig. 4. Schematic layout of the experimental setup.

Table 4
Physical properties of diesel, Karanja oil blends

Property	Unit	Procedure	Equipment	K100	K75	K50	K20	K10	Diesel
Density	g/m^3	ASTM 1298	KEM Density-meter	0.938	0.913	0.882	0.849	0.841	0.833
Viscosity @40 °C	cSt	ASTM D-445	Setavis Kinematic Viscometer	35.98	21.13	10.47	4.66	3.74	2.68
Flash point	°C	ASTM D-93	Seta flash UK	237	196	154	105	88	71
Fire point	°C	ASTM D-93	Pensky–Martens closed cup tester	258	220	180	134	118	103
Calorific value	MJ/Kg	ASTM D-420	Bomb Calorimeter	41.66	42.01	42.36	42.77	42.93	43.06

Brake specific fuel consumption (BSFC) is a measure of volumetric fuel consumption for any particular fuel. Fig. 5c and d show the BSFC for unheated and preheated Karanja oil and its blends with respect to mineral diesel. BSFC for unheated Karanja oil blends up to 50% is lower than mineral diesel (Fig. 5c). This is mainly due to the combined effects of the fuel density, viscosity and lower heating value of blends. Higher density of blends containing higher percentage of Karanja oil leads to more fuel flow rate for the same displacement of the plunger in the fuel injection pump, thereby increasing BSFC. However on preheating, it is observed that all Karanja oil blends show lower BSFC compared to mineral diesel. This is due to higher thermal efficiency demonstrated by all Karanja oil blends.

Brake specific energy consumption (BSEC) is an ideal parameter for comparing engine performance of fuels having different calorific values. Fig. 5e and f represent BSEC for unheated and preheated Karanja oil and blends with respect to mineral diesel. These figures show that the BSEC is lower for all Karanja oil blends (unheated and preheated) compared to mineral diesel however the difference is significantly larger in preheated Karanja oil blends due to improved combustion. Fig. 5g and h represent exhaust gas temperature for unheated and preheated Karanja oil and its blends with respect to mineral diesel. Exhaust gas temperature is generally higher for all Karanja oil blends compared to mineral diesel.

The emissions of the engine were measured. Fig. 6 shows CO, HC, NO and smoke opacity versus brake mean effective pressure (BMEP) for Karanja oil and its blends (unheated and preheated) with baseline data of mineral diesel.

Fig. 6a and b show CO mass emission curved for unheated and preheated Karanja oil and blends. It can be noticed from these curves that blends up to 20% give lower CO emissions than mineral diesel. Blends higher than 20% showed higher CO emissions compared to mineral diesel at high engine load. Due to the high viscosity, the air–fuel mixing process is affected by the difficulty in atomization and vaporization of Karanja oil and blends. The resulting locally rich mixtures cause more incomplete combustion products such as CO, HC and PM because of lack of oxygen. Higher the engine load, richer fuel–air mixture is burned, and thus more CO is produced.

Karanja oil and blends generally exhibit lower HC emission at lower engine loads and higher HC emission at higher engine load compared to mineral diesel (Fig. 6c and d). This is because of relatively less oxygen available for the reaction when more fuel is injected into the engine cylinder at high engine load.

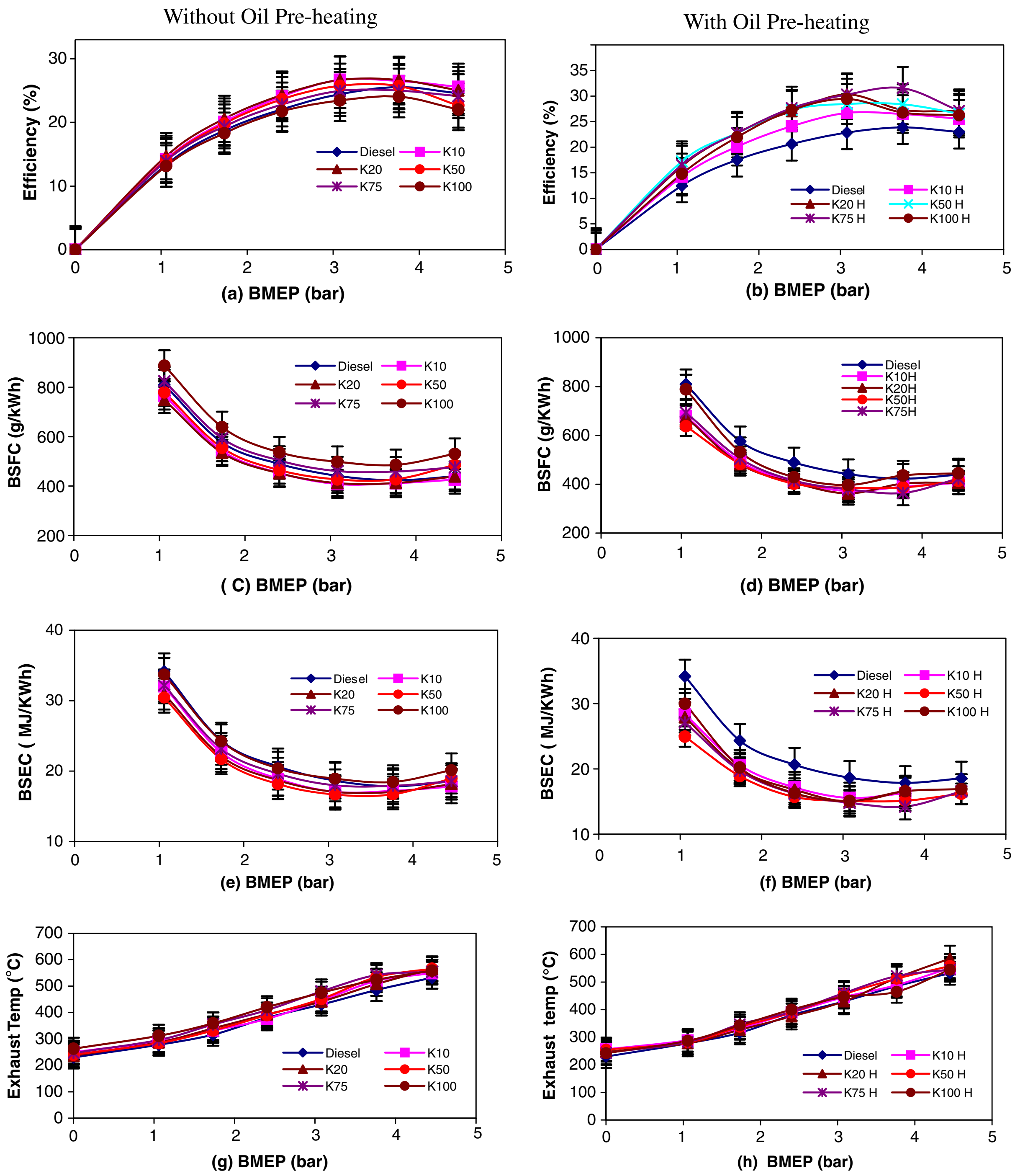

Fig. 5. Karanja oil blend performance results without preheated and with preheated oils.

The nitric oxide emissions from Karanja oil and blends with respect to mineral diesel are shown in Fig. 6e and f for unheated and preheated blends, respectively. The emission of NO is found to be significantly lower for Karanja oil and blend (both unheated and preheated) at lower engine load. As the engine load is increased, the mass emission of NO reduces however the gap between the emissions from Karanja oil blends and mineral diesel gets narrowed. The most important factor for the formation of NO is the combustion temperature in the engine cylinder and the availability of oxygen. The vegetable oils have higher viscosity therefore the fuel droplet size in the engine is expected to be larger than the mineral diesel. Larger droplets have longer combustion duration and they demonstrate significant energy release during the late burning phase. This suggest that the peak combustion chamber temperature is possibly lower (because of the lower heat release in the pre-mixed combustion phase as well as mixing controlled combustion phase) for Karanja oil and its blends compared to mineral diesel, leading to lower formation and emission of NO. At the same time, since there is higher amount of heat release in late combustion phase, the exhaust gas temperature from the Karanja oil fuelled engine is relatively higher. However finding out combustion chamber temperatures is beyond the scope of this study.

The smoke opacity increases with increase in engine loads (Fig. 6g and h). Higher blend concentration gives higher smoke at

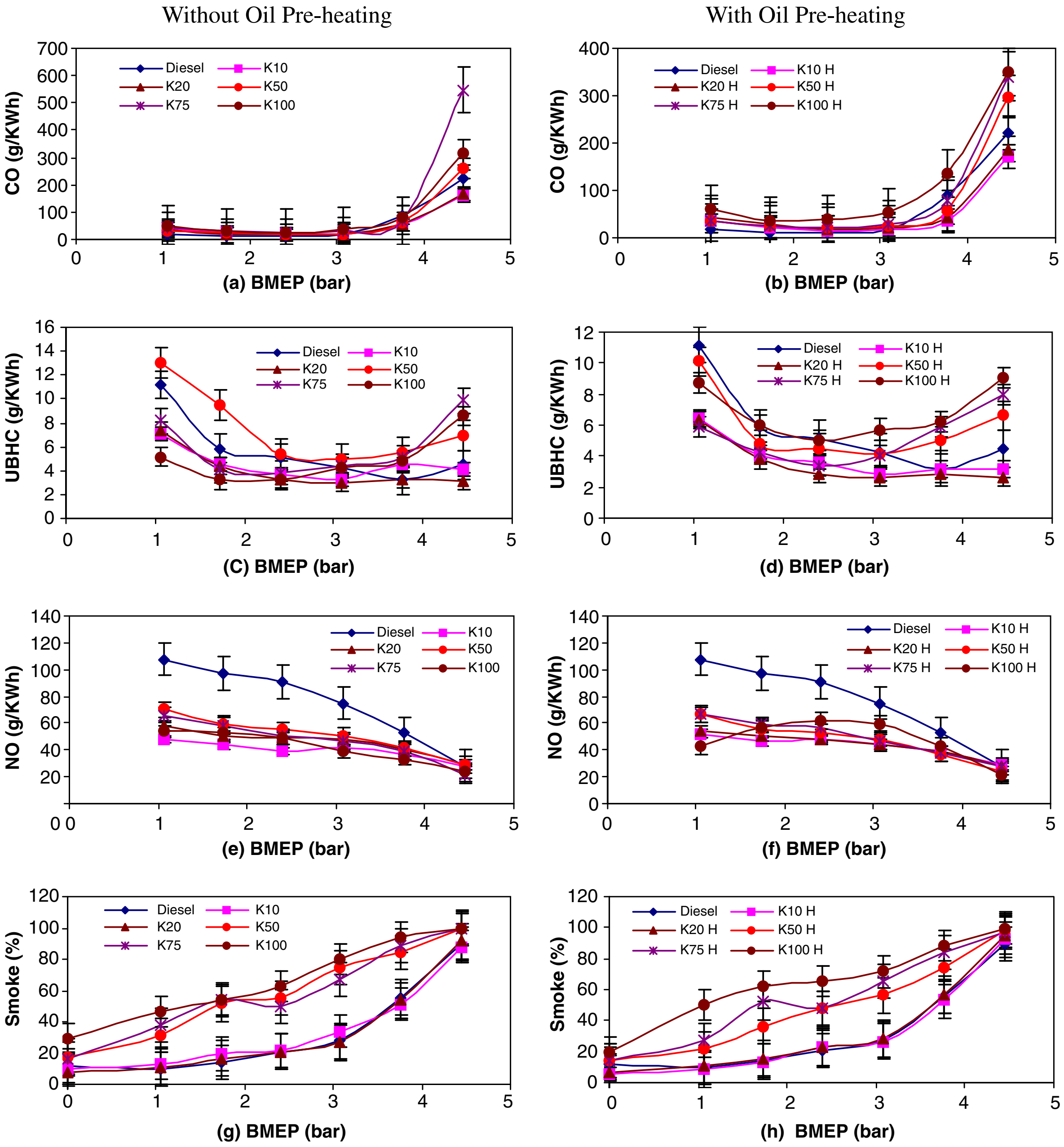

Fig. 6. Karanja oil blend emission results without preheated and with preheated oils.

even lower loads, and it was higher than that of mineral diesel but the increase was not as high. Higher smoke opacity may be due to poor atomization of the Karanja oil. Bulky fuel molecules, higher viscosity of vegetable oil and low volatility results in poor atomization of fuel. Karanja oil blends (preheated) give lower smoke opacity compared to mineral diesel. Heating vegetable oils result in lower smoke opacity compared to unheated oil but it is still higher than mineral diesel (Fig. 6h).

5. Conclusions

Single cylinder diesel engine ran successfully during tests on Karanja oil and its blends even without preheating and require no modification in engine hardware. However while using preheated fuel, engine efficiency improved slightly. Performance and emission characteristics of Karanja oil and its blends were found to be comparable to that of mineral diesel.

Thermal efficiency of the engine with preheated oil blends is nearly 30% and for lower blends (unheated) such as K10, K20 and K50, it was 24–27%. The brake specific fuel consumption and brake specific energy consumption of the engine with preheated lower blends showed an improved trend. The unheated oil blends up to K50 also showed an improved trend compared to mineral diesel. The smoke density from exhaust gas of preheated lower blends as well as unheated lower blends was almost similar to that of diesel fuel. The HC emissions from unheated and preheated lower blends (K10 and K20) are lower than that of mineral diesel. The emission of NO from all blends with and with out preheating are lower than mineral diesel at all load conditions. This is a significant advantage over mineral diesel while using vegetable oil and their blends. Hence it can be concluded that the Karanja oil blends with diesel up to 50% (v/v) without preheating as well as with preheating would replace diesel for running the CI engine for lower emissions and improved performance.

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