WASTE VEGETABLE OILS (WVO) AS COMPRESSION IGNITION ENGINE FUEL: A REVIEW

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ABSTRACT-Escalating fuel crisis and environmental pollution have generated interest in alternative fuel. Vegetable oils present promising alternate to diesel, since most of their properties are in good agreement with those of petro-diesel. Obviously, inedible and waste vegetable oils can be seriously considered as fuels for engines as edible vegetable oils are far too expensive. In this work, available information on utilization of waste vegetable oil (WVO) as an alternative fuel in compression ignition engine has been collected and arranged in a systematic order. The present paper discusses method of biodiesel production and characteristics of WVO in comparison with diesel. Engine performance, emission and combustion characteristics using waste vegetable oil as a fuel have been deeply analyzed. In short, a meticulous report has been prepared to give an insight into the progress of research in the field of waste vegetable oil as fuels for compression ignition engine.

Keywords: **waste vegetable oil, alternate fuel, biodiesel, energy from waste.**

INTRODUCTION

The shortage of fossil fuel reserves and increasing environmental pollution has created an interest in alternative fuels which should not only be sustainable but also eco-friendly. The vegetable oils are most suitable candidates for the alternative to diesel, since their properties are quite comparable to diesel. Also, they have several advantages like- they are renewable, non-toxic, biodegradable, eco-friendly and can be easily obtained. Vegetable oil based fuels operate in conventional diesel engine just like petro-diesel thereby requires no major engine modification.

The concept of using vegetable oil based fuels in compression ignition (C.I.) engine is not new. Dr. Rudolph Diesel first developed the diesel engine in 1895 with the intention of operating it on a variety of fuels including vegetable oil. Dr. Rudolph Diesel used peanut oil to fuel one of his engines at the Paris Exposition of 1900 [1-3]. In 1912, Rudolph Diesel said "The use of vegetable oils for engine fuel may seem insignificant today. But such oils may become in course of time as important as petroleum and the coal tar products of the present time" [4]. Unfortunately, Rudolph Diesel died 1913 before his vision of a vegetable oil fueled engine was fully realized and implemented.

The use of vegetable oil in engine was forgotten due to the lower cost and higher availability of diesel. Engines were designed to work with petro-diesel having a lower viscosity. In the 1930s and 1940s vegetable oils were used as diesel fuels from time to time, but usually only in emergency situations [5]. Figure 1 shows photograph of Dr. Diesel.

Figure 1. Dr. Rudolph Diesel [6]

The interest in vegetable oils got renewed in the recent times and many vegetable oils have been tested in diesel engine, which have showed positive results. Nag et al. [7] conducted a study on the seed oils natively grow in India. Performance test using 50-50 seed oil from Indian Amutable plant and diesel fuel showed no loss of power. Raadnui et al. [8] investigated the effects of refined palm oil (RPO) on wear of diesel engine components. The experiment was conducted on IDI diesel engine fueled with 100% RPO, 50% RPO and 50% diesel, and 100% diesel respectively. Arkoudeas et al. [9] tested C.I. engine operating with pure JP-8 and JP-8 fuel blended with 10%, 30% and 50% of sunflower and olive oil.

Usta [10] conducted the engine tests on a turbocharged IDI diesel engine fueled with diesel and 10%, 17.5% and 25% tobacco seed oil methyl ester (TSOME) and diesel blends. TSOME addition did not show any significant variation in engine performance. However, significant reduction in SO_2 emission was noticed. Rakopoulos et al. [11] conducted experiments to compare the use of different vegetable oils such as corn oil, cotton seed oil, soybean oil, sunflower oil, rapeseed oil, palm oil, and olive kernel oil and their corresponding methyl esters at blend ratios of 10/90 and 20/80 in C.I. engine. Aydin et al. [12] tested 20% kerosene and 80% cottonseed oil biodiesel blend in C.I. engine. Lawrence et al. [13] suggested that prickly poppy methyl ester blended with diesel can be used as an alternative fuel in C.I. engine.

Rashed et al. [14] investigated diesel engine performance and emission characteristics fueled with moringa biodiesel. Yadav et al. [15] investigated performance and emission characteristics of transportation diesel engine using methyl esters of Oleander, Kusum and Bitter Groundnut oil. Srithar et al. [16] prepared mixture of pongamia pinnata oil based biodiesel and mustard oil based biodiesel. They blended mixture of dual biodiesel with diesel at various mixing ratios and evaluated performance and emissions characteristics of CI engine. Khan et al. [17] conducted performance and emission test on Kirloskar diesel engine running on 10/90 blend of sesame oil and diesel.

VISCOSITY: PROBLEM AND SOLUTIONS

The main problem associated with the use of vegetable oils in C.I. engine is their high viscosity. The high viscosity of vegetable oils affects the flow properties, such as spray atomization, consequent vaporization and air/fuel mixing tendency. They result in improper complete combustion of fuel. Due to the high viscosity, vegetable oil based fuels develop various long-term engine problems such as fuel pump/ injector problems, carbon deposits on different parts of engine, piston ring sticking etc. [18-26].

The problem of high viscosity can be overcome through different methods such as blending (mixing with lighter oils such as diesel), preheating prior to injection and trans-esterification (i.e. conversion to esters referred as biodiesel).

Pramanik [25] achieved significant reduction in viscosity of jatropha curcas oil, by mixing with diesel in varying proportions and compared the performance of diesel engine using blends with that obtained with diesel alone. Ramadhas et al. [26] investigated engine performance and emission characteristics running of various blends of rubber seed oil and diesel. Almeida et al. [27] utilized refined palm oil (RPO) as an alternative fuel in a DI diesel generator set in 300-hour test. In order to reduce viscosity, RPO was heated to 100ºC before injection. Bhatt et al. [28] evaluated engine performance fueled with blends of mahua oil (20%, 40%, 60% and 80% by volume) and diesel.

Martin et al. [29] observed effect of cottonseed oil-diesel blends on the performance and emission of C.I. engine. Nwafor [30] studied the effect of increasing fuel inlet temperature on viscosity and performance of an IDI diesel engine. The performance results were compared when running engine on diesel and unheated rapeseed oil fuel under similar operating conditions. Nazar et al. [31] evaluated the effect of increasing fuel temperature on viscosity of vegetable oil based fuels and consequent effects on performance of a single cylinder, water-cooled C.I. engine. The tests were conducted on raw neem oil and karanj oil. Kalam et al. [32] evaluated emission and deposit characteristics of a small diesel engine when operated on preheated crude palm oil and its emulsion with 1%, 2%, and 3% water.

Delalibera et al. [33] experimentally investigated the potential of four vegetable oils (linseed, crambe, rapseed and jatropha) with preheating and engine work temperature. Arkoudeas et al. [9] investigated the impact of biodiesel on the emission characteristics of JP-8 aviation fuel. The experiment was carried out on a single cylinder stationary diesel engine. The engine was fueled with fuel blends containing two different types of biodiesel (sunflower oil and olive oil) at proportions up to 50%. Senatore [34] investigated the performance and emission characteristics of a turbocharged DI diesel engine fueled with a blend of rapeseed oil methyl ester and diesel.

Monyem et al. [35] evaluated the impact of oxidized soybean oil-based biodiesel on engine performance and emissions. Agarwal et al. [36] studied emission characteristics of biodiesel blends and their performance as compared to conventional diesel. They prepared linseed oil methyl ester and compared its properties to those of diesel.

WASTE VEGETABLE OILS AS POTENTIAL FEEDSTOCKS FOR FUELS

Over 350 oil bearing crops have already been identified, out of which the most predominantly considered as diesel fuel substitute are jatropha curcas oil, palm oil, linseed oil, seesameseed oil, sunflower oil, soybean oil, karanj oil, rapeseed oil, cottonseed oil, peanut oil etc. [37-39]. Subramanian et al. [40] reported that there are over 300 different species of plants which produce oil bearing seeds. Considering the cost and high demand of edible oils as food items, the use of non-edible and waste vegetable oils seems more significant [41-43]. This also takes into account the biodiversity and the "food vs. fuel" debate in mind [44].

Waste Vegetable Oils (WVO) are also referred as used vegetable oils. Different oils used for cooking purpose include sunflower oil, soybean oil, mustard oil, olive oil, palm oil, coconut oil etc. When these oils are heated for an extended time, they undergo oxidation and give produces oxides such as hydro peroxides, peroxides and polymeric substances. These oxides have shown adverse effects on health such as growth retardation, increase in size of liver and kidney as well as cellular damage to various organs when tested on laboratory animals [45-47]. Large quantity of WVO is available through the world from activities in the food sectors. US restaurants produce about 300 million US gallons of WVO a year, much of which ends up in landfills. An estimated 1.5 million US gallons of grease and oil goes into the sewage system every year for every one million people in some US metropolitan areas. Extended nationwide that's hundreds of millions of gallons wasted every year [48]. The estimated amount of waste cooking oil collected in Europe is about 0.49-0.7 million gallons per day [49]. In Japan, nearly 4-6 lakhs tons of waste cooking oils are generated annually of which only about 50% is retained for industrial use. [50].

WVO poses significant disposal problems. Most of the waste vegetable oils are disposed inappropriately, mostly let into the municipal drainage [51]. Large quantities of WVO are dumped into rivers and lands causing severe environment pollution [52-53]. Utilizing WVO as fuel will reduce this dumping crisis and hence will be beneficial for environment [54-55]. The use of WVO as a source of alternative fuel is a practice of increasing popularity among the researchers all over the world. It is usually collected from restaurants and used to power C.I. engines after filtration. Presently, WVO is used as additive oil for the preparation of animal fodder and for manufacturing of soap [56]. Extensive research has been conducted to investigate the utility of WVO as an alternative diesel engine fuel. In this paper, feasibility of using waste vegetable oil as a fuel in C.I. engine has been studied. Different aspects of WVO have been thoroughly investigated to find the suitability of these alternative fuels in diesel engines. The available literature has been arranged in a systematic manner so that it can give an insight into the progress of research done in this field.

FUEL CHARACTERIZATION

Vegetable oils consists of 98% triglycerides and small quantity of mono- and di-glycerides. Triglycerides are esters of three molecules of fatty acids with one glycerol i.e. esters of glycerin and long chain fatty acids. The carbon chain length and number of double bond varies in fatty acids. Various vegetable oils are distinguished by their fatty acid composition. Vegetable oils contain substantial amount of oxygen in their molecular structure. Triglyceride molecules have molecular weights between 800 and 900 and are about 3 to 4 times larger than diesel. [23].

Many researchers have already studied the important properties of waste vegetable oils. Khan et al. [57] determined important properties of Used Sunflower Oil (USO) and compared with those of diesel. The results of this experimental investigation are presented in Table 1.

Table 1. Characteristic properties of used sunflower oil compared with diesel [57]

Fuel	Used Sunflower Oil	Diesel
Flash Point (ºC)	276.0	78
Cloud Point (ºC)	-3.9	-8.1
Pour Point (ºC)	-7.3	-13.7
Iodine Number (cg I/g oil)	143.0	40.2
Calorific Value (MJ/kg)	34.6	42.2
Density (kg/m^3)	0.930	0.860
Carbon Residue (%)	0.298	0.035
Kinematic Viscosity at 40˚C (cSt)	40.23	2.82
Cetane Number	37.1	50

A close look over the properties of USO reveals that they possess some of the properties better than diesel while some are inferior to diesel. The flash point of a fuel is the minimum temperature at which the fuel will ignite (flash) on application of source of ignition. The higher flash point indicates safety in handling, storage and transportation of the fuel. The cloud point and pour point depend upon the feedstock used and must be considered if the fuel is to be used in cold climate [58]. It can be seen from the table that the flash point of USO is much higher than diesel. Therefore, USO is less feasible to produce explosive air/fuel vapors and hence, safer in handling, storage and transportation. High flash point also attributes to its lower volatility characteristics [54]. The cloud point is that temperature below which waxes in fuel form cloudy appearance. The presence of solidified waxes thickens the fuel and clogs fuel filters and injectors. While the pour point of a fuel is that temperature at which it becomes semi-solid and ceases to flow. While operating an engine at temperatures below these temperatures, heating will be required. The entire fuel system including all fuel lines and fuel tank will require to be heated. It can be noted that the cloud point and pour point of USO are high enough to cause flow problems in cold climates.

Iodine number is a value of the amount of iodine (in grams) absorbed by 100 grams of given fuel. Iodine number gives the degree of unsaturation of the fuel. Unsaturated compounds contain molecules with double or triple bonds, which are very reactive toward iodine. Unsaturation results in deposit formation [58]. Iodine number of the USO is quite high as compared to diesel. Thus, USO have higher deposit formation tendency as compared to diesel. The calorific value is the amount of heat released by a unit volume of a fuel during complete combustion [59]. Calorific value of USO was quite lower in comparison to diesel. This value will have direct influence on the engine performance. The presence of chemically bound oxygen in vegetable oils lowers their calorific value by about 10% [2, 54].

The density is defined as mass per unit volume. The density of USO is quiet higher than that of the diesel. The higher density means more mass consumption of the fuel for the same amount of volume injected. Thus, fuel consumption rate with USO operation is expected to be higher than that for diesel. Also, the density of fuel is connected with particulate emissions. The higher density means greater particulate emissions [60].

The carbon residue value is related to the combustibility and deposit forming tendencies of the fuel. The carbon residue of USO is higher than that of the diesel. The carbon residue is connected with the amount of carbonaceous deposits the fuel will form in the combustion chamber. The higher carbon residue is due to high molecular mass and chemical structure of vegetable oil based fuel. [41].

Viscosity is a measure of resistance of fuel to flow, which affects its handling by the pump and injector system of engine [61]. It can be noted from the table that the kinematic viscosity of USO is several times higher than that of diesel. The high viscosity of this vegetable oil is due to their large molecular mass and chemical structure [23, 62]. This difference in values of viscosity is a big barrier in direct use of vegetable oil based fuels in C.I. engine. The cetane number indicates the lag time of the fuel's self-ignition. The lower the cetane number, the larger the lag time of the ignition and, hence, the more quantity of non-burning fuel in the combustion chamber before start of combustion, leading to an abrupt increase in pressure without work being done. This phenomenon is known as knocking. The cetane number of USO is lower as compared to that of diesel. Thus, the propensity is higher for diesel knock in case of used sunflower oil operation. The vegetable oils SVOs have lower cetane number due to poor volatility, which is lower than that of diesel. [59]

TRANSESTERIFICATION

Vegetable oils consist of 98% triglycerides. Triglycerides are esters of three molecules of fatty acids and one glycerol i.e. esters of glycerin and long chain fatty acids. The conversion reaction of fatty acids (vegetable oil or animal fat) with methyl or ethyl alcohol to form esters and glycerin is known as transesterification. Methyl or ethyl ester of fatty acids formed is referred as *biodiesel*. The stoichiometry of transesterification process requires atleast three moles of alcohol per mole of vegetable oil to yield three moles of fatty acid ester and one mole of glycerol. [23, 36]

$$\text{Triglyceride} + 3\text{ROH} \xrightleftharpoons{\text{catalyst}} 3\text{R'CO}_2\text{R} + \text{glycerol} \qquad (1)$$

Transesterification process consists of a sequence of three consecutive reversible reactions. The first step is the conversion of triglycerides to diglycerides, followed by the conversion of diglycerides to monoglycerides and lastly monoglycerides into glycerol, yielding one ester molecule from each glyceride at each step [63]. The process take place at moderate temperature range (60 to 80°C). A catalyst is employed to improve the rate of reaction and yield. The transesterification reaction is affected by various factors such as- temperature of reaction, time of reaction, type of catalyst, concentration ratio of alcohol to fuel and stirring rate [23, 36]. The reactions can be alkali-catalyzed, acid-catalyzed or enzyme-catalyzed. Research has been carried out to investigate the extraction of biodiesel from waste vegetable oil using alkaline catalysis [64], acid catalysis [65] and enzyme catalysis [66]. The alkali and acid catalyzed processes are more commonly employed. While the enzyme-catalyzed system is not generally preferred as it requires a much longer reaction time than the other two systems [67-70]. With an alkali catalyzed system, high purity and yield of biodiesel can be achieved in a short duration of time (30–60 min) [71-73]. However, it is very sensitive to the purity of the reactants. Only well refined vegetable oil with less than 0.5 wt% free fatty acid (FFA) can be used as the reactant in such process [70].

Waste cooking oils exhibit properties different than those of refined and crude oils. The high temperatures of frying processes and the water from the foods accelerate the hydrolysis of triglycerides and increase the FFA content in the oil [74]. An acid catalyzed process is preferred for waste vegetable oil having more than 10 wt% FFA, but this process needs excess of methanol, high pressure (170–180 kPa) and high cost stainless steel equipment [68]. Many studies have recommended acid-catalysis as pretreatment step followed by alkaline catalyzed step [74]. Issariyakul et al. [75] obtained an ethyl ester of waste cooking oil up to 97%. The oil contained approximately 5-6% weight of free fatty acid. They carried out two stage acid and alkali catalyzed transesterification.

The conversion of triglycerides into methyl or ethyl ester brings significant change in their properties [76-77] . It reduces the molecular mass to one-third thus a considerable reduction in viscosity and density is achieved. Biodiesel has almost comparable viscosity and density as that of petro-diesel. They have slightly lower calorific value and higher cetane number. The flash point of triglycerides also gets lowered after transesterification process but it remains still higher than diesel [23, 36, 37, 41]. The conversion of waste vegetable oil into biodiesel by the transesterification process has economic and environmental benefits. Number of investigators has successfully extracted biodiesel from waste vegetable oils by transesterification process [65-75, 78-81].

ENGINE PERFORMANCE USING WASTE VEGETABLE OIL

Nye et al. [82] collected used frying oil composed of partially hydrogenated soybean oil and margarine and converted it to biodiesel, which was tested in diesel engines. Experiments showed that methyl, ethyl and butyl esters of used frying oil performed reasonably well when tested in the diesel engine in short-term engine tests. Also, no problems were observed in starting and running of engine. Reed et al. [83] developed esters of waste vegetable oils and called it as "M-Diesel". They conducted test on engine fueled with this fuel in a Denver public bus. The power output of the engine was found to be comparable with that of diesel. Also, the smoke opacity was observed to reduce when M-Diesel was utilized. Mittelbach et al. [84] investigated emissions characteristics of four stroke, DI diesel engine with exhaust gas recirculation (EGR) running on methyl esters of waste cooking oil. The ester fuel showed slightly lower HC and CO emissions while higher NO_x emissions were observed as compared to diesel. The particulate emissions were also observed to be significantly lower with used frying oil.

Yoshimoto et al. [85] investigated the potential of emulsified fuel based on used frying oil to evaluate DI diesel engine performance. With the water to fuel volume ratios of 15-30%, emulsified fuels prepared from equal proportions of used frying oil and diesel, displayed that the NO_x emissions and smoke density had got reduced without worsening BSFC. While maintaining the minimum BSFC value achieved with diesel, significant reduction in NO_x emissions was noticed in biodiesel emulsion with 30% (by volume) water. Murayama et al. [86] conducted test to evaluate performance and emission characteristics of DI and IDI diesel engines using methyl ester of waste frying oil. The results showed that engine performance improved when biodiesel was used. The particulate emissions from DI engine were found to be considerably higher than IDI engine. Gonzalez-Gomez et al. [87] evaluated emission characteristics of a Toyota van, powered by a 2L IDI naturally aspirated diesel engine, running on a waste cooking oil methyl ester. Tests results showed that waste cooking oil methyl ester produces significantly lower smoke opacity level and reduced emissions of CO, CO_2 and SO_2. However, emissions of NO_2, NO and O_2 were higher with the waste vegetable oil based fuel.

Hamasaki et al. [88] investigated combustion characteristics of waste vegetable oil methyl ester (WME) both in engine test run and observable burning flames in a visual engine. An engine test showed that although CO and HC emissions from WME were slightly higher than that from diesel while smoke emissions were found to be lower. Further, by emulsifying WME with water, 18% less NO_x emission accompanied by lower smoke emission was observed. With 15% water content, brake specific fuel consumption also improved. Grimaldi et al. [89] tested three different bio-derived fuels (rapeseed, soybean, waste cooked oil) in DI, common-rail, turbocharged diesel engine. They observed that emissions of NO_x emissions using vegetable oil based fuels were same or slightly higher than those of diesel. Smoke emissions were observed to reduce significantly for bio-derived fuels. Emission of HC and CO were marginally affected by the nature of fuel, with an appreciable decrease in HC emissions with bio-derived fuels, CO emissions showed a slight increase at part loads while at full load CO emissions were lower for bio-fuels in comparison with diesel. Leung [90] tested blends of waste cooking oil methyl ester-diesel fuel in various diesel engines. The first test was conducted in Cummine LT10 engine and a reduction of 7% in smoke opacity at a blending ratio of 15% was observed. The second test was carried out in an Isuzu 5-tonne lorry with a blend ratio of 10%. The results showed a reduction in emission of CO and HC while emission of NO_x showed a moderate reduction at idle condition but increased at 2500 rpm.

Al-Widyan et al. [91] evaluated performance of a single cylinder DI diesel engine using blends of waste palm oil ester and diesel. Test results showed that the best performance was obtained with blend containing 100% ester and 75% ester. They showed better performance over the speed range considered as indicated by the maximum brake power, lowest BSFC and highest thermal efficiency. Yu et al. [92] conducted experiments to determine performance and emission characteristics of diesel engine when fueled with waste cooking oil (WCO) collected from noodle industry. The WVO was used without further treatment. They found that the combustion characteristics of engine running on WCO were identical to that obtained diesel. Also there was a close similarity in the engine performance of two fuels. Compared to diesel, the emissions of CO, NO and SO_2 were higher for WCO operation. Moreover, at high temperatures, tar like substance was found to be depositing in the combustion chamber. Zaher et al. [93] evaluated performance of diesel engine fueled with its blend used frying oil with diesel fuel (50% blend). The frying oil used was first chemically modified to achieve reduction in by thermal cracking in the presence of 2% calcium oxide as a catalyst. The test results showed that engine performance didn’t markedly changed by blending diesel oil with the cracked product (50% blend). Further, the cracked product obtained was free from sulfur and non-burnable matters.

Ulusoy et al. [94] investigated performance and emission characteristics of Fiat Doblo 1.9 DS diesel engine using biodiesel obtained from used frying oil. The emission analysis showed that used frying oil based biodiesel is a more environment friendly than diesel. Performance test showed that when biodiesel was used as a fuel, reduction in wheel force by 3.35% and wheel power by 2.03% was observed. In the acceleration tests, 40-100 km/h and 60-100 km/h acceleration periods were measured and a reduction of 7.32% and 8.78% were observed respectively. Pugazhvadivu et al. [95] reduced high viscosity of the waste frying oil by preheating. The effect of temperature on the viscosity of waste frying oil was evaluated before investigating the performance and emission characteristics of diesel engine operating on preheated waste frying oil. The engine performance improved while emissions of CO and smoke were reduced when preheated waste frying oil was used. Centinkaya et al. [96] utilized used cooking oil for production of biodiesel and investigated the Renault Megane diesel engine performance of biodiesel in winter conditions. The viscosity improver and pour point improver additives were also added to biodiesel. The biodiesel application caused a decrease in brake power while the fuel consumption rate was found to be similar to that of diesel. The exhaust gas temperature with biodiesel was found to be less than that of diesel fuel.

Khan et al. [97] collected waste soybean oil from hotel and filtered it properly. They investigated effects of addition of diesel on viscosity of waste soybean oil and evaluated performance of diesel engine operating on various blends of waste soybean oil and diesel. Blend containing 5 % waste soybean oil showed an engine performance comparable to diesel. Sudhir et al. [98] conducted engine performance test on DI diesel engine. The test were carried out at various loads starting from no load condition to the rated full load using diesel, fresh oil based biodiesel and WCO based biodiesel. Results showed that the performance of the WCO based biodiesel was only slightly poorer at part loads as compared that obtained with diesel. At higher loads the engine suffers 2% brake thermal efficiency loss. Also, hydrocarbon emissions of WCO based biodiesel were observed to be significantly lower diesel. Ozsezen et al. [99] evaluated performance and combustion characteristics of DI diesel engine fueled with waste palm oil based methyl ester (WPOME) and canola based methyl ester. Engine performance decreased slightly when WPOME was used as fuel. The emissions of UBHC, CO and smoke opacity decreased significant while NO_x emissions increased when WPOME was employed.

Roskilly et al. [100] tested small marine craft diesel engine fueled with biodiesel obtained from recycled cooking fat and vegetable oil. The tests were conducted on Perkins 404C-22 and Nanni diesel 3.100HE engines. The test results showed that the power output for test engines running on biodiesel were comparable to that fuelled with diesel, but with an increase in fuel consumption rate. Emissions of NO_x decreased with biodiesel while emissions of CO emissions were observed to be lower when the engines operated at higher loads using biodiesel. Lapuetra et al. [101] tested methyl and ethyl ester of waste cooking oil to evaluate performance and emissions of DI Nissan diesel engine. The authors studied effect of the alcohol used in production of biodiesel. When pure biodiesel was utilized a slight increase in fuel consumption and emissions of NO_x was observed. NO_x emissions decreased slightly when ethyl esters of waste cooking were used in comparison to their methyl esters. Smoke opacity, total hydrocarbon and particle emissions were reduced with the use of biodiesel and their blends as compared to diesel. Rao et al. [102] investigated performance and emission characteristics of Kirloskar DI diesel engine using waste cooking oil (WCO) and observed that ignition delay of waste oil and its blends were lower than that of diesel. Higher BSFC and lower brake thermal efficiency was obtained with WCO and its blends as compared to diesel. They further observed that emission of CO and HC reduced significantly with WCO and its blends. Increase in emission of NO_x was noticed with increase in percentage of WCO in the fuel blend.

Ozsezen et al. [103] analyzed performance of naturally aspirated IDI diesel engine operating on biodiesel obtained from used frying palm oil and its blends with diesel. The test results showed slight increase in BSFC when engine was fueled with biodiesel and its blends. Further, a slight drop in power output with increase in peak cylinder pressure and reduction in ignition delay were observed for biodiesel and its blends operation. Muralidharan et al. [104] experimentally investigated performance, emission and combustion characteristics of a variable compression ratio engine using various blends of methyl ester of waste sunflower oil and diesel. The effect of compression ratio on different parameters has been studied. They concluded that blend containing 40% biodiesel produces maximum efficiency at the compression ratio of 21. Reduction in emissions of CO and HC and increase in emission of NO_x were observed when blends were used. Abu-Jrai et al [105] evaluated combustion and emission characteristics of diesel engine running on blend of treated waste cooking oil and diesel. The combustion of blend containing 50% waste cooking oil resulted in a significant decrease in the smoke opacity and UBHC associated with an increase in the CO_2 and NO_x emissions. The test results also showed an increase in BSFC with simultaneous reduction in the thermal efficiency compared to diesel.

Ali et al. [106] experimentally studies performance and emission characteristics of Toyota 4 cylinder turbo-charged diesel engine using untreated waste cooking oil blends. The test results showed that the brake power and brake thermal efficiency of engine using WCO and its blends was lower than that for diesel. The emissions of CO from waste oil blends are slightly higher while the emissions of CO_2 and NO_x are lower and closer to that of diesel fuel. Murali Krishna et al. [107] investigated performance of low heat rejection diesel engine with ceramic coated head operating on crude waste fried vegetable oil. Conventional engine showed deteriorated performance, while LHR engine showed improved performance when waste oil was used. Brake thermal efficiency and NO_x increased while volumetric efficiency and smoke levels decreased with waste oil operation on LHR engine, when compared with diesel operation on conventional engine. Murali Manohar et al. [108] experimentally evaluated performance and emission characteristics of single cylinder CI engine using waste cooking oil. They observed that higher BSFC noticed for waste oil. It was further observed that emissions of HC and CO decreases and NO_x increases with WCO compared to diesel.

Srinivas et al. [109] experimentally investigated performance and emission characteristics of diesel engine operating on the blends of diesel-biodiesel (obtained from waste vegetable oil). Ethanol and ethyl hexyl nitrate (EHN) were used as additives in fuel blends. It was observed that brake thermal efficiency and BSFC increased for all blends when compared to diesel. There was a slight increase in brake thermal efficiency when additive was added. CO and HC emissions are decreased significantly with the blends when compared with diesel. Comparatively a slighter increment in NO_x emission was found while working with all blend at all loads and there is a slight decrease by adding additive. Sherwani et al. [110] evaluated performance and emission characteristics of diesel engine using blends of three biodiesel (Mahua oil methyl ester, Mahua oil ethyl ester and Waste cooking oil methyl ester) with diesel. The fuel properties and the combustion characteristics of waste cooking oil methyl ester were observed to be similar to those of diesel. Among all fuels tested, higher brake specific fuel consumption, lower brake thermal efficiency and higher emissions of HC, CO, CO_2 and NO_x were observed for waste cooking oil based biodiesel. Subramaniam et al. [111] experimentally evaluated performance, emission and combustion characteristics of methyl esters of punnai, neem, waste cooking oil and their diesel blends in a C.I. engine. The biodiesel-diesel blends were prepared by mixing 10%, 30%, 50%, and 70% of biodiesel with diesel. The engine test results showed that up to 30% of methyl esters did not affect the performance, combustion, and emissions characteristics. Among various biodiesel, they observed methyl esters of waste cooking oil performed better than the methyl esters of punnai and neem oil.

Mensah et al. [112] evaluated the engine performance using biodiesel obtained from waste palm kernel oil (WPKO) and mixed waste vegetable oils (WVO). The results showed that blend containing 10% and 5% WVO biodiesel has the least sulphur content. Blend containing 10% and 20% WPKO indicated higher brake power, higher thermal efficiency but lower exhaust temperatures at all engine loading conditions. Kumar et al. [113] tested C.I. engine fuelled with waste cooking palm oil and waste cooking palm oil emulsified with water, ethanol and surfactant. They measured efficiency, peak pressure, ignition delay, combustion duration, smoke opacity and emissions. The test result showed that waste vegetable oil produces more CO and less NO_x than diesel. Patel et al. [114] tested blends of waste cooking oil-diesel in unmodified diesel engine. They observed that with increase in waste cooking oil concentration in diesel, brake thermal efficiency decreased and fuel consumption increased. For blend containing 10% waste cooking oil, brake thermal efficiency was observed to close to that of diesel. For blend containing 30% vegetable oil, specific fuel consumption was found to be comparable with diesel.

Hwang et al. [115] conducted test on diesel engine using Waste Cooking Oil (WCO) based biodiesel produced to evaluate emission of the soot particles. It was seen that the soot emission using diesel was mainly composed of carbon and hydrogen while WCO biodiesel soot contained high amount of oxygen species. Corsini et al. [116] performed an engine test to evaluate the behavior of a common-rail Diesel engine when fuelled with blends of Diesel and waste cooking oil. They also developed in-house software to read all the quantities read by the engine ECU. The test results showed the trend in torque and global efficiency at different gas pedal position and different engine speed. They also observed that the combustion process and the injection time played an important role in the engine behaviour. Bali [117] prepared biodiesel from waste cooking oil and evaluated performance and emission characteristics of diesel engine using various blends of biodiesel-diesel. The fuel consumption of the blends was observed to be higher than the diesel while the brake thermal efficiency was found to be comparable to that of diesel. Higher exhaust gas temperature was observed with biodiesel blends. Further when biodiesel blends were used, reduction in emissions of CO, CO_2, and HC as compared with diesel was observed.

CONCLUSIONS

This review work presents an in-depth review of the experimental investigations carried out on different waste vegetable oils, characteristics of these oils and their performance as diesel engine fuel. WVO is collected and recycled by filtering down, then made available as feedstock for biodiesel production. WVO is a residue from a variety of sources e.g. restaurant and food industry, which is not only harmful for human's health but also causes disposal problems. Using WVO as a fuel is much better option. The use of WVO to produce biodiesel reduce the raw material cost.

Findings of various researchers have shown that WVO has a higher viscosity and lower calorific value; this is a major limitation of using WVO as fuel in diesel engine. Most of the studies reported that WVO and its esters gave performance characteristics comparable to that of diesel. Some researchers find that engine performance using WVO and its esters are even better. When emulsified WVO was utilized better performance was observed. Thermal cracking was also employed for reducing viscosity. The test result showed that engine performance didn't markedly changed by blending diesel oil with the cracked product. Effect of fuel inlet temperature on performance of diesel engine running on WVO has also been investigated and an improvement in engine performance was observed.

It has been observed that WVO and its esters have comparable combustion characteristics as that of diesel. However, a comparatively high disparity of results has been noticed regarding the emissions characteristics of WVO and its esters. In most of the cases, a slight increase in emissions of NO_x while emissions of CO and HC were found to decrease. Emission of NO_x decrease when emulsified fuel was used. Increase in fuel inlet temperature also reduced emissions of WVO.

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