



Use of Waste Frying Oil as C.I. Engine Fuel—A Review

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Abstract

The research activities from past two decades have been vigorously done in the area of alternate fuel for CI engine and still it is on. The rapid industrialization and motorization air is a serious threat to the draining of petroleum resources. Many investigations and studies revealed that the oils from the vegetable origin can be successfully implemented to the existing CI engines without any major hardware modification and still further research is necessary to find a fuel resource from a waste recovery point of view. In this regard, waste cooking oil/frying can be used as a potential alternative fuel. This paper reviews the production, potential, characterization, engine performance and exhaust emissions of the waste cooking oil biodiesel through the experimental work carried out in various part of the world.

Subject Areas

Environmental Chemistry

Keywords

Alternative Fuel, Biodiesel, Methyl Ester, Transesterification, Waste Cooking Oil Methyl Ester (WCME)

1. Introduction

The global requirements for the transport fuel are increasing exponentially all over the world for automobile vehicular application. The diesel operated automobiles are gaining its importance due to its superiority in fuel efficiency and fuel cost is concerned in comparison with gasoline automobiles. The wide usage

of diesel fuel in transportation, power plant, construction, and industrial activity has raised serious concern over the availability of fuel and also environmental degradation.

1.1. Global Scenario

Presently, wide open research is going on to replace the petroleum diesel by a non-petroleum product which is friendly and cost effective and efficient. The United States Energy Information Administration predicted in 2006 that world consumption of oil will increase to 98.3 million barrels per day (15,630,000 m³/d) (mbd) in 2015 and 118 million barrels per day in 2030 [1]. With 2009 world oil consumption at 84.4 mbd, [2] reaching the projected 2015 level of consumption would represent an average annual increase between 2009 and 2015 of 2.7% per year. In June, BP provided an intriguing update to its global oil reserves estimates in the company's yearly review of energy statistics. It raised its reserve estimate by 1.1% to 1687.9 billion barrels-just enough oil to last the world 53.3 years at the current production rates [3].

According to the Institute of Mechanical Engineers, there are 1.3 trillion barrels of proven oil reserve left in the world's major fields, which at present rates of consumption should last 40 years. However, the organization also emphasizes that by 2040, production levels may be down to 15 million barrels per day-just 20% of what we currently consume. By that time, it is probable that the world's population will be double what it is today and much more industrialized, and therefore oil dependent [4].

1.2. Energy Conversion Technology

The heat engine is one which converts the heat energy to mechanical energy. Internal combustion engine is one of the popular mechanism which does the job of energy conversion, thanks to its simplicity, lower ratio of weight and bulk to the output, higher overall efficiency and ease of cooling system, today the total kW installations of I C engines in automobiles is much larger than for other energy related area.

Diesel engine is one such invention by Rudolf diesel a German engineer and the major credit goes to him towards the development of compressed ignition diesel engines [5]. The heart of automotive is I C engine which will provide the primary motive force. The application of diesel engine as a prime mover is obvious in trucks, busses, locomotives, farming equipments, construction equipments, stationary generator sets and so on. The diesel engine invented by Rudolph diesel was run using peanut oil from very beginning only the diesel engine was able to run on variety of vegetable oils at high temperature [6].

1.3. Biodiesel

Biodiesel is chemically converted oil which is obtained from biological sources viz. plant origin and animal origin. Biodiesel is a liquid bio-fuel obtained by

chemical processes from vegetable oils or animal fats and an alcohol that can be used in diesel engines, alone or blended with diesel oil. ASTM International (originally known as the American Society for Testing and Materials) defines biodiesel as a mixture of long-chain monoalkylic esters from fatty acids obtained from renewable resources, to be used in diesel engines [7] [8].

1.3.1. Advantages of Biodiesel

Biodiesel is a Renewable fuel, obtained from vegetable oils or animal fats. It is Low toxic, in comparison with diesel fuel and also it degrades more rapidly than diesel fuel, minimizing the environmental consequences of biofuel spills. Some of the fuel properties are also advantageous like Higher flash point (100C minimum) and it can be easily blended with diesel fuel at any proportion it also shows an excellent lubricating properties. The advantages of biodiesel will also expand to its clean combustion as compared with petro diesel, Lower emissions of carbon monoxide, particulate matter, polycyclic aromatic hydrocarbons, aldehydes their by Lower health risk, due to reduced emissions of carcinogenic substances.

1.3.2. Environmental Problems of Disposing Used Cooking Oil

Used cooking oil causes severe environmental problems, “a liter of oil poured into a water course can pollute up to 1000 tanks of 500 liters”. It’s feasible to demonstrate the contamination with the dumping of these oils to the main water sources. The oil which reaches the water sources increases its organic pollution load, to form layers on the water surface to prevent the oxygen exchange and alters the ecosystem. The dumping of the oil also causes problems in the pipes drain obstructing them and creating odors and increasing the cost of wastewater treatment. For this reason, has been necessary to create a way to recover this oil and reuse it. Also due to the wear and tear resulting in sewer pipes may cause overflows of the system, generating diseases that can cause mild stomach cramps to diseases potentially fatal, such as cholera, infectious hepatitis and gastroenteritis, due to the sewage contains water which can transport bacteria, viruses, parasites, intestinal worms and molds [9].

1.4. Biodiesel from Waste Cooking Oil

Vegetable oil and its methyl esters are the prominent candidates for alternative diesel fuels. These fuels are now under its initial stage of commercialization they are technically feasible and economically competitive as compared with conventional diesel fuel [9].

Used cooking oils/waste cooking oils/waste frying oil and fat residues from meat processing may be used as raw materials which are obtained after repetitive frying of the food products. Previously the waste vegetable oil was used as an ingredient in animal feed but, it was banned by European Union due to animal health hazards [10]. The disposal of waste cooking oil is a problem since, it contaminates water resource and blocks the drainage systems. So, using it as an alternative fuel is therefore found most suitable solution not only for disposal but

also to manage the fuel crisis. In Some instances the waste cooking oils are used to manufacture soaps and detergents but a major volume of waste cooking oil is discharged to environment.

1.5. Global Estimates of Major Vegetable Oils Production

Vegetable oils are oils or fats extracted from a plant. Their texture can be described as liquid, oily and fatty. Most vegetable oils are able to fulfill two functions: they can either be used as cooking oil or for fuel and diesel production. The most common oil types include palm oil, soybean oil, canola oil and sunflower seed oil. Palm oil is extracted from the flesh of the palm fruit, which is primarily found in the tropical climate of Africa, South America and South East Asia. It is estimated that about 90 percent of palm oil is used for food consumption, whereas industrial consumption such as cosmetic products or fuel and diesel claim the remaining 10 percent.

This statistic shows the global production of major vegetable oils from 2000/2001 to 2014/2015, by different vegetable oil types is shown in **Figure 1**.

Global Estimates of Waste Cooking Oil

The estimated quantity of waste cooking oil from selected countries is depicted in **Table 1**.

From the above data one can have a clear image that, waste cooking oil, which is otherwise wasted after frying the foodstuff; it can be used as biofuel as such it, will be the one of the most economical choice for waste disposal in the form of biodiesel production.

1.6. Chemistry of Frying Process

During frying process, oil is continuously or repeatedly subjected to high

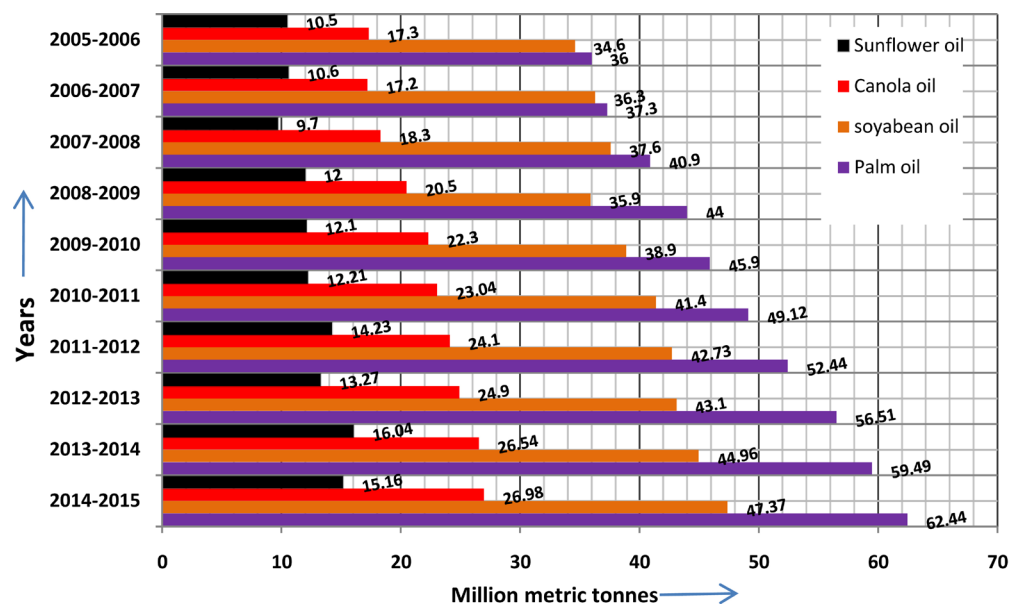


Figure 1. Global production of vegetable oil [10].

Table 1. Worldwide waste edible oil production [11] [12] [13].

| Country | Estimated waste cooking oil |
|----------|--------------------------------|
| USA | 1,00,00,000 gallons/day |
| Canada | 1,35,000 tons/year |
| E.U. | 7,00,000 - 10,00,000 tons/year |
| UK | 2,00,000 tons/year |
| China | 45,00,000 tons/year |
| Malaysia | 5,00,000 tons/year |
| Taiwan | 70,000 tons/year |
| Japan | 4,50,000 - 5,70,000 tons/year |
| India | 90,00,000 tons/year |

temperatures in the presence of air and moisture.

Three essential degradation reactions occurs under these conditions are;

- Hydrolysis causing from the moisture content of fried food. This reaction produces free fatty acids (FFA), mono- and diglycerides.
- Oxidation causing from the contact with oxygen. Reaction products are oxidized monomeric, dimeric and oligomeric triglycerides and volatile materials such as aldehydes and ketones.
- Polymerization causing from these two reactions, and high temperatures. This reaction produces dimeric and polymeric triglycerides with ring structure [14] [15].

Because of these degradation reactions mentioned above, a number of physical and chemical changes occur in frying oils including increase in viscosity, density, FFA content, total polar material (TPM), polymerized triglycerides, and decrease in smoke point, the number of double bonds, etc. If the frying process is continued, these materials will undergo further degradation and finally the oil will not be appropriate for frying. The frying oil has to be discarded. Since all degradation products are of polar character, TPM content of frying oil is a good indicator of its degradation level. Thus, in many countries, TPM content of frying oil has been legally accepted as the limit value to decide discard it or not. For example, in Turkey, TPM content of frying oil must not exceed the top level of 25%. In addition to TPM, as the oil deteriorates, some changes in its physical and chemical properties occur. For instance, during frying, oil's double bonds are ruptured and so its fatty acid composition changes, FFA level and saturation degree increase [16] [17].

The change in the fatty acid composition influences some oil properties such as iodine value, viscosity, density, heating content. Thus, these properties can also be used to monitor the quality of the frying oil [18].

2. Production Technologies

Many standard methods and procedures are developed by number of researchers

for the production of waste cooking oil into biodiesel. Most prominent and efficient conversion techniques are discussed below.

2.1. Transesterification

The most common way to produce biodiesel is by transesterification, which refers to a catalyzed chemical reaction involving vegetable oil and an alcohol to yield fatty acid alkyl esters and glycerol and these fatty acid alkyl esters are commonly called as biodiesel. Transesterification is the general term used to describe the important class of organic reactions where an ester is transformed into another through interchange of the alkoxy moiety (Freedman *et al.*, 1986) [19]. These transesterification reactions may be alkali-catalyzed or acid catalyzed or enzyme catalyzed.

Alkali-Catalyzed Transesterification

In alkali catalyzed transesterification method, the catalyst (KOH or NaOH) is dissolved into methanol by vigorous stirring in a reactor. The bio-oil is transferred into a reactor and then the catalysts/alcohol mixture is pumped into the oil. The final mixture is stirred continuously for 2 hours at 100°C in ambient pressure.

A good transesterification reaction produces two liquid phases: ester and crude glycerin (Demirbas, 2007).

Graille J, 1986 *et al.* used Boiler ashes, potassium hydroxide (KOH) amongst other catalysts were successful in the ethanolysis and methanolysis of palm and coconut oils with yields as high as 90% [20].

In an another investigation, It is reported that methyl and ethyl esters with 90% yield can be obtained from palm and coconut oil from the press cake and oil mill and refinery waste with the ashes of the wastes (fibers, shell, and husks) of these two oil seeds, and with lime, clay, zeolites, etc [21] [22].

Faheem H. Akhtar, 2014 *et al.* analyzed the rice bran oil and waste cooking oil for their potential use as an alternative source for biodiesel production. The rice bran oil gave a yield of 87% at 55°C, 6:1 molar ratio, and 90 min, while waste cooking oil showed a maximum yield of 84% under optimum conditions of 60°C temperature, molar ratio of 9:1 and consuming 75 min [23].

Alkaline metal hydroxides (e.g. KOH and NaOH) are cheaper than metal alkoxides, but less active. Nevertheless, they are a good alternative since they can give the same high conversions of vegetable oils just by increasing the catalyst concentration to 1 or 2 mol%. However, even if water-free alcohol/oil mixture is used, some water is produced in the system by the reaction of the hydroxide and the alcohol. The presence of water gives rise to hydrolysis of some of the produced ester (Scheme 3), with consequent soap formation [33].

The alkali catalytic process is more effective when the FFA level is less than 1%. When the FFA contents of the raw material are greater than 1% then acid catalyzed process is preferred. Anyhow, this process requires higher catalyst concentration and high molar ratio that results in corrosion issues [24].

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Prafulla D. Patil *et al.* Investigated, Biodiesel Production from Waste Cooking Oil Using Sulfuric Acid and Microwave Irradiation Processes two-step transesterification process was used to convert the high free fatty acid oil to its ester. Microwave assisted transesterification of waste cooking oil using heterogeneous and homogeneous was investigated for optimum reaction conditions. Microwave-assisted catalytic transesterification using BaO and KOH was evaluated for the efficacy of microwave irradiation in biodiesel production from waste cooking oil. On the basis of energy consumptions for waste cooking oil (WCO) transesterification by both conventional heating and microwave-heating methods evaluated in this study, it was estimated that the microwave-heating method consumes less than 10% of the energy to achieve the same yield as the conventional heating method for given experimental conditions. The preliminary experimental study performed in this work has demonstrated that the micro-wave-heating method is energy-efficient and better than the conventional heating method [26].

In an experimental work “Transesterification of biodiesel from waste cooking oil using ultrasonic technique” by Darwin Sebayang *et al.* Proposed new type of transesterification process from waste cooking oil to biodiesel using ultrasonic technique. The conversion of waste cooking oil with NaOH as catalyst used ultrasonic type of clamp on tubular reactor at 20 kHz. The reaction time, molar ratio, and biodiesel quality of this process were compared with conventional transesterification. The main equipment used ultrasonic type of clamp on tubular reactor with specification tube tank diameter 21 mm and 60 mm length. Ultrasonic systems based on unique MMM (Multi-frequency, Multimode, Modulated) technology. The ultrasonic was used modular ultrasonic generators MSG.1200.IX utilize the MMM Technology. WCO was screened to remove food residues and solid precipitate. Then, WCO dried by heating to 110°C during 10 min. NaOH in the concentration of 1%wt to WCO was pre-mixed with methanol for each experimental condition. In each experiment, 100 gram of WCO was fed with mixture methanol-sodium hydroxide to the ultrasonic tubular reactor. The process ultrasonic technique obtained conversion WCO to TG about 95.6929% wt with the methanol to oil molar ratio of 6:1, 1 %wt sodium hydroxide as catalyst and 5 minute reaction time. Ultrasonic technique has fast reaction time and with a less amount of methanol high conversion of methyl ester was observed [27].

Amore recent study by Lima *et al.* (2008) used Fourier Transform Infrared Photo acoustic Spectroscopy (FTIR-PAS) in identifying or monitoring spectral changes induced in the vegetable oils due to a degradation effect. Besides, the method can be used to contribute to the biodiesel wash process to separate the

glycerol from the biodiesel. The authors argued that the method is efficient, fast and exhibits some advantages when compared with conventional processes, such as attenuated total reflectance (ATR). Some key parameters were selected for determining the viability of the vegetable oil transesterification process. These parameters include: acid value and FFA content, moisture content, viscosity and fatty acid profile of the used oil [28].

2.2. Acid Catalyzed Transesterification

Most of the biodiesel that is currently made uses high quality vegetable oil and an alkaline catalyst. However, there are large amounts of waste oils (restaurant waste, frying oils, trap grease, etc.) that could be converted to biodiesel. The problem with processing waste oils is that they often contain significant amounts of free fatty acids that cannot be converted to biodiesel using an alkaline catalyst. These free fatty acids react with an alkaline catalyst to produce soaps that inhibit the separation of the ester, glycerin, and wash water. An alternative way of processing these waste oils, that may have a greater tolerance for free fatty acids, is to use an acid catalyst.

Nye *et al.* (1983) have shown that it is possible to produce methyl esters from used frying oil using an acid catalyst. The objective of this study was to investigate the effect of the molar ratio of alcohol, the reaction temperature, the catalyst amount, the reaction time, and the presence of water and free fatty acids on the completeness of acid-catalyzed transesterification [29].

Schwab *et al.* (1987) and Liu (1994) compared acid and base catalysts. They noted that acid catalyzed transesterification requires heating to accelerate the reaction and that the reaction time may vary from a few minutes to several hours.

M. Canakci, J. Van Gerpen (1999) investigated the effect of process variables on acid-catalyzed transesterification. The molar ratio of alcohol, reaction temperature, catalyst amount, reaction time, water content, and free fatty acids were investigated to determine the best strategy for producing biodiesel. Food grade soybean oil was used to prepare esters using excess methanol and sulfuric acid as a catalyst. To compare the effect of different alcohol types on ester formation, methanol, ethanol, 2-propanol, and n-butanol were compared. The American Oil Chemists' Society Method Ca 14 - 56 was used to measure the biodiesel's total glycerin amount as an indicator of the completeness of the reaction. It was found that acid catalysis can provide high conversion rates but much longer times are required than for alkaline catalysts. The acid catalyst also requires the concentration of water to be less than 0.5%, which is about the same as is required for alkaline catalysts. Water formed by the esterification of free fatty acids limited their presence in the oil to 5% [30].

Guoqing Guana (2012) in this study, BDF synthesis from waste oily sludge (WOS) was investigated. The feed stock oil was extracted from WOS by hexane, and the extracted oil was reacted with methanol to produce BDF by using a sulfuric acid or ferric sulfate catalyst. FFA-rich oil extracted from WSO was used as

a feedstock of BDF production. H_2SO_4 and $\text{Fe}_2(\text{SO}_4)_3$ were successfully used as catalysts for the esterification of FFA. The FAME yields reached approximately 86% for both catalysts under suitable condition. $\text{Fe}_2(\text{SO}_4)_3$ was appropriate as a solid catalyst for repeated use [31].

Adepoju, T. F (2014) in his experimental investigation titled Acid-Catalyzed Esterification of Waste Cooking Oil with High FFA for Biodiesel Production used restaurant waste frying oil with Two steps (esterification and transesterification) approach employed to convert the WCO to biodiesel. In the first step, six experimental run was carried out until the % FFA was constant. Meanwhile, the second step required five experimental runs, and the average WCO biodiesel yield (95.06% w/w) was computed at the following variable conditions, 0.55% KOH, 5:1 Methanol/oil molar ratio, 60°C reaction temperature and 30 min reaction time. Meanwhile, the produced WCO biodiesel possess some fuel properties which satisfied both ASTM D6751 and EN 1424 standards. Hence, it can be concluded that WCO is a potential raw material for biodiesel production which are biodegradable, economical, environmental friendly and always available [32].

Yu *et al.* reported biochar based catalyst for the transesterification of canola oil. It's a heterogeneous catalyst bearing sulfonic acid group prepared using biochar as the carbon support. The reaction yield was found to be dependent on both catalyst surface area and total acid density, suggesting that the maximum yield would be obtained for a catalyst prepared from char carbonized between 675°C and 875°C. Reusability of the catalyst was poor under high temperature/pressure conditions [33].

2.3. Enzyme-Catalyzed Transesterification

As discussed above, the Industrial production of bio-diesel is mostly conducted by the transesterification process with methanol in the presence of acid or basic catalysts where biodiesel and glycerol are produced. A disadvantage of this process is the soap formation that needs to be separated from the product mixture leading to an increased amount of wastewater generation and additional energy consumption. Therefore, downstream processing costs, by-product recovery and environmental problems have imposed the need to explore alternative methods, so enzyme catalyzed transesterification process is current trend of investigation.

Mohammad. Pazouki *et al.* (2001) opined in his research that, the Biodiesel can be produced by methanolysis of waste edible oil with a whole cell biocatalyst utilizing whole cell biocatalyst instead of free or immobilized enzyme is a potential approach to reduce the cost of catalyst in lipase-catalyzed biodiesel production. In this study *Rhizopus oryzae* (*R. oryzae*) PTCC 5174 cells were cultured with polyurethane foam biomass support particles (BSPs) and the cells immobilized within BSPs were used for the methanolysis of pretreated used cooking oil. The inhibitory effect of un-dissolved methanol on lipase activity was eliminated by stepwise addition of methanol to the reaction mixture. The optimum condi-

tions for the reaction were as follows: 50 BSPs, molar ratio of methanol to UCO 3:1, 15.54% (wt) water (in the form of buffer phosphate with pH = 6.8) based on UCO weight and temperature 35°C in three-step addition of methanol. The maximum methyl ester yield of 98.4% was obtained after 72 h of reaction in a shaken Erlenmeyer at mentioned conditions. The study shows that pretreated used cooking oil (UCO) can be efficiently converted to biodiesel fuel in a shaking Erlenmeyer methanolysis reaction using immobilized *Rhizopus Oryzae* (PTCC 5174) on polyurethane foam biomass support particles (BSPs) [34].

Nikhil Gharat (2012) in his research paper “Enzyme catalyzed transesterification of waste cooking oil with dimethyl carbonate” proved that biodiesel can be successfully produced from waste cooking oil and diethyl carbonate by transesterification, instead of the conventional alcohol. In this optimization study, the effect of various reaction conditions such as solvent, time and temperature, molar ratio of DMC to oil, enzyme loading and reusability, on the yield of fatty acid methyl ester (FAME) has been studied. The Maximum conversion of FAMEs achieved was 77.87% under optimum conditions (solvent free system, reaction time of 24 h, 60°C, molar ratio of DMC to oil 6:1, catalyst amount 10% Novozym 435 (based on the oil weight)). Moreover, there was no obvious loss in the conversion after lipases were reused for 6 batches under optimized conditions. Novel approach for enzyme (Novozym 435) catalyzed transesterification of waste cooking oil with dimethyl carbonate (DMC) has been studied. DMC proved to be efficient acyl acceptor and hence methanol deactivation of enzyme could be completely avoided. Thus lipase catalyzed transesterification of WCO with DMC is very promising for FAMEs production. DMC to WCO molar ratio of 6:1 was found to be the most effective for enhanced transesterification of WCO. Maximum conversion of FAMEs achieved was 77.87% under optimum conditions (solvent free condition, 24 h, 60°C, molar ratio of DMC to oil 6:1, catalyst amount 10% Novozym 435 (based on the oil weight)). The immobilized lipase Novozym 435 could be recycled without any significant change in activity and conversion till six batch reactions [35].

Laura Azócar (2014) Enzymatic catalyst for biodiesel production Novozym 435 4 wt% was used as enzymatic catalyst to produce biodiesel of rapeseed oil and with mix rapeseed oil/WFO ratio 4:1 (w/w). Three step protocols consisting of the stepwise addition of 1 M equivalent of ethanol was applied in order to avoid enzyme inhibition (Soumanou and Bornscheuer, 2003). The reaction was carried out with an ethanol/oil molar ratio of 4.5:1, during 14 hours, between 35°C - 40°C at 200 rpm. Due the low solubility of alcohols in oils, short-chain alcohols like methanol could lead to enzyme inactivation (Al-Zuhair *et al.*, 2006; Kaieda *et al.*, 2000). Thus, the solubility in molar ratio for methanol/oil is only 1.5:1. Alcohols of carbon chain lengths higher than 3, are completely dissolved in oil in a stoichiometric amount, *i.e.*, 3 mol of alcohol are dissolved in 1 mol of oil. However, high cost and low reactivity are drawbacks of long-chain alcohols. To solve the inhibition problem, ethanol was used as acyl acceptor because its solu-

bility in oil is higher than methanol (ethanol/oil 2:1 mol/mol) (Shimada *et al.*, 2002). Besides, ethanol is a renewable alcohol.

The stepwise addition also was applied in order to avoid lipase inhibition (Soumanou and Bornscheuer, 2003).

Biodiesel properties produced from transesterification with enzymatic catalyst Novozym 435, do not accomplish the normative (**Table 2**, BIO 3). However, Du *et al.* (2004), showed that only a 67% yield was reached under similar conditions (Novozym 435 4 wt%, methanol/oil molar ratio 3:1, at 40°C and 150 rpm, during 40 hours of reaction). Ethanol used as acyl acceptor presented advantages in enzymatic catalysis. In addition, the use of immobilized enzymes has some advantages, because lipase can be recovered and a washing step of the produced biodiesel is unnecessary, avoiding wastewater generation and it has been concluded finally that Transesterification with Novozym 435 4 wt%, ethanol oil molar ratio of 4.5:1, stepwise addition of 1 Methanol, 35°C - 40°C, 14 hours reaction and 300 rpm, reached a FFAE yield of 76.8% for biodiesel from rapeseed oil and 68% for biodiesel from rapeseed oil/WFO 1 mixture, 4:1 (w/w) [36].

S. BUDŽAKI *et al.*, (2015) said in his research work “Enzyme-catalyzed Biodiesel Production from Edible and Waste” that the Application of enzymes such as immobilized or free lipases originating from different microorganisms for biodiesel production brings several advantages. Beside the well-known fact that enzymatic processes are performed under mild conditions and without additional energy consumption, enzymatic biodiesel production leads to the production of food-grade glycerol without soap generation. However, enzymes have certain disadvantages which move them away from wider application in the synthesis of biodiesel, such as high costs. Lipases (triacylglycerol acylhydrolase, EC 3.1.1.3) catalyze the hydrolysis of triacylglycerols to di- and mono-acylglycerols. However, they can be used in biodiesel production due to their ability to simultaneously catalyze hydrolysis, esterification and transesterification [37].

Abdulkarim Ali Deba *et al.* (2015) in his research on Waste Cooking oil: A Resourceful Waste for Lipase Catalyzed Biodiesel Production aims to discuss the potentiality of waste cooking oil as a resourceful waste in biodiesel production and to bring out its cost effective prospect of biodiesel production. It includes the production of quantum lipase using recombinant DNA technology; immobilized lipases and immobilized whole cell technology have tendencies to lower the overall cost. Lipase catalyzing the production of biodiesel from waste cooking oil has been successful as reported in the bulk of this review article [38].

2.4. Difference between Acid, Alkali & Enzyme Catalyzed Transesterification

The major difference observed in the acid, alkali & enzyme catalyzed transesterification is as depicted in **Table 2**.

3. Characterization of Waste Cooking Oil Biodiesel

Waste frying oils are one of the low cost feedstock. However, the feedstock

Table 2. Difference between acid, alkali & enzyme catalyzed transesterification.

| Sl. no | Major factors | Acid catalyzed | Alkali catalyzed | Enzyme catalyzed |
|--------|---------------------------------|---|--|---|
| 1 | Yield of biodiesel | High, nearly 95% - 96% | High, nearly 99% | Relatively lower than alkali catalyst, around 90% |
| 2 | Downstream processing | Multi-step purification of end products | Multi-step purification of end products | None |
| 3 | Production cost | Little bit expensive as compared with alkali catalyzed process | Cheap, as catalysts are comparatively cost less | Synthesis of biocatalyst are expensive |
| 4 | Commercialization | Fully commercialized | Fully commercialized | Not yet commercialized |
| 5 | Waste water generation | Water washing is required to remove the acidic content in biodiesel | Saline and alkaline effluents need treatment, No waste water generation before discharge | No waste water generation |
| 6 | Reaction temperature | 100 °C | 60 °C - 80 °C | 20 °C - 60 °C |
| 7 | Presence of FFA's in feed stock | No soap formation | Soap formation | Completely conversion into the methyl ester and no soap formation |

properties to be understood must be controlled in detail prior to transesterification reaction, since the physical and chemical properties of the feedstock significantly influence biodiesel production reaction as well as fuel properties.

Frying oils which are used in various facilities in different conditions such as frying temperature, time, kind of food fried etc. have significantly different physico-chemical properties. Therefore, the detail physico-chemical properties such as acid value, saponification value, iodine value, kinematic viscosities and Fatty acid composition are very important in the view point of utilization of biodiesel.

As per ASTM and EN standards there are some general test procedures followed to characterize the obtained biodiesel and the norms has to be satisfied for its potential usage. Oil companies and vehicle manufacturers are actively working with Biofuel extender producers to have agreed standards for transesterified vegetable oils suitable for blending with conventional diesel to ensure that the product meets the technical requirements of modern diesel engines. The minimum test requirements for Biodiesel blend extenders are specified in ASTM D6751 in USA and EN 14214 within Europe.

3.1. Biodiesel Fuel Characterizations

The biofuel sample has to be tested to determine the fuel characteristics according to ASTM Biodiesel Fuel Quality Assurance Standard Test. **Table 3** shows the summary of test method used, the standard limits recommended by ASTM and

Table 3. ASTM standards [39].

| Sl. no. | ASTM standards | Properties | Method of testing | Limits |
|---------|----------------|---|---|----------------------------------|
| 1 | D93 | Flash point | Pensky-Martens closed cup tester & small scale closed cup tester | 130 °C min |
| 2 | D445 | Kinematic viscosity of transparent and opaque liquids @ 40 °C | Calculation by dynamic viscosity | 1.9 - 6.0 min ² /sec. |
| 3 | D613 | Cetane number | Test method for petroleum based diesel | 47 min. |
| | D287 | Specific gravity | Not required | 0.86 |
| | D664 | Acid number of petroleum products | Potentiometric titration | 0.80 mg KOH/gm max |
| 4 | D974 | Acid and base number | Color-indicator titration | -- |
| 5 | D6584 | Free glycerin | 0.020% mass max. | 0.02 |
| 6 | D6584 | Total glycerin | 0.240% mass max. | 0.02 |
| 7 | D4951 | Phosphorus content | 0.001% mass max | -- |
| 8 | D976 | Distillation temp., atmospheric equiv. temp., 90% recovered | At reduced pressure | 360 °C max |
| 9 | D1266 | Sulfur in petroleum products | Lamp method & wavelength dispersive x-ray fluorescence spectrometry | 0.05% mass max |
| 10 | D1796 | Water and sediment in fuel oils | Centrifuge method (laboratory procedure) | -- |
| 11 | D2274 | Oxidation stability of distillate fuel oil at 110 °C | Accelerated method | 6 hours |
| 12 | D2500 | Cloud point of petroleum products | Optical detection stepped cooling method | -1 °C |
| 13 | D6584 | Test method for determination of total monoglycerides, diglycerides, triglycerides, and free and total glycerin in biodiesels | Gas chromatography | -- |

Table 4 shows the summary of test method used, the standard limits recommended by EN standards.

3.1.1. Monoglycerides, Triglycerides and Triglyceride Content

ASTM does not have a standard limit for triglyceride, diglyceride and monoglyceride content in the final product. However, European biodiesel standard (EN14214) recommends that the triglyceride, diglyceride and monoglyceride content should not exceed 0.8, 0.2 and 0.2, respectively.

1) Flash Point

Flash point is the lowest temperature at which a liquid can form an ignitable mixture in air near the surface of the liquid.

Table 4. European standards for utility of Bio-diesel.

| Property | Units | Lower limit | Upper limit | Test-Method |
|---|--------------------|-------------|-------------|---------------------|
| 1. Ester content | % (m/m) | 96.5 | - | EN 14,103 |
| 2. Density at 15°C | kg/m ³ | 860 | 900 | EN 3675 - 12,185. |
| 3. Viscosity at 40°C | mm ² /s | 3.5 | 5.0 | EN 3104 |
| 4. Flash point | °C | > 101 | - | EN 3679 |
| 5. Sulfur content | mg/kg | - | 10 | - |
| 6. Tar remnant (at 10% distillation remnant) | % (m/m) | - | 0.3 | EN 10,370 |
| 7. Cetane number | - | 51.0 | - | EN 5165 |
| 8. Sulfated ash content | % (m/m) | - | 0.02 | EN 3987 |
| 9. Water content | mg/kg | - | 500 | EN 12,937 |
| 10. Total contamination | mg/kg | - | 24 | EN 12,662 |
| 11. Copper band corrosion (3 hours at 50°C) | rating | Class 1 | Class 1 | EN ISO 2160 |
| 12. Thermal stability | - | - | - | - |
| 13. Oxidation stability, 110°C | hours | 6 | - | EN 14,112 |
| 14. Acid value | mg KOH/g | - | 0.5 | EN 14,104 |
| 15. Iodine value | - | - | 120 | EN 14,111 |
| 16. Linoleic Acid Methylene | % (m/m) | - | 12 | EN 14,103 |
| 17. Polyunsaturated (≥4 Double bonds) Methylene | % (m/m) | - | 1 | - |
| 18. Methanol content | % (m/m) | - | 0.2 | EN 14,110 |
| 19. Monoglyceride content | % (m/m) | - | 0.8 | EN 14,105 |
| 20. Diglyceride content | % (m/m) | - | 0.2 | EN 14,105 |
| 21. Triglyceride content | % (m/m) | - | 0.2 | EN 14,105 |
| 22. Free Glycerine | % (m/m) | - | 0.02 | EN 14,105/EN 14,106 |
| 23. Total Glycerine | % (m/m) | - | 0.25 | EN 14,105 |
| 24. Alkali Metals (Na + K) | mg/kg | - | 5 | EN 14,108/EN 14,109 |
| 25. Phosphorus content | mg/kg | - | 10 | EN 14,107 |

The lower the flash point, the easier it is to ignite the material. The flashpoint of the test fuel should be within 130°.

2) Total Acid Number

The ASTM standard for total acid number (TAN) for pure biodiesel is 0.8 mgKOH/g. The TAN or acid value is the total amount of potassium hydroxide

necessary to neutralize the free acids in biodiesel sample. High TAN or acid values on the feedstock indicates unrefined or poorly refined product oil source due to poor process control, such as ethanol carryover. Higher acid number could also cause degradation of rubber parts in older engines resulting in filter clogging. The total acid number can also be determined by titration.

3) Cloud Point and Pour Point

The cloud and pour point are also the important properties of biodiesel fuel. When oil is cooled to the Temperature at which a cloud of wax crystals first appear in the oil is called as Cloud point.

The pour point is the lowest temperature at which the oil sample can still be moved. These properties are related to the use of biodiesel in the cold temperature.

4) Cetane Number

Cetane number of the diesel fuel is the indicator of the ignition quality. The higher the Cetane number, the more efficient the ignition will be. Due to the higher oxygen content, biodiesels has a higher Cetane number compared to petroleum diesel.

5) Water and Sediment

The water and sediments will hamper the fuel quality. The water content will decrease the calorific value of the fuel and sediments will cause problems in fuel injection. The ASTM standard limit for water and sediment was is 0.05% by volume of the sample.

3.1.2. ASTM Specification & Testing Methods for Biodiesel Fuel Blend Stock (B100)

3.1.3. EN 14214 Specification & Testing Methods for Biodiesel Fuel Blend Stock (B100) [40]

3.2. Physiochemical Properties of WCO Biodiesel from Some Significant Investigations

In an investigation by Arjun B. Chhetri *et al.* (2008), the ethyl ester was prepared from waste cooking oil sample collected from a local restaurant in Halifax. The fatty acid composition of final biodiesel esters was determined by gas chromatography and found that the waste cooking oil contains mainly oleic acid in the final products. This is because the original oil used was found to be canola oil. The biodiesel was characterized for its physical and fuel properties using ASTM standard methods for biodiesel fuel quality assurance. From the tests, the flash point was found to be 164°C, the phosphorous was 2 ppm, calcium and magnesium was 1 ppm together, water and sediment was 0%, sulfur content was 2 ppm, total acid number was 0.29 mg KOH/g, viscosity at 40°C was 5.02 mm²/sec, Cetane index was 61, cloud point was -1°C and pour point was -16°C. Out of 18 properties tested, 14 of them met the ASTM criteria for fuel standard. The reasons why the tests failed have been explained and measures are suggested to improve the overall results process to produce biodiesel of ASTM fuel quality standard. Production of biodiesel from waste cooking oils for diesel substitute is par-

ticularly important because of the decreasing trend of economical extracted oil reserves and the environmental problems caused due to the use of fossil fuel [41].

The author also says that the, Fatty acid contents are the major indicators of the properties of biodiesel. In this study Duplicate samples were used to determine the fatty acid content of the biodiesel product. **Table 5** shows the summary of fatty acid content in the waste cooking oil. From Gas Chromatography analysis, it was found that the biodiesel derived from the sample of waste cooking oil contains oleic acid (59.7%) followed by linoleic acid (19.31%), linolenic acid (6.82%), palmitic acid (5.18%), stearic acid (2.1%), eicosenoic acid (1.21%) and rest the others (4.36%). Biodiesel from the sampled waste cooking oil contained the highest amount of oleic acid among other fatty acids in the product and that reported by Issariyakul *et al.* [17].

In waste cooking oil biodiesel, approximately 60% of the fatty acids were found to be monounsaturated (C18:1). Poly-unsaturated fatty acids were found to be approximately 26% (C18:2, C18:3). Only approximately 8% fatty acids were saturated. Palmitic acid and stearic acid were the major saturated fatty acids found in waste cooking oil ethyl ester. Over 4% of the products were unidentified. These values were found from the GC analysis.

Table 5. Fuel Properties of Waste Cooking Oil (WCO) Reference: Arjun B. Chhetri *et al.* (2008).

| Sl. no | Tests | ASTM nomenclature | Standard limit | Result |
|--------|---------------------------------------|-------------------|----------------|--------|
| 1 | Density @15°C g/cm ³ | - | - | 0.87 |
| 2 | Pour Point (°C) | ASTM D 97 | -1°C | -16°C |
| 3 | Cloud Point (°C) | ASTM D 2500 | | -1°C |
| 4 | Cetane Index | ASTM D 976 | Min 47 | 61 |
| 5 | Distillation., 90% recovery (°C) | ASTM D 2887 | Max 360 | 366 |
| 6 | Viscosity @ 40°C mm ² /sec | ASTM D 445 | 1.9 - 6.0 | 5.03 |
| 7 | TAN (mg KOH/g) | ASTM D 664 | Max 0.80 | 0.29 |
| 8 | Sulfur by UV (ppm) | ASTM D 5453 | Max 15 | 2 |
| 9 | Water + Sediment (vol%) | ASTM D 2709 | Max 0.05 | 0 |
| 10 | Sodium + potassium (ppm) | EN 14,538 | Max 5 | 66 |
| 11 | Calcium + Magnesium (ppm) | EN 14,538 | Max 1 | 1 |
| 12 | Phosphorous (ppm) | ASTM D 4951 | Max 10 | 2 |
| 13 | Flash Point, Closed cup (°C) | ASTM D 93 | Min 130 | 164 |
| 14 | Total Glycerin (mass%) | ASTM D 6584 | 0.024 | 0.566 |
| 15 | Triglycerides (mass%) | ASTM D 6584 | 0.061 | 0.2 |
| 16 | Diglycerides (mass%) | ASTM D 6584 | 0.19 | 0.2 |
| 17 | Monoglycerides (mass%) | ASTM D 6584 | 0.293 | 0.8 |
| 18 | Free Glycerin (mass%) | ASTM D 6584 | Max 0.020 | 0.022 |

The amount and type of fatty acid content in the biodiesel are the major factors that determine the viscosity of biodiesel. The author also did the qualitative and quantitative analyses of fatty acid content which were comparable with the study reported by Issariyakul *et al.* for waste cooking oils.

Huseyin Sanli *et al.* (2011) in his work “Characterization of Waste Frying Oils Obtained from Different Facilities” aimed to study the physicochemical properties of oil after and before frying. The different vegetable oils are used for different food purpose. In this study, 30 different waste frying oil samples (14 from fish restaurants, 5 from fast-foods, 5 from hospitals, 4 from pastry shops, and 2 from restaurants) were collected and their density, viscosity, total polar material, water content, acid value, iodine value, peroxide value, and heating content were determined and compared to each others. He says that the characterization is important due to the reason that oils or fats are likely exposed to varying degrees of use such as temperature and time. But to study the acid value and viscosity is especially useful, because these two properties have been shown to an increase steadily during degradation and is expected from the used cooking oils. When the waste frying oil samples obtained from fast-foods are examined and compared to each other, it is seen that FF1 has the TPM content of 30% and exceeded the top limit of 25%. Moreover, in addition to TPM, water content, PV and AV of this waste frying oil was the highest. Its AV (17.85 mg KOH/g) was more than twice of that of FF5 which was the second highest. FF4’s TPM content (24.5%) was close to the top limit value. In addition, density and viscosity values of this sample were the highest. Its viscosity was 6.95 mm²/s higher than that of the second highest viscosity. It was a reasonable result that the peroxides values of FF1 and FF4 which had the highest TPM contents were almost same (50.61 and 50.42 meq/kg). However, among the samples obtained from fast-foods, FF4’s AV (1.78 mg KOH/g) was the lowest and its IV (95.38 gI₂/100g) which is the indicator of un-saturation level was the highest. Whereas its iodine value was expected to be low as the result of destruction of double bonds, the result was not in this expectation. As the heating content increases with saturation, the highest heating content (39,741 kJ/kg) belonged to FF5 which was the most saturated sample having an IV of 52.17 gI₂/100g [42].

In an another investigation titled “Characterization of Waste Palm Cooking Oil for Biodiesel Production” by Zahoor Ullah (2014), characterized the used cooking oil collected from the cafeteria in Universiti Teknologi PETRONAS. The spectroscopic analysis was performed for the used and unused cooking oil samples. Comparison of the data indicated that no significance spectroscopic and structural changes occurred for used and unused oil samples [42]. The physiochemical properties of oil mentioned in **Table 6** were determined by the already established methods to check their properties before and after frying.

In A recent investigation “Characterization of Used Cooking Oils by High Performance Liquid Chromatography and Corona Charged Aerosol Detection” by Marc Plante, Bruce Bailey and Ian N. Acworth have a purpose to develop

Table 6. Physiochemical properties of used and unused cooking [42].

| Sl no. | Properties | Oil before frying | Oil after frying |
|--------|--|-------------------|------------------|
| 1 | Acid value (mg KOH/gm) | 0.3 | 4.03 |
| 2 | Calorific value (J/gm) | ----- | 39,658 |
| 3 | Saponification value (mg KOH/gm) | 194 | 177.97 |
| 4 | Peroxide value (meq/kg) | <10 | 10 |
| 5 | Density (gm/cm ³) | 0.898 | 0.9013 |
| 6 | Kinematic viscosity (mm ² /s) | 39.994 | 44.956 |
| 7 | Dynamic viscosity (mpa.s) | 35.920 | 40.519 |
| 8 | Flash point (°C) | 161 - 164 | 222 - 224 |
| 9 | Moisture content (wt%) | 0.101 | 0.140 |

analytical methods to characterize used cooking oils by High-pressure liquid chromatography (HPLC). A variety of cooking oils, five used oils (“gutter oils”) and two fresh oils were analyzed, and their results are presented. The universal lipids method provided the fastest and most differentiating results to distinguish different oil qualities, and the HPLC-FLD-MS method provided information on aldehyde content of the samples.

The researcher says that “cooking oil must be monitored for quality and contamination”. When cooking oil is heated, it can undergo many chemical changes including oxidation of unsaturated fatty acids, triglyceride decomposition, and the formation of potentially cytotoxic oxidation products such as 4-hydroxy-trans-2-nonenal (HNE) and other aldehydes that are purported to be associated with Parkinsons, Alzheimers, Huntingtons, atherosclerosis, liver diseases, and stroke. Rancidity during long term storage can also occur and is associated with the content of polyunsaturated fatty acid content. Although these issues make used oil unfit for use in the kitchen, and unhealthy for human consumption, it can still act as a useful resource as a raw material for biofuel production [43]. As there is a significant price difference between high quality cooking oils and lower quality biofuel raw materials, the possibility exists for unscrupulous people to filter and decolorize used cooking oils and sell them as high quality cooking oils. Such treated used oils are referred to as gutter oils (GO).

4. Performance Characteristics of Waste Cooking Oil Biodiesel Fueled Diesel Engine

Numerous Experiments has been carried out around the globe to estimate the performance of a compressed ignition engine fuelled with waste cooking oil methyl ester and its blends with standard diesel.

4.1. Performance Parameters

The primary performance parameters includes Brake thermal efficiency, specific fuel consumption, brake power, indicated mean effective pressure, mechanical

efficiency and exhaust gas temperature which will give a complete representation of heat and work transfer.

4.1.1. Brake Thermal Efficiency (BTE)

The Brake thermal efficiency is defined as the ratio of output energy available at the engine shaft to the net brake power developed by engine neglecting all other power losses. Brake Thermal Efficiency is referred as brake power of a heat engine as a function of the thermal input from the fuel. It is a tool to evaluate how well an engine converts the heat from a fuel to mechanical energy.

4.1.2. Brake Specific Fuel Consumption (BSFC)

Brake specific fuel consumption (BSFC) is a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational, or shaft, power. It is the quantity of Fuel consumed by engine in gm/ kg to develop a kW of power in an hour known as Brake specific fuel consumption (BSFC) it is usually expressed in kg/kWh.

4.1.3. Brake Specific Energy Consumption (BSEC)

Brake Specific Energy Consumption (B.S.E.C.) is the energy used by the engine to produce unit power. KJ/kg-kWh.

4.1.4. Brake Mean Effective Pressure (BMEP)

Brake Mean Effective Pressure is the average (mean) pressure which, if imposed on the pistons uniformly from the top to the bottom of each power stroke, would produce the measured (brake) power output. It is usually expressed in bars.

4.1.5. Mechanical Efficiency

Mechanical efficiency is the measure of effectiveness of a machine's energy and power that is input into the device into an output that makes force and movement. Mechanical advantage by comparing the input and output force you can find the advantage of a machine.

4.1.6. Exhaust Gas Temperature

The exhaust gas temperature indicates the effective use of the heat energy of a fuel.

4.2. Review of Engine Performance Results of Various Investigations

In this section, the results obtained from significant experimental researches have been compared and analyzed with different waste cooking oil samples used in various blending proportions.

M. Canakci, J. H. Van Gerpen *et al.* (2003) investigated the effect of the biodiesel produced from high free fatty acid feedstock on engine performance. Biodiesel was prepared from soybean oil. The neat fuels and their 20% blends with diesel fuel were studied at steady-state engine operating conditions in a four-cylinder turbocharged diesel engine. A John Deere 4276T, four-cylinder, four-stroke, turbo-

charged diesel engine was used for the testing. The engine was connected to a 112 kW General Electric (Schenectady, N.Y.) model TLC2544 direct current dynamometer. The combustion system of the diesel engine was a bowl-in-piston, direct-injection, medium-swirl type. The engine was equipped with a rotary-type fuel pump. In order to understand the effect of the biodiesel on engine efficiency, the brake specific fuel consumption (BSFC) and thermal efficiency of the engine were measured at full load (258 N-m) and at an engine speed of 1400 rpm. The engine load and speed were kept constant for all of the test fuels [44]. From **Table 7** it can be concluded that The BSFCs for the soya esters were higher than for diesel fuel. The increases in the BSFCs were 13.5% SME the higher BSFCs for the neat esters may be attributed to their lower heating values. The heating values of the methyl esters are about 12%.

Rajinder Kumar Moom *et al.* in his research on “Evaluation of DI Diesel Engine Performance on Biodiesel from Waste Cooking Oil at Different Load Conditions” collected waste cooking oil, obtained from KC College of Engineering and IT, Nawanshahr, Punjab messes. Through which waste cooking oil biodiesels were prepared and its performance has also been carried out on a direct injection (DI) compressed ignition (CI) diesel engine fuelled with blends of Diesel-biodiesel, biodiesel-ethanol and diesel-ethanol ethyl acetate over the entire range of load on the engine. A Kirloskar make, single cylinder four strokes DI diesel engine (water cooled) is selected for the work with a rated Output 4.8/6.5 KW/bhp @ 1500 rpm.

It is experimentally observed that fuel blends of D50/E27/E23, B70/E40 and higher substitution of diesel (or biodiesel) with ethanol and ethyl acetate produced knocking and unstable engine operations due to lower cetane number and lower calorific values. But all Diesel-Biodiesel blends ran engine smoothly. From the above pilot test some fuel blend is selected to investigate the performance of engine for different load conditions. Brake thermal efficiency (BTE) is increased with the increase of load and dropped abruptly for higher loads for pure diesel and for all of its blends. BSFC decreased as the load increased for all type of fuel blends, which may be due to increase in cylinder wall temperature by increasing load reduces the ignition delay. It is found that value of BSEC of pure diesel (D100) is almost lower and closer to all blends of fuels except B100 blend. At higher load the difference in BSEC is less prominent this may be due to deterioration in the combustion quality of ethanol at higher loads. It is found that value of BMEP of pure diesel (D100) is closer to D80/E13/EA7.

In an another investigation by Ahmet Necati Ozsezen *et al.* (2008) [45]

Table 7. Comparison of soybean oil waste cooking oil and standard diesel fuel [44].

| Fuel Type | BSFC (g/kW-hr) | % Change in BSFC | Thermal Efficiency (%) | % Change in Thermal Efficiency |
|-----------------------------|----------------|------------------|------------------------|--------------------------------|
| Petro diesel | 228.42 | - | 36.96 | - |
| Soyabean methyl ester (SME) | 259.33 | 13.53 | 37.13 | 0.45 |

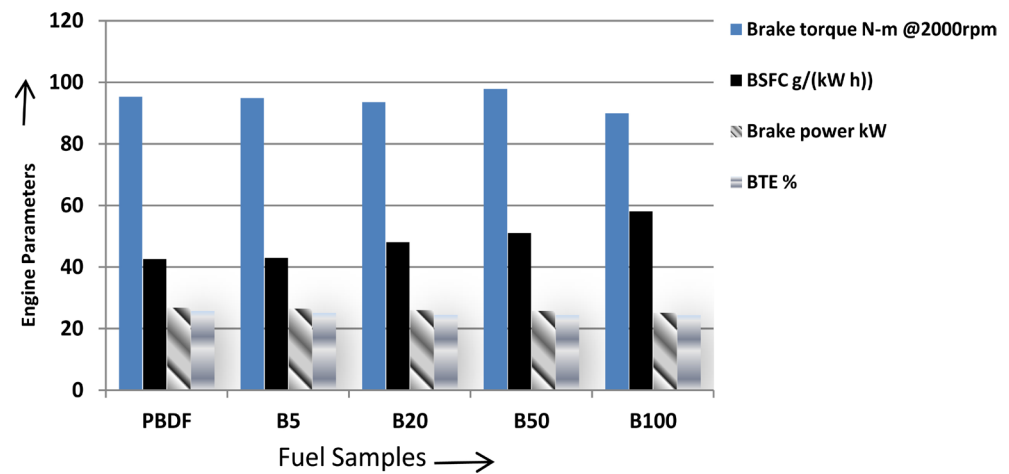


Figure 2. Performance characteristics as investigated by *et al.* Ahmet Necati Ozsezen [45].

prepared biodiesel from used frying palm oil and its blends with diesel fuel were used in a four cylinder, naturally aspirated indirect injection (IDI) diesel engine. Using petroleum-based diesel fuel (PBDF), biodiesel, and its blends, the engine performance, were investigated over a range of engine speeds at full load. When the engine was fueled with the biodiesel and its blends, the brake torque was slightly dropped compared with PBDF. The consolidated performance at full load and at an engine speed of 2000 rpm is depicted in the **Figure 2**.

The findings from the investigations were;

When the engine was fueled with the biodiesel and its blends, the brake torque was slightly dropped compared with PBDF. BSFC slightly increased with the increase of biodiesel percentage in the fuel blend. The brake power and brake thermal efficiencies were decreased with increasing biodiesel concentration in the fuel blend when compared with PBDF.

Wail M. Adaileh *et al.* (2012) [46] did an investigation to evaluate the “Performance of Diesel Engine Fuelled by a Biodiesel Extracted From A Waste Coking Oil The waste vegetable oil (coking oil) used in this investigation transferred from Tafila Technical University restaurant collected and disposed in a suitable way. Waste Sunflower oil was selected to produce the biodiesel and alkaline catalyzed transesterification is done to convert the WCO into its methyl esters. The performance of biodiesel and its blends (B5, and B20) were studied in comparison with diesel fuel. The biodiesel is mixed with the standard diesel in an external tank, in proportion of 5% biodiesel with 95% standard diesel, 20% biodiesel with 80% standard diesel. The compression ignition engine used for the study was a single cylinder, four strokes, direct injection, air-cooled engine the engine performance and exhaust emissions were studied at different engine loads and constant engine speed. The results were as followed;

The variation of engine power with respect to engine speed at full load is presented in **Figure 3**. The power initially increases with increasing of engine speed until it reaches a maximum value and then decreases with further increasing engine speed. At the same time, engine power has the same trend according to ad-

dition of biodiesel content in the blend. The power initially increases with the addition of biodiesel content in the blend, reaches a maximum value and then decreases with more increase of the biodiesel content. The researcher quoted that the biodiesel includes approximately 10% (in weight) oxygen that can be used in combustion, especially in the fuel rich zone. This is a possible reason for more complete combustion, thereby increasing the torque and power and also diesel fuel is pumped to the diesel engine cylinder on volumetric basis and the density of the biodiesel blend is higher than that of diesel fuel. Therefore, a larger mass flow rate for the fuel volume is pumped to the engine, resulting in the increase in torque and power. Meanwhile, the more viscous blend means the less internal leakage in the fuel pump is seen. Again, this results in an increase in the torque and power. The power increases with the addition of biodiesel content in the blend until the B20 blend and reaches a maximum value, when the biodiesel content continues to increase in the blend, the power was decreased below that of the diesel fuel.

The experimental results show that the fuel consumption rate, brake thermal efficiency and bsfc decreased with an increase of engine brake power. Moreover, the engine power and Brake specific energy consumption increased when increasing the biodiesel percentage for B20 blend it is evident from **Figures 3-5**.

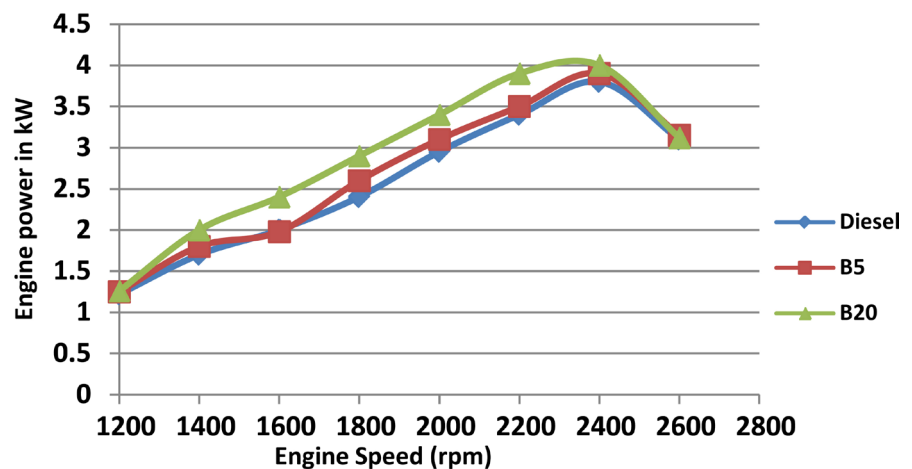


Figure 3. Variation of engine Power V/s Speed [46].

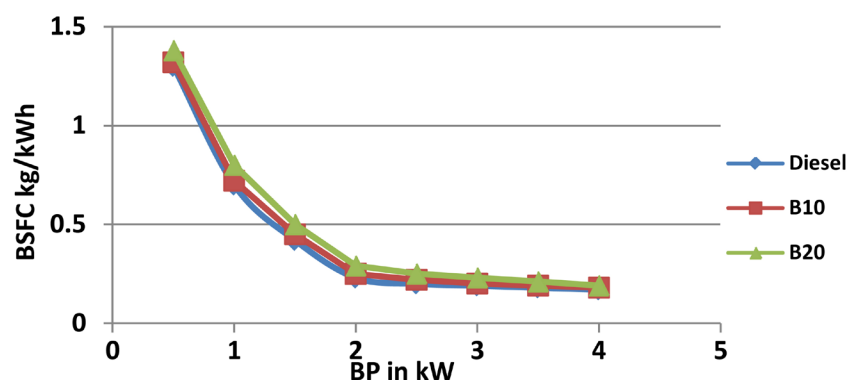


Figure 4. Variation of BSFC V/s BP [46].

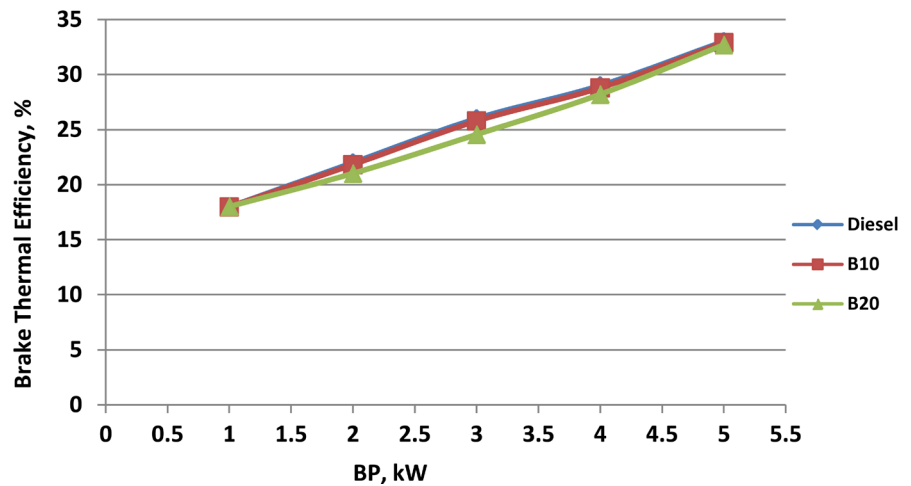


Figure 5. BTE V/s Brake Power [46].

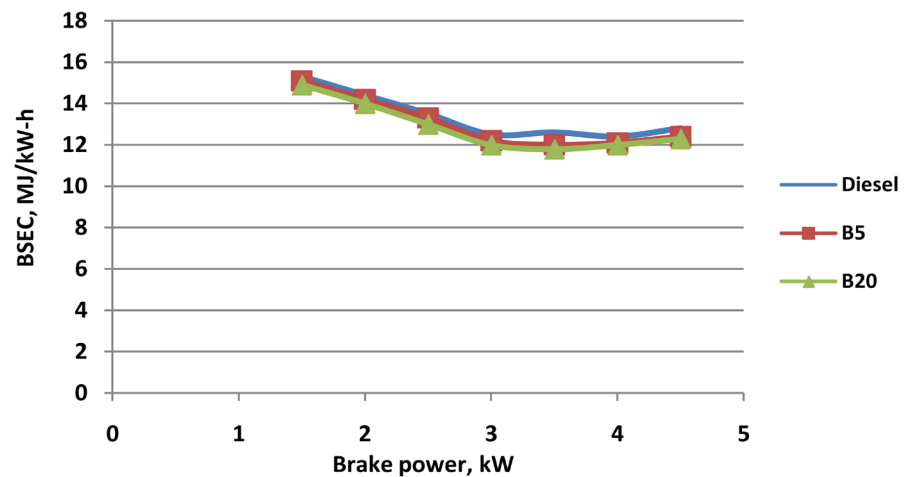


Figure 6. Variation of BSEC V/s Brake Power [46].

As shown in **Figure 6**. Addition of biodiesel content in the blend makes BSEC initially to decrease until it reaches a maximum value at B20 blend and then increases with more increase of the biodiesel content in blend. In using of blends B5 and B20, the BSEC of the engine is lower than that of diesel for all loads for the reason that, biodiesel includes oxygen which improves combustion of fuel.

In another work titled “Performance of Diesel Engines Burning Used Cooking Oil (UCO) Biodiesel” by M. S. Gad *et al.* Says that Used Cooking Oil (UCO) is an environmental friendly renewable resource of energy and can be produced from used cooking oil (UCO) by transesterification process & properties of biodiesel have comparable performance and emission characteristics to diesel fuel.

The present study was carried out to investigate the performance and emission characteristics of biodiesel derived from waste cooking oil blends with diesel fuel in diesel engine and compared to diesel fuel. UCO for the particular investigation was obtained from Tagadod Company & found out that Viscosity of used cooking oil is about ten times, greater and its density is about 10% higher

than that of diesel fuel. The test engine used was Kirloskar make, single cylinder, four stroke, water cooled, direct injection, AV1 model diesel engine with a rated power of 6.5 HP @ 1500 rpm and the engine performance was evaluated.

From the study the following results were drawn;

Variation of specific fuel consumption with brake power for diesel and diesel-biodiesel blends was shown in **Figure 4**. Specific fuel consumption for biodiesel blends was higher than diesel fuel because of lower heating value of biodiesel. Thermal efficiency for biodiesel blends was lower than diesel fuel this may be due to poor atomization, higher viscosity and reduction in heat loss of biodiesel blends compared to diesel fuel. Decrease of thermal efficiencies of biodiesel blends compared to diesel fuel in all loads was due to higher fuel consumption and lower heating value of biodiesel. So, from the above trend it is understood that the Diesel-biodiesel blends showed an increase in fuel consumption and specific fuel consumption in comparison with diesel fuel. Biodiesel blends showed a decrease in engine thermal efficiency about diesel fuel.

Siva prasad Kondapalli *et al.* (2015) says Biodiesel is an alternative fuel that can be used directly in diesel engine as pure or blended with diesel fuel. In this analysis, the effects of biodiesel produced from waste cooking oil (WCO) [47] Waste cooking oil bio-diesel and methanol in a molar proportion of 1:6 were reacted to produce biodiesel. Then 1% weight of KOH of the waste cooking oil was added as a catalyst in the transesterification reaction. Potassium methoxide and water was first mixed and KOH was added as a catalyst with methanol. The mixture of potassium Methoxide and water was then poured into a reacting tank to mix with the waste cooking oil and stirred by a homogenizer to obtain a transesterification reaction. The blends were prepared was Bio-diesel, B75, B50, B25 and their properties like density, viscosity, flash point and Cetane numbers were found out. Experimental setup consists of diesel engine the test rig of kirloskar make, single cylinder, DI CI type with a max power of 5 hp @ 1500 rpm, water cooling system with a rope brake dynamometer attached to the power shaft for loading the engine the test runs were done with varying of pressure (*i.e.* 180 to 200 bar, to 225 bar, to 250 bar).

The consolidated results of the experiment were;

The Mechanical efficiencies and brake thermal efficiencies were higher at an injection pressure 225 bar for all compositions of fuel for fuel blend (D25B75, D50B50, D75B525). The trends of the above said parameters are evident from the **Figures 7-9** respectively.

Finally, the researcher has opined that the optimum results on a 4-stroke diesel engine are achieved at an injection pressure of 225 bar and using B25 biodiesel. Although, the increase of the WCO percentage in the fuel blend reduces the engine torque and power, the results show some torque and power recovery for this reduction.

The lower heating value of WCO results in increased BSFC but the engine brake thermal efficiency is not affected significantly.

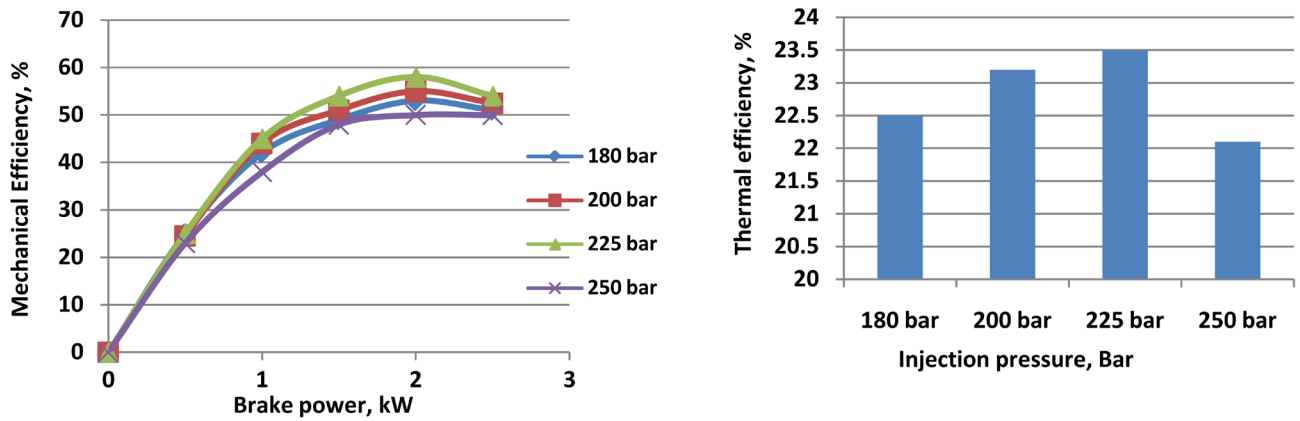


Figure 7. Variations in mechanical efficiency, brake thermal efficiencies at various injections pressure for fuel blend D25B75 [47].

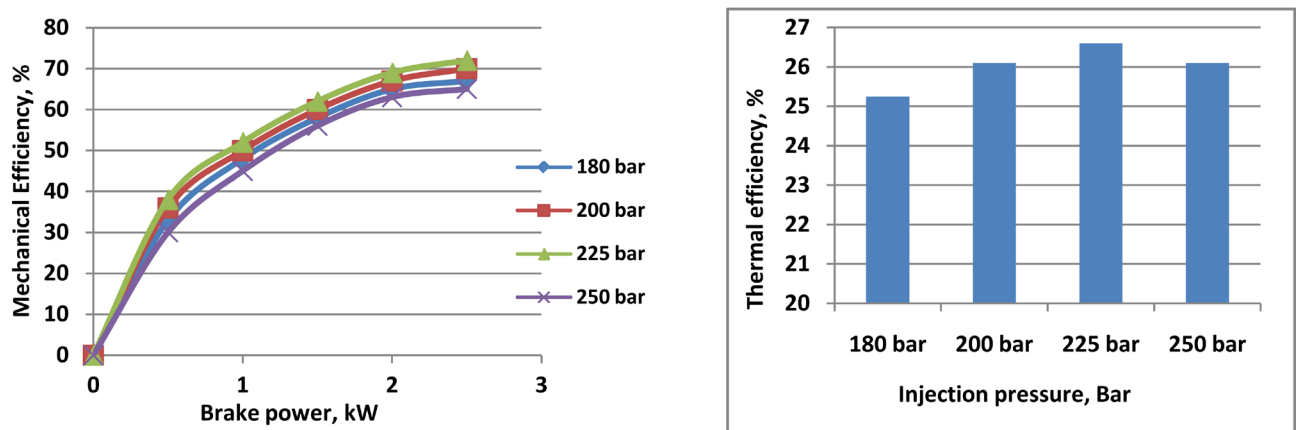


Figure 8. Variations in mechanical efficiency, brake thermal efficiencies at various injections pressure for fuel blend D50B50 [47].

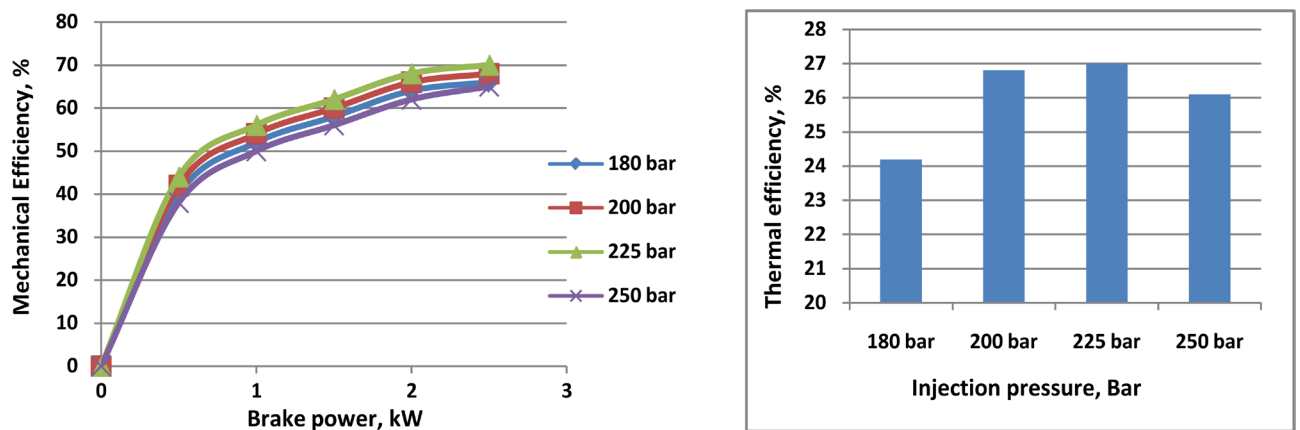


Figure 9. Variations in mechanical efficiency, brake thermal efficiencies at various injections pressure for fuel blend D75B25 [47].

S Bari and his co-workers (2004) [48] Conducted experimental investigation to investigate the effect of injection timing on a DI CI engine fuelled with waste cooking oil. He articulates that the injection timing is a major parameter that sensitively affects the engine performance, emission and durability. The physical and chemical properties of vegetable oils are known to be different from that of diesel so this has a serious effect on injection and combustion parameters. The

researcher made a study to examine the changes in the behavior of waste cooking oil (WCO) with the changes in injection timing of a direct injection (DI) diesel engine, compared with those of diesel. The aspects taken were effects of injection timing on combustion and emission.

The experiments were done on YANMAR L60AE-DTM single-cylinder, four stroke, direct injection, blow-in-piston type engine. Engine compression ratio of 20, fuel injection timing $14^\circ \pm 1^\circ$ BTDC, fuel injection pressure of 19.6 Mpa with an air cooling electrical dynamometer was used to provide loading to the engine.

An AVL quartz pressure transducer was placed in the engine head to measure the in cylinder pressure. Two magnetic pick up sensors placed on the output shaft, to measure the engine speed and picking up the TDC position. Both pressures transducers were connected to an electronic indication system to condition the signals. A Pico ADC100 analogue to digital convertor was used to convert the analogue voltages into digital signals for computer data acquisition and further processing. The test was carried out at the rated speed of 3600 Rpm and repeated for each of the changes to the injection timing setting at 16° , 16.3° , 19° BTDC. Selection of ignition timing is also considered as an important factor. The designer has to select the injection timing such that if injection starts earlier, the initial air temperatures and pressures are lower, so ignition delays increase. On the other hand, if injection starts later (closer to TDC), the temperatures and pressures are initially slightly higher. However, both physical and chemical reactions must take place before a significant fraction of chemical energy in the fuel is released, these reaction need a finite time to occur. However as ignition delay proceeds, the in-cylinder pressures and temperatures decreases and reduce the favorable conditions for ignition. The most favorable timing for ignition lies in between these two conditions.

The results were as follows;

Effects of injection timing on combustion was observed and the trend was that, as injection started earlier, peak pressures became higher, which applied to both the fuels. Also, the peak pressures occur earlier with advancing injection timings. Regardless of the injection timing used, WCO always reached higher peak pressures at an average of 2.5° crank angles earlier than diesel (**Figure 10**).

Effects of injection timing on engine performance is also estimated found out that for WCO, the BSFC is always higher than that for diesel advancing the injection timing, the minimum BSFC for WCO and much minimum BSFC for diesel. The trend was also similar for brake thermal efficiency as shown in **Figure 11**.

Waste cooking oil behaved similarly to diesel in terms of combustion & performance in accordance with fuel injection timings. With earlier injection timing, the combustion started earlier and reached higher peak pressures at earlier crank angles for both the fuels. This resulted in better performance, reaching higher brake thermal efficiency. For the test engine, the optimum injection timing for shortest ignition delay was at an earlier angle for WCO than for diesel. The closer the injection timing for shortest ignition delay, the closer the

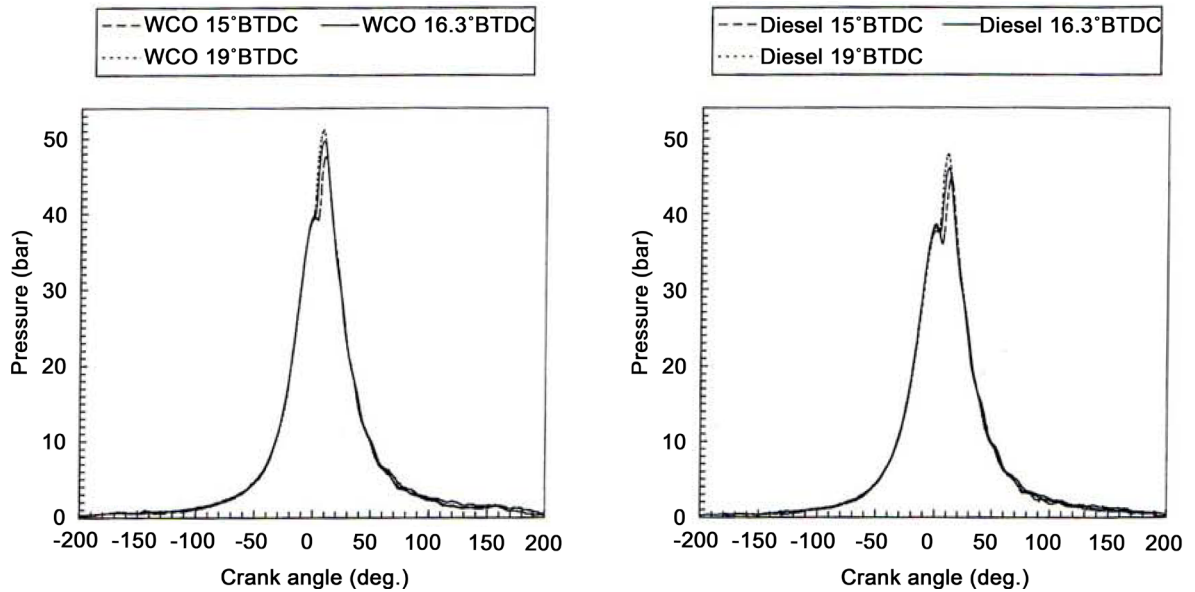


Figure 10. Comparison of in cylinder pressure for different injection timings at 85% of full load.

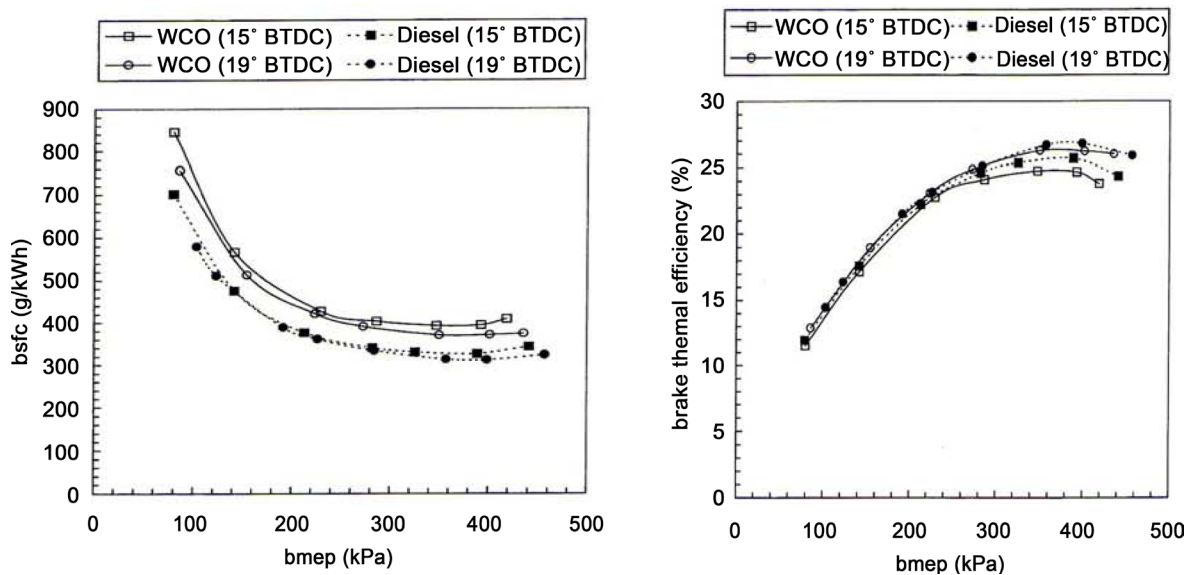


Figure 11. Comparison of BSFC & BTE at different injection timings at full load.

injection timing to the optimum timing, the shorter is the ignition delay, as the pre mixed combustion intensity is reduced. WCO is more sensitive to the engine load and injection timing changes than diesel. The reduction in ignition delay with increasing load and advancing timing is more significant for waste cooking oil. As greater chemical reactions may take place at higher temperatures.

4.3.1. Diesel Engine Tail Pipe Emissions

With continuous utility of diesel engines in vehicle operations and power generators, emissions have increased at a higher rate. Pollution of atmospheric air is required to be reduced. Diesel engines emit lower carbon monoxide (CO) and hydrocarbon (HC) emissions but emit higher NO_x and particulate matter [49].

The necessity is to use cleaner fuels to protect environment from harmful gases. Alongside increasingly strict regulations in emission standards, there is still considerable concern that unregulated pollutants have deleterious effect on human health and the environment and the emissions of engine should be checked to ensure the emissions standards. Increasing numbers of transportation vehicles is causing an increase in global emissions, with NO_x being the main pollutant from diesel exhaust. Inside the engine, generation of CO_2 and H_2O indicates complete combustion of fuels consisting of hydrocarbons. Incomplete combustion of hydrocarbons may lead to wide range of harmful components. **Table 8** provides emission standards for heavy duty diesel engines. Strict emissions norms were inculcated in Bharat stage IV [50] is being used since April 2010 in 13 major cities of India. The maximum level of various exhaust emissions is trimmed down in Bharat Stage-IV which helped in bringing down pollution levels and invariably resulted in inflated vehicle cost due to usage of new technology & higher fuel prices. However, this increase in cost is compensated by savings in health related costs, because of lesser diseases due to particulate matter and pollution in the air.

4.3.2. Review of Waste Frying Oil Exhausts Analysis from Various Investigations

Full Length Research Paper on “Emission Characteristics of Diesel Engine Using Waste Cooking Oil as Biodiesel Fuel” by Ridvan Arslan *et al.* (2011) studied the use of waste cooking oil (WCO) methyl ester as an alternative fuel in a four-stroke turbo diesel engine with four cylinders, direct injection and 85 HP was analyzed. A test was applied in which an engine was fueled with diesel and three different blends of diesel/biodiesel B25, B50 and B75 blends made from WCO. The test engine was run at 18 different speeds with a full load, and the results were analyzed. An AVL Smoke 415 sampling smoke meter was used to measure the smoke, the tail pipe emissions viz. CO, CO_2 , O_2 , HC, NO_x was measured using HORIBA MEXA-7100D and particulate emission using PARTICULATE HORIBA MDLT-1300.

The smoke emissions of WCO methyl ester were lower than those for diesel fuel at all the engine speeds. All the fuels produced a large amount of smoke at low engine speeds, and the smoke concentration dropped sharply after 1300 rpm. The smoke emissions reduced in all WCO blends under all the operating conditions. Smoke emissions progress to low values at and above 1600 rpm. CO emissions were also decreased with increasing engine speeds for all the fuels. The CO emissions of biodiesel blends and diesel fuel showed similar trends at all the operation conditions. Total hydro carbons (THC) emissions were lower when WCO methyl ester was added to the diesel fuel. The results demonstrated that

Table 8. Bharat Stage-IV Emission norms for Heavy Diesel vehicles.

| Co (g/kmhr) | HC (g/kmhr) | NO_x (g/kmhr) | PM (g/kwhr) |
|-------------|-------------|------------------------|-------------|
| 1.5 | 0.96 | 3.5 | 0.02 |

THC emissions decreased when the diesel engine was run with B25, B50 and B75 at all operation conditions. NO_x emissions varied considerably with the test fuels at all the engine speeds. All the fuel blends produced higher NO_x emissions relative to diesel fuel and B75 has produced highest NO_x emission at an engine speed of 1800 rpm. Finally the author concludes that WCO methyl esters have similar properties with diesel fuel, and they support the statement that exhaust emissions from biodiesel fuels are lower than those of fossil diesel fuels, which may indicate that biodiesel has better effects on air quality [51].

Zafer Utlu & Mevlut Su reyya Kocak (2008) investigated the “Effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions” in this research the authors demonstrated the usage of methyl ester obtained from Waste Frying Oil (WFO) is examined as an experimental material. The methyl ester was tested in a four cylinder, DI turbo-charged diesel engine & the results were compared with fossil diesel fuel. Primary aim of the investigation is to compare the measures of emission such as CO, CO₂, NO_x, and smoke darkness of waste frying oils with the fossil diesel fuel at several steady state operating conditions.

Smoke density was measured at an engine speed of 4000 rpm, Maximum smoke density was observed between 3500 - 4000 rpm, where the Maximum power was also obtained. The Amount of smoke density has decreased and numerically it was 22.46% lesser compared to diesel fuel. Maximum CO was produced as 876 ppm for diesel fuel and 665 ppm for WFOME at 1750 rpm. Average shrinking of CO was determined as 17.13% less than diesel fuel, CO₂ was also lesser by 8.05%. The Occurring of maximum NO_x was noticed as 482 ppm for diesel fuel and 465 ppm for WFOME at 3000 rpm again the NO_x values were found to be decreased. The results of the experiments have given an optimistic result in favor of WFO and its potential usage as CI engine fuel. WFO stands itself apart in exhaust emission characteristics, which in turn results in lower tail pipe emissions as compared with fossil diesel [52].

Osmano Souza Valente *et al.* (2012) and his co-investigators studied the exhaust emissions from a diesel power generator operating with waste cooking oil biodiesel blends on A 50 kW diesel power generator was used to carry out the experiments with the biodiesel blends. Aim of the work was to investigate the exhaust emissions of HC, CO, NO_x and CO₂ and the exhaust gas opacity from a diesel power generator fuelled by WCO biodiesel blends, operated with varying load. The diesel engine used was a MWM D229/4 model, with less than 200 h of operation, naturally aspirated, four-stroke, four in-line cylinders and mechanically controlled direct injection fuel system. Using 50% of biodiesel in diesel oil, the average increase of CO₂, CO, HC and NO_x throughout the load range investigated. It is observed that exhaust CO₂ concentration is reduced with increasing load power for all fuels tested. From the experimentation it is obvious that that operation of a power generator at loads much lower than the rated value is not recommended if one aims at reduced carbon dioxide emission. The concentra-

tion of CO₂ also increases with higher biodiesel concentration in the fuel blend, showing higher differences in comparison with diesel oil at high loads. Increasing biodiesel concentration in the fuel blend causes increased CO emission. The main reason for CO formation in diesel engines is reduced fuel atomization, as the biodiesel density is higher than that of diesel oil; the fuel mass amount injected is larger when the engine is operated with biodiesel which causes difficulty in fuel atomization. THC emissions are decreased with higher load power and increased with higher biodiesel concentration, as mentioned before, the larger mass amount injected due to the higher NO_x concentration with increasing load power and biodiesel concentration in the fuel blend. The presence of oxygen in the biodiesel molecular structure is probably responsible for the slight increment of NO_x production when the biodiesel fuel blends are used instead of diesel oil (**Table 9**).

From the investigation, increased exhaust concentrations of CO and HC and smoke opacity observed when WCO biodiesel blends were used in place of diesel oil with diesel oil. Although the author confess that the biodiesel properties play a major role, engine model, operating conditions and fuel injection system settings also affect smoke opacity and the formation of CO and HC [53].

An “Experimental investigation on regulated and unregulated emissions of a diesel engine fueled with ultra-low sulfur diesel fuel blended with biodiesel from waste cooking oil” by Yage Di *et al.* (2009) conducted experiments on a 4-cylinder direct-injection diesel engine using ultra-low sulfur diesel, bio diesel and their blends, to investigate the regulated and unregulated emissions of the engine under five engine loads at an engine speed of 1800 rev/min. Blended Fuels containing 19.6%, 39.4%, 59.4% and 79.6% by volume of waste cooking oil biodiesel,

Table 9. Percentage differences between CO₂, CO, HC and NO_x emissions from the biodiesel blends and from diesel oil [53].

| Load | Co ₂ Difference% | | | Co Difference% | | | HC Difference% | | | NO _x Difference% | | |
|---------|-----------------------------|------|------|----------------|------|-------|----------------|------|-----|-----------------------------|------|------|
| | B25 | B50 | B75 | B25 | B50 | B75 | B25 | B50 | B75 | B25 | B50 | B75 |
| 2.5 | 7.8 | 7.8 | 12.2 | - | - | - | 5.3 | 21.3 | - | 13.6 | 9.4 | 15.1 |
| 5.0 | 6.3 | 8.1 | 13.6 | - | 34.1 | 42.9 | -2.2 | 18.1 | - | 16.1 | 11.3 | 7.9 |
| 7.5 | - | - | - | - | 19.5 | 23.2 | 2.4 | 9.5 | - | 8.1 | 7.5 | 8.7 |
| 10.0 | 6.5 | 10.1 | 15.3 | - | 13.5 | 20.4 | -1.5 | 21.3 | - | 10.9 | 5.5 | 9.3 |
| 12.5 | 6.3 | 9.2 | 13.2 | - | 4.9 | 17.9 | -3.0 | 15.4 | - | 8.6 | 7.0 | 8.2 |
| 15.0 | 4.3 | 6.7 | 12.4 | 15.5 | -2.4 | 22.1 | -3.6 | 19.7 | - | 10.2 | 4.7 | 9.3 |
| 17.5 | 3.7 | 6.6 | 12.7 | 22.1 | 1.4 | 31.3 | -3.4 | 28.3 | - | 1.1 | 1.0 | 5.0 |
| 20.0 | 3.8 | 8.2 | 12.5 | 17.0 | 15.0 | 55.6 | 3.1 | 31.2 | - | 2.5 | -1.4 | 4.5 |
| 22.5 | 4.4 | 9.0 | 14.6 | 15.7 | 33.0 | 95.7 | 3.9 | 32.1 | - | 1.8 | -3.8 | -1.6 |
| 25.0 | 4.1 | 10.5 | - | 25.7 | 61.4 | 105.9 | 4.6 | 39.3 | - | -2.2 | 4.8 | -1.0 |
| Average | 5.3 | 8.5 | 13.3 | 19.2 | 20.1 | 46.1 | 0.6 | 23.5 | - | 7.1 | 4.8 | 6.5 |

corresponding to 2%, 4%, 6% and 8% by mass of oxygen in the blended fuel, was used. On the regulated emissions, in general, HC and CO emissions are higher at low engine loads and lower at high engine loads while NO_x , smoke and particulate mass concentration increase with engine loads. After the addition of biodiesel in the blended fuel, HC and CO emissions decrease due to improved combustion with oxygen enrichment of the fuel. However, NO_x/NO emissions increase due to the higher combustion temperature and the increased oxygen level in the combustible mixtures, while, as an adverse effect, there is an increase of NO_2 emission. The smoke opacity and particulate mass concentration decrease with increase of biodiesel in the blended fuel, especially at higher engine loads, due mainly to the increase of oxygen content and the decrease of carbon content in the fuel. However, there is an increase in total number concentration and a decrease in of the submicron particles. The HC and CO emissions decrease while NO_x and NO_2 emissions increase. The smoke opacity and particulate mass concentrations reduce significantly at high engine load. The results indicate that the combination of ultra-low sulfur diesel and biodiesel from waste cooking oil gives similar results to those in the literature using higher sulfur diesel fuels and biodiesel from other sources [54].

K. Nantha Gopal *et al.* (2013), in his research article “Investigation of emissions and combustion characteristics of a CI engine fueled with waste cooking oil methyl ester and diesel blends” the author in-depth research and comparative study of blends of biodiesel made from WCO and diesel is carried out to bring out the benefits of its extensive usage in CI engines. In the study, a constant speed, single cylinder, 4-stroke, air cooled DI diesel engine designed for agricultural purpose was used to test the fuels. The engine is coupled to an air cooled eddy current dynamometer. Using a load cell the engine torque was measured. Load on smoke were analyzed for all blends of biodiesel along with fuels with petroleum diesel at different engine loads. Different blends of biodiesel (WCME20, WCME40, WCME80 and WCME100) are prepared for conducting experiments on CI engine to investigate its performance and emission characteristics. Exhaust gas temperature was measured using K-type thermocouple. The exhaust gas emissions such as CO, HC, and NO_x and fuel-air equivalence ratio were measured using an AVL digas 444 exhaust gas analyzer. The smoke opacity was measured by AVL 437C smoke meter. The experiments are carried out with fixed injection timing of 23 bTDC at an injection pressure of 200 bar. Engine was run at 1500 rpm and load was varied from no load to maximum load in 5 steps.

Emission characteristics from the investigation;

The unburned hydro carbons emissions decrease with increasing WCME percentage in the blend. It is also observed that UBHC emission increases as the load of the engine was increasing with diesel and blends of WCME as the result of increase in fuel consumption at high engine loads. CO is one of the intermediate compounds formed during the intermediate combustion stage of

hydro-carbon fuels. The formation of CO formation depends on air fuel equivalence ratio, fuel type, combustion chamber design, starting of injection timing, injection pressure and speed. Experimental results reveal that CO concentration of biodiesel and its blends is lesser for WCME20, WCME40, WCME80 and WCME100, respectively, when compared to diesel fuel. NO_x formation of all biodiesel and blends is slightly higher than that of diesel fuel. The formation of NO_x in the cylinder is affected by oxygen content, combustion flame temperature and reaction time. It is also observed that as load increases, the NO_x formation increases and attains maximum value at maximum load. This is due to higher temperature of combustion and the presence of oxygen with biodiesel cause higher NO_x emission [55].

5. Conclusions

The following conclusions can be drawn:

- 1) The primary raw material for biodiesel preparation used is waste cooking oil, which can be collected from different sources such as hostels, restaurants, canteen and cafeterias which will reduce the Environmental problems of disposing used cooking oil.
- 2) The alkali catalytic process is more effective when the FFA level is less than 1%, since the FFA level is more in WCO, acid catalyzed process is preferred.
- 3) Physiochemical properties of WCO biodiesel were found acceptable in accordance with ASTM D6751 standards.
- 4) The performance graphs obtained from the various experiments show a good result in terms of Brake power, BSFC, BTE. It can be also observed that in some investigations results were quite random due to the variation in Physiochemical properties of WCO biodiesel. The results were optimistic with the usage of soybean oil as WCO sample unlike of palm oil based WCO.
- 5) The NO_x emission from the engine has been projected as a major problem in all investigations. So a special attention may be appreciated towards the reduction of NO_x and rest of the exhaust gases were found satisfactory as per emission norms.

Finally, it can be concluded that WCO biodiesel could replace the diesel in order to help in controlling air pollution, encouraging the collection and recycling of waste cooking oil to produce biodiesel and reduce the dependency on fossil fuel resources to some extent with a little sacrifice in the engine performance.

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Abbreviations

| | |
|-------------------|---------------------------------|
| aTDC | After top dead center |
| BP | Brake power in kW |
| bTDC | Before top dead center |
| BTE | Brake Thermal Efficiency |
| CI | Compression ignition |
| CR | Compression Ratio |
| CO | Carbon monoxide |
| CO ₂ | Carbon dioxide |
| CR | Compression ratio |
| DI | Direct injection |
| FFA | Free fatty acid |
| HC | Hydrocarbon emissions |
| IC | Internal combustion |
| ID | Ignition delay |
| K | Kelvin |
| KME | Karanja oil methyl esters |
| kW | Kilo Watt |
| kg | Kilogram |
| kJ | Kilo Joule |
| N | Engine Speed |
| NO _x | Nitrogen oxide |
| O ₂ | Oxygen |
| POME | Palm oil methyl esters |
| p _{max} | Peak pressure in bar |
| ppm | Parts Per Million |
| Q | Heat release rate |
| Rpm | Revolutions per minute |
| SFOME | Sunflower oil methyl esters |
| TFC | Total Fuel Consumption |
| TDC | Top dead center |
| WCOME | Waste Cooking Oil Methyl Ester |
| H _{b,th} | Brake thermal efficiency |
| Θ | Crank angle |
| WCO | Waste cooking oil |
| BSFC | Brake specific fuel consumption |
| WCME | Waste Cotton oil Methyl Ester |
| UBHC | Un-Burnt Hydrocarbons |
| Co | Carbon monoxide |
| HC | Hydrocarbon |
| WFOME | Waste frying oil methyl ester |
| HP | Horse Power |
| PBDF | Petroleum based diesel fuel |