Effect of Biodiesel on the Performance and Emission Characteristics of Diesel Engines

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Abstract

Biodiesel has become one of the main sources of renewable energy. Their positive impact on the environment has earned a lot of attention in past few decades. Biodiesel has several effects on emission and performance attributes of a CI engine. This paper deals with those effects of biodiesels derived from various sources like Jatropha, Mahua, Karanja, soybean, palm, waste cooking oil (WCO) and many other edible and non-edible oils. It has been noticed that excessive use of biodiesel will lead to food shortage and therefore blending of biodiesel with conventional diesel has been suggested by various researchers. In blending, biodiesel and petro-diesel is mixed in a proper ratio to give a mixture of diesel-biodiesel. It has been stated that, blending up to 20% has no effect on properties and is same as that of diesel and provides better results. The emissions like CO, UHC and PM, reduced and was significantly lesser than that of diesel but NOx emission was found to have much higher value when compared with diesel. When BSFC and BTE of diesel and biodiesel were compared, it was found that, BTE reduced but BSFC increased with blending. By considering all these factors and from this review, it can be said that biodiesel and its blend with diesel can be used in CI engine without any major tempering when blending is done up to a certain limit.

Keywords: Jatropha biodiesel, Thermal efficiency, Brake specific fuel consumption, NOx emissions, HC emissions.

I. INTRODUCTION

Energy is required in almost every field of research & development. It plays a vital role in development of a nation. Fossil fuels are becoming the main origin of energy. But because of the excessive use of fossil fuels and growing pollutant level in environment, search for alternative fuels have become a necessity [1-3]. Fuel consumption is estimated to increase from 8.61 million barrels per day to approximately 110.6 million barrels per day in 2035 [4]. We have limited reservoirs or stocks of petroleum and now we need a replacement for fossil fuels which can work in more efficient way than them. Some other problems like increased of fossil oil have also increased the requirement to have some better alternatives.

Biodiesel has become one of the best alternatives of fossil fuels. Biodiesel was firstly used by Rudolf Diesel. In 1900, He used peanut oil to run his diesel engine [5]. He used neat biodiesel but biodiesel can be mixed with diesel in a definite proportion. This mixing of biodiesel with diesel is called blending. If blending of biodiesel is done properly, its properties become similar to that of diesel fuel. It has been found that if the blending ratio of diesel to biodiesel is 80:20, it does not cause any harm to the engine and can perform very well [5-6]. Blending is also done to decrease the high viscosity of biodiesel. Viscosity of biodiesel is very high [4, 14, 16, 19, 22, 23, 25, 26, 33, 35, 43, 53, 54, 79-86, 87, 88]. So, diesel engine cannot be directly used with used biodiesel. This problem can be overcome by the process of blending.

Transesterification, of vegetable oils animal fats, is used to produce biodiesel. Figure 1 shows the transesterification reaction. In transesterification, the oil is converted chemically into its corresponding fatty ester [7]. E Duffy and J. Patrick conducted this test in 1853 and since then, lots of studies have been done on biodiesel till now using different oils like soybean oil [9,10], cotton seed [11-14], waste cooking oil[40], rapeseed oil [14,16], Sunflower oil [14,17], Tyre pyrolysis oil [TPO] [18], Jatropha [7,10,19-27] and many others. A study tells that there are around 300 different kinds of oil seeds, amongst which “Oleander”, “Bitter Groundnut” and Kusune are the only vegetable oils which are considered to be a potential alternatives fuel for CI Engines [27].

Figure 1. Transesterification Reaction

Biodiesel obtained from waste cooking oil (WCO) is much more economic source than any other source [15]. So many
researchers have observed that WCO biodiesel decreases harmful exhaust emissions than diesel [28,29]. Kulkarni et al. [30] stated that WCO gives much better engine performance than that of diesel fuel and produces less emissions than diesel except NOX.

It is widely agreed that biodiesel is much more useful than diesel. It is inexhaustible and can be produced again and again, non-toxic and is less harmful to environment and biodegradable which prevents soil pollution [10]. It produces NOX but is completely free of SOX. It produces less amount of hydrocarbons (HC), CO, PM and CO2 [5, 16, 17, 19-25, 31-42], Wang et al [32] concluded that with increase in blending, NOX emissions also increases. Same Conclusion was given by Leila et al [13]. On the other hand, a study tells that other emissions like total Hydrocarbon, Smoke Opacity and PM decreases with blending [43]. Another study [19] observed that NOX emission increase in Jatropha biodiesel when blending is done but other emission decreases. A research found that when compared with diesel, HC, CO emission increase when brake power is increased in biodiesels [20]. Some researchers also concluded that NOX emissions decreases along with CO and UHC when blending is increased [22]. The high emission of NOX could be due to the high temperature inside the cylinder when the combustion of biodiesel is done [44].

Brake specific fuel consumption (BSFC) got mixed results from various authors. Some studies reported that it increases [27] with blending while other reported that it decreases [45] with blending. In Brazil, around 80% of all the biodiesel produced is obtained from soybean [46] whereas in Argentina, soybean gives 100% of it. In US, around Soybean contribution is 74% and in European nations it is around 16% [47, 48].

II. PROPERTIES OF BIODIESEL AND ITS BLEND

Performance and emission characteristics depend on fuel properties like viscosity, density, calorific value, cetane number etc. Table 1 lists the fuel properties of various biodiesels with their blends.

II.1 Viscosity

For better performance of engine, the viscosity of biodiesel should be low, because if viscosity is high than that would lead to poor spray and atomization of the fuel [49-51]. It is also the cause of higher fuel consumption [52]. Ghosh et al. [31] observed that viscosity of biodiesel varies from 3.5 to 5.5(cSt). Similar results were obtained by Ocatvio and Gomez [17] for sunflower oil. They got results by testing various blends of sunflower oil. For B30, B70 and B100 kinematic viscosity was 2.8502, 3.8502 and 4.3991 cSt respectively. Monirul et al. [23] found that the viscosity of Palm oil B10, B20, B100 was 3.3624, 3.4589, 4.3847 cSt, respectively. He also added that the viscosity of Jatropha oil B10, B20 and B100 was 3.7638, 8.8972 and 4.7128 cSt, respectively. Further information on the viscosity of biodiesel and various blends are given in the table 1.

II.2 Density

Density is the distribution of mass on a given volume. Greater density means greater viscosity which causes poor atomization and combustions which affects the performance and emission properties of engine. Table 1 gives the detailed data on the density of different biodiesels. Monirul et al. [23] noticed that the densities of Palm and Jatropha oil varies from 832 – 857.6 and 835.8 – 840.5 respectively for different blends (B10, B20, B100). Nabi et al. [54] reported that, at low load densities of B20, B40 and B60 are 845, 852 and 858 respectively. They found that blend up to 20% with diesel gives density very much similar to that of pure diesel (840). Hence 20% blending of biodiesel with diesel is found to be much better. Similar outcomes have been stated by Masjuki et al. [136] who said that 20% blending doesn’t require and kind of modification in the engine.

II.III Cetane Number

Cetane number is directly associated with the ignition delay. This has been agreed by several researchers that cetane number of conventional diesel is less than that of biodiesel [19, 35, 43]. Hence, when concentration of biodiesel in the blend is increased, CN also increases [56, 57]. Further data on CN of biodiesel is given in the table 1.

II.IV Calorific Value

Performance and emission of engine is very much influenced by calorific value of the fuel used. Benjamin M. Wood [14] stated that diesel has a calorific value of 42.70 MJ/Kg. Whereas Soybean, Rapeseed and Sunflower oil has a value of 38.38, 38.33, 38.54 MJ/Kg respectively. This is lower than that of diesel. Same kind of results were achieved by Thapa et al. [19] who stated that diesel - biodiesel blends have slightly less value of calorific value than that of petro-diesel. The experiment was done by taking Karanja, Polanga, Mahua, Rubber seed oil, Cotton seed, Tobacco oil, Neem, Linseed oil, Palm oil, and Jatropha as biodiesel. The different calorific values have been mentioned in the table 1.

III. EFFECT OF BIODIESEL ON PERFORMANCE OF AN ENGINE

Performance parameters are one of the most important factors that indicate whether the engine and fuel is good enough to use. These parameters are Brake Specific Fuel Consumption (BSFC), Brake Specific Energy Consumption (BSEC), Brake Thermal Efficiency (BTE) and Brake Power etc. Brief discussion on some of these parameters is given below and comparison between different biodiesels and diesel-biodiesel blends has been shown in table 2.

III.I Effects of biodiesel on Brake Specific Fuel Consumption of an engine

According to most of the researchers [55, 63, 64, 112, 123-132], BSFC of biodiesel increases when biodiesel blend is increased in biodiesel – diesel blends.

A study at Southwest Research Institute (USA) experimented with pure soybean and stated that around 13%- 19% fuel consumption increases with respect to diesel fuel [112]. It was reported that when pure biodiesel is used, BSFC increases from 0.4209 (Kg/KWh) to 0.60 (Kg/KWh) at low load and at high load it increases from 0.3229 (Kg/KWh) for diesel to 0.73 (Kg/KWh). RizwanaulFattah et al. [55] Stated that catalyst increases the value of BSFC for same amount of
blending. They used KOH, 2, b-di-tert-butyl-4-methylphenol (BHA) and 2(3)-tert-butyl-4-methoxy phenol (BHT) as a catalyst in PME B20 (Palm oil) to study the effects. It was observed that when using biodiesel only, the BSFC has a value of 267.4 g/KWh. While this value for B20 + BHA and B20 + BHT are 278.2 g/KWh and 279.5 g/KWh respectively at the engine speed of 2500 rpm. Same kind of observation was reported by Singh and Singla [113] who used 4 stroke, single cylinder, direct injection diesel engine with rated power 3.67 KW and injection timing 24.5° BTDC. Karanja was used as a biodiesel. BSFC was observed to have slightly higher value than that of pure biodiesel. Gosh et. Al. [31] observed that biodiesel of jatropha, karanja and putranjiva shows higher value of BSFC than that of diesel fuel. But Jatopha showed much better results for BSFC than any other fuel. This could be because the calorific value of jatropha (38.5-42 MJ/Kg) is higher than that if other two biodiesels (for karanja-37 MJ/Kg) and viscosity is lower [19]. For putranjiva, karanja and jatropha the values of BSFC are 268 g/KWh, 311 g/ KWh and 382 g/KWh respectively for B10. Thapa et.al. [19] observed that when engine speed is changed, change in the value of BSFC also observed. They experimented with different engine speed. They observed that when engine speed is increased, the value of BSFC is decreased but when blending is increased BSFC also increased.

Most of the researchers agree with the fact that when engine speed and load increase then BSFC decreases. Paval et al. [21] observed that for jatopha oil, at low load, the value of BSFC is 0.60 Kg/ KWh and at high load it decreases to 0.4529 Kg/KWh. Same kind of results were obtained by Praveen et.al. [59] who stated that BSFC decreases with increase in load. But when blending is increasing BSFC also increases. Chiatti et.al. [33] observed that when blending is increased, BSFC also increased. For B20 (Jatropha) BSFC increased by 3.9% while with B40 (Jatropha) it increased by 7.1% compared to that of pure petro-diesel.

This is due to that fact that calorific value of biodiesel is less than that of pure diesel, which has been mentioned in the earlier sections, and hence justifies the above statements [21].

In conclusion, most of the authors agreed that biodiesel has higher value of BSFC than that of diesel and it increases when blending in increased in diesel-biodiesel blends.

Further data on BSFC of different biodiesel has been stated in the table 2.

III.II Effect of biodiesel on Brake Thermal Efficiency (BTE)

Efficiency is the ratio of the output of a system to its input. BTE, in case of IC engines, can be stated as the ratio of brake power output to heat input. Most of the researchers [20, 21, 33, 35, 37, 60, 71, 72, 118-122] agreed with the fact that as the concentration of biodiesel in the blend increases, BTE decreases. But some of them also observed that BTE increases with increase of biodiesel in the blend [22, 23, 37, 41, 45]. Chiatti et al. [33] did experiments for performance of engine with ULSD (ultralow sulphur Diesel) as biodiesel. It was observed that, at full load, BTE decreases by 1% when blending is increased from B20 to B40 (diesel is taken as reference). Agarwal et al. [134] investigated for performance of engine for different percentage of biodiesel (B20, B50 and B75). The experiment was done on a 4 stroke- single cylinder engine. It was found that when biodiesel blending is increased, BTE got decreased. Paval et al. [21] Observed similar kind of results where they observed that, for jatropha, BTE decreased with increase in blending. For B0 and B100, BTE was found to be 29.6% and 21.1% respectively. Prevene et al. [59] found that BTE, for a diesel engine and CalophyllumInophyllum biodiesel blends with TiO2 nanoadditives and EGR, is decreased by 1.8%. Agrawal et,al.[67] observed that, for Karanja(B50) in a single cylinder agricultural diesel engine, BTE was found to be 30%.

These results could be due to the properties of biodiesel such as higher viscosity [4,17], low cetane number [33], lower heating value [21] etc.

But some researchers observed that with the increase in diesel-biodiesel blending, BTE increases. Nalgunwad et.al[36] did experiments on a CI engine using two biodiesel blends, jatropha(JB) and palm(PP). For D90JB5PPB5, D80PB10JB10 and D70JB15PB15, BTE was found to be increased by 3.2%, 2.1% and 27.83% respectively. Similar outcomes were obtained by Jayashri et al.[37] who analysed performance and emission of Neem biodiesel on a CI engine. They observed that BTE of Neem biodiesel increased by 34% when compared to diesel. Thangaraj et al.[41] found that at no load and at full load, BTE increases by 2.61% and 21.67% respectively for Karanja oil methyl ester biodiesel blend enriched with HHO gas when compared to diesel. Krishna et al. [45] stated that, at a speed of 1800 rpm, BTE of EGR coupled semi adiabatic diesel engine fuelled with blended rubber seed biodiesel is increased by 7% when diesel is taken as reference. Mosarak et al. [69] did experiments with palm biodiesel at 1500 rpm speed. BTE of B25 was found to be 30.895%.

This could be due the fact that biodiesel contains more oxygen than that of pure diesel which ultimately results in good combustion of the fuel and hence BTE increases [36, 37, 41].

Further data on Brake Thermal Efficiency is given in the table 2.

IV. EFFECTS OF BIODIESEL ON EMISSION OF AN ENGINE

Emissions in a CI engine are unburnt hydrocarbon (UHC), carbon monoxide(CO), NOx, carbon dioxide(CO2), and particulate matter (PM) etc. Diesel-biodiesel blend has been resulted in low emissions of PM, CO, UHC and CO2, however, NOx increases with blending [4,13,17,58.] compared with diesel. In this section, a review is given on emission characteristics of an engine when operated with neat biodiesel or diesel-biodiesel blend and the results have been compared in the table 3.

IV.1 Effect of biodiesel on NOx emission

Most researchers agree with the fact that NOx emission increases with increase in diesel-biodiesel blend and has a value higher than that of neat diesel [4,13,17,19-21,23,25,33,34,36,41,49,58,59,60,61]. Octavia et al. [17]
performed experiment on a baseline engine operated with different injection system and EGR with sunflower oil (B30, B70) as biodiesel. It was recorded that NO\textsubscript{x} emissions increased when blending is increased. Leila et al. [13] reported that, for soybean oil, NO\textsubscript{x} emissions was 5% higher than diesel. Similar conclusions were obtained by Kathimelu et al. [20], he stated that NO\textsubscript{x} emission increased when blending was increased. The experiment was done by taking jatropha and fish oil as biodiesels. It had a value of 7.3 – 11.2 g/KWh. Monirul el al. [23] stated that NO\textsubscript{x} emission escalated by 22.13% compared to diesel when operated with jatropha oil at 800 rpm engine speed. Pi-qiang et al. [25] experimentated on a light-duty petro-diesel engine with jatropha biodiesel fuel. He found that for B5, B10, B20, B30 and B100, NO\textsubscript{x} increased by 1.2%, 2.06%, 4.74%, 5.71% and 13.9%.

Thangaraj et al. [41] found that, for a diesel engine operated with karanja oil methyl ester biodiesel blends, NO\textsubscript{x} emission increased by 5.4% for B10 and 13.70% for B20 at full load when diesel is taken as a reference. Shahir et al. [68] experimented on a common rail, direct injection engine using animal fat biodiesel blends. They observed that NO\textsubscript{x} emission increased upto 56 ppm to 313 ppm when blending is increased. Jayaprabakar et al. [7] experimented on a CI engine with rice bran and algae biodiesel and its blends. They operated their engine on different loading conditions. At a load of 25%, 50%, 75% and 100%, it was found that NO\textsubscript{x} had a value of 80ppm, 195ppm, 250ppm and 430ppm respectively.

This could be due to the difference in the flame temperature and ignition delay caused by higher oxygen content [33].

But some studies also reported that, NO\textsubscript{x} emission decreases when blending is increased. Ahmed et al. [22] reported that when additives like graphene nanoplatelet are added in biodiesel NO\textsubscript{x} emission decreases. For jatropha oil, it got decreased by 15%. Similar result was obtained by Jayashri et al. [37] who reported that, for neem biodiesel, NO\textsubscript{x} emission got decreased by 21.875%, 8.375% and 18.875% for B10 B20 and B30 respectively. Krishna et al. [45] experimented on an EGR coupled semi adiabatic diesel engine fuelled by DEE blended rubber seed biodiesel. They observed that NO\textsubscript{x} emission decreased by 19.5% when operated at an engine speed of 1800 rpm. Pryor et al. [62] stated that, for a small diesel engine operated with soybean oil, NO\textsubscript{x} emission decreased by 5%.

The decrease in NO\textsubscript{x}emission could be due to the low calorific value of blends and less exhaust temperature of gases [31].

Further details on NO\textsubscript{x} emission is given in the table 3.

**IV.II Effect of biodiesel on Unburnt Hydrocarbon (UHC) emission**

The use of biodiesel and its blends with diesel reduces the HC emission and this has been agreed by most of the researchers [7, 19, 22, 23, 25, 31, 33, 37-39, 63-65]. Octavia et al. [17] reported that, for a baseline engine and sunflower biodiesel having EGR, HC emission decreases and it was found to be less than 50 ppm. HC emission decreased by 25% when biodiesel is used. Similar conclusion was obtained by Cercerle et al. [4] who stated that HC emission decreases when blending is done. Bueno et al. [34] experiment on a single cylinder diesel engine with Caster oil biodiesel. It was found that HC emission decreased by 18% and 21% for B10 and B20 respectively.

The reason stated for this was the high content of oxygen in biodiesel and better combustion of it compared to diesel. When the percentage of biodiesel is increased in diesel-biodiesel blend, it shortens ignition delay and hence decreases the UHC [64].

It has been reported in various studies that change in engine speed also affects HC emission. Jayashri et al [37] observed that HC emission got decreased when engine speed was increased. At 1500 rpm and 2000 rpm, HC emission was reduced by 22% and 26% respectively. Neem biodiesel was used on a compression ignition engine. Similarly, Monirul el al. found that, for palm oil, HC emission was reduced by 14.29% when operated at engine speed of 800 rpm. However, HC emission decreases steadily when engine speed is increased above 1500 rpm.

This could be due to the increased inlet air flow speed, which ultimately intensifies atomization of the fuel and hence makes the blend more homogenous and as a result decreases HC emission [64].

Change in load on engine also affects emissions. Pi-qiang [25] experimentated on a light duty diesel engine with jatropha biodiesel fuel. It was observed that HC emission increases when load is increased. For load of 0.10 MPa, 0.26 MPa, 0.57 MPa and 0.77 MPa, HC emission was found to be reduced by 26.5%, 27.6%, 30.9% and 46.7% respectively. Similar results were obtained by Suja et al. [41] who observed that, for a diesel engine with karanja biodiesel oil, HC emission was reduced by 12.25% and 24.54 % at no load and full load respectively for B10. For B20, it got decreased by 16.47% and 30.71% at no load and full load respectively.

The reason of this effect, given by various authors [25,41], are that, at lower loads, the amount of fuel injection is low, cylinder temperature is low, large amount of air and poor fuel distribution HC emission is high and is low when the engine load is high.

It has been observed that additives to biodiesel also changes HC emission. Jayaprabakar et al. [7] experimented on a CI engine and observed that, when load increases, HC emission decreases. It was found that, for algae biodiesel, HC emissions were reduced by 33%, 35%, 35.2% and 45% at 25%, 50%, 75% and 100% load respectively. Reddy et al. [66] observed that, for CI engine and jatropha biodiesel oil, HC emission got decreased by 33.3% at full loading condition. For example, Tewari et al. [133] found that when carbon nanotubes are added to biodiesel blends, HC emission got decreased by 50% compared to diesel. This may be due to the higher oxygen content of biodiesel than that of diesel which results in better fuel combustion and hence emission becomes low.

Further data on HC emissions are given in table 3.

**IV.III Effect of biodiesel on CO emissions:** Many researchers concluded that CO emission decreases when biodiesel or diesel-biodiesel blend is used in place of diesel [17, 19, 31, 33, 37, 39, 43, 50, 58, 59, 68, 69, 100, 103, 112,
Zhang et al. [12] experimented for emission characteristics of pure diesel and diesel–biodiesel blends. It was found that CO emissions were low when biodiesel is used instead of diesel and it decreases further more when blending of diesel with biodiesel is increased. For Puranjiva (B90), Karanja (B90) and Jatropha (B90), CO emissions were 0.31%, 0.014% and 0.011% respectively. Maryam et al. [16], on their researcher, found that CO emissions were lower than that of diesel. The tests were executed on a single cylinder, 4 stroke engine with animal fat biodiesel. Rounce et al. [43] compared diesel and biodiesel emissions with DMC (Dimethyl Carbonate) as biodiesel. They experimented at an engine speed 1500 rpm. It was found that CO emission reduced when biodiesel is used. Similar observation has been obtained by Kathimelu et al. [20], who found that, for a single cylinder and 4 stroke city car engine, CO emission reduces when diesel is replaced by biodiesel. Gumus et al. [129] experimented on a single-cylinder, four-stroke, direct-injection diesel engine with diesel-biodiesel blend with different percentages of biodiesel. The experiment was done at a constant engine speed of 2200 rpm under various loading conditions. They observed that CO emission got reduced significantly when diesel-biodiesel blend is used instead of diesel.

Lower CO emission when using biodiesel could be due to the high combustion rate of the biodiesel and this has been stated by many researchers [17, 43, 58].

Some of the researchers also found that CO emission increases when biodiesel is used. For example, Seesy et al. [22] observed that, CO emission increased when biodiesel is used. They used FOME (Fish oil methyl esters) and JOME (Jatropha oil methyl ester) biodiesel on a CI engine. It was found that, CO emission increases when brake power is increased. They also concluded that JOME had more CO emission than FOME.

The authors stated that poor combustion of the biodiesel fuel could be the reason of high CO emission.

Fuel additives to the biodiesel also affect CO emissions. Ahmed et al. [27] studied the effects of grapheneno-plateate addition to jatropha biodiesel on performance and emission characteristics of a diesel engine. It was observed that for B20, CO emission reduced by 60%. Similar observations were observed by two other studies [131, 132] that found that CO emissions were reduced by 40% and 51% when zinc oxide and cerium oxide is used as additives to biodiesel respectively.

CO emission also depends on loading conditions and it has been observed by many authors. Qiang et al. [32] observed that CO emissions were different at different loads. They experimented on a light-duty diesel engine with jatropha biodiesel fuel. At low load of (0.10-0.26) MPa, CO emission reduced by 17.6% to 23.8% and at high load of (0.57-0.77) MPa, it was 15% to 23.1%. Most of the researchers agree on a fact that, CO emission decreases when load is increased and it increases when engine speed is increased.

Most of the researchers [100, 103, 130] found that properties of biodiesel like high cetane number, high oxygen content etc. are the reasons for low CO emission from biodiesel fuel. From the above observations, it can be concluded that, when load increases, CO emission decreases and when engine speed increases, emission also increases. Similarly, CO emission decreases when biodiesel percentage is increased in diesel-biodiesel blend.

Further details on CO emissions are given in the table 3.

### IV. Effect of biodiesel on PM and Smoke opacity

A number of researches have been done on PM emissions and smoke opacity from diesel engine using biodiesel or diesel-biodiesel blended fuels. Many authors found that, use of diesel-biodiesel blend reduces PM emissions and Smoke opacity when compared with diesel [4, 7, 10, 17, 19, 23, 27, 31, 32, 33, 37, 345, 358, 63, 64, 71, 73, 122]. For example, Octavia et al. [17] experimented on a baseline, common-rail injection system with split injection engine with exhaust gas recirculation. For smoke opacity, as the biodiesel percentage is increased in diesel-biodiesel mixture, smoke opacity was observed to be reduced. PM emissions were also found to be reduced. Similar observation was observed by Maryam et al. [58], who stated that, for second generation biofuels on a CARB diesel engine, PM emissions got reduced when biodiesel is used instead of diesel. Monirul et al. [23] studies emissions characteristics of palm, jatropha and calophyllinophyllum biodiesel. At full load and a constant speed of 1000 rpm, smoke opacity reduced by 31.09% for B10 (Jatopha) when compared with diesel. Further information, about other biodiesels, has been given in the table.

Effect of biodiesel on PM and Smoke opacity

| Biodiesel | PM Emissions | Smoke Opacity |
|-----------|--------------|---------------|
| Diesel    | 100%         | 100%          |
| B10       | 90%          | 90%           |
| B20       | 80%          | 80%           |
| B30       | 70%          | 70%           |
| B40       | 60%          | 60%           |

A number of researches have been done on PM emissions and smoke opacity from diesel engine using biodiesel or diesel-biodiesel blended fuels. Many authors found that, use of diesel-biodiesel blend reduces PM emissions and Smoke opacity when compared with diesel [4, 7, 10, 17, 19, 23, 27, 31, 32, 33, 37, 345, 358, 63, 64, 71, 73, 122]. For example, Octavia et al. [17] experimented on a baseline, common-rail injection system with split injection engine with exhaust gas recirculation. For smoke opacity, as the biodiesel percentage is increased in diesel-biodiesel mixture, smoke opacity was observed to be reduced. PM emissions were also found to be reduced. Similar observation was observed by Maryam et al. [58], who stated that, for second generation biofuels on a CARB diesel engine, PM emissions got reduced when biodiesel is used instead of diesel. Monirul et al. [23] studies emissions characteristics of palm, jatropha and calophyllinophyllum biodiesel. At full load and a constant speed of 1000 rpm, smoke opacity reduced by 31.09% for B10 (Jatopha) when compared with diesel.

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phenomenon occurs due to the high fuel rate because of high engine load which increases smoke opacity.

Hence, it can be concluded that, smoke opacity decreases when blending is increased.

V. Conclusion

A wide number of results have been found by several studies and researchers on influence of biodiesel on performance and emission of diesel engine. Almost all the results have same trends but some results also contradicted others. There could be several reasons of this trend. One is the presence of large number of different engine technologies, fuel types, additives and environmental conditions. Used under different instrument, different methodology and by different researchers.

However, we can conclude some following results:

- Break specific fuel consumption is observed to be increased by 2% to up to 35% than that of diesel, while operating on different blending.
- Average BTE of the diesel engine was found to be decreased with increase in blending percentage. Although, some biodiesels, like neem, showed a different trend, i.e., BTE was found to be increased rather than decreased.
- Most of the results agree on the fact that, NOx increases with increase in blend percentage. This could be due to the difference in the flame temperature and ignition delay caused by higher oxygen content. Some researchers also came up with a different trend of results. Due to the use of different additives, NOx was found to get decreased by up to 22%.
- Use of biodiesel with diesel reduces the HC emission which has been agreed by almost all the researchers. Change in load, change in engine speed and use of additives played different roles in minimizing the value of hydrocarbons.
- After many researches, it has been found that CO emissions decrease when blending of biodiesel is increased in diesel-biodiesel mixture. Lower CO, as stated by many authors, could be due to the high oxygen content which leads to the higher combustion rate of fuel.
- For smoke opacity and PM, results had mixed trends. For some biodiesels (like Pinus oil) smoke opacity was found to be decreased and for some biodiesels (like waste cooking oil and soybean oil), it was found to be increased.

In conclusion, these results show that, biodiesels can be used in blending the diesel fuel up to a certain limit (say 20%) in order to have better efficiency and better emissions.

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Table 1: Properties of biodiesel as compared to diesel [14,15,19,20,21,24,25,27,28,32,39,43,70,83-93]

| Specification          | Unit   | Diesel | Polanga  | Mahua   | Cotton seed | Jajoba oil | Linseed oil | Putranjiva | Karanja | Jatropha |
|------------------------|--------|--------|----------|---------|-------------|------------|-------------|------------|---------|----------|
| Density(15°C)          | Kg/m³  | 810-860| 888.6-910| 904-916 | 874-911     | 863-866    | 865-950     | 876-891    | 864-880 |          |
| Viscosity(°40C)        | cSt    | 2-5.7  | 4.5-5.34 | 3.98-5.8| 4-4.9       | 19.2-25.4  | 16.2-36.6   | 5.18       | 4.37-9.60| 3.7-5.8  |
| Cetane No.             |        | 40-55  | #REF!    | 51-52   | 41.2-59.5   | 63.5       | 28-35       | 40.2       | 35.6-58 | 41-55    |
| Cloud Point            | °C     | -20-0  | 13.2-14  | 3.5     | 1.7         | 1.6        | 1.7         | 13-15      | 5       |          |
| Pour Point             | °C     | -20-5  | 4.3      | 1-6     | -10 to -15  | -6-6       | -4 to -18   | 2          | -3-5.1  | 3-5.2    |
| Lower Heating Value    | MJ/Kg  | 39-44  |          |         |             |            |             | 30.5       |         |          |
| Calorific Value        | MJ/Kg  |        |          |         | 39.2-41.3   | 39.5-40.1  | 42.7-47.3   | 33.7-39.8  | 39.2    | 36.0-38.1| 38.5-42.0|
| Specific Gravity       |        | 0.834  |          |         | 0.883       | 0.899      | 0.878       |            |         |          |
| Flash Point            | °C     | 50-98  | 151-170  | 127-129 | 210-243     | 61-75      | 108         | 152        | 163-190 | 162-183.6|
| Fire Point             | °C     | 85     |          |         | 155         | 192        | 175         |            |         |          |
| Percent C(wt%)         |        | 64.8-87|          |         |             |            |             |            |         | 76.6     |
| Percent H(wt%)         |        | 12.6-13.6|       |         |             |            |             |            |         | 12.1     |
| Percent O(wt%)         |        | 4-21.6 |          |         |             |            |             |            |         | 11.3     |
| Molecular weight       |        | 190    |          |         |             |            |             |            |         | 282      |
### Table 2: Effect of biodiesel on Performance of the engine

| S.No | Engine type and test condition | Biodiesel | Blend percentage | Brake Thermal Efficiency (BTE) | Brake Specific Fuel Consumption (BSFC) | Reference |
|------|--------------------------------|-----------|-----------------|------------------------------|----------------------------------------|-----------|
| 1    | 6-cylinder, 7.81 engine        | Rapeseed  | B20             | ↑ 2.95% than diesel          | 89                                     |
| 2    | 6-cylinder engine, 170kW rated power, ECE R49 test cycle | Rapeseed | B100            | ↑14% than diesel             | 90                                     |
| 3    | 6-cylinder, 9.61 engine        | Sunflower | B5              | No significant change        | 91                                     |
|      |                                |           | B30             | No significant change        |                                        |
| 4    | Heavy-duty engine, 11.11254kW  | methyl esters | B100            | No significant change        | 92                                     |
| 5    | Single-cylinder, 11.77 kW at different load | waste oil | B100            | No significant change        | 93                                     |
| 6    | Single-cylinder, 5.5 kW        | Indian rubber seed oil | B50 10% | -                           | 94                                     |
|      |                                |           | B100 20%        | -                           |                                        |
| 7    | 4-stroke, DI diesel engine, 1500rpm, 4.4 kW rated power | Tyre pyrolysis oil (TPO) | B20 28.5% at full load | Slightly change | 95 |
|      |                                |           | B90             | Slightly change             |                                        |
| 8    | 4-stroke, Compression ignition engine, full load: 4.4 kW | Waste cooking oil | B100 26% less than diesel | 0.351 kg/kWh | 96 |
| 9    | 2-cylinder diesel engine 1500rpm | Jatropha oil | B0 14.6% at low load (2 kW) | 0.531 kg/kWh at low load | 135 |
|      |                                |           | B100 10.3% at low load (2 kW) | 0.73 kg/kWh at low load |                                        |
|      |                                |           | B0 29.69% at high load | 0.73 kg/kWh at high load |                                        |
|      |                                |           | B100 27.45% at high load | 0.49 kg/kWh at high load |                                        |
| 10   | 4-stroke, water cooled, 42 kW rated power, 4000 rpm rated speed, 2500 rpm current speed | Palm oil | B20 32.10% | 0.267 kg/kWh | 97 |
|      |                                |           | B100 31.70% | 0.307 kg/kWh |                                        |
|   | Description                                                                 | Oil Type       | B50       | Note                          |   |
|---|----------------------------------------------------------------------------|----------------|-----------|-------------------------------|---|
| 11| 4-stroke direct injection water cooled diesel engine, 3.67 kW rated power, 1500 rpm | Jatropha       | B50       | 28.40% slightly higher        | 65|
|   |                                                                           | Putranjiva     | B10       | 31.70% 0.268 kg/kWh           |   |
|   |                                                                           |                | B30       | 27.50% 0.314 kg/kWh           |   |
|   |                                                                           |                | B50       | 26.50% 0.332 kg/kWh           |   |
|   |                                                                           |                | B70       | 25.90% 0.345 kg/kWh           |   |
|   |                                                                           |                | B70       | 27.80% 0.328 kg/kWh           |   |
| 12| Single cylinder 4-stroke engine, 1000-3000 rpm rated speed                | Jatropha       | B10       | 30.20% 0.282 kg/kWh           | 98|
|   |                                                                           |                | B30       | 30.30% 0.286 kg/kWh           |   |
|   |                                                                           |                | B50       | 29.90% 0.295 kg/kWh           |   |
|   |                                                                           |                | B70       | 29.68% 0.302 kg/kWh           |   |
| 13| Baseline engine with exhaust gas recirculation (EGR)                       | Sunflower      | B30, B70  | Less than diesel fuel More than diesel fuel | 17|
| 14| City-car diesel engine at full load                                        | Biodiesel      | B20       | ↓ 1% compared to diesel ↑ 3.9% compared to diesel | 33|
|   |                                                                           |                | B40       | ↓ 1% compared to diesel ↑ 7.1% compared to diesel |   |
| 15| Single-cylinder, 4 stroke diesel engine                                    | Jatropha       | variable blends (B5,10,30,30,100) | Lower with the increase in fuel Greater than diesel fuel and increased with the increase in fuel blends at 20% blend, it was lower than diesel fuel at 1500 rpm and different loads Greater than diesel fuel at 2200 rpm Greater than diesel fuel at 3800 rpm Greater than diesel fuel at 3600 rpm | 21|
|   |                                                                           |                |           |                              |   |
| 16| Single cylinder, 4 stroke, air cooled, direct injection, CI engine, rated speed: 1500 rpm, load: 4.4 kW | Jatropha and fish oil | B100       | 24.8-28.4% -                   | 20|
| 17| Diesel powered generator                                                  | Caster oil     | B35       | - ↑ 3.2-7.1%                  | 99|
| 18| 4-stroke diesel engine at low load                                         | Caster oil     | B25       | - 14.4%                      | 100|
| 19| 4-stroke diesel engine, 1500 rpm rated speed, varying load condition      | Jatropha       | B100       | 10.3% which is lower than diesel at 0.13 kg/kWh which is higher than that of diesel fuel at low load (2kW) 21% which is lower than diesel fuel at high load 0.491 kg/kWh which is higher than that of diesel fuel at high load | 21|
|   | Engine Type                                      | Oil                  | Blend | % Increase/Decrease |   |
|---|-------------------------------------------------|----------------------|-------|---------------------|---|
| 20| Diesel engine with graphene nanoplatelets       | Jatropha B20         | ↑ 25% | ↑ 20%               | 22|
| 21| 4-stroke diesel engine, rated speed: 1000-2400 rpm| Palm oil B10, Jatropha oil B20 | -     | Average increase: 10.15% (for all oils) | 23|
| 22| Diesel engine, rated speed: 800, at full load  | Waste palm oil methyl ester B100 | -     | ↑ 7.5%              | 77|
| 23| DI CI diesel engine at constant engine speed and fixed load | Palm, jatropha and diesel oil D90 JB5 PB5 | ↑ 3.2% | ↓ 0.91%             | 36|
|   |                                                 | Palm, jatropha and diesel oil D80 JB10 PB10 | ↑ 2.2% | ↑ 2.36%             |   |
|   |                                                 | Palm, jatropha and diesel oil D70 JB15 PB15 | ↓ 21.83% | ↑ 16.52%             |   |
| 24| Compression ignition engine, rated engine speed: 1500 rpm | Neem oil B10, B20 | Average increase: 34% | - | 37|
| 25| Diesel engine, rated engine speed: 1500 rpm, hydrogen additives | Tea seed oil B10 | -     | ↑ 4.37-6.5%         | 40|
|   |                                                 | Tea seed oil B20 | -     | ↑ 4.9-11.59%        |   |
| 26| 4-stroke Diesel engine with constant engine speed and varying load, additive: HHO gas | Karanja oil methyl ester B10 | ↑ 2.03% at no load | ↓ 0.28% at no load | 36|
|   |                                                 | Karanja oil methyl ester B20 | ↑ 41.40% at full load | ↓ 1.30% at full load |   |
|   |                                                 | Karanja oil methyl ester B20 | ↑ 4.33% at no load | ↓ 4.01% at no load |   |
|   |                                                 | Karanja oil methyl ester B20 | ↑ 26.64% at full load | ↓ 10.16% at full load |   |
| 27| Common rail direct injection engine             | Waste animal fat B30 | -     | 0.23 kg/kWh         | 68|
| 28| Transportati-on engine, rated speed: 1700 rpm   | Karanja varies blends | Decrease-d with increase in blending at low load | Increased- with increase in blending | 101|
| 29| EGR coupled semi-adiabatic diesel engine        | DEE blended Rubber seed B100 | ↑ 7% compared to diesel | ↓ 5.5% compared to diesel | 45|
| 30| DI diesel engine, rated engine speed: 1500 rpm   | Methyl ester B25     | 30.90% | ↑ 2.59% compared to diesel | 100|
|   |                                                 | Methyl ester B50     | 30.56% | ↑ 8.93% compared to diesel |   |
|   |                                                 | Methyl ester B75     | 29.22% | ↑ 9.25% compared to diesel |   |
|   |                                                 | Methyl ester B100    | 29.58% | -                   |   |
| 31| 4-stroke diesel engine with exhaust gas recirculation (EGR) additive: TiO₂ | Calophyllium ophylum oil B100 | ↓ 1.8% | -                   | 59|
| 32| Compression ignition engine, Rated engine speed: 2900 rpm | Oleander B100 | Higher than diesel, 20.20% | Lower diesel, 0.314 kg/kWh | 27|
|   |                                                 | Kusum B100           | Lower than diesel, 19.7% | Higher than diesel, 0.34 kg/kWh |   |
Bitter groundnut B100 Lower than diesel Higher than diesel, 0.331kg/kWh

| S. NO. | Engine type and test conditions                                      | Biodiesel          | Blend percentage | NOₓ | CO | UHC | PM & Smoke Opacity | Reference |
|--------|---------------------------------------------------------------------|--------------------|------------------|-----|----|-----|--------------------|-----------|
| 1      | 6-cylinder, 4 stroke, turbocharged, DI, CI engine. Constant load:   | Soybean            | B10, B20, B30, B40 | ↑15% for B40 | -  | -   | -                  | 104       |
| 2      | Waste cooking oil                                                   |                    |                  |     |    |     |                    |           |
| 3      | 6-cylinder, 4stroke, WC, DI, CI engine, constant engine speed: 1800 rpm. | Waste fry oil      | B100             | ↑ average 1.89% | ↑75 g/kWh |     |                    | 102       |

Table 3: Effect of biodiesel on Emissions of the engine
| Table | Details | B40 | B80 | B100 |
|-------|--------|-----|-----|------|
| 1     | Rated speed: 2000 rpm | ↑ 15% | - | ↓ 18% |
| 2     | 2-cylinder, 4 stroke CI engine, constant engine speed: 1500 rpm, engine load: 7.35 kW | Jatropha | B100 | 470 ppm | - |
| 3     | Single cylinder, 4 stroke, direct injection, water cooled, diesel engine, constant rated speed: 1500 rpm, rated power: 3.67 kW | Jatropha(JB) | JB50 | 935 ppm | 0.42% |
| 4     | Karanja(KB) | KB50 | 952 ppm | 0.15% | 54 ppm | - |
| 5     | Putanjiva | B10 | 118 ppm | 0.04% | 111 ppm | 8.1 Hsu & 17.8 mg/m³ |
| 6     | | B30 | 108 ppm | 0.03% | 102 ppm | 7.3 Hsu & 17.1 mg/m³ |
| 7     | | B50 | 91 ppm | 0.03% | 89 ppm | 6.7 Hsu & 14.4 mg/m³ |
| 8     | | B70 | 83 ppm | 0.03% | 78 ppm | 5.9 Hsu & 12.5 mg/m³ |
| 9     | Karanja | B10 | 99 ppm | 0.02% | 116 ppm | 6.4 Hsu & 18.9 mg/m³ |
| 10    | | B30 | 86 ppm | 0.02% | 104 ppm | 4.9 Hsu & 18.3 mg/m³ |
| 11    | | B50 | 78 ppm | 0.02% | 95 ppm | 4.2 Hsu & 17.6 mg/m³ |
| 12    | | B70 | 72 ppm | 0.02% | 84 ppm | 4.0 Hsu & 17.1 mg/m³ |
| 13    | Jatropha | B10 | 76 ppm | 0.01% | 105 ppm | 4.4 Hsu & 15.4 mg/m³ |
| 14    | | B30 | 71 ppm | 0.02% | 93 ppm | 4.1 Hsu & 14.8 mg/m³ |
| 15    | | B50 | 59 ppm | 0.02% | 87 ppm | 3.8 Hsu & 14.0 mg/m³ |
| 16    | | B70 | 56 ppm | 0.01% | 71 ppm | 3.2 Hsu & 12.6 mg/m³ |
| 17    | Biodiesel | B100 | ↑ | ↓ | ↓ | ↓ smoke opacity and PM |
| 18    | Soybean | B20 | ↑ 3.9%-6.9% | - | - | - |

**Table Notes:**
- ↑ increase
- ↓ decrease
- smoke opacity and PM
- Hsu = Haze Scattering Unit
- mg/m³ = milligrams per cubic meter
| Engine Type | Fuel Type | Biodiesel Blend | % Improvement | % Decrease | % Decrease | % Decrease | % Decrease |
|-------------|-----------|----------------|---------------|------------|------------|------------|------------|
| City Car Diesel Engine | Biodiesel | B20 & B40 | 17.4% - 47.4% | - | - | - |
| 4 Stroke Diesel Engine, Constant Engine Speed: 1500 rpm | Jatropha | B100 | 25.97% | ↓ 73% | ↓ 67% | ↓ 72.73% PM |
| Single Cylinder, 4 Stroke Diesel Engine | Jatropha | Varies blends | 5.58% - 25.97% | ↓ 50% - 73% | ↓ 45% - 67% | ↓ 50% - 72.73% |
| Compression Ignition Engine Operated at Constant Engine Speed at Fixed Load | Caster Bean Oil | B10 | - | - | ↓ 18% | - |
| 4 Stroke Direct Injected Diesel Engine | Low Sulphur Diesel Oil | B10 | - | - | ↓ 21% | - |
| 4 Stroke Diesel Engine, Rated Engine Speed: 1500 rpm with Varying Loads | Jatropha | B100 | 470 ppm at low | - | - | - |
| Direct Injection, Single Cylinder, Diesel Engine, Constant Engine Speed, Additive: Aluminium Oxide | Pongamia Methyl Ester | B100 | 30% | ↓ 40% | ↓ 55% | 25% Smoke Opacity |
| Single Cylinder Diesel Engine, AVL Di-gas Analyser, Additive: Carbon Nano Tubes | Water-Diesel Emulsion | B100 | 28% | ↓ 50% | ↓ 50% | - |
| Compression Ignition Diesel Engine, Additive: Alumina | Jatropha | B100 | 22% | ↓ 40% | ↓ 45% | - |
| 4 Stroke Diesel Engine, Constant Engine Speed: 800 rpm | Palm Oil Methyl Ester | B100 | 22.13% | ↓ 86.89% | ↓ 14.29% | ↓ 67.65% |
| DI CI Diesel Engine at Constant Engine Speed and Fixed Load | Palm, Jatropha and Diesel Oil | D90 JB5 PB5 | 5.3% | ↓ 7.1% | - | - |
| 25 Compression Ignition Engine, Rated Engine Speed: 1500 rpm | Neem Oil | B10 | 21.875% | ↓ 26% | ↓ 17% | ↑ 12% |
| Table Entry | Engine Type and Specifications | Fuel Blends | Smoke opacity | Load | Smoke opacity | Load |
|-------------|--------------------------------|-------------|---------------|------|---------------|------|
| 26 | Light-duty diesel engine, constant rated speed: 1500rpm | Jatropha | B20 | ↓ 8.375% | ↓ 22% | ↓ 10% | ↑ 21% |
| | | | B30 | ↓ 18.875% | ↓ 5% | ↓ 9% | ↑ 21% |
| | | | B5 | ↑ 1.02% | - | ↓ 26.5% | ↓ 4.54% |
| | | | B10 | ↑ 2.06% | - | ↓ 27.6% | ↓ 14.1% |
| | | | B20 | ↑ 4.74% | - | ↓ 3.9% | ↓ 24.9% |
| | | | B50 | ↑ 5.71% | - | ↓ 46.7% | ↓ 54% |
| | | | B100 | ↑ 13.9% | ↓ 17.6% at low | - | ↓ 80.5% |
| 27 | 4 stroke diesel engine with varying load, additive: HHO gas | Karanja | B10 | ↑ 5.43% | - | ↓ 12.25% - 24.54% from no load to full load | - |
| | | | B20 | ↑ 13.7% | - | ↓ 16.47% - 30.71% from no load to full load | - |
| 28 | Common rail direct injection engine | Waste animal fat | B30 | 56-313 ppm | ↓ 32% | - | - |
| 29 | EGR coupled with semi adiabatic diesel engine, rated engine speed: 1800 rpm | DEE blended Rubber seed oil | B100 | ↓ 19.5% | - | - | ↓ 48.5% |
| 30 | Diesel engine, constant rated engine speed: 1500 rpm | Palm | B100 | ↓ 3.3% | ↓ 8.8% | ↓ 2.2% | - |
| 31 | 4 stroke diesel engine with exhaust gas recirculation (EGR) | Calophyllum Inophyllum oil | B20 | ↑ 63 ppm | ↓ 23% | ↓ 12% | ↓ 16.23% smoke |
| 32 | Compression ignition engine, Rated engine speed: 2900 rpm | Kusum | B100 | 1887 ppm | 0.14% | 60 ppm | ↓ 27.3% smoke |
| | | | Bitter Groundnut | B100 | 1923 ppm | 0.13% | 55 ppm | ↓ 25.9% smoke |
| | | | Oleander | B100 | 1750 ppm | 0.15% | 70 ppm | ↓ 28.8% smoke |
| 33 | 6-cylinder, 4 stroke, turbocharged, DI, CI engine. Constant load: 600Nm, constant speed: 1800 rpm | Waste cooking oil | B20 | ↑ slightly | ↓ slightly | 10ppm at 4.6 kW | - |
| 34 | 6-cylinder, 4stroke, WC, DI, CI engine, constant engine speed: 1800 rpm. | Waste fry oil | B10 | ↓ 1.68% | - | ↑ 33.28% | ↑ 78.84% smoke opacity |