Technical Sustainability of Biodiesel and Its Blends with Diesel in C.I. Engines: A Review

Shashi Kumar Jain, Sunil Kumar, and Alok Chaube

***Abstract*—This paper reviews the technical sustainability of biodiesel and its blends with diesel in C.I. engines. Besides exploring historical background of biodiesel production from vegetable oils, it also provides insight of different methodologies evolved for the conversion of vegetable oil in biodiesel. Properties of Jatropha biodiesel have been compared with the properties of petro-diesel; showing a comparable regime for satisfactory performance of a C.I. engine with biodiesel. Biodiesel reportedly has number of technical advantage over petro-diesel especially on safety and environmental considerations. Cold starting, clogging and storage are some serious technological disadvantages associated with biodiesel. Use of B100 (100% biodiesel) requires some modifications in injection timing and fuel pump. Slight increase in NOx emissions has been also reported. Higher maintenance is also reported with the use of biodiesel.**

Index Terms— Biodiesel; C.I. engine; NOx emissions

I. Introduction

Bio-diesel is an alternative to petroleum-based fuels derived from vegetable oils, animal fats, and used waste cooking oil including triglycerides. Since the petroleum crises in 1970s, the rapidly increasing petroleum prices and uncertainties concerning its availability, growing concern of the environment and the effect of greenhouse gases (GHGs) during the last decades, has revived more and more interests in the use of vegetable oils as a substitute of fossil fuel [1]. Vegetable oils are widely available from various sources, and the glycerides present in the oils can be considered as a viable alternative for diesel fuel [2]. They have good heating power and provide exhaust gas with almost no sulfur and aromatic polycyclic compounds. Vegetable oils are produced from plants, their burning leads to a complete recyclable carbon dioxide (CO2) [3]. CO2 associated with solar energy falling on earth gets converted in to the feedstock through photosynthesis. Vegetable oils available through this feedstock can be used to produce biodiesel. The combustion of this biodiesel results in release of CO2. Vegetable oils can be used as fuel for diesel engines, but their viscosities are much higher than usual diesel fuel and require modifications of the engines [4].

'Oil shock' in 2008 has also revived research interests on the usage of alternative fuels in internal combustion engines. Important research issues related to such fuels are renewable, available locally, and cleaner than fossil fuels.

The term biodiesel commonly refers to fatty acid methyl or ethyl esters made from vegetable oils or animal fats, whose properties are good enough to be used in diesel engines. The regulations limiting such properties are BIS-15607:2005, EN-14214 in Europe and ASTM D-6751-03 in USA.

Biodiesel, derived from the oils and fats of plants like sunflower, rape seeds, Canola or Jatropha Curcas, can be used as a substitute or an additive to diesel. As an alternative fuel biodiesel can provide power similar to conventional diesel fuel and thus can be used in diesel engines. Biodiesel is a renewable liquid fuel that can be produced locally thus helping reduce the country's dependence on imported crude. Production and utilisation of locally developed biodiesel may lead to overall sustainable development in developing nations.

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II. Likely Impact of Localized Renewable Energy Generation Using Biodiesel in Developing Countries [5]

Likely important outcomes of localized energy generation using biodiesel in developing countries are as follows:

1) As fuel in stationary or mobile engines for water pumping (irrigation), grain milling, transportation, lighting and heating and cooking.
2) Poverty reduction, especially that of women, by stimulating economic activities in rural areas by using the products of such plants for the manufacture of soap, medicines, lubricants, chemicals, fertilizers, insecticides.
3) Environment improvement through land reclamation, erosion control, enhanced soil fertility, a better microclimate and GHG mitigation i.e. expanded options for carbon dioxide abatement.
4) A reduced consumption of firewood and residues in rural areas hence a decrease in the deforestation rate.
5) An increase in the gross domestic product (GDP).
6) A reduction of expenditure of imported fuels for rural consumption.
7) The establishment of decentralized energy generation based on the use of plant oil.

III. Bio-Diesel Production From Vegetable Oils: Literature Review

The use of vegetable oils as alternative fuels has been around for one hundred years when the inventor of the diesel engine Rudolph Diesel first tested peanut oil, in his compression-ignition engine [6]. In the 1930s and 1940s vegetable oils were used as diesel fuels from time to time, but usually only in emergency situations [7]. In 1940 first trials with vegetable oil methyl and ethyl esters were carried out in France and, at the same time, scientists in Belgium were using palm oil ethyl ester as a fuel for buses. Not much was done until the late 1970s and early 1980s, when concerns about high petroleum prices motivated extensive experimentation with fats and oils as alternative fuels [8]. Biodiesel (mono alkyl esters) started to be widely produced in the early 1990s and since then production has been increasing steadily. In the European Union (EU), bio-diesel began to be promoted in the 1980s as a means to prevent the decline of rural areas while responding to increasing levels of energy demand. However, it only began to be widely developed in the second half of the 1990s [9]. Bio-diesel production is a very modern and technological area for researchers due to the relevance that it is winning everyday because of the increase in the petroleum price and the environmental advantages [10]. The most common way of producing biodiesel is the transesterification of vegetable oils and animal fats. Transesterification is not a new process. It was conducted as early as 1853 by two scientists E. Duffy and J. Patrick. Since that time several studies have been carried out using different oils such as cotton seed [11], soybean [12,13], waste cooking [14], rapeseed [15–17], sunflower seed [18], winter rape [19], frying [20,21], different alcohols such as methanol [22], ethanol [23], buthanol [24] as well as different catalysts, homogeneous ones such as sodium hydroxide [23,25], potassium hydroxide [23,26], sulfuric acid [27], and supercritical fluids or enzymes such as lipases [28–30].

IV. Derivatives of Vegetable Oils as Diesel Fuels

Considerable efforts have been made to develop vegetable oil derivatives that approximate the properties and performance of the hydrocarbon-based diesel fuel. The problems with substituting triglycerides for diesel fuels are mostly associated with their high viscosities, low volatilities and polyunsaturated character [31]. The viscosity of vegetable oils, when used as diesel fuel, can be reduced in at least four different ways: (1) dilution with hydrocarbons (blending), (2) emulsification, (3) pyrolysis (thermal cracking), and (4) transesterification (alcoholysis). Pyrolysis, cracking, or other methods of decomposition of vegetable oils to yield fuels of varying nature is an approach that accounts for a significant amount of the literature in ‘‘historic” times [32].

V. Dilution

Vegetable oils may be used with dilution modification technique as an alternative diesel fuel [33]. Dilution is an additional possible solution to the viscosity problem of vegetable oils as discussed above [34]. Viscosity of vegetable oil can be lowered by blending with pure ethanol. 25% of sunflower oil and 75% of diesel were blending as diesel fuel. The viscosity was 4.88 cSt at 40°C, while the maximum specified ASTM value is 4.0 cSt at 38°C. This mixture was not suitable for long-term use in a direct injection engine [35,36]. A study was carried out by using the dilution technique on the same frying oil [37]. Results with this technology have been mixed and engine problems similar to those found with neat vegetable oils as fuels were observed here also.

VI. Microemulsion

Various derivatives such as microemulsions or blends of various vegetable oils with conventional fuel have been proposed as alternative fuels for diesel engines [3]. Microemulsions are isotropic, clear, or translucent thermodynamically stable dispersions of oil, water, surfactant, and often a small amphiphilic molecule, called co-surfactant [31,38–40]. The formation of microemulsions (cosolvency) is one of the four potential solutions for solving the problem of vegetable oil viscosity. Microemulsions are defined as transparent, thermodynamically stable colloidal dispersions in which the diameter of the dispersed-phase particles is less than one-fourth the wavelength of visible light. Microemulsion-based fuels are sometimes also termed ‘‘hybrid fuels”, although blends of conventional diesel with vegetable oils have also been called hybrid fuels [34].

VII. Pyrolysis (Thermal Cracking)

The pyrolysis refers to chemical change caused by the application of thermal energy in the presence of an air or nitrogen sparge [38]. The pyrolysis of fats has been investigated for more than 100 years, especially in those areas of the world that lack deposits of petroleum [6]. The pyrolysis of different triglycerides was used for fuel supply in different countries during the First and Second World Wars. These hydrocarbons were used as raw materials for gasoline and diesel like fuel production in a cracking system similar to the petroleum process now used [41].

Thermal decomposition of triglycerides produces the compounds of classes including alkanes, alkenes, alkadienes, aromatics and carboxylic acids. Different types of vegetable oils produce large differences in the composition of the thermally decomposed oil. It is believed that as the reaction progresses the residue becomes less reactive and forms stable chemical structures, and consequently the activation energy increases as the decomposition level of vegetable oil residue increases [42]. Many kinds of vegetable oil species have been subjected to pyrolysis conditions. Some of these vegetable oils are as follows: soybean [41,43,44], rapeseed [45], palm tree [41,46], castor [41], safflower [45], olive husk [47], and tung [48]. Recently, the yields of decarboxylation products by pyrolysis from vegetable oil soaps have been investigated by Demirbas and Kara [49]. The maximum decarboxylation products of pyrolyses were 96.8%, 97.1%, 97.5%, and 97.8%, respectively, from sunflower oil, corn oil, cottonseed oil, and soybean oil at 610 K (337°C), respectively. Oxidative pyrolysis of Na-soaps is given as following reaction [49,50,36]:

$$4RCOONa + O_2 \longrightarrow 2R\text{-}R + 2Na_2CO_3 + 2CO_2 \quad (1)$$

The soaps obtained from the vegetable oils can be pyrolyzed into hydrocarbon-rich products according to Equation (1) with higher yields at lower temperatures.

VIII. Transesterification (Alcoholysis)

Transesterification is the reaction of vegetable oil or animal fat with an alcohol, in most cases methanol, to form esters and glycerol. The transesterification reaction is affected by alcohol type, molar ratio of glycerides to alcohol, type and amount of catalyst, reaction temperature, reaction time and free fatty acids and water content of vegetable oils or animal fats. The transesterification reaction proceeds with or without a catalyst by using primary or secondary monohydric aliphatic alcohols having 1–8 carbon atoms as follows [22,35,34]:

Triglycerides + Alcohol ⟷ Glycerin + Mono-alkyl esters

Generally, the reaction temperature near the boiling point of the alcohol is recommended. Nevertheless, the reaction may be carried out at room temperature [51]. The reactions take place at low temperatures (~65°C) and at modest pressures (2 atm, 1 atm = 101.325 kPa). Bio-diesel is further purified by washing and evaporation to remove any remaining methanol. The oil (87%), alcohol (9%), and catalyst (1%) are the inputs in the production of bio-diesel (86%), the main output [52]. Pre-treatment is not required if the reaction is carried out under high pressure (9000 kPa) and high temperature (~240°C), where simultaneous esterification and transesterification take place with maximum yield obtained at temperatures ranging from 60 to 80°C at a molar ratio of 6:1 [53]. The alcohols employed in the transesterification are generally short chain alcohols such as methanol, ethanol, propanol, and butanol. It was reported that when transesterification of soybean oil using methanol, ethanol and butanol was performed, 96–98% of ester could be obtained after 1 h of reaction [2].

IX. Mportant Issues Pertaining to Sustainability of Biodiesel

Adoption of biodiesel as a substitute to diesel requires a critical analysis of its sustainability issues. A careful identification of various sustainability issues and establishing their dynamic relationship is a prerequisite for such critical analysis. Analysis of various sustainability parameters related to biodiesel such as technological, environmental, economical and social needs critical analysis before its adoption. Technical sustainability is the most important aspect related to long-term viability of any biodiesel for its production and usage.

X. Technological Issues in Internal Combustion (I. C.) Engines

For successful adoption and promotion of biodiesel like: Jatropha biodiesel, the most critical issue is its physical and chemical properties as compared to that of diesel so that it can be used straight away in existing I.C. engines without any major modifications. Important physio-chemical properties of Jatropha biodiesel as compared to diesel are listed in Table I.

Technically Jatropha biodiesel possesses the required properties to ensure satisfactory performance of a diesel engine. Biodiesel gives considerably lower emissions of particulate matter (PM), carbon monoxide (CO) and hydrocarbon (HC) without any increase in fuel consumption or decrease in engine performance.

Biodiesel is a cleaner-burning diesel replacement fuel made from natural, renewable sources such as new and used vegetable oils and animal fats. Just like petroleum diesel, biodiesel operates in compression-ignition engines or Diesel engines. Biodiesel has physical properties very similar to conventional diesel [55]. The biodiesel was characterized by determining its density, viscosity, high heating value, cetane index, cloud and pour points, characteristics of distillation, and flash and combustion points according to ISO norms [23,56].

TABLE I: Properties Of Diesel And Jatropha Biodiesel [54]

Property	Diesel	Jatropha biodiesel
Density (kg/m^3)	840± 1.732	879
Kinematic viscosity at 40 ˚C (cSt)	2.44± 0.27	4.84
Cetane Number	48-56	51 - 52
Pour point (˚C)	6 ± 1	+3
Flash point (˚C)	71± 3	191
Conradson carbon residue (%, w/w)	0.1 ± 0.0	0.01
Ash content (%, w/w)	0.01 ± 0.0	0.013
Calorific value (MJ/kg)	45.34	38.5
Sulfur (%, w/w)	0.25	<0.001
Carbon (%, w/w)	86.83	77.1
Hydrogen (%, w/w)	12.72	11.81
Oxygen (%, w/w)	1.19	10.97

Viscosity is the most important property of biodiesel since it affects the operation of the fuel injection equipment, particularly at low temperatures when the increase in viscosity affects the fluidity of the fuel. Biodiesel has a viscosity close to that of diesel fuel [22,35]. The higher viscosity range of biodiesel helps to reduce barrel/plunger leakage and increases injector efficiency in engines [57]. Viscosity measurements have been made over the temperature range 20–100°C for blends of different biodiesel with No. 2 diesel fuel [58]. The viscosity of the distillate was 10.2 mm^2/s at 38°C, which is higher than the ASTM specification for No. 2 Diesel fuel (1.9–4.1 mm^2/s) but considerably below that of soybean oil (32.6 mm^2/s) [59].

Biodiesel offers safety benefits over petroleum diesel because it is much less combustible, with a flash point greater than 150°C, compared to 77°C for petroleum diesel [60]. The cetane number of biodiesel is generally higher than conventional diesel. The cetane number of biodiesel is around 50. Biodiesel has lower volumetric heating values (about 12%) than diesel fuels but has a high cetane number and flash point [31]. Density is another important property of biodiesel. It is the weight of a unit volume of fluid. Specific gravity is the ratio of the density of a liquid to the density of water. Specific gravity of biodiesels ranges between 0.87 and 0.89. Fuel injection equipment operates on a volume metering system, hence a higher density for biodiesel results in the delivery of a slightly greater mass of fuel [35,61]. Two important parameters for low temperature applications of a fuel are Cloud Point (CP) and Pour Point (PP). The CP is the temperature at which wax first becomes visible when the fuel is cooled. The PP is the temperature at which the amount of wax out of solution is sufficient to gel the fuel, thus it is the lowest temperature at which the fuel can flow. Biodiesel has higher CP and PP compared to conventional diesel [35,62]. The esters have CP and PP that are 15–25°C higher than those of diesel fuels [31]. Methyl esters of vegetable oils have several outstanding advantages among other new-renewable and clean engine fuel alternatives [22,63,64]. A number of technical advantages of biodiesel [56,65]: (1) it prolongs engine life and reduces the need for maintenance (biodiesel has better lubricating qualities than fossil diesel); (2) it is safer to handle, being less toxic, more biodegradable, and having a higher flash point; (3) it reduces some exhaust emissions (although it may, in some circumstances, raise others). Biodiesel fuels have many advantages over petroleum diesel fuel: produce less smoke and particles, have higher cetane number, produce lower carbon monoxide and hydrocarbon emissions, are renewable, biodegradable and non-toxic. When ethyl esters are used as fuel the advantage of totally recyclable carbon dioxide cycle is obtained since ethyl alcohol could be of vegetal origin [3].

The technical disadvantages of bio-diesel/fossil diesel blends include problems with fuel freezing in cold weather, reduced energy density, and degradation of fuel under storage for prolonged periods. One additional problem is encountered when blends are first introduced into equipment that has a long history of pure hydrocarbon usage. Hydrocarbon fuels typically form a layer of deposits on the inside of tanks, hoses, etc. Biodiesel blends loosen these deposits, causing them to block fuel filters. However, this is a minor problem, easily remedied by proper filter maintenance during the period following introduction of the bio-diesel blend [65].

Biodiesel can be blended at any level with petroleum diesel to create a biodiesel blend. It can be used in compression-ignition (diesel) engines with little or no modifications [25]. Several studies show biodiesel can run in a conventional diesel engine for an extended time. Researchers in several states including Missouri and Idaho, have run diesel engines in pickups, city buses, large trucks and tractors on various mixes of bio-diesel/diesel fuel. These mixtures have ranged from B2 (a blend of 98% petro-diesel with 2% biodiesel), B20 (a blend of 80% petro-diesel with 20% biodiesel) up to B100 (100% biodiesel) [50,56,66].

Biodiesel is often used as a blend B20 rather than using B100. It is asserted that 90% of air toxics can be eliminated by using B100 whereas 20–40% are reduced using B20. A further assertion is that the risk of illness and life threatening diseases can be reduced using bio-diesel blends [58]. Biodiesel blends of up to 20% reduce the emissions of HC, CO, SO_2, and particulates, as well as improve the engine performance [67,68].

Biodiesel's particulate reducing effect could be attributed to its lower aromatic and short-chain paraffin HC and higher oxygen content. It has been observed that carbon deposits on the cylinder head, piston top, piston ring grooves, and injector of biodiesel-fueled engine are substantially lower compared to the diesel-fueled engine [69].

Effect of biodiesel on PM emissions together with other parameters, such as the load conditions, the quality of diesel fuel used for blending, the type of engine or even the operation temperature has been reported by many researchers [70] and they found that the oxygen content of biodiesel may be more effective in reducing PM.

When the engine is fueled with B100, exhaust gas temperature is lower than that for diesel fuel. This indicates that biodiesel has earlier combustion and longer expansion period and the shorter ignition delay period than for diesel. This implies that the injection pump timing needs to be adjusted [71].

The increase of biodiesel percentage in the blend involves a slight decrease of both power and torque over the entire speed range. In particular, with B100 there is a reduction by about 3% of the maximum power and about 5% of the maximum torque. Moreover, with pure biodiesel, the maximum torque is reached at higher speed; this fact might be related to an increase of the flame velocity observed with biodiesel. This may result in a pressure peak shift to a crank angle closer to top dead centre (TDC) [72].

For blended diesel with Jatropha biodiesel experimentally it has been observed that a blend of 50% petro-diesel with 50% Jatropha biodiesel (B50) fuel gives performance comparable to that of pure diesel (D100). A blend of 80% petro-diesel with 20% Jatropha biodiesel (B20) gives good mechanical efficiency at full loading conditions [73]. In some studies, higher thermal efficiencies with lower brake specific fuel consumption (BSFC) and higher exhaust temperatures have been reported for all blends of biodiesel compared to mineral diesel [74]. But in some other studies the higher BSFC and lower exhaust temperature have been reported [75]. It has been observed that biodiesel does not cause any loss of power unless the maximum power is demanded from the engine [70]. Some experiments have reported increase [76] or decrease [77] in thermal efficiency when using biodiesel. Researchers [78, 79] have obtained about 2.5% increases in BSFC from their tests with B20 and about 14% from those with B100.No correlation has been found between the specific gravity and the cetane number of various biodiesel. It is important to note that Cetane Index, commonly used to indicate the ignition characteristics of diesel fuels, does not give correct results for biodiesel [80].

The properties of biodiesel at low temperatures are poorer than those of diesel. The cold flow pour point (CFPP) is generally higher than that of diesel and this may involve some complications for the operation in cold weather [72]. Certain technological complications require to be addressed to make biodiesel acceptable to automobile industry. Oxidation during storage, poor lubrication properties and problem in cold starting are some of such issues [72]. Basic problem with biodiesel is that it oxidizes while in contact with environment with respect to time which further lead to increase in fuel viscosity [81]. The concern about oxidation problems is more important in the case of biodiesel than diesel. It involves a time-progressive change of the aromatic properties and a reduction of the flash point. Oxidation products originated with biodiesel affect storage life and contribute to deposit formation in tanks, fuel systems and filters. Nevertheless, the improved decomposition implies a better biodegradability, which is very important when fuel is dispersed in the environment [72].

Biodiesel is more prone to oxidation when exposed to higher temperature due to the formation of oxidation products like aldehydes, alcohols, shorter chain carboxylic acids, insolubles, gum and sediment in the biodiesel, which may often be responsible for fuel filter plugging, injector fouling, deposits formation in engine combustion chamber and various components of the fuel system [82]. Biodiesel has detergent characteristics, which may bring in suspension fuel tank sludge that may block fuel-ways in the fuel injection system. Moreover, biodiesel is not compatible with some plastic materials used in pipes and seals, which must be changed [72].

The amount of carbonious residue from the hot decomposition of vegetable compounds with high molecular weight is greater than that of the diesel. This feature is crucial for proper use of biodiesel in new advanced injection systems [72].

The oxidation stability of Jatropha biodiesel has been found to increase with increase in dosage of antioxidant. It is found that dosing of 200 ppm of antioxidant is the minimum requirement to meet EN 14112 specification for biodiesel oxidative stability [83].

In a long term performance evaluation, the engine and fuel system components were disassembled, inspected and evaluated to compare wear characteristics after 4 years of operation and more than 6,00,000 miles accumulation on B20, no difference in wear or other issues were noted during the engine teardown. The cylinder heads of B20 engines contained a heavy amount of sludge around the rocker assemblies that was not found in the diesel engines. The sludge contained high levels of sodium possibly caused by accumulation of soaps in the engine oil. The B20 engines required injector nozzle replacement over the evaluation and teardown period this is due to out of specification fuel. The biological contaminants may be the cause of filter plugging [84].

The cold fuel property of biodiesel requires improvement for large scale penetration of biodiesel [72, 85]. Required hardware modifications may involve all modified injection timing and duration for better combustion of biodiesel in diesel engines [86]. The addition of biodiesel to diesel fuel changes the physico-chemical properties of the blends. With the increase of biodiesel concentration in diesel–biodiesel blends density, kinematic viscosity, cetane number, high heat value, flash and fire point of the blends increase [87].

The brake power and torque of the engine with diesel fuel are higher than those with biodiesel for both naturally aspirated (NA) and turbocharger (TU) operations. Because of higher fuel density and lower heating value, biodiesel shows slightly higher BSFC for both NA and TU operations in comparison with diesel fuel. The use of biodiesel improves the performance and exhaust emissions of the turbocharged engine better compared with the use of diesel fuel [88].

Particle size distributions (PSDs) provide important information about the harmful effect of particulate emissions. It is widely accepted that such an effect is higher for smaller particles for various reasons: (a) longer residence time in atmospheric suspension [89], and thus higher probability of inhalation, (b) higher specific surface and thus higher capability to adsorb organic compounds, some of which are potentially carcinogenic [90–92], (c) higher capability to penetrate into the respiratory system, to be retained in the interstitial tissue of the lung or even to penetrate into the cardiovascular system [89–91], thus causing pulmonary or vascular diseases, and (d) lower filtrability in traps and filter, thus reducing the efficiency of after-treatment systems [89,93]. It is difficult to evaluate the effect of biodiesel on the PSD because these are very sensitive to the dilution needed prior to the sampling and to the engine operating conditions [90, 94]. This may cause wide disparities in the measurements. There may be wide range of difference in mean diameter when they compared biodiesel and diesel [95].

The characteristics of exhaust emissions and PSDs of PM from a common rail direct injection (CRDI) diesel engine were investigated with the use of biodiesel and bioethanol blended diesel fuels. The use of biofuel-blended diesel fuels reduced the total number of particles emitted from the engine. However, when compared to the use of D100, the use of biodiesel–diesel blends caused the emission of more particles smaller than 50 nm, which are harmful to human body [96].

Biodiesel has good lubricant properties with respect to diesel oil, in particular diesel with a very small amount of sulphur. This is very important to reduce wear in the engine and the injection system [72].

In most of the reported studies 20% blend of Jatropha biodiesel with petro-diesel is found to be suitable for normal operations without any modifications in engine specifications. Thus as a technological dimension it would be more appropriate to go for blends rather targeting usage of 100% biodiesel in existing engines or developing engines for operating on biodiesel only.

XI. Emissions from Biodiesel and Its Blend with Diesel

Researchers [53, 70, 72, 97-100] have reported that CO, CO2 and unburnt hydrocarbon (UBHC) emissions are less with bio-diesel and its blends, because bio-diesel has oxygen in its molecular structure leading to better combustion. Advanced injection and combustion when using biodiesel may also justify the CO reduction with this fuel. Reductions in CO emissions with the injection timing were advancement has already been reported [101]. It has also been reported that NOx emissions are slightly increased with bio-diesel and its blends with petro-diesel [70, 98, 99]. This may be due to the higher temperature in the combustion chamber while using biodiesel. Impact of cetane number, flame temperature, oxygen availability and injection advance on NOx levels in emissions using Biodiesel as fuel under varying load conditions is also reported [70]. The other most frequently pointed out reason is the use of slightly advanced injection process with biodiesel. NOx emissions may be reduced by operating engine in dual fuel mode i.e., fuel with high octane number as primary fuel and high cetane number as pilot fuel [98]. The sensitivity of NOx to changes in cetane number is higher at low load than at high load [70]. Exhaust gas recirculation can result in NOx emissions reduction up to 50% and reduce smoke emissions by 15% [102,103]. The emission of aromatic and polyaromatic compounds, as well as their toxic and mutagenic effect, has been generally reported to be less with biodiesel. No conclusive trend has been observed regarding the emissions of oxygenated compounds such as aldehydes and ketones [70]. Experimental evidences suggest that overall toxicity of emissions in terms of metals reduces in biodiesel exhaust compared to diesel exhaust [104].

XII. DEDICATED BIODIESEL ENGINE [105]

A comprehensive solution is modified dedicated biodiesel engine is the only solution to compensate engine compatibly problems caused by high viscous, high cetane number biodiesel. The fuel supply system is required for modification in fuel filter, fuel pump, and adjustment of injection timing by retardation. As biodiesel has higher cetane number, the injection timing should retard a bit to adjust. For low energy content of biodiesel, the engine loses some power, but it runs quieter and the fuel burns cooler, reducing NO_x emissions. Fuel Injection Equipment (FIE) Manufacturers (Delphi, Stanadyne, Denso, and Bosch) showed their concern on the following fuel properties of biodiesel:

1) Free methanol: Corrosion of fuel injection equipment.
2) Dissolved and free water: It causes reversion of biodiesel to fatty acid and finally results to filter plugging.
3) Free glycerin: Free glycerin corrodes non-ferrous metals, soaks cellulose filters, sediments on moving parts and lacquering which causes filter clogging, injector coking.
4) Free fatty acids: Organic compounds are formed resulting in corrosion of fuel injection equipment, filter plugging, sediments on parts.
5) Total solid impurity levels.
6) Alkaline metal compounds in solution.
7) Oxidation and thermal stability.

Fuel pump also suffers badly while operating in biodiesel blends. A list of fuel pump problems is given below:

1) Corrosion of fuel injection equipment components.
2) Elastomeric seal failures.
3) Low pressure fuel system blockage.
4) Fuel injector spray hole blockage.
5) Increased dilution and polymerization of engine sump oil.
6) Pump seizures due to high fuel viscosity at low temperatures.
7) Increased injection pressure.

Even though various research approaches on troubleshooting the problems of biodiesel is carried out, a definite solution for all of this may not be possible without a dedicated biodiesel engine. Like Brazil's flex-fuel vehicles (FFV) a modified diesel engine for different biodiesel blends (B5–B20) is quite achievable by modifying the fuel supply system (fuel pump, filter, injector, fuel tank, fuel lines and injection controller). Such a project on dedicated biodiesel engine may spur the biodiesel production and use along with automobile sales like Brazil, who produced 17 million FFV automobiles by 2009. Some suggestions on modifications of a diesel engine to a dedicated biodiesel automotive engine are listed below:

Fuel pump: Pump material (like aluminum alloy, iron based alloy) should be changed to a more corrosion resistive material. To reduce the seizure of the pump, a heating system can be run by radiator's heat.

Fuel filter: As prescribed by many automobile manufacturer and researchers, engine requires quicker fuel filter change while running on biodiesel due to clogging by sediments and wear debris and pitting corrosion. But this quick disposal incurs cost to user and regular inspection as well. So a reinforced fuel filter container (to prevent the crash of highly viscous biodiesel) and smaller meshed fuel filter which can provide a good solution to this problem.

Fuel injectors: Jones et al. [106], have recommended that checking for fuel injectors should be at least twice as often for biofuel than that for diesel because of their coking and rapid ageing. Carbon deposition on tip of injector is obvious if the fuel contains biodiesel even in minor proportions. To avoid plugging and coke formation, the temperature of the nozzle has to be measured and kept (acting on the cooling water flow rate) below 250°C [107].

XIII. CONCLUSION

Biodiesel is a cleaner-burning diesel replacement fuel made from natural, renewable sources such as new and used vegetable oils and animal fats. Just like petroleum diesel, biodiesel operates in compression ignition engines or Diesel engines. The biodiesel is mainly characterized by: viscosity, high heating value, cetane index, cloud and pour points, characteristics of distillation, and flash and combustion points. Viscosity is the most important property of biodiesel since it affects the operation of the fuel injection equipment, particularly at low temperatures when the increase in viscosity affects the fluidity of the fuel.

The major economic factor to consider for input costs of biodiesel production is the feedstock, which is about 80% of the total operating cost. Other important costs are labor, methanol and catalyst, which must be added to the feedstock.

In order to provide a wide and complete evaluation of the potentialities of biodiesel as alternative fuel, further investigations have to be performed at larger scale. An economic evaluation is required to show what the potential convenience of using biodiesel can be in complete or partial substitution of diesel oil, according to actual conditions.

Installing an in-tank or fuel line heater may also be needed to keep the fuel flowing in cold weather. A blend of biodiesel/diesel has a lower pour point than B100, but gelling may still occur unless care as mentioned earlier is taken.

Biodiesel must have improved oxidation stability that reduces or eliminates sedimentation and gum formation within the fuel and as such reduces or eliminates corrosion and plugging in injection pumps and/or fuel lines in engines.

One additional problem is encountered when blends are first introduced into equipment that has a long history of pure hydrocarbon usage. Hydrocarbon fuels typically form a layer of deposits on the inside of tanks, hoses, etc. Biodiesel blends loosen these deposits, causing them to block fuel filters. However, this is a minor problem, easily remedied by proper filter maintenance during the period following introduction of the biodiesel blend.

Exhaust gas temperature as well controlling the NOx levels needs a critical analysis for various blends of biodiesel in order to maintain the optimum atmospheric NOx level as well as proper utilization of calorific value of fuel. Particulate matter and NOx emission needs a careful examination also as normally various biodiesel blends shows increase in NOx level with decrease in particulate matter and vice versa as shown in Table II.

TABLE II: EMISSION DATA FOR DIESEL, B20 AND B100 [80]

Test Fuel	HC (g/hp-hr)	CO(g/hp-hr)	NO_x (g/hp-hr)	PM (g/hp-hr)
Diesel	0.06	1.49	4.5	0.102
B20	0.06	1.38	4.66	0.088
B100	0.01	0.92	5.01	0.052

Impact of cold start on particulate emissions needs further investigation.

There are reasons which could explain both increases and decreases in the number of small particles emitted. On the one hand, the nil or very low sulfur content of biodiesel fuels could contribute to reduce the smallest particles, as sulfur has often been associated to the formation of the nucleation mode (consisting of particles below 50 nm) [89, 108]. On the other hand, the increased viscosity of biodiesel and the electronic control system may lead to some increase in the injection pressure and to some injection advance, both changes being associated in the literature to an increased number of small particles [109,110] but it needs further investigation.

Residues formed in case of diesel at high temperatures like 370˚C may cause serious problems in the long run to the engine life where as impact of complete distillation of Jatropha biodiesel observed at the temperature of 370˚C needs further examination [72].

Increase in BSFC is observed in case of Jatropha biodiesel as compared to diesel by around 14% and it is only observed when the oxygen enrichment comes from the fuel but not from the intake air [70]. Impact of oxygen available in the fuel composition for combustion needs proper analysis as most of the researchers have found it to be a useful property for complete combustion of the fuel.

P-θ and T- θ curves needs to be plotted and analysed properly for getting a clear knowhow of combustion of biodiesel and its blends on important phenomenon like: detonation, ignition delay, exhaust gas temperature etc.

Ignition-accelerator property of biodiesel needs proper correlation with its chemical properties in order to ensure wide spread usage of biodiesel as a blend with petro-diesel.

Impact of lubricity of biodiesel on the thermal efficiency of a diesel engine is a research area where most researchers are not able to find any thing concrete as on date.

An improved knowledge of the potential to reduce regulated emissions from the use of biodiesel and its blends with petro-diesel could help (a) engine manufacturers to adapt their engines to the use of biodiesel and to optimize them, readjusting the compromise between efficiency, costs (mainly due to after treatment systems) and emissions within the regulation limits, (b) national administrations to design their energy policies and to define measures to externalize environmental costs, (c) local administrations to promote its use in urban areas, especially in countries with extreme dieselization, where particle concentrations in the air are reaching alarming levels, and (d) private users, to encourage them to use biodiesel, attesting to their environmental concern.

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