Progress and Recent Trends in Biofuels for Internal Combustion Engines

Junjie Chen*, Deguang Xu
School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo, China

*Corresponding author: Junjie Chen, E-mail: comcjj@163.com,
Received: November 14, 2014, Accepted: December 6, 2014, Published: December 6, 2014.

ABSTRACT
The increasing industrialization and motorization of the world has led to a steep rise for the demand of fossil fuels. Fossil fuels are obtained from limited reserves. These finite reserves are highly concentrated in certain regions of the world. Therefore, those countries not having these resources are facing energy/foreign exchange crisis, mainly due to the import of crude oil. Hence, it is necessary to look for alternative fuels which can be produced from resources available locally within the country such as alcohol, biodiesel, vegetable oils etc. This paper reviews the production, characterization and current statuses of vegetable oil and biodiesel as well as the experimental investigation carried out in various countries. This paper touches upon well-to-wheel greenhouse gas emissions, well-to-wheel efficiencies, fuel versatility, infrastructure, availability, economics, engine performance and emissions, effect on wear, lubricating oil etc.

Keywords: Biofuels, Alcohol, Biodiesel, Combustion characteristics, IC engine

INTRODUCTION
During the last decades two main concerns have arisen in the energy generation and transportation sectors, namely the increasing energy demand coupled with the limited availability of oil reserves and the detrimental environmental effect produced by their exploitation to deliver energy and motion [1]. The use of fossil fuels has increased the energy dependence of many countries around the world, since oil production is extremely localized with the Middle East possessing over 55% of the proved oil reserves worldwide as of 2009 [2]. This impacts all countries and citizens around the world, since the oil prices are reflected on virtually every commodity. Moreover, it creates and sustains energy insecurity among countries with high energy dependence. Another detrimental effect of the use of fossil fuels is related to the environmental impact from their use for energy production and transportation. The fuel combustion in internal combustion engines produces-among others-CO₂, a major greenhouse gas that is known to contribute to the global warming effect. The main issue is not the production of CO₂ itself, since the combustion of most fuels leads to its production, but the fact that in the case of fossil fuels the CO₂ emitted cannot be reconverted to the original fuel by any short-term, natural- and therefore energy neutral-process [3].

In view of the first issues analyzed, i.e. the energy dependence of most of the countries, the instability of the oil prices and the increasing demand of fossil fuel energy, alternative fuels have been sought after [4]. Among those, biofuels have received increasing attention due to their additional attribute of being renewable. The term “biofuel” refers to any fuel that can be produced from biomass, such as starch, sugars, animal fat, oleaginous plants, etc. The main advantage of a biofuel is that it can be reconstructed by natural processes using the CO₂ emitted from its combustion. This is part of the photosynthetic process of the plants, which use sunlight and CO₂ to build their cells [5]. Thus, biofuels have the potential to be CO₂ neutral. This is depicted in Fig. 1, in which a comparison is made between the biofuel energy system and the fossil fuel energy system.

![Fig. 1. Comparison of bioenergy and fossil fuel energy systems.](image)

**Primary Alcohols as Engine Fuels**
Ethanol has been known as a fuel for many decades. Indeed, when Henry Ford designed the Model T, it was his expectation that ethanol, made from renewable biological materials would be a major automobile fuel. However, gasoline emerged as the...
dominant transportation fuel in the early twentieth century because of the ease of operation of gasoline engines with the materials then available for engine construction, and a growing supply of cheaper oil from oil field discoveries. But gasoline had many disadvantages as an automotive fuel. The “new” fuel had a lower octane rating than ethanol, was much more toxic (particularly when blended with tetra-ethyl lead and other compounds to enhance octane rating), was generally more dangerous, and emitted harmful air pollutants. Gasoline was more likely to explode and burn accidentally, gum would form on storage surfaces, and carbon deposits would form in combustion chamber. Pipelines were needed for distribution from “area found” to “area needed”. Oil was much more physically and chemically diverse than ethanol, necessitating complex refining procedures to ensure the manufacture of a consistent “gasoline” product. Because of its lower octane rating relative to ethanol, the use of gasoline meant the use of lower compression engines and larger cooling systems. Diesel engine technology, which developed soon after the emergence of gasoline as the dominant transportation fuel, also resulted in the generation of large quantities of pollutants. However, despite these environmental flaws, fuels made from oil have dominated automobile transportation for the past three-quarters of a century. There are two key reasons: first, cost per kilometer of travel has been virtually the sole selection criteria. Second, the large investments made by the oil and auto industries in physical capital, human skills and technology make the entry of a new cost-competitive industry difficult. Until very recently, environmental concerns have been largely ignored [3].

Ethanol is one of the possible fuels for diesel replacement in compression ignition (CI) engines also. The application of ethanol as a supplementary CI engine fuel may reduce environmental pollution, strengthen agricultural economy, create job opportunities, reduce diesel fuel requirements, and thus contribute in conserving a major commercial energy source. Ethanol was first suggested as an automotive fuel in USA in the 1930s, but was widely used only after 1970 [3]. Nowadays, ethanol is used as fuel, mainly in Brazil, and as a gasoline additive for octave number enhancement and improved combustion in USA, Canada and India. As gasoline prices increase and emission regulations become more stringent, ethanol could be given more attention as a renewable fuel or gasoline additive [6].

Alcohol is made from renewable resources like biomass from locally grown crops and even waste products such as waste paper, grass and tree trimmings etc. Alcohol is an alternative transportation fuel since it has properties, which would allow its use in existing engines with minor hardware modifications. Alcohols have higher octane number than gasoline. A fuel with a higher octane number can endure higher compression ratios before engine starts knocking, thus giving engine an ability to deliver more power efficiently and economically. Alcohol burns cleaner than regular gasoline and produce lesser carbon monoxide, HC and oxides of nitrogen [7]. Alcohol has higher heat of vaporization; therefore, it reduces the peak temperature inside the combustion chamber leading to lower NOx emissions and increased engine power. However, the aldehyde emissions go up significantly. Aldehydes play an important role in formation of photochemical smog.

Stump et al. [3] examined tailpipe and evaporative emissions from three passenger motor vehicles operating on an ethanol (9 % v/v) and a non-oxygenated fuel. A general reduction in hydrocarbon, carbon monoxide, benzene and 1, 3-butenadiene emissions was observed when the ethanol fuel was used. Both formaldehyde and acetaldehyde emissions increased (almost double) with the ethanol blend.

Methanol (CH₃OH) is a simple compound. It does not contain sulfur or complex organic compounds. The organic emissions (ozone precursors) from methanol combustion will have lower reactivity than gasoline fuels hence lower ozone forming potential. If pure methanol is used then the emission of benzene and PAHs is very low. Methanol gives higher engine efficiency and is less flammable than gasoline but the range of the methanol-fueled vehicle is as much as half less because of lower density and calorific value, so larger fuel tank is required. M100 has invisible flames and it is explosive in enclosed tanks. The cost of methanol is higher than gasoline. Methanol is toxic, and has corrosive characteristics, emits ozone creative formaldehyde. Methanol poses an environmental hazard in case of spill, as it is totally miscible with water. Ethanol is similar to methanol, but it is considerably cleaner, less toxic and less corrosive. It gives greater engine efficiency. Ethanol is grain alcohol, and can be produced from agricultural crops e.g. sugar cane, corn etc. Ethanol is more expensive to produce, has lower range, poses cold starting problems and requires large harvest of these crops. Higher energy input is required in ethanol production compared to other energy crops and it leads to environmental degradation problems such as soil degradation.

**Vegetable Oils as Engine Fuels**

Recently, because of increase in crude oil prices, limited resources of fossil oil and environmental concerns, there has been a renewed focus on vegetable oils and animal fats to make biodiesel. Continued and increasing use of oil will intensify local air pollution and magnify the global warming problems caused by carbon dioxide. In a particular case, such as the emission of pollutants in the closed environment of underground mines, biodiesel has the potential to reduce the level of pollutants and the level of potential for probable carcinogens [8].

The advantages of using vegetable oils as fuels are [3]:

- Vegetable oils are liquid fuels from renewable sources.
- They do not over-burden the environment with emissions.
- Vegetable oils have potential for making marginal land productive by their property of nitrogen fixation in the soil.
- Vegetable oil's production requires lesser energy input in production.
- Vegetable oils have higher energy content than other energy crops like alcohol. Vegetable oils have 90% of the heat content of diesel and they have a favorable output/input ratio of about 2.4:1 for un-irrigated crop production.
- The current prices of vegetable oils in world are nearly competitive with oil fuel price.
- Vegetable oil combustion has cleaner emission spectra.
- Simpler processing technology.

But, These are not economically feasible yet. These are need further R&D work for development of on-farm processing technology.

Due to the rapid decline in crude oil reserves, the use of vegetable oils as diesel fuels is again promoted in many countries.
Depending upon climate and soil conditions, different nations are looking into different vegetable oils for diesel fuels. For example, soybean oil in the USA, rapeseed and sunflower oils in Europe, palm oil in Southeast Asia, and coconut oil in Philippines are being considered as substitutes for mineral diesel.

An acceptable alternative fuel for engine has to fulfill the environmental and energy security needs without sacrificing operating performance. Vegetable oils can be successfully used in CI engine through engine modifications and fuel modifications. Engine modifications include dual fueling, injection system modification, heated fuel lines etc. Fuel modifications include blending of vegetable oils with diesel, transesterification, cracking/pyrolysis, micro-emulsion, and hydrogenation to reduce polymerization and viscosity [8].

From amongst the large number of vegetable oils available in the world, if any specific oil needs to be adopted as a continuing energy crop, it is then essential that an oilseed variety having higher productivity and oil content must be produced. Nevertheless, technologies must be developed for the use of vegetable oils as an alternative diesel fuel that will permit crop production to proceed in an emergency situation. Vegetable oil in its raw form cannot be used in engines. It has to be converted to a more engine-friendly fuel called biodiesel. System design approach has taken care to see that these modified fuels can be utilized in the existing diesel engine without substantial hardware modification. It will be expensive and time-consuming to incorporate even a minor design alteration in the system hardware of a large number of existing engines operating in the rural agricultural sector of any country.

In its simplest form, the carbon cycle of vegetable oil consists of the fixation of carbon and the release of oxygen by plants through the process of photosynthesis and then combining of oxygen and carbon to form CO_2 through processes of combustion. It is appropriate to mention here that the CO_2 released by oil diesel was fixed from the atmosphere during the formative years of the earth, whereas the CO_2 released by biodiesel gets continuously fixed by plants and may be recycled by the next generation of crops. The carbon cycle time for fixation of CO_2 and its release after combustion of biodiesel is quite small as compared to the cycle time of fossil fuel. Since biodiesel is a fuel made up of esters derived from oils and fats from renewable biological sources, it has been reported to emit substantially lower quantities of most of the regulated pollutants compared to mineral diesel [8]. Biodiesel has comparable energy density, cetane number, heat of vaporization, and stoichiometric air/fuel ratio with mineral diesel. The large molecular size of the component triglycerides result in the oil having higher viscosity compared with that of mineral diesel. Viscosity affects the handling of the fuels by pump and injector system, and the shape of fuel spray. The high jet penetration and poor atomization results in larger droplets. The fuel Jet tends to be a solid stream instead of spray in small droplets hence the fuel does not get mixed with air required for burning. Larger droplets have poor combustion leading to loss of engine power and fuel economy. In small engines, the fuel spray may even impinge upon the cylinder walls, washing away the lubricating oil film and causing the dilution of crank case oil leading to excessive wear of moving parts.

**Biodiesel as Engine Fuels**

The best way to use vegetable oil as fuel is to convert it in to biodiesel. Biodiesel is the name of a clean burning mono-alkyl ester-based oxygenated fuel made from natural, renewable sources such as new/used vegetable oils and animal fats. The resulting biodiesel is quite similar to conventional diesel in its main characteristics. Biodiesel contains no oil products, but it is compatible with conventional diesel and can be blended in any proportion with mineral diesel to create a stable biodiesel blend. The level of blending with oil diesel is referred as Bxx, where xx indicates the amount of biodiesel in the blend (i.e. B10 blend is 10% biodiesel and 90% diesel. It can be used in CI engine with no major modification in the engine hardware.

**Transesterification**

Transesterification is the reaction of a fat or oil with an alcohol to form esters and glycerol. Alcohol combines with the triglycerides to form glycerol and esters. A catalyst is usually used to improve the reaction rate and yield. Since the reaction is reversible, excess alcohol is required to shift the equilibrium to the product side. Among the alcohols that can be used in the transesterification process are methanol, ethanol, propanol, butanol and amyl alcohol [9, 10]. Alkali-catalyzed transesterification is much faster than acid-catalyzed transesterification and is most often used commercially.

The process of transesterification brings about drastic change in viscosity of vegetable oil. The biodiesel thus produced by this process is totally miscible with mineral diesel in any proportion. Biodiesel viscosity comes very close to that of mineral diesel hence no problems in the existing fuel handling system. Flash point of the biodiesel gets lowered after esterification and the cetane number gets improved. Even lower concentrations of biodiesel act as cetane number improver for biodiesel blend. Calorific value of biodiesel is also found to be very close to mineral diesel. Some typical observations from the engine tests suggested that the thermal efficiency of the engine generally improves, cooling losses and exhaust gas temperature increase, smoke opacity generally gets lower for biodiesel blends. Possible reason may be additional lubricity properties of the biodiesel; hence reduced frictional losses (FFP). The energy thus saved increases thermal efficiency, cooling losses and exhaust losses from the engine. The thermal efficiency starts reducing after a certain concentration of biodiesel. Flash point, density, pour point, cetane number, calorific value of biodiesel comes in very close range to that of mineral diesel [9, 10]. Diesel engine can perform satisfactory for long run on biodiesel without any hardware modifications. Twenty percent biodiesel is the optimum concentration for biodiesel blend with improved performance. Increase in exhaust temperature however lead to increased NO_x emissions from the engine. While short-term tests are almost positive, long-term use of neat vegetable oils or their blend with diesel leads to various engine problems such as, injector coking, ring sticking, injector deposits etc. [9, 10]. High viscosity, low volatility and a tendency for polymerization in the cylinder are root causes of many problems associated with direct use of these oils as fuels. The process of transesterification yield vegetable oil ester, which has shown promises as alternative diesel fuel as a result of improved viscosity and volatility. Several researchers investigate the different vegetable oil esters and find esters comparable to mineral diesel [11]. The yield of biodiesel in
the process of transesterification is affected by several process parameters/variables.

The most important variables affecting the yield of biodiesel from transesterification are:

- Reaction temperature.
- Molar ratio of alcohol and oil.
- Catalyst.
- Reaction time.
- Presence of moisture and free fatty acids (FFA).

**Properties of Biodiesel**

The characteristics of biodiesel are close to mineral diesel, and, therefore, biodiesel becomes a strong candidate to replace the mineral diesel if the need arises. The conversion of triglycerides into methyl or ethyl esters through the transesterification process reduces the molecular weight to one-thirds that of the triglycerides, the viscosity by a factor of about eight and increases the volatility marginally. Biodiesel has viscosity close to mineral diesel. These vegetable oil esters contain 10-11% oxygen by weight, which may encourage combustion than hydrocarbon-based diesel in an engine. The cetane number of biodiesel is around 50. Biodiesel has lower volumetric heating values (about 10%) than mineral diesel but has a high cetane number and flash point. The esters have cloud point and pour points that are 15-25 °C higher than those of mineral diesel [12].

**Engine Performance Characteristics of Biodiesel**

Biodiesel has low heating value, (10% lower than diesel) on weight basis because of presence of substantial amount of oxygen in the fuel but at the same time biodiesel has a higher specific gravity (0.88) as compared to mineral diesel (0.85) so overall impact is approximately 5% lower energy content per unit volume. Thermal efficiency of an engine operating on biodiesel is generally better than that operating on diesel. Brake-specific energy consumption (bsec) is a more reliable criterion compared to brake-specific fuel consumption (bsfc) for comparing fuels having different calorific values and densities. Several experimental investigations have been carried out by researchers around the world to evaluate the engine performance of different biodiesel blends. Masjuki et al. investigated preheated palm oil methyl esters (POME) in the diesel engine. They observed that by preheating the POME above room temperature, the engine performance, especially the brake power output and exhaust emission characteristics improved significantly. Scholl and Sorensen [3] studied the combustion of soyabean oil methyl ester (SME) in a direct injection diesel engine. They found that most of the relevant combustion parameters for SME such as ignition delay, peak pressure, and rate of pressure rise were close to those observed for diesel combustion at the same engine load, speed, timing and nozzle diameter. They also investigated combustion and emissions characteristics with SME and diesel for different injector orifice diameter. It was found that ignition delay for the two fuels were comparable in magnitude, and the ignition delay of SME was found to be more sensitive to nozzle diameter than diesel. CO emissions from SME were slightly lower, HC emissions reduced drastically, NOx for two fuels were comparable and smoke numbers for the SME were lower than that of diesel [3]. Results of their experiments are shown in Fig. 2, Fig. 3 and Fig. 4.

**Engine Emissions from Biodiesel**

Since biodiesel is free from sulfur hence less sulfate emissions and particulate reduction is reported in the exhaust. Due to near absence of sulfur in biodiesel, it helps reduce the problem of acid rain due to transportation fuels. The lack of aromatic hydrocarbon (benzene, toluene etc.) in biodiesel reduces unregulated emissions as well like ketone, benzene etc. Breathing particulate has been found to be hazard for human health, especially in terms of respiratory system problem. PM consists of elemental carbon (≥31%), sulfates and moisture (≥14%), unburnt fuel (≥7%), unburnt lubricating oil (≥40%) and remaining may be metals and others substances.

Biodiesel is oxygenated fuel (hence more complete combustion) and causes lesser particulate formation and emission. Smoke opacity is a direct measure of smoke and soot. Various studies show that smoke opacity for biodiesel is generally lower [13].
Several experimental investigations are performed on 4-stroke DI diesel engines with vegetable oil methyl esters and found that hydrocarbon emissions are much lower in case of biodiesel compared to diesel. This is also due to oxygenated nature of biodiesel where more oxygen is available for burning and reducing hydrocarbon emissions in the exhaust [13]. Biodiesel use also shows reduction in PAH's, which are identified as carcinogen compounds, so it reduces health risks also.

**Combustion Characteristics of Biodiesel**

Kumar et al. [14] found that for Jatropha oil methyl ester, ignition delay was higher as compared to ignition delay for diesel as a fuel on a constant speed diesel engine. Selim et al. [15] tested jojoba oil methyl ester (JME) as a fuel on Ricardo compression swirl diesel engine and found that the pressures and pressure rise rates for JME are almost similar to that as gas oil. JME, however, exhibits slightly lower pressure rise rate than gas oil, and JME seems to have slightly delayed combustion.

Experimental investigations have been carried out by Agarwal et al. [16] to examine the combustion characteristics in a direct injection transportation diesel engine running with diesel, biodiesel (rice bran oil methyl ester) blend. A Mahindra & Mahindra make four cylinder direct injection diesel engine was instrumented for measurement of combustion pressure, rate of pressure rise and other in-cylinder parameters such as rate of instantaneous heat release, cumulative heat release rate, mass fraction burned etc. Tests were performed at different loads ranging from no load to 100% rated load, at constant engine speed. A careful analysis of heat release and other combustion parameters has been done, which gives precise information about the combustion process, when using biodiesel.

In a CI engine, cylinder pressure depends on the burned fuel fraction during the premixed burning phase, i.e., initial stage of combustion. Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. High peak pressure and maximum rate of pressure rise correspond to large amount of fuel burned in premixed combustion stage. The cylinder pressure crank angle history is obtained at different loads for diesel and B20. Peak pressure and maximum rate of pressure rise are obtained at different loads from these measurements.

Fig. 5, Fig. 6 and Fig. 7 show the \( P-\theta \) diagram for both fuels at different loads. From these figures it is clear that peak pressure increases as the load increases and for B20, fuel combustion starts earlier in comparison to mineral diesel.

Fig. 5. \( P-\theta \) diagram at no load, 1400 rpm for medium duty DI transportation engine.

Fig. 6. \( P-\theta \) diagram at 50% load, 1400 rpm for medium duty DI transportation engine.

Fig. 7. \( P-\theta \) diagram at 100% load, 1400 rpm for medium duty DI transportation engine.

Fig. 8 and Fig. 9 show that peak pressure and rate of pressure rise are higher for B20 at low engine loads (up to 10% load) but becomes lower when the engine load is increased. However, the change in pressure is not significant. The crank angle where the peak pressure occurs is shown in Fig. 10. It shows that maximum pressure occurs within the range of 2-7 crank angle degrees after top dead center for both fuels at all loads. Pressure reaches its maximum somewhat later for B20 at higher loads which reconfirm that rate of pressure rise is lower at higher loads for B20.

Fig. 8. Variation of peak cylinder pressure with engine load (at 1400 rpm) for medium duty DI transportation engine.
Potential to reduce particulate emissions in compression-ignition bio-based resource and it is oxygenated, thereby providing the lubricating oil etc. Economics, engine performance and emissions, effect on wear, efficiencies, fuel versatility, infrastructure, availability, greenhouse gas, and economic feasibility. This paper touches upon well-to-wheel greenhouse gas emissions, well-to-wheel efficiencies, fuel versatility, infrastructure, availability, economics, engine performance and emissions, effect on wear, lubricating oil etc.

Ethanol is an attractive alternative fuel because it is a renewable bio-based resource and it is oxygenated, thereby providing the potential to reduce particulate emissions in compression-ignition engines. In this review, the properties and specifications of ethanol blended with diesel and gasoline fuel are also discussed. Special emphasis is placed on the factors critical to the potential commercial use of these blends. The effect of the fuel on engine performance and emissions (SI as well as compression ignition (CI) engines), and material compatibility is also considered.

Biodiesel is methyl or ethyl ester of fatty acid made from virgin or used vegetable oils (both edible and non-edible) and animal fat. The main resources for biodiesel production can be non-edible oils obtained from plant species such as Jatropha curcas (Ratanjyot), Pongamia pinnata (Karanj), Calophyllum inophyllum (Nagchampa), Hevca brasilienis (Rubber) etc. Biodiesel can be blended in any proportion with mineral diesel to create a biodiesel blend or can be used in its pure form. Just like oil diesel, biodiesel operates in compression ignition (diesel) engine, and essentially require very little or no engine modifications because biodiesel has properties similar to mineral diesel. It can be stored just like mineral diesel and hence does not require separate infrastructure. The use of biodiesel in conventional diesel engines result in substantial reduction in emission of unburned hydrocarbons, carbon monoxide and particulate. This review focuses on performance and emission of biodiesel in CI engines, combustion analysis, wear performance on long-term engine usage, and economic feasibility.

Hence, biodiesel may be considered as diesel fuel substitutes. The use of biofuels as IC engine fuels can play a vital role in helping the developed and developing countries to reduce the environmental impact of fossil fuels.

REFERENCES
10. K. Pramanik, Properties and use of Jatropha curcas oil and diesel fuel blends in compression ignition engine, Renew...


Citation: Junjie Chen. et al., (2014) Progress and Recent Trends in Biofuels for Internal Combustion Engines J. of Advancement in Engineering and Technology. V2I2. DOI: 10.15297/JAET.V2I2.02

Copyright: © 2014 Junjie Chen. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.