Biodiesel

Biodiesel refers to a diesel-equivalent processed fuel derived from biological sources (such as vegetable oils) which can be used in unmodified diesel-engine vehicles. It is thus distinguished from the straight vegetable oils (SVO) or waste vegetable oils (WVO) used as fuels in some diesel vehicles.

In this article's context, biodiesel refers to alkyl esters made from the transesterification of vegetable oils or animal fats.

On August 31, 1937, G. Chavanne of the University of Brussels (Belgium) was granted a patent for a 'Procedure for the transformation of vegetable oils for their uses as fuels' (fr. 'Procédé de Transformation d'Huiles Végétales en Vue de Leur Utilisation comme Carburants') Belgian Patent 422,877. This patent described the alcoholysis (often referred to as transesterification) of vegetable oils using ethanol (and mentions methanol) in order to separate the fatty acids from the glycerol by replacing the glycerol with short linear alcohols. This appears to be the first account of the production of what is known as 'biodiesel' today.

Biodiesel is biodegradable and non-toxic, and typically produces about 60% less net carbon dioxide emissions than petroleum-based diesel, as it is itself produced from atmospheric carbon dioxide via photosynthesis in plants. Though this figure can actually differ widely between fuels depending upon production and processing methods employed in their creation. Pure biodiesel is available at many gas stations in Germany.

Some vehicle manufacturers are positive about the use of biodiesel, citing lower engine wear as one of the fuel's benefits. Biodiesel is a better solvent than standard diesel, as it 'cleans' the engine, removing deposits in the fuel lines. However, this may cause blockages in the fuel injectors. For this reason, car manufacturers recommend that the fuel filter be changed a few months after switching to biodiesel (the fuel filter, as part of a routine maintenance plan, is generally replaced anyway). Most manufacturers release lists of the cars that will run on 100% biodiesel.
Other vehicle manufacturers remain cautious over use of biodiesel. In the UK many only maintain their engine warranties for use with maximum 5% biodiesel — blended in with 95% conventional diesel — although this position is generally considered to be overly cautious. Scania and Volkswagen are exceptions, allowing most of their engines to operate on 100% biodiesel. Peugeot and Citroën are also exceptions in that they have both recently announced that their PSA HDI engine can run on 30% biodiesel. The Ford Focus has recently been converted to run on Biodiesel.

Biodiesel can also be used as a heating fuel in domestic and commercial boilers. Existing oil boilers may require conversion to run on biodiesel, but the conversion process is believed to be relatively simple.

Biodiesel can be distributed using today's infrastructure, and its use and production are increasing rapidly. Fuel stations are beginning to make biodiesel available to consumers, and a growing number of transport fleets use it as an additive in their fuel. Biodiesel is generally more expensive to purchase than petroleum diesel but this differential may diminish due to economies of scale, the rising cost of petroleum and government tax subsidies. In Germany, biodiesel is generally cheaper than normal diesel at gas stations that sell both products.

**Description**

Biodiesel is a liquid which varies in color — between golden and dark brown — depending on the production feedstock. It is practically immiscible with water, has a high boiling point and low vapor pressure. Typical methyl ester biodiesel has a flash point of ~ 150 °C (300 °F), making it rather non-flammable. Biodiesel has a density of ~ 0.88 g/cm³, less than that of water. Biodiesel uncontaminated with starting material can be regarded as non-toxic.

Biodiesel has a viscosity similar to petrodiesel, the current industry term for diesel produced from petroleum. It can be used as an additive in formulations of diesel to increase the lubricity of pure Ultra-Low Sulfur Diesel (ULSD) fuel, which is
advantageous because it has virtually no sulfur content. Much of the world uses a system known as the "B" factor to state the amount of biodiesel in any fuel mix, in contrast to the "BA" or "E" system used for ethanol mixes. For example, fuel containing 20% biodiesel is labeled B20. Pure biodiesel is referred to as B100.

Biodiesel is a renewable fuel that can be manufactured from algae, vegetable oils, animal fats or recycled restaurant greases; it can be produced locally in most countries. It is safe, biodegradable and reduces air pollutants, such as particulates, carbon monoxide and hydrocarbons. Blends of 20 percent biodiesel with 80 percent petroleum diesel (B20) can generally be used in unmodified diesel engines. Biodiesel can also be used in its pure form (B100), but may require certain engine modifications to avoid maintenance and performance problems. Biodiesel has about 5–8% less energy density, but better lubricity and more complete combustion can make the energy output of a diesel engine only 2% less per volume when compared to petrodiesel — or about 35 MJ/L.

Historical background

Transesterification of a vegetable oil was conducted as early as 1853 by scientists E. Duffy and J. Patrick, many years before the first diesel engine became functional. Rudolf Diesel's prime model, a single 10 ft (3 m) iron cylinder with a flywheel at its base, ran on its own power for the first time in Augsburg, Germany, on August 10, 1893. In remembrance of this event, August 10 has been declared "International Biodiesel Day". Diesel later demonstrated his engine and received the Grand Prix (highest prize) at the World Fair in Paris, France in 1900.

This engine stood as an example of Diesel's vision because it was powered by peanut oil — a biofuel, though not biodiesel, since it was not transesterified. He believed that the utilization of biomass fuel was the real future of his engine. In a 1912 speech Diesel said, "the use of vegetable oils for engine fuels may seem insignificant today but such oils may become, in the course of time, as important as petroleum and the coal-tar products of the present time."
During the 1920s, diesel engine manufacturers altered their engines to utilize the lower viscosity of petrodiesel (a fossil fuel), rather than vegetable oil (a biomass fuel). The petroleum industries were able to make inroads in fuel markets because their fuel was much cheaper to produce than the biomass alternatives. The result, for many years, was a near elimination of the biomass fuel production infrastructure. Only recently, have environmental impact concerns and a decreasing price differential made biomass fuels such as biodiesel a growing alternative.

Despite the widespread use of fossil petroleum-derived Diesel fuels, interest in vegetable oils as fuels in internal combustion engines is reported in several countries during the 1920's and 1930's and later during World War II. Belgium, France, Italy, the United Kingdom, Portugal, Germany, Brazil, Argentina, Japan and China have been reported to have tested and used vegetable oils as Diesel fuels during this time. Some operational problems were reported due to the high viscosity of vegetable oils compared to petroleum Diesel fuel, which result in poor atomization of the fuel in the fuel spray and often leads to deposits and coking of the injectors, combustion chamber and valves. Attempts to overcome these problems included heating of the vegetable oil, blending it with petroleum-derived Diesel fuel or ethanol, pyrolysis and cracking of the oils.

On August 31, 1937, G. Chavanne of the University of Brussels (Belgium) was granted a patent for a 'Procedure for the transformation of vegetable oils for their uses as fuels' (fr. 'Procédé de Transformation d'Huiles Végétales en Vue de Leur Utilisation comme Carburants'Belgian Patent 422,877. This Patent described the alcoholysis (often referred to as transesterification) of vegetable oils using methanol and ethanol in order to separate the fatty acids from the glycerol by replacing the glycerol by short linear alcohols. This appears to be the first account of the production of what is known as 'Biodiesel' today.

More recently, in 1977, Brazilian scientist Expedito Parente produced biodiesel using transesterification with ethanol, and again filed a patent for the same process. This process, is classified as Biodiesel by international norms, conferring a
"standardized identity and quality. No other proposed biofuel has been validated by the motor industry”. Currently, Parente's company Tecbio is working with Boeing and NASA to certify bioquerosene (bio-kerosene), another product produced and patented by the Brazilian scientist.

Research into the use of transesterified sunflower oil, and refining it to diesel fuel standards, was initiated in South Africa in 1979. By 1983, the process for producing fuel-quality, engine-tested biodiesel was completed and published internationally.[10] An Austrian company, Gaskoks, obtained the technology from the South African Agricultural Engineers; the company erected the first biodiesel pilot plant in November 1987, and the first industrial-scale plant in April 1989 (with a capacity of 30,000 tons of rapeseed per annum).

Throughout the 1990s, plants were opened in many European countries, including the Czech Republic, Germany and Sweden. France launched local production of biodiesel fuel (referred to as *diester*) from rapeseed oil, which is mixed into regular diesel fuel at a level of 5%, and into the diesel fuel used by some captive fleets (e.g. public transportation) at a level of 30%. Renault, Peugeot and other manufacturers have certified truck engines for use with up to that level of partial biodiesel; experiments with 50% biodiesel are underway. During the same period, nations in other parts of the world also saw local production of biodiesel starting up: by 1998, the Austrian Biofuels Institute had identified 21 countries with commercial biodiesel projects. 100% Biodiesel is now available at many normal service stations across Europe.

**Technical standards**

The common international standard for biodiesel is EN 14214.

There are additional national specifications. ASTM D 6751 is the most common standard referenced in the United States and Canada. In Germany, the requirements for biodiesel are fixed in the DIN EN 14214 standard and in the UK the requirements for biodiesel is fixed in the BS EN 14214 standard, although these last two standards are essentially the same as EN 14214 and are just prefixed with the respective national standards.
There are standards for three different varieties of biodiesel, which are made of different oils:

- RME (rapeseed methyl ester, according to DIN E 51606)
- PME (vegetable methyl ester, purely vegetable products, according to DIN E 51606)
- FME (fat methyl ester, vegetable and animal products, according to DIN V 51606)

The standards ensure that the following important factors in the fuel production process are satisfied:

- Complete reaction.
- Removal of glycerin.
- Removal of catalyst.
- Removal of alcohol.
- Absence of free fatty acids.
- Low sulfur content.

Basic industrial tests to determine whether the products conform to the standards typically include gas chromatography, a test that verifies only the more important of the variables above. Tests that are more complete are more expensive. Fuel meeting the quality standards is very non-toxic, with a toxicity rating (LD50) of greater than 50 mL/kg.

**Applications**

Biodiesel can be used in pure form (B100) or may be blended with petroleum diesel at any concentration in most modern diesel engines. Biodiesel will degrade natural rubber gaskets and hoses in vehicles (mostly found in vehicles manufactured before 1992), although these tend to wear out naturally and most likely will have already been replaced with FKM, which is nonreactive to biodiesel.

Biodiesel's higher lubricity index compared to petrodiesel is an advantage and can contribute to longer fuel injector life. However, biodiesel is a better solvent than petrodiesel, and has been known to break down deposits of residue in the fuel lines of vehicles that have previously been run on petrodiesel. As a
result, fuel filters and injectors may become clogged with particulates if a quick transition to pure biodiesel is made, as biodiesel “cleans” the engine in the process. Therefore, it is recommended to change the fuel filter within 600–800 miles after first switching to a biodiesel blend.

Use

Pure, non-blended biodiesel can be poured straight into the tank of any diesel vehicle. As with normal diesel, low-temperature biodiesel is sold during winter months to prevent viscosity problems. Some older diesel engines still have natural rubber parts which will be affected by biodiesel, but in practice these rubber parts should have been replaced long ago. Biodiesel is used by millions of car owners in Europe (particularly Germany).

Research sponsored by petroleum producers has found petroleum diesel better for car engines than biodiesel. This has been disputed by independent bodies, including for example the Volkswagen environmental awareness division, who note that biodiesel reduces engine wear. Pure biodiesel produced 'at home' is in use by thousands of drivers who have not experienced failure, however, the fact remains that biodiesel has been widely available at gas stations for less than a decade, and will hence carry more risk than older fuels. Biodiesel sold publicly is held to high standards set by national standards bodies.

Gelling

The temperature at which pure (B100) biodiesel starts to gel varies significantly and depends upon the mix of esters and therefore the feedstock oil used to produce the biodiesel. For example, biodiesel produced from low erucic acid varieties of canola seed (RME) starts to gel at approximately −10 °C. Biodiesel produced from tallow tends to gel at around +16 °C. As of 2006, there are a very limited number of products that will significantly lower the gel point of straight biodiesel. A number of studies have shown that winter operation is possible with biodiesel blended with other fuel oils including #2 low sulfur diesel fuel and #1 diesel / kerosene. The exact blend depends
on the operating environment: successful operations have run using a 65% LS #2, 30% K #1, and 5% bio blend. Other areas have run a 70% Low Sulfur #2, 20% Kerosene #1, and 10% bio blend or an 80% K#1, and 20% biodiesel blend. According to the National Biodiesel Board (NBB), B20 (20% biodiesel, 80% petrodiesel) does not need any treatment in addition to what is already taken with petrodiesel.

Some people modify their vehicles to permit the use of biodiesel without mixing and without the possibility of gelling at low temperatures. This practice is similar to the one used for running straight vegetable oil. They install a second fuel tank (some models of trucks have two tanks already). This second fuel tank is insulated and a heating coil using engine coolant is run through the tank. There is then a temperature sensor installed to notify the driver when the fuel is warm enough to burn, the driver then switches which tank the engine is drawing from.

**Contamination by water**

Biodiesel may contain small but problematic quantities of water. Although it is hydrophobic (non-miscible with water molecules), it is said to be, at the same time, hygroscopic to the point of attracting water molecules from atmospheric moisture; in addition, there may be water that is residual to processing or resulting from storage tank condensation. The presence of water is a problem because:

- Water reduces the heat of combustion of the bulk fuel. This means more smoke, harder starting, less power.
- Water causes corrosion of vital fuel system components: fuel pumps, injector pumps, fuel lines, etc.
- Water freezes to form ice crystals near 0 °C (32 °F). These crystals provide sites for nucleation and accelerate the gelling of the residual fuel.
- Water accelerates the growth of microbe colonies, which can plug up a fuel system. Biodiesel users who have heated fuel tanks therefore face a year-round microbe problem.
Previously, the amount of water contaminating biodiesel has been difficult to measure by taking samples, since water and oil separate. However, it is now possible to measure the water content using water in oil sensors.

**Heating applications**

Biodiesel can also be used as a heating fuel in domestic and commercial boilers. A technical research paper published in the UK by the Institute of Plumbing and Heating Engineering entitled "Biodiesel Heating Oil: Sustainable Heating for the future" by Andrew J. Robertson describes laboratory research and field trials project using pure biodiesel and biodiesel blends as a heating fuel in oil fired boilers. During the Biodiesel Expo 2006 in the UK, Andrew J. Robertson presented his biodiesel heating oil research from his technical paper and suggested that B20 biodiesel could reduce UK household CO2 emissions by 1.5 million tonnes per year and would only require around 330,000 hectares of arable land for the required biodiesel for the UK heating oil sector. The paper also suggests that existing oil boilers can easily and cheaply be converted to biodiesel if B20 biodiesel is used.

**Demand and availability**

Global biodiesel production reached 3.8 million ton in 2005. Approximately 85% of biodiesel production came from the European Union.

**Production**

Chemically, transesterified biodiesel comprises a mix of mono-alkyl esters of long chain fatty acids. The most common form uses methanol to produce methyl esters as it is the cheapest alcohol available, though ethanol can be used to produce an ethyl ester biodiesel and higher alcohols such as isopropanol and butanol have also been used. Using alcohols of higher molecular weights improves the cold flow properties of the resulting ester, at the cost of a less efficient transesterification reaction. A lipid transesterification production process is used to convert the base oil to the desired esters. Any Free fatty acids (FFAs) in the base oil are either converted to soap and
removed from the process, or they are esterified (yielding more biodiesel) using an acidic catalyst. After this processing, unlike \textit{straight vegetable oil}, biodiesel has \textit{combustion} properties very similar to those of petroleum diesel, and can replace it in most current uses.

A byproduct of the transesterification process is the production of glycerol. For every 1 tonne of biodiesel that is manufactured, 100kg of glycerol are produced. Originally, there was a valuable market for the glycerol, which assisted the economics of the process as a whole. However, with the increase in global biodiesel production, the market price for this crude glycerol (containing 20% water and catalyst residues) has crashed. Research is being conducted globally to use this glycerol as a chemical building block. One initiative in the UK is The Glycerol Challenge.

Usually this crude glycerol has to be purified, typically by performing vacuum distillation. This is rather energy intensive. The refined glycerol (98%+ purity) can then be utilised directly, or converted into other products. The following announcements were made in 2007: A joint venture of Ashland Inc. and Cargill announced plans to make propylene glycol in Europe from glycerol and Dow Chemical announced similar plans for North America Dow also plans to build a plant in China to make epichlorhydrin from glycerol. Epichlorhydrin is a raw material for epoxy resins.

\textbf{Biodiesel feedstock}

A variety of oils can be used to produce biodiesel. These include:

- Virgin oil feedstock; rapeseed and soybean oils are most commonly used, soybean oil alone accounting for about ninety percent of all fuel stocks; It also can be obtained from field pennycress and Jatropha other crops such as mustard, flax, sunflower, canola, palm oil, hemp, and even algae show promise (see List of vegetable oils for a more complete list);[18]
- Waste vegetable oil (WVO);
• Animal fats including tallow, lard, yellow grease, chicken fat, and the by-products of the production of Omega-3 fatty acids from fish oil.
• Sewage. A company in New Zealand has successfully developed a system for using sewage waste as a substrate for algae and then producing bio-diesel.
• Thermal depolymerization is an important new process that reduces almost any hydrocarbon based feedstock, including non oil based feedstocks, into light crude oil.

Worldwide production of vegetable oil and animal fat is not yet sufficient to replace liquid fossil fuel use. Furthermore, some environmental groups object to the vast amount of farming and the resulting over-fertilization, pesticide use, and land use conversion that they say would be needed to produce the additional vegetable oil.

Many advocates suggest that waste vegetable oil is the best source of oil to produce biodiesel. However, the available supply is drastically less than the amount of petroleum-based fuel that is burned for transportation and home heating in the world. It is important to note that one gallon of waste oil is not equivalent to one gallon of biodiesel.

Although it is economically profitable to use WVO to produce biodiesel, it is even more profitable to convert WVO into other products such as soap. Therefore, most WVO that is not dumped into landfills is used for these other purposes. Animal fats are similarly limited in supply, and it would not be efficient to raise animals simply for their fat. However, producing biodiesel with animal fat that would have otherwise been discarded could replace a small percentage of petroleum diesel usage.

Biodiesel feedstock plants utilize photosynthesis to convert solar energy into chemical energy. The stored chemical energy is released when it is burned, therefore plants can offer a sustainable oil source for biodiesel production. Most of the carbon dioxide emitted when burning biodiesel is simply recycling that which was absorbed during plant growth, so the net production of greenhouse gases is small.
Feedstock yield efficiency per acre affects the feasibility of ramping up production to the huge industrial levels required to power a significant percentage of national or world vehicles. The highest yield feedstock for biodiesel is algae, which can produce 250 times the amount of oil per acre as soybeans.

**Efficiency and economic arguments**

The debate over the energy balance of biodiesel is ongoing, however. Transitioning fully to biofuels could require immense tracts of land if traditional crops are used. The problem is especially severe for nations with large economies, since energy consumption scales with economic output. If using only traditional plants, most such nations do not have sufficient arable land to produce biofuel for the nation's vehicles. Nations with smaller economies (hence less energy consumption) and more arable land may be in better situations, although many regions cannot afford to divert land away from food production. For third world countries, biodiesel sources that use marginal land could make more sense, e.g. honge oil nuts grown along roads or jatropha grown along rail lines. More recent studies using a species of algae with up to 50% oil content have concluded that only 28,000 km² or 0.3% of the land area of the US could be utilized to produce enough biodiesel to replace all transportation fuel the country currently utilizes. Furthermore, otherwise unused desert land (which receives high solar radiation) could be most effective for growing the algae, and the algae could utilize farm waste and excess CO₂ from factories to help speed the growth of the algae. In tropical regions, such as Malaysia and Indonesia, oil palm is being planted at a rapid pace to supply growing biodiesel demand in Europe and other markets. It has been estimated in Germany that palm oil biodiesel has less than 1/3 the production costs of rapeseed biodiesel. The direct source of the energy content of biodiesel is solar energy captured by plants during photosynthesis.

Biodiesel is becoming of interest to companies interested in commercial scale production as well as the more usual home brew biodiesel user and the user of straight vegetable oil or waste vegetable oil in diesel engines. Homemade biodiesel processors are many and varied. The success of biodiesel homebrewing, and micro-economy-of-scale operations,
continues to shatter the conventional business myth that large economy-of-scale operations are the most efficient and profitable. It is becoming increasingly apparent that small-scale, localized, low-impact energy keeps more resources and revenue within communities, reduces damage to the environment, and requires less waste management.

**Thermal depolymerization**

Thermal depolymerization (TDP) is an important new process for the reduction of complex organic materials into light crude oil. These materials may include non oil-based waste products, such as old tires, offal, wood and plastic. The process mimics the natural geological processes thought to be involved in the production of fossil fuels. Under pressure and heat, long chain polymers of hydrogen, oxygen, and carbon decompose into short-chain petroleum hydrocarbons.

Conversion efficiencies can be very high: Working with turkey offal as the feedstock, the process proved to have yield efficiencies of approximately 85%. That is, the end products contained 85% of the energy contained in the inputs to the process - most notably the energy content of the feedstock, but also accounting for electricity for pumps and natural gas for heating.

**Environmental benefits**

Environmental benefits in comparison to petroleum based fuels include:

- Biodiesel reduces emissions of carbon monoxide (CO) by approximately 50% and carbon dioxide by 78% on a net lifecycle basis because the carbon in biodiesel emissions is recycled from carbon that was in the atmosphere, rather than the carbon introduced from petroleum that was sequestered in the earth's crust. However, it does produce more NOx emissions than standard diesel fuel. (Sheehan, 1998)
- Biodiesel contains fewer aromatic hydrocarbons: benzo[floranthene: 56% reduction; Benzopyrenes: 71% reduction.
Biodiesel can reduce by as much as 20% the direct (tailpipe) emission of particulates, small particles of solid combustion products, on vehicles with particulate filters, compared with low-sulfur (<50 ppm) diesel. Particulate emissions as the result of production are reduced by around 50%, compared with fossil-sourced diesel. (Beer et al, 2004).

Biodiesel has a higher cetane rating than petrodiesel, which can improve performance and clean up emissions compared to crude petrodiesel (with cetane lower than 40).

Biodiesel is biodegradable and non-toxic — the U.S. Department of Energy confirms that biodiesel is less toxic than table salt and biodegrades as quickly as sugar. (See Biodiesel handling and use guidelines)

Since biodiesel is more often used in a blend with petroleum diesel, there are fewer formal studies about the effects on pure biodiesel in unmodified engines and vehicles in day-to-day use. Fuel meeting the standards and engine parts that can withstand the greater solvent properties of biodiesel is expected to—and in reported cases does—run without any additional problems than the use of petroleum diesel.

The flash point of biodiesel (>150 °C) is significantly higher than that of petroleum diesel (64 °C) or gasoline (~45 °C). The gel point of biodiesel varies depending on the proportion of different types of esters contained. However, most biodiesel, including that made from soybean oil, has a somewhat higher gel and cloud point than petroleum diesel. In practice this often requires the heating of storage tanks, especially in cooler climates.

Pure biodiesel (B100) can be used in any petroleum diesel engine, though it is more commonly used in lower concentrations. Some areas have mandated ultra-low sulfur petrodiesel, which reduces the natural viscosity and lubricity of the fuel due to the removal of sulfur and certain other materials. Additives are required to make ULSD properly flow in engines, making biodiesel one popular alternative. Ranges as low as 2% (B2) have been shown to restore lubricity. Many municipalities have
started using 5% biodiesel (B5) in snow-removal equipment and other systems.

Environmental concerns

The locations where oil-producing plants are grown is of increasing concern to environmentalists, one of the prime worries being that countries will clear cut large areas of tropical forest in order to grow such lucrative crops, in particular, oil palm. This has already occurred in the Philippines and Indonesia; both countries plan to increase their biodiesel production levels significantly, which will lead to the deforestation of tens of millions of acres if these plans materialize. Loss of habitat on such a scale could endanger numerous species of plants and animals. A particular concern which has received considerable attention is the threat to the already-shrinking populations of orangutans on the Indonesian islands of Borneo and Sumatra, which face possible extinction.

The oils for biodiesel, and biodiesel itself, produced in Asia, South America and Africa are far cheaper than those produced in Europe and North America. Most biodiesel is therefore not a local, carbon neutral product. Biodiesel requires a large investment of energy before it arrives at petrol pumps. Coupled with the deforestation, and monoculture farming techniques used to grow crops, biodiesel represents a serious threat to the environment. Forests contain large quantities of carbon which are released when they are burnt to make space for farming. Forests also trap carbon in humus and soil, something that farming biodiesel crops does not do. Clearing forests is a cause of global warming and desertification. These problems will be exacerbated as biodiesel becomes more popular unless stringent laws are introduced and enforced to control biodiesel production. Biodiesel produced from clear cut forest land offers no environmental advantage over petroleum diesel.

The Union of Concerned Scientists writes:

When it comes to buying a new car, gasoline-powered models are better than diesels on toxic soot and smog-forming emissions. The downside to current diesels is that they produce 10 to 20 times more toxic particulates than their gasoline
counterparts, more than can be made up for with the use of biodiesel. Diesels fare even worse when it comes to smog-forming nitrogen oxide emissions, with greater than 20 times the emissions of a comparable gasoline vehicle.

Biodiesel is estimated to produce between 10% and 25% more nitrogen oxide NO\textsubscript{x} tailpipe-emissions than petrodiesel. As biodiesel has a low sulfur content, NO\textsubscript{x} emissions can be reduced through the use of catalytic converters to less than the NO\textsubscript{x} emissions from conventional diesel engines. Nonetheless, the NO\textsubscript{x} tailpipe emissions of biodiesel after the use of a catalytic converter will remain greater than the equivalent emissions from petrodiesel. As biodiesel contains no nitrogen, the increase in NO\textsubscript{x} emissions may be due to the higher cetane rating of biodiesel and higher oxygen content, which allows it to convert nitrogen from the atmosphere into NO\textsubscript{x} more rapidly. Debate continues over NO\textsubscript{x} emissions. In February 2006 a Navy biodiesel expert claimed NO\textsubscript{x} emissions in practice were actually lower than baseline. Further research is needed.

Recent advances in the use of cerium oxide, however, hold the potential to nearly eliminate NO\textsubscript{x} emissions from both petrodiesel and biodiesel, and diesel fuel additives based on cerium oxide can improve fuel consumption by 11% in unmodified diesel engines.

(Source: Wikipedia)