Briefing

Biodiesel carbon intensity, sustainability and effects on vehicles and emissions

Authors: Francisco Posada, Chris Malins, Anil Baral

Date: January 2012

Keywords: biodiesel, Jatropha, emissions, ILUC

Summary

This paper summarizes direct and indirect emission and sustainability impacts of biodiesel and assesses the effect of biodiesel blends from the most common feedstocks on compression ignition engine emissions and performance. Key takeaways include:

- Existing biodiesel production pathways are unlikely to deliver significant net climate benefits due to indirect emissions.
- Models of production have been proposed (e.g 'Responsible Cultivation Areas') to avoid indirect emissions from biodiesel production. *Jatropha curcuas L.* (Jatropha) production carefully planned on land without existing provisioning services could offer meaningful carbon benefits.
- Without safeguards, driving biodiesel demand is likely to negatively affect food security and land rights.
- Biodiesel expansion is likely to have negative impacts on biodiversity and the local environment, as is expected from any expansion of industrial agriculture.
- For both social and environmental risks, there are models of production that would avoid or minimise negative impacts – in particular smallholder focused production models implementing sustainability schemes such as the 'Roundtable on Sustainable Biofuels'.
- Biodiesel will have both positive and negative air quality impacts, depending on the pollutant. Biodiesel reduces emissions of HC, CO and PM. The impact on NOx emissions is less significant and more difficult to predict. An increase in particulate number (PN) is expected from biodiesel blends due to condensation of unburned fuel.
- Regarding aldehydes, carbonyls and polycyclic aromatic compounds (PAH)

emissions, the amount of information is very limited, especially for Jatropha and other feedstock of interest to India. Thus, research on this area should be conducted, especially for Bharat III and newer engines and vehicles.

- It is expected that a particle trap would be highly effective in eliminating nucleation mode particles. Given that biodiesel is virtually sulphur-free, biodiesel would allow the use of DPFs in any Euro III or newer vehicle technology.
- Biodiesel is likely to have minor but non-negligible adverse impacts on vehicle reliability.
- The use of biodiesel for automotive applications should be developed in collaboration with local automotive manufacturers. Performance and fuel consumption will be reduced with biodiesel compared to diesel, thus new calibrations for similar performance under emissions compliance are required. The effect of antioxidants should be addressed regarding its effect on emissions of criteria pollutants and toxic organic compounds (aldehydes, carbonyls and PAHs).
- Production processes like vegetable oil hydrogenation may result in products with better conventional pollutants profiles than fossil diesel across the board, and avoid negative impacts on vehicle reliability.

Carbon intensity

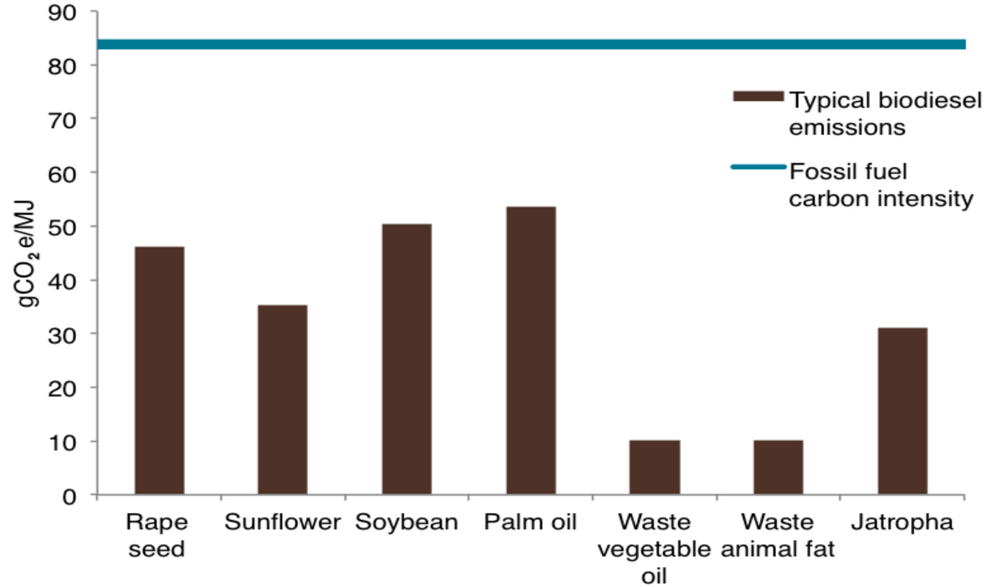
Biodiesel is the generic name given to fatty acid methyl esters made from vegetable oils or animal fats used to power a compression ignition (diesel) engine. Biodiesel is often referred to as a renewable and/or low carbon fuel. However, in actuality most biodiesel pathways result in higher net emissions than the combustion of conventional diesel fuel.

Direct emissions

Direct emissions from biodiesel production are largely the result of agriculture and processing, and can have a wide range. Figure 1 shows typical emissions for various biofuel pathways as determined by the European Commission’s Joint Research Centre. These emissions would go up or down depending on the carbon intensity of electricity used (coal powered electricity would be the highest carbon intensity, renewable electricity the lowest) and factors such as fertiliser application rate.

These direct emissions intensities assume no carbon loss from the field in which biofuels are grown. However, if biofuels are planted directly on areas with high existing carbon stocks (e.g. forests) there will be significant carbon emissions. For instance, one study (Bailley, and Baka 2010) found that if Jatropha is planted on cerrado woodlands there would be an additional emission of 1010 gCO_2e/MJ, on top of cultivation and processing emissions. This would make Jatropha biodiesel much more climate damaging than fossil diesel.

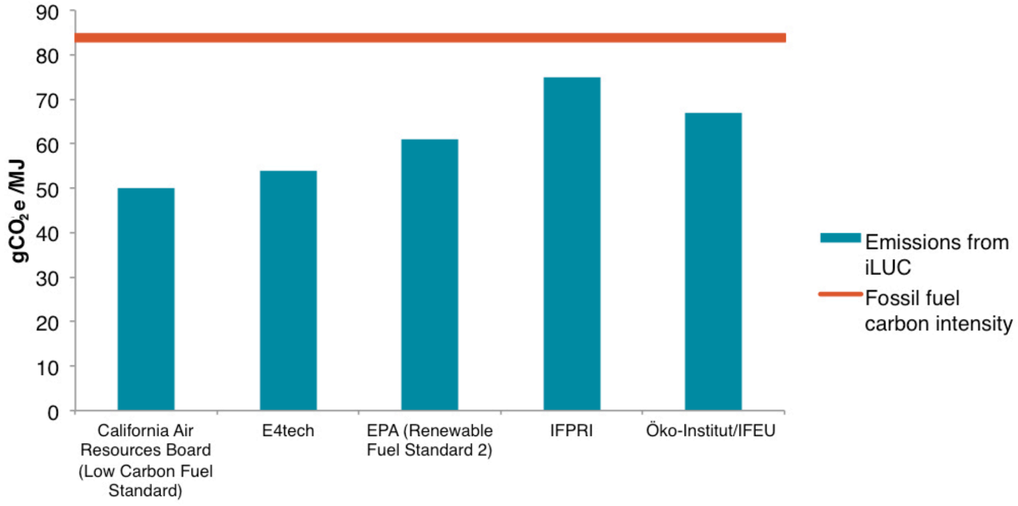
Figure 1. Biodiesel direct emissions (EU LCA)



Indirect emissions

As well as the direct emissions of biofuel production, it is important when considering implementing a biofuel policy to consider the net system wide emissions consequences. For crop-based biofuels, the most important question is indirect land use change (ILUC). This occurs when increasing demand for crops causes land to be converted to agricultural use, with a resulting emission of carbon dioxide. Two of the world's major vegetable oil crops, palm and soy, are known to have strong links to tropical deforestation. Increasing world vegetable oil demand with biodiesel mandates will cause substantial carbon emissions. ILUC results for soy biodiesel from various models are summarized in Figure 2.

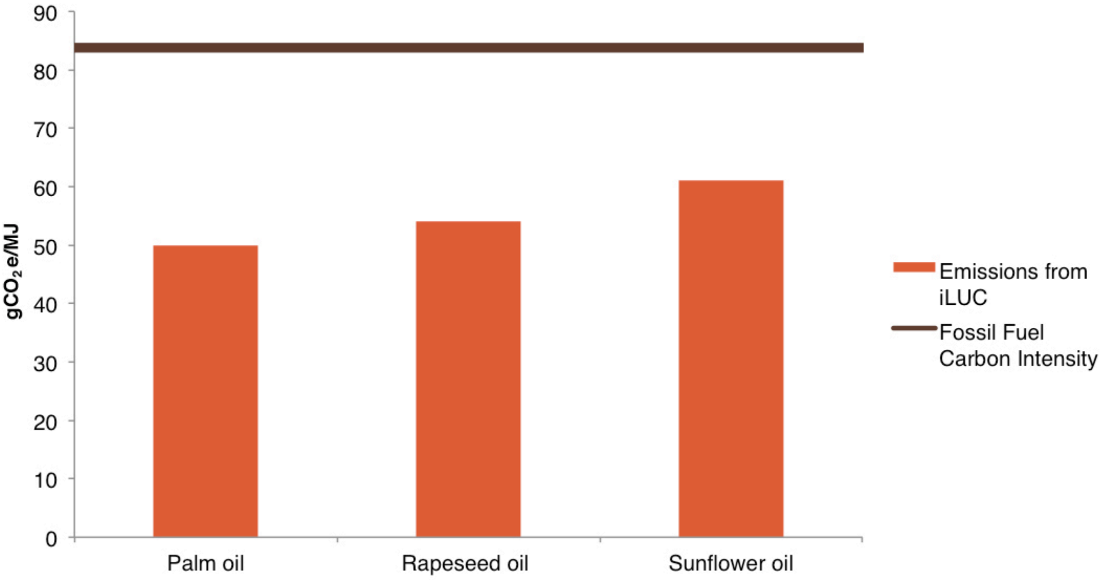
Figure 2. Emissions from ILUC



It is worth noting that the lower result from the United States Environmental Protection Agency (EPA) is based on the projection that soy will displace rice paddies, reducing rice production. In the EPA modelling, this reduces methane emissions from paddies and gives a carbon credit.

Other biodiesel feedstocks have similarly large indirect emissions implications. International Food Policy Research Institute (IFPRI) calculates emissions for oilseed rape, palm oil and sunflower oil, presented in Figure 3.

Figure 3. Emissions from ILUC (IFPRI MIRAGE)



India intends for Jatropha to be a key biodiesel feedstock in the future. Jatropha could, in some circumstances, be a low or even zero ILUC crop. This would be true in cases where Jatropha was able to achieve a worthwhile yield on low quality land with little or no other provisioning value (cf. Ecofys pilot project in Mozambique for certifiably low-ILUC Jatropha production). However, without policy guidance or incentives, such projects will not be the norm for Jatropha. There are numerous examples to date of industrial Jatropha plantations replacing existing farming on good arable land – where this happens, there will be some combination of a loss of food for consumption and indirect land use change – however, as an emerging sector the Jatropha sector is not well-modelled by existing economic models, and hence we are not aware of credible ILUC factor estimates for Jatropha specifically.

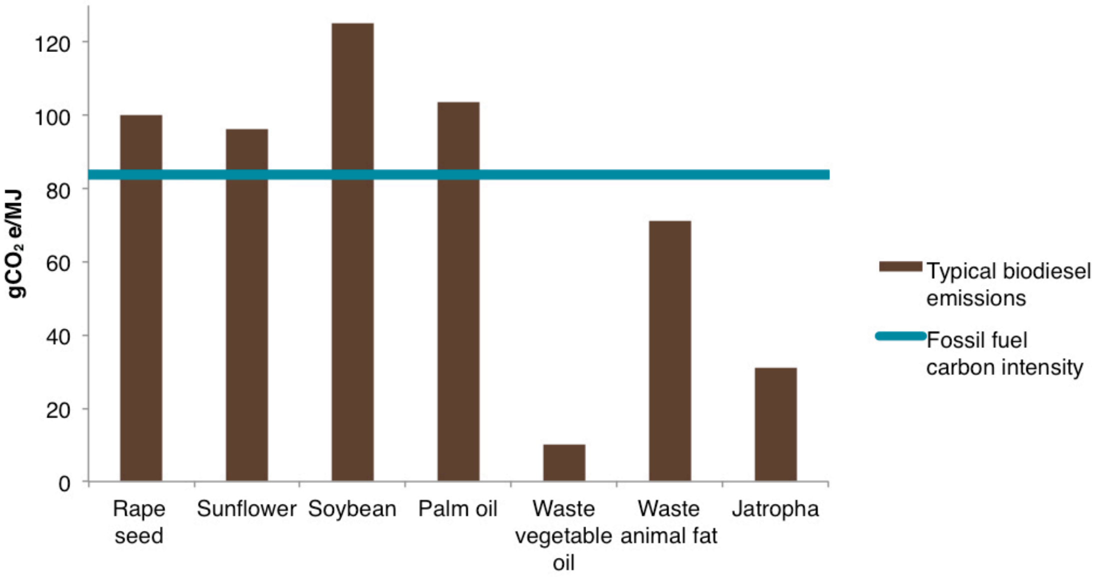
Using materials potentially considered as ‘wastes’ may also result in indirect emissions, if these ‘wastes’ would have been put to use in other sectors. In the UK, for instance, the Department for Transport and Renewable Fuels Agency investigated the consequences of using animal fat for biodiesel. Their conclusion was that there would be significant indirect emissions, as the material would otherwise have been combusted for heat and power, a requirement that would otherwise be met with fossil fuel. The central estimate for these indirect emissions was 61 gCO_2e/MJ.[1]

Total emissions

The sum of direct emissions for biodiesel based on the European methodology with the indirect emissions from the IFPRI MIRAGE model (for crops) and Renewable Fuels Agency work (for 'wastes') is shown in Figure 4.

Clearly, based on these analyses of biodiesel carbon intensity, replacing fossil diesel with biodiesel would not help to mitigate climate change, unless biodiesel could be produced entirely from wastes with no other use, crops grown on low value land (cf. Ecofys' 'Responsible Cultivation Area' methodology) or some other policy could be put in place to substantially improve performance on emissions.

Figure 4. Biodiesel total emissions (EU LCA +IFPRI/RFA)



Sustainability

Carbon emissions are not the only environmental impact of cultivating crops for biodiesel production. There is also potential for other types of environmental degradation and the risk of social impacts.

---

[1] http://webarchive.nationalarchives.gov.uk/20110407094507/http://renewablefuelsagency.gov.uk/reportsandpublications/indirecteffectsofwastes

Land use change, whether indirect or direct, will often impact biodiversity. The same forest habitats that are threatened by soy and palm expansion and have very high carbon content tend to also have high biodiversity value. When industrial agriculture expands, biodiversity is almost always substantially reduced. There is also the risk of conventional pollution. Intensive application of fertiliser and pesticides can be detrimental to both wildlife and humans.

Further, there are social risks. In Latin America, Africa and Asia there are well-documented cases of land conflict arising due to expansion of industrial agriculture – in some regions land conflict is almost ubiquitous. Without frameworks in place to ensure that companies act responsibly, it is to be expected that this pattern of conflict and land grabbing will be repeated many times. Also, unless biofuel support is structured to actively favour smallholders it is almost certain that large plantation companies will supply the majority of feedstock, and without safeguards there is no guarantee that this will be positive for local populations. In Malaysia, for instance, new palm oil plantations typically offer low paid, low quality jobs with much of the workforce supplied by immigration from Indonesia, and hence may provide little or no benefit to local populations.

Food versus fuel

Vegetable oils are an important part of many diets in the developing and developed world, and demand for biodiesel will compete with demand for oil for food use. Economic modelling consistently shows that the most significant food price increases related to biofuels occur for oilseeds. It is a fairly simple tenet of economics that increased demand will tend to increase price, and the economic modelling of biofuel mandates has consistently suggested small but significant food price increases in the medium term due to biofuel mandates.

Studies that have attempted to connect price changes due to biofuels to predictions of poverty rates have suggested that biofuel mandates of the scale seen in Europe, for instance, could push tens of millions of people in the developing world over the poverty line. Because most poor people are net buyers of food, even many in rural areas, the welfare consequences of increased food prices are largely negative for the poor in developing nations. One paper has tried to connect the possible increase in poverty rates to the likelihood of poverty related mortality to estimate the number of additional deaths that might have occurred in the last decade due to biofuel mandates, suggesting a value around 200,000.

There are numerous case studies of the advantages to relatively poor communities that might be available from small-scale, smallholder cultivation of biofuels, primarily for local use. The prevailing policy environment, however, largely favours large-scale export led production, and without specific support, policy and incentives the welfare negative model of biofuels development is likely to dominate.

Effect of Biodiesel on Vehicles and Emissions

Given that biodiesel is chemically and physically different from conventional diesel, significant differences are expected in terms of engine performance, emissions and interaction with engine parts. In Europe, the physical-chemical properties of biodiesel for automotive applications are specified in the EN-14214 standard, while in the US they are described in the ASTM standard called ASTM D-6751-01. In India, biodiesel quality is defined in PCD3(2242)C Draft BIS Specifications.

Biodiesel has approximately 9% less energy content per unit volume than conventional diesel; lower energy content implies that its fuel consumption is higher and vehicle operational range is lower than diesel. In addition, biodiesel has a different chemical composition and might interact with engine parts leading to corrosion and deposit formation.

The effect of biodiesel on engine emissions and performance is highly dependent on feedstock. Although Jatropha is officially suggested as the most suitable plant for the production of biodiesel in India[2], there are very few documented effects of using Jatropha biodiesel in engines. This following paragraphs summarize the effect of biodiesel blends from the most common feedstock on compression ignition engine emissions and performance. A literature review of the tests performed using other biodiesel feedstock is presented to indicate likely impacts on emissions and engine performance of using Jatropha biodiesel.

Biodiesel Effects on Emissions

The use of biodiesel has a mixed effect on conventional pollutant emissions. For most pollutants we expect to see some degree of benefits, but this is not true for all pollutants, NOx in particular. Biodiesel reduces hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM) emissions. The effect of biodiesel on NOx emissions is difficult to assess, as NOx emissions tend to rise with biodiesel use. The number of particulate matter emitted tends to increase with biodiesel, as particulate matter from biodiesel has different characteristics than fossil diesel particulates (smaller particle size), which may increase the potential for adverse health effects. Biodiesel is sulphur free, so biodiesel blends will reduce sulphur emissions. The effect on emissions of toxic hydrocarbons (aromatic and polyaromatic compounds) is mixed and requires studies by feedstock types. The impact of biodiesel on emissions is described below in more detail.

NOx: There is no unanimity on the effect of biofuels on NOx emissions, although most studies point towards a slight NOx increase for biodiesel. A study conducted

---

[2] The Planning Commission of the Government of India selected Jatropha because of its high oil-yielding seeds and ability to grow in a variety of agro-climatic conditions (Planning Commission, 2003).

by the National Renewable Energy Laboratory (NREL) (2003) on 28 pure biodiesel and four B20 blends tested according to the US Federal Test Procedure for HD engines, showed an increase in NOx emissions for all biodiesel tested. Moreover, feedstock containing unsaturated fatty acid chains (soy, canola and soapstock) produce significantly higher NOx emissions than the feedstock containing more saturated fatty acids. Tests conducted by Clark et al. (2010) on HD vehicles in accordance with MY2007 emission standards, show that the use of B20 increased NOx emission by 2.4-2.7% for all vehicles. Tests conducted by Agarwal and Dhar (2009) using mixtures of petroleum diesel and Jatropha at different concentrations show that NO emissions increase at low to mid loads, but no significant differences were experienced at full load conditions. While most research work shows that NOx emissions increase with biodiesel addition, there have been some reports stating the opposite. Reasons for the differences are that the vehicles tested had different technologies and were tested under different conditions, in addition to basic differences in fuel feedstock, qualities and blending (Lapuerta et al., 2007).

The reason most frequently cited for NOx increase is that the ignition occurs more quickly with biodiesel. The physical properties of biodiesel or the response of the engine control unit could cause such early ignition. Injection delay, which causes a small increase in particulate emissions, has been proposed as a mean to delay the ignition (Lapuerta et al., 2007).

According to a recent literature review performed by the Coordinating Research Council (CRC), in modern electronically controlled diesel engines multiple inter-related factors contribute to the overall effect of biodiesel on NOx emissions. These factors include fuel composition, fuel injection strategies, engine operation conditions and engine control/calibration. The CRC report concludes that with all factors being equal NOx emissions increase with increasing fuel unsaturation and decreasing hydrocarbon chain length (CRC, 2011).

Particulate Matter (PM): Biodiesel reduces engine-out PM levels. The majority of studies have found sharp reductions in particulate emissions with biodiesel. Results from the NREL study (2003), show PM reductions with biodiesel fuels. The study concluded that PM emission reductions were dependent only upon the fuel oxygen content, roughly 2.5% for B20 blends and 12% for neat biodiesel (NREL, 2003). Clark and coworkers found that B20 use resulted in a significant reduction on average PM emissions compared to petroleum diesel when tested on HD engines (Clark et al., 2010). The beneficial impact of B20 on PM emission reductions was reduced when a diesel particulate filter was used.

PM reduction is mainly caused by reduced soot formation and enhanced soot oxidation. The oxygen content and the absence of aromatic content in biodiesel have been pointed to as the main reasons of increased oxidation. Under cold-start conditions the mentioned reduction could be eliminated or even reversed (Lapuerta et al., 2007). The experimental work conducted at General Motors confirmed that under steady state conditions an Euro 5 LDV fuelled with a blend of petroleum diesel and Jatropha biodiesel (30%) emits less particulate matter by mass than when fuelled with pure petroleum diesel.

Particulate Number (PN): Biodiesel tends to increase nanoparticles relative count. The majority of authors have reported decreases in the mean diameter of particles obtained when biodiesel fuels are used. Although such a shift is mainly caused by a sharp decrease in the number of large particles, some studies have also found a certain increase in the number of the smallest ones (Lapuerta et al., 2007).

A post-DPF increase in smaller particles was reported by De Filippo et al. (2011) while testing B30-Jatropha, but further explanation was not provided. Cold start results show that rapeseed biodiesel blends present significantly higher particulate number emissions, especially in the nanoparticles range (<30 nm).

Tests in a modern light duty diesel engine powered by different Jatropha-based biodiesel blends showed an increase in particulate numbers with blend levels under steady state tests. It was observed that the number of nucleation mode particles (<20nm) increased, while the number of accumulation mode particles decreased (hence PM decreased). One reason suggested for this increase in nucleation mode particle numbers (PN) with biodiesel blend level is the low volatility of the Jatropha-based biodiesel, resulting in greater formation of condensation particles (Tan et al. 2009).

A detailed explanation for the increase in PN with biodiesel blend was provided by Schonborn et al. (2009) by demonstrating the relationship between fuel boiling point and number of nucleation mode particles. Biodiesel blends derived from rapeseed, tallow, palm and Jatropha were tested. Of these four, Jatropha biodiesel produced the largest number of nucleation mode particles. This was attributed to high molecular weight species present in Japtropha biodiesel.

CO and HC: CO and HC decrease with biodiesel use. A more complete combustion caused by the increased oxygen content in the flame coming from the biodiesel molecules has been pointed to as the main reason in both cases (Lapuerta et al., 2007).

Non-regulated emissions: The emissions of aromatic and polyaromatic compounds, as well as their toxic and mutagenic effect reduce with biodiesel use. However, no conclusive trend has been found regarding the emissions of oxygenated compounds such as aldehydes and ketones. We did not find any study on toxic emissions from Jatropha based biodiesel blends. Emissions test results from some tests of different biodiesel feedstock are presented here.

Tests on soy-based biodiesel in a heavy duty engine showed that the dominant aldehyde emissions were formaldehyde, acetaldehyde and acrolein/acetone. When tested over the 8-mode ISO 8178 test cycle, total carbonyl emissions were nearly 3 times higher from the B100 fuel compared to the petroleum diesel (He et al., 2009).

Interestingly, some studies suggest that the aldehydes emissions are dependent on biodiesel feedstock. Results of chassis testing on a Euro 3 passenger vehicle showed different emissions of aldehydes for B10 blends of rapeseed, sunflower, soybean palm and yellow grease. Under the NEDC and Artemis test cycle, generally higher aldehyde emissions rates were observed from palm, rapeseed and sunflower derived FAME as compared to petroleum diesel. Blends of soy and yellow grease derived FAME gave slightly lower aldehyde emissions compared to petroleum diesel (Fontaras et al., 2010).

New biodiesel pathways such as Neste oil's hydrogenated vegetable oil (HVO) pathways may improve the emissions profile of biodiesel (such fuels are sometimes referred to as 'renewable diesel'). Neste's testing in Finland reported reductions in NOx emissions with HVO, along with particulate emission reductions and zero sulphur. As a drop-in fuel, HVO also should minimise or remove entirely the risk of adverse effects on engines. The process does, however, require more capital investment than esterification[3]. It is worth mentioning, however, that most current Neste production is based on palm oil as a feedstock, which carries some of the highest carbon and sustainability risks. Nevertheless, HVO derived from low-ILUC vegetable oil or waste vegetable oil might be a promising technology.

Overall, while biodiesel will change the emissions profile of diesel blends, it is difficult to authoritatively state whether this will have net benefits or costs.

Biodiesel Effects on Vehicles

The literature review on biodiesel effects confirms that the lower energy density of biofuels sensibly impacts vehicle performance and fuel economy. In addition, biodiesel chemical properties have an impact on the fuel injection system; this is exacerbated with the rapid oxidation (stability) of biodiesel.

Performance: The effect of biodiesel blends use on performance depends on power demands. At partial load operation, no differences in power output were reported, since an increase in fuel consumption in the case of biodiesel would compensate its reduced heating value. On the other hand, at full-load conditions a certain decrease in power has been found with biodiesel, but such a decrease is lower than that corresponding to the decrease in heating value, which means that a small power recovery is often observed. Ignition timing changes can also contribute to performance deterioration (Lapuerta et al., 2007).

Fuel Consumption: An increase in brake specific fuel consumption has been found when using biodiesel in most of the reviewed studies. Such an increase is generally in proportion to the reduction in heating value (9% in volume basis, 14% in mass basis) (Lapuerta et al., 2007). Experimental work conducted on a Euro 5 diesel passenger car with Jatropha B30 by De Filippo et al. (2011) shows that specific engine calibration is required to keep the same performance under

---

[3] http://www.biofuelsjournal.com/articles/Neste_Oil_Reports_Excellent_Results_From_NExBTL_Renewable_Diesel_Fuel_Trials-104905.html

emission compliance. This was attributed to the significant differences between fuel characteristics (i.e. lower heating value of biodiesel), rather than combustion characteristics of fuels.

Stability: The stability of a biofuel refers to how long it can be stored without changing its chemical composition. Depending on feedstock, process and water content, biodiesel experiences different ageing rates. During the ageing process, polymer, acids and peroxides concentrations increase in biodiesel. Polymers tend to clog fuel filters and create deposits that lead to nozzle coking; acids tend to corrode surfaces, especially between adjacent parts; peroxides tend to damage seals (NREL, 2006). Synthetic antioxidants[4] have been used for improving biodiesel stability.

Some auto manufacturers have warned that if the engine is not run for a prolonged period, biodiesel can polymerize, with a risk of the resulting resinous material blocking injector ports (Lapuerta et al., 2007).

Antioxidants: In response to reducing the problems associated with biofuel stability, anti-oxidants for biodiesel are being developed. These products are claimed to prevent oxidation of the fuel's inherent fatty acids into corrosive volatile acids. It is also said to inhibit the formation of undesirable insoluble polymers in the fuel. According to Bayer, their noncorrosive, nonhazardous stabilizer meets the requirements of DIN EN 14214 requiring biodiesel to be "oxidation stable," especially after delivery in bulk to forecourts (Automotive Environment Analyst, 2003). However, literature studying the effect of these anti-oxidants on emissions is scarce and almost unavailable for some specific biodiesel feedstock.

In India, the effect of antioxidant additives on biodiesel emissions has been investigated by the Indian Institute of Technology Kanpur (Khurana & Agarwal, 2011). Biodiesel blends derived from Karanja, Neem and Jatropha were tested with and without antioxidant additions for stability and emissions performance. Jatropha blends were found the most stable. The addition of petroleum diesel improved the oxidation stability of Jatropha, suggesting that blending with petroleum diesel reduces antioxidant requirements. NOx emissions were higher for biodiesel and than petroleum diesel as the literature suggests. The addition of antioxidant increased the rate of NOx emissions. Unfortunately, the set of data presented does indicate how significant the differences were among tests and load conditions.

---

[4] Synthetic antioxidants reported in literature for biodiesel applications are: 2-tert butyl hydroquinone (TBHQ), 6- di-tert butyl-4-methyl phenol (BHT), 2-tert butyl-4-methoxy phenol (BHA), 3,4,5-tri hydroxy benzoic acid (PG), a- Tocopherol (a-T) and 1,2,3 tri-hydroxy benzene (PY).

Research Centers in India Involved in Biodiesel Vehicle Emissions and Performance:

Indian Institute of Technology Kanpur

Sethu Institute of Technology

Delhi Technological University

Indian Institute of Technology Bombay

Bibliography

Agarwal A. K., and Dhar, A., Performance, Emission and Combustion Characteristics of Jatropha Oil Blends in a Direct Injection CI Engine, SAE Technical Paper 2009-01-0947, 2009.

Automotive Environment Analyst. “Preventing biodiesel oxidation.” September. 101:11, 2003

Bockey, D., “Situation and Development Potential for the Production of Biodiesel—An International Study.” www.ufop.de/FAL_Bockey_english.pdf, 2003.

Clark, N., McKain, D., Sindler, P., Jarrett, R., Nuszkowski, J., Gautam, M., Wayne, W., and Thompson, G., “Comparative Emissions from Diesel and Biodiesel Fueled Buses from 2002 to 2008 Model Years,” SAE Technical Paper 2010-01-1967, 2010.

Coordinating Research Council, Investigation of Biodiesel Chemistry, Carbon Footprint and Regional Fuel Quality, Final Report prepared by Kent Hoekman, Amber Broch, Curtis Robins and Eric Ceniceros, February, 2011.

De Filippo, A., Ciaravino C., MIllo F., Vezza D., Fino D., Russo N., Vlachos T., Particle Number, Size and Mass Emissions of Different Biodiesel Blends Versus ULSD From a Small Displacement Automotive Diesel Engine, SAE Technical Paper 2011-01-0633, 2011.

Fontaras, G., G. Karavalakis, M. Kousoulidou, L. Ntziachristos, E. Bakeas, S. Stournas, and Z. Samaras; Effects of low concentration biodiesel blends application on modern passenger cars. Part 2: Impact on carbonyl compound emissions. Environmental Pollution, 158,(7), 2496-2503. 2010.

He, C., Y. Ge, J. Tan, K. You, X. Han, J. Wang, Q. You, and A.N. Shah; Comparison of carbonyl compounds emissions from diesel engine fueled with biodiesel and diesel. Atmos. Environ., 43,(24), 3657-3661. 2009

Khurana D. and Agarwal A.K., Oxidation Stability, Engine Performance and Emissions Investigations of Karanja, Neem and Jatropha Biodiesel and Blends, SAE Technical Paper 2011-01-0617, 2011.

Lapuerta M., Armas O., Rodriguez-Fernandez J., Effect of biodiesel fuels on diesel engine emissions, Progress in Energy and Combustion Science, Volume 34, Issue 2, Pages 198-223, April 2008

NREL, Stability of Biodiesel and Biodiesel Blends: Interim Report, Prepared by R.L. McCormick, T.L. Alleman, J.A. Waynick, S.R. Westbrook and S. Porter, for National Energy Renewable Laboratory, 2006.

NREL, The Effect of Biodiesel Composition on Engine Emissions from a DDC Series 60 Diesel Engine, Final Report, National Renewable Energy Laboratory, February 2003.

Planning Commission, Government of India, "Report of the Committee on Development of Bio-fuel," New Delhi, India April 13, 2003.

Schonborn, A., N. Ladommatos, J. Williams, R. Allan, and J. Rogerson; The influence of molecular structure of fatty acid monoalkyl esters on diesel combustion. Combustion and Flame, 156,(7), 1396-1412. 2009.

Tan, P., Z. Hu, D. Lou, and B. Li; Particle Number and Size Distribution from a Diesel Engine with Jatropha Biodiesel Fuel. SAE Technical Paper, 2009-01-2726, 2009.