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A review of production and use of first generation biodiesel in agriculture

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Abstract. Biofuels manufactured by transesterification from organic fats and oils, usually known as first generation biodiesel, have often been rejected in recent energy policy discussions. Major reasons for this have been the low energy return on investment ratio and greenhouse gas emissions emerging from the production of biodiesel raw material. Studies have indicated that total greenhouse gas emissions from the production chain of first generation biofuels can be equal to fossil fuels or even somewhat bigger.

However, considering the constantly rising energy prices and decreasing fossil energy resources, and the fact that a true substituent for fossils does not exist at the moment, first generation biodiesel could still offer some new possibilities as an energy source at farm level. Because of the limited production capacity and competition with food production, it would be rational to focus the use of this kind of fuel inside the agriculture system.

The object of this review was to examine the use and production of first generation biodiesel at farm level in the present situation. This includes production of biodiesel, suitability for different applications, and economical and environmental evaluation. It was concluded that even though the first generation biodiesel would not reduce emissions, it can assist to save nonrenewable energy. Farm scale biodiesel production is not economically viable at the moment, but the viability is strongly influenced by feedstock price and several other factors.

Key words: biodiesel, biofuel, rapeseed, RME, FAME, energy ratio, energy analysis.

INTRODUCTION

Biofuels refer to fuels manufactured from different kinds of organic biomass. Since also the fossil fuels are fundamentally organic, another criterion for biofuels is renewability: the raw materials have to renew with the same rate they are used in fuel production. Biofuels can be solid, gaseous or liquid, for example wood in different forms, biogas or carbon monoxide, alcohols and several biodiesel fuels. Absolute advantages of liquid biofuels are the high energy density, homogenous composition and good manageability, which lead to reduced storage space, long operation time without refueling and simple and familiar storage and handling technology. These factors are crucial especially in vehicle and moving machinery applications.

Liquid biofuels are usually divided into first and second generation biofuels according to the raw materials and production methods. First generation includes the 'conventional' biofuels, such as alcohols produced by fermentation and fatty acid esters produced from vegetable oils or animal fats. Second generation biofuels can be produced also from lignocellulosic biomass, which means that they do not necessarily compete with food production. (Naik et al., 2010)

For small or moderate scale farm production the most suitable biofuel alternative would be the first generation biodiesel (fatty acid methyl or ethyl ester). Production processes of the second generation biofuels are more complicated and they are best suited for the large production capacities of industrial scale production. Furthermore, first generation biodiesel fuels can be used in existing farm machinery diesel engines without additives or severe modifications to the engine (Bart et al., 2010).

Production and use of first generation biodiesel fuels has aroused some criticism amongst scientists as well as in public discussion. Principal reasons for this have been the competition with the food production, disagreement about the final GHG-emissions and energy balance and the suspicious social sustainability (Singh et al., 2011). Therefore the use and production of biodiesel has sometimes been labeled as non-profitable in terms of ecology and sustainability. In spite of this, the annual production of conventional biodiesel has increased in Europe from ca. 1 million tons in year 2000 to over 9.5 million tons in 2010 (European biodiesel board, 2013). This is mainly caused by the EU biofuel directive 2003/30/EC, which obligated the member nations to increase the share of biofuels to 5.75% of all transportation fuels by the year 2010 (European Union, 2003). Furthermore, directive 2009/28/EC (the RES-directive) sets the member nations a target of increasing the share of biofuels to 10% of all transportation fuels by the year 2020 (European Union, 2009).

Because of limited production capacity, any first generation biofuel cannot replace fossil fuels without having a serious impact on the food production (Hill et al., 2006). However, considering the absence of true alternatives for fossil fuels at the moment, first generation biodiesel could still offer some new possibilities as an energy source inside agriculture. Farms have often suitable properties for small scale biodiesel production, and farmers often possess the applicable technical skills to manage this kind of production system. When biodiesel is produced and used on site, the needs for transportation of the feedstock and the fuel are minimised, and it is possible to utilise the residue oil cake directly as animal feed.

The aim of this paper was to review farm scale production and use of first generation biodiesel in the present situation, including suitability in different applications and economical and environmental evaluation of the fuel. Transesterification reaction of fats and oils is also introduced briefly.

BIODIESEL PRODUCTION

Raw materials and transesterification process

In Europe the most common biodiesel raw material is rapeseed oil, which represents about two thirds of the total input in EU biodiesel production. Other important feedstock materials are soybean and palm oil. Also recycled vegetable oil and animal fats are notable inputs, representing roughly 5% of the total input each. (Flach et al., 2011) In industrial scale production the oil is separated from the rapeseed by solvent extraction or by a combination of solvent and mechanical extraction. In farm scale production the oil extraction can be done mechanically with a simple and inexpensive screw press. Oil content of rapeseed varies between 36–50%, and about 70–75% of the oil can be extracted by pressing (Bart et al., 2010; Norén, 1990). Oil yield may thereby vary between 25–37% of the rapeseed in mass basis, depending on the crop variety, yield properties and pressing efficiency. 25–30% percent of the oil content of the seeds remains in the pressing residue (oil cake) which is therefore valuable feed material in animal production.

Vegetable oils and other lipids are esters of glycerol and three carboxyl acid (fatty acid) molecules, commonly known as triglycerides. In transesterification reaction the glycerol molecule is replaced by three methanol molecules. One triglyceride molecule is hence divided into three methyl ester molecules, and as a result the molecular weight of oil is reduced to about one third. Glycerol is formed as a by-product of the reaction (Srivastava & Prasad, 2000). Vegetable oil methyl esters provide almost similar fuel properties to conventional petroleum based diesel fuels (Graboski et al., 1998). Transesterification reaction is illustrated in Fig. 1.

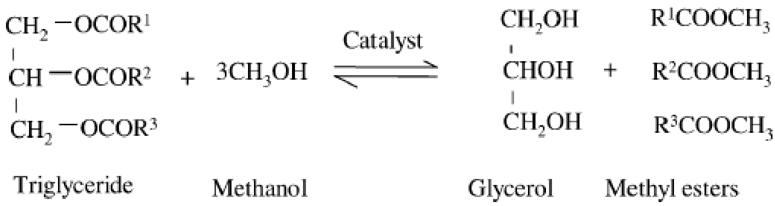

Figure 1. Transesterification of triglyceride with methanol (Naik et al., 2010).

The most commonly used alcohol in biodiesel production is methanol. Also ethanol and other alcohols can be used, but methanol has some advantageous properties, such as low price and high reactivity, which makes the overall production costs of fatty acid methyl ester (FAME) lower than ethyl ester (FAEE) and other alcohol esters. The most common transesterification method in biodiesel production is catalytic transesterification. The reaction occurs spontaneously in atmospheric pressure in the presence of alkaline catalyst, with methyl and ethyl esters usually potassium hydroxide (KOH). Molar ratio of methanol to refined rapeseed oil is 1:6 and the amount of the KOH catalyst is 1%. In practice the reaction solution is usually heated close to the boiling point of methanol to increase the reaction rate. Also mixing during the reaction is required (Bart et al., 2010).

The essential parts of the biodiesel production process are transesterification, recovery of unreacted methanol, purification of biodiesel and treatment of the by-product glycerol. Unreacted methanol can be removed from ester by distillation and the remaining catalyst and other water soluble impurities by washing, followed by drying the water from the product. In industrial scale production the transesterification reaction may be preceded by pretreatment of the oil and esterification of free fatty acids. Also crude oils can be used in biodiesel production, but the impurities cause lower ester yields. For unrefined oils and used cooking oil, a larger amount of KOH catalyst is required to neutralise the free fatty acids (Bart et al., 2010).

Biodiesel production is basically quite simple and small scale reactors are available as ready to use systems. The major problem for small producers is the quality assurance of the produced fuel. Engine manufacturers demand the biodiesel fuel to meet the requirements of European standard EN 14214 for automotive fuel. This standard defines the highest requirements for biodiesel fuel worldwide. Fuel analyses in a third party laboratory may be too expensive for small scale producers (Bart et al., 2010). Another problem is the purification and use of the by-product glycerol, which is the principal valuable raw material in the chemical industry. In small scale production, the profitability of glycerol purification is questionable (Mäkinen et al., 2006). One possible solution for these problems could be a cooperative system that would manage the fuel analyses and glycerol purification and marketing for several small producers. As the volumes of the by-product glycerol are considerably smaller than feedstock and the produced biodiesel, even the transport distances would not be so crucial. Since glycerol has a relatively high heating value (ca. 17 MJ kg^{-1}), it can also be utilised as energy by combustion, for example mixed with wood chips or logs.

BIODIESEL APPLICATIONS

Biodiesel as engine fuel in agriculture

Biodiesel can be used pure in diesel engines or as mixtures with petroleum diesel fuel. Strict emission regulations have contributed to the utilisation of modern diesel engine technology in agriculture, which has set some limits on the use of biodiesel. According to notifications by Finnish tractor distributors, the engine manufacturers allow the use of different kinds of biodiesel blends in their engines. Some engine manufacturers allow the use of 100% biodiesel, some others allow a maximum 7% biodiesel blend. A smaller biodiesel share is usually allowed in the latest engine models, as the older engines from the same manufacturers can often operate with 100% biodiesel. There are usually some limitations and conditions related to the use of biodiesel fuel, such as reduced engine oil and fuel filter change frequency and obligation to use some fuel additive. In some cases an installation of an additional fuel filter is required. The biodiesel fuel must always meet the requirements defined in the EN 14214 -standard.

Biodiesel fuels have 9–13% lower gross heating value in mass basis compared to petroleum diesel fuel, but this is partially compensated by a few percents higher density (Bozbas, 2008). Therefore some 10% decrease in the engine maximum power can be expected when operating with biodiesel fuel. Another disadvantage of biodiesel fuels is poor suitability to cold conditions. Rapeseed methyl and ethyl esters (RME and REE) are one of the most suitable fatty acid esters to be used in cold conditions, having a pour point of – 15°C (Lang et al., 2001).

Crude vegetable oil as engine fuel

The use of crude vegetable oils as engine fuels have been studied a lot. Their advantages are: a very simple production process, lower costs. However, severe problems have been encountered with crude vegetable oil fuels. Problems are mainly caused by the high viscosity and poor volatility of vegetable oils (Peterson et al., 1983). High viscosity causes poor atomisation when the fuel is sprayed in the combustion chamber. Combined with the poor volatility, this results in some unburned fuel remaining in the combustion chamber. The unburned vegetable oil polymerises in high temperatures, forming gummy deposits in engine parts (Fig. 2). Unburned fuel can also leak onto the crankcase between piston and cylinder, causing sticking of piston rings and engine oil dilution. (Darcey at al., 1983; Peterson et al., 1983; Monyem & Gerpen, 2001).

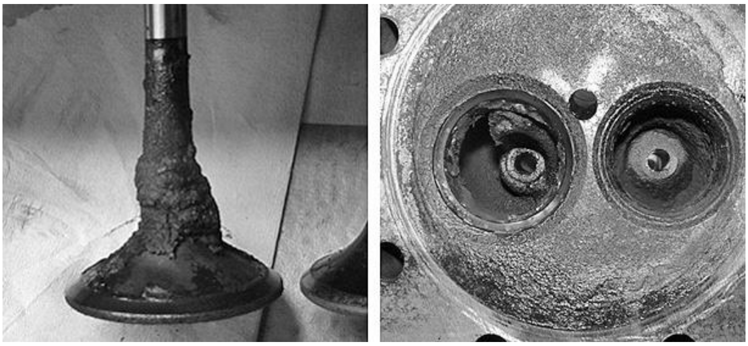

Figure 2. Carbon deposits caused by crude mustard seed oil and rapeseed oil fuels in four cylinder direct injection tractor engine.

The use of crude vegetable oil fuel is prohibited practically by all agriculture machinery engine manufacturers. Some successful engine trials with vegetable oil and diesel fuel blends have been conducted. Ma & Hanna (1999) reported of successful trials with 20% soybean oil / diesel fuel blend. Also Bart et al. (2010) suggest the upper limit of 20% for vegetable oil in a fuel blend based on several studies. However, the engine performance and durability of long term use cannot be guaranteed.

Despite the problems reported with the crude vegetable fuels, some applications have been in serial production recently. In 2007, Deutz Fahr presented the 'Natural Power'-engine that could run on pure rapeseed oil fuel (Deutz Fahr, 2007). The engine was based on a dual fuel system with separate fuels tanks for diesel and rapeseed oil. Rapeseed oil fuel was used only when the engine was warm enough and running under adequate load, and it was heated prior to injection to reduce its viscosity. Also several retrofitted systems to modify vehicles to run on pure vegetable oil are on the market, even though they are not approved by engine manufacturers. For example in Germany in 2009, 100,000 tons of pure vegetable oil was used as fuel, representing 3% of all used biofuels. Most of this was consumed in the agriculture sector (Rauch & Thöne, 2012).

Biodiesel as heating fuel

Heating applications do not usually have such high requirements for energy density and storage space as moving machinery, and they can be considered of a lower level in the energy hierarchy. Therefore it would be reasonable to favour other energy sources in heating than liquid fuels. Exceptions are applications, where high power is needed for a relatively short time, for example grain drying. In these cases the investment costs for other energy sources may become unreasonably high. Biodiesel can be used to replace light fuel oil as heating fuel. It has similar combustion characteristics in heating a furnace as diesel fuel (Tashtoush et al., 2003). However, the poor cold-weather characteristics of biodiesel have to be taken into account in heating applications, as well as the possible deterioration of the organic biodiesel during long term storing. Requirements for biodiesel heating fuel are defined in the European standard EN 14213 (Bart et al., 2010).

Economy of farm scale biodiesel production

Economical viability of biodiesel production depends on the price of feedstock material, costs of oil extraction and esterification, price of the by-products, agriculture subsidies, biodiesel taxation and the price of diesel fuel. In some countries, for example in Europe's largest biodiesel producer Germany, 100% biodiesel used to be free of motor fuel taxes (Bozbas, 2008). Partial taxation was introduced for transportation biofuels in 2006 (Rauch & Thöne, 2012). In Finland the total taxation of biodiesel for agriculture use is at the moment 8.05–16.05 c l^{-1}, depending on the feedstock material. If the feedstock is classified as waste, like for example used cooking oil, tax is 8.05 c l^{-1}. When the raw material is produced according to sustainability requirements defined in the RES-directive, tax is 12.05 c l^{-1}. For other biodiesel fuels the tax is 16.05 c l^{-1} (Finnish customs, 2012).

If biodiesel is produced and used on the farm, the price of the feedstock material is practically the same as the market price of rapeseed, since this is the money the farmer will lose if he does not sell his yield. In practice this means production costs plus the profit from producing rapeseed. At the moment the world market price of rapeseed is ca. 450 € t^{-1}. With the average 30% oil yield, the amount of the oil cake is 2.33 kg per one kilogram of oil, and the current price is ca. 250 € t^{-1}. According to Vihma et al. (2006), the RME production costs in a small or moderate scale plant vary from 0.30 to 0.50 € l^{-1}. Total costs of RME biodiesel production are presented in table 1. Value of the by-product glycerol is ignored in this calculation.

Table 1. Production costs of RME biodiesel in the current market situation

	Costs per oil unit
Rapeseed	1.5 € kg^{-1}
Compensation from oil cake	– 0.58 € kg^{-1}
Total feedstock cost (oil density 0.92 kg l^{-1})	0.84 € l^{-1}
RME production costs	0.30–0.50 € l^{-1}
Tax*	0.12 € l^{-1}
Biodiesel total costs	**1.26–1.46 € l^{-1}**

*Current Finnish taxation for biodiesel used in agriculture when the raw material is produced according to sustainability requirements defined in directive 2009/28/EC.

According to this simplified calculation, the small or moderate scale production of biodiesel on farms is not profitable for the farmer currently. However, the economical viability of biodiesel production is strongly influenced by the rapeseed market price, diesel price and availability of other feedstock. If for example used cooking oil is available, the price of the biodiesel fuel will consist only of the esterification process and the tax of 8.05 c l^{-1} (in Finland), added with collecting and possible filtering and pre-treatment of the feedstock.

Biodiesel energy balance and environmental effects

In order to be viable in terms of energy, the produced biodiesel must contain more energy than what is used in the production. If also the sun radiation energy is included in the analyses, this is not thermodynamically possible. Sun energy is thus often excluded in the energy balance analyses of biofuels, because it is considered as a free and renewable energy input. The ratio of the energy used in production of biofuel and the energy received when using it is called energy balance.

Energy balance can be an ambiguous term yet it can be defined in several different ways. Analysis methods contain many uncertainties and the definition of system borders and the allocation of energy use and emissions are not very clear. Bart et al. (2010) reported energy ratios of 1:1 to 1:3.9 for soy biodiesel, based on information collected from different sources. Differences between the figures are caused by different analysis methods. In addition to the produced biodiesel, all the by-products must also be taken into account and correct amounts of energy and emissions must be allocated to them (Bart et al., 2010). For example the oil cake can be used to substitute some other feed material in animal nutrition, and it is to be held accountable for some fraction of the production energy and emissions.

Mäkinen et al. (2006) conducted a detailed study of energy balances and greenhouse gas emissions of several biofuels in Finnish conditions. Fig. 3 presents the production energy of various biofuels with respect to the energy content of the fuels according to their study. Fig. 3 shows that ethanol production from barley uses almost as much energy as the fuel delivers in combustion. Biodiesel is somewhat more energy efficient, as the production uses only about half of the energy content of the fuel (energy balance 1:2).

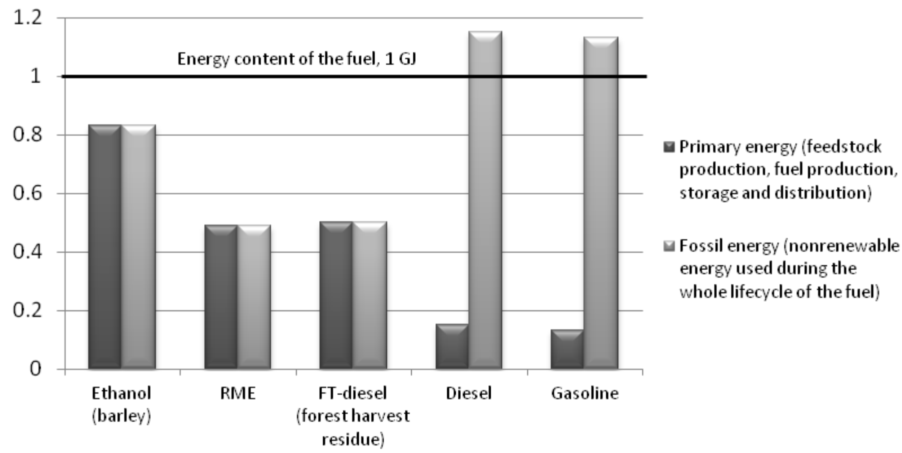

Figure 3. Primary energy inputs and the total fossil energy inputs of various biofuels with respect to the energy content of the fuel (edited from the information provided by Mäkinen et al., 2006).

In addition to the production energy of different fuels, Fig. 3 presents also the amount of fossil energy used during the lifecycles of the fuels. If all of the production energy of biofuels is considered to be of fossil origin, one litre of biodiesel will save more than half a litre of nonrenewable fossil energy. This is because the whole energy content of diesel and gasoline, in addition to primary energy, is of fossil origin.

Combustion of biofuels is usually considered as carbon neutral, because the carbon released in combustion has been captured from the atmosphere during the growth of the plants (Bart et al., 2010). Other exhaust emissions (NO_x, HC, CO, particulates) may differ from conventional fuels to some extent, but the differences are not crucial (Graboski & McCormick, 1998). Feedstock production is hence responsible for the major share of the GHG-emission and a large portion of the production energy of biofuels. This is particularly evident with the first generation biofuels, which use the same energy-intensive production chain as the food production. GHG-emissions of various biofuels are presented in Fig. 4.

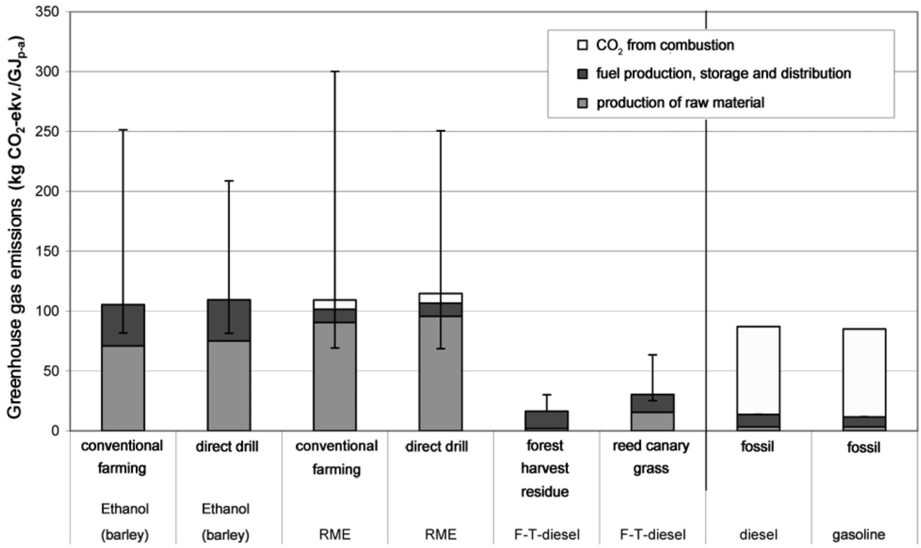

Figure 4. Greenhouse gas emissions of various biofuels (Mäkinen et al., 2006).

Fig. 4 shows that the GHG-emissions from RME are of the same magnitude with fossil fuels. Major part of the GHG-emissions of rapeseed production arises from the manufacturing of fertilisers, especially nitrogen fertiliser. Also the nitrous oxide, which is released as a result of nitrogen fertilisation, is a significant GHG-emission source, since it is a 300 times stronger greenhouse gas than carbon dioxide. Other remarkable emission sources are soil CO_2-emissions due to lime application, use of farm machinery and grain drying (Mäkinen et al., 2006).

There is a great variation in the GHG-emissions of the biofuel production, which can be seen also in Fig. 4. Emissions are strongly influenced by several things, such as the yield level. If the same inputs produce higher yield, for example due to a more successful timing of field operations, the emissions will decline accordingly. Same effect is received if a small extra input, for example plant protection agent application, produces significantly higher yield.

CONCLUSIONS

It is evident that first generation biodiesel cannot substitute fossil fuels due to the limited production capacity and the competition with food production. The key factors in the production are thus the price and availability of feedstock. However, there is no reason to reject the production and use of biodiesel on the basis of environmental aspects. Biodiesel has a positive energy balance, and though the emissions appear to be on the same level with fossil fuels, biodiesel contains twice as much energy as the production consumes. One litre of biodiesel saves therefore about half a litre of nonrenewable fuel.

Because of the limitations in production capacity, it would be reasonable to focus the production and use of biodiesel in the agriculture system. This would increase the security of food production by reducing the need of imported fuels and protein feeds. Biodiesel production would suit well in combination with animal production, when the oil cake as feed would be equally as valuable a product as the biodiesel fuel. Advantages of this decentralised production system would be minimised transportation of feedstock and products. The by-product glycerol, however, could be transported to centralised purification facilities because the volumes are considerably smaller compared to the biodiesel production feedstock.

Technical challenges in small scale biodiesel production are the oil yield and quality level of the product. Lower oil yield is received by pressing compared to industrial scale solvent extraction. However, when the oil cake is used as feed, the remaining oil is utilised in animal nutrition. In order to use the produced biodiesel as engine or heating fuel, it has to meet the requirements of EN 14214 or EN 14213 – standards, respectively. This sets some requirements to the technical level of the production plant. Also the quality assurance may cause problems in small scale production, since fuel analyses by a third party may cause unreasonable costs. This could be solved by cooperation between several small producers.

Biodiesel can be used in diesel engines as well as in heating applications. However, without any new groundbreaking innovations, the decline of fossil fuel resources will inevitably lead to some prioritisation of fuels. Therefore it would be reasonable to save liquid fuels to be used in moving machinery and vehicles, and favour some other renewable energy sources in stationary heating applications.

Authorities could promote the use of biodiesel in agriculture by removing the obstacles that aggravate the local production. This could be done for example by subsidising the biodiesel fuel and oil cake feed analyses for small scale producers to enable the simultaneous feed and fuel production without expensive and continuous laboratory analyses. Some of the conventional agriculture subsidies could also be directed to the measures that generally improve the sustainability and security of agriculture production, such as self-sufficient fuel and protein feed production.

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