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Biodiesel: an Alternative to Conventional Fuel

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Abstract

Due to the increasing awareness of the depletion of fossil fuel resources and environmental issues, biodiesel became more and more attractive in the recent years. Biodiesel production is a promising and important field of research because the relevance it gains from the rising petroleum price and its environmental advantages. This paper reviews the history and recent developments of Biodiesel, including the different types of biodiesel, the characteristics, processing and economics of Biodiesel industry. The application of biodiesel in automobile industry, the challenges of biodiesel industry development and the biodiesel policy are discussed as well.

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Keywords: Biodiesel; Transesterification; Emission; Energy; Challenge; Policy

1. Introduction

Energy is one of the most important resources for mankind and its sustainable development. Today, the energy crisis becomes one of the global issues confronting us. Fuels are of great importance because they can be burned to produce significant amounts of energy. Many aspects of everyday life rely on fuels, in particular the transport of goods and people. Main energy resources come from fossil fuels such as petrol oil, coal and natural gas. Fossil fuel contributes 80% of the world’s energy needs. Most industries use diesel machines for the production process. In the transportation sector, private vehicles, buses, trucks, and ships also consume significant amounts of diesel and gasoline. This situation leads to a strong dependence of everyday life on fossil fuels. However, the growth of the population is not covered by domestic crude oil production [5-6]. Fossil oils are fuels which come from ancient animals and microorganisms. Fossil fuel formation requires millions of years. Thus, fossil oils belong to non-renewable energy sources. An increase of the oil price often leads to economic recessions, as well as global and international conflicts. Especially in some developing countries, the great development in the economy in
fossil fuel resources will be consumed in only 65 more years. In addition the emission produced by the combustion of fossil fuels also contributes to the air pollution and global warming [1-4]. Most countries also experience more and more international pressure on global warming issues. [7-9]. Hence, renewable and clean alternative fuels have received increasing attention for current and future utilization.

Biodiesel as one promising alternative to fossil fuel for diesel engines has become increasingly important due to environmental consequences of petroleum-fuelled diesel engines and the decreasing petroleum resources. Biodiesel can be produced by chemically combining any natural oil or fat with an alcohol such as methanol or ethanol. Methanol has been the most commonly used alcohol in the commercial production of biodiesel. Lots of researches on biodiesel have shown that the fuel made by vegetable oil can be used properly on diesel engines [10-13]. In fact the energy density of biodiesel is quite close to regular diesel. Biodiesel can be produced by soybean and methanol via transesterification in the presence of acid catalysts. Similarities between the combustion properties (Table 1) of biodiesel and petroleum-derived diesel have made the former one of the most promising renewable and sustainable fuels for the automobile [14].

2. The Type of Biodiesel and Its Service Condition

Feedstocks for biodiesel can be divided into oil crops, including soybean, rapeseed and so on; oil trees including Chinese pistachio and palm oil; and other animal fat, waste oil food. Due to its outstanding environmental and renewable characters, fatty acid methyl ester (FAME) is of particular importance. One of the advantages of this fuel is that the raw materials used for production are natural and renewable. All these types of oils come from vegetables or animal fat, making it biodegradable and nontoxic. The typical chemical properties of vegetable oils are given in Table 2 [15]. The typical fractions of fatty acids in different vegetable oils are given in Table 3 [16,17]. Some fuel properties of biodiesel from different oils are shown in Table 4 [18].

The feedstock of biodiesel depends greatly on climate and local soil conditions, consequently different regions are focusing their efforts on different types of oil. As shown in figure 1, in the United States soybean oil is mainly used as raw material, whereas Germany uses mainly rapeseed oil which even set up a special economic sector in order develop biodiesel. Currently, biodiesel has already emerged in 1,500 German gas stations. In the US, biodiesel is specified by ASTM D6751, an authoritative body in 1996 and in 2000 published standards [19,20].

3. Biodiesel Conversion Technologies

Conventional methods of the application of vegetable oil in diesel engines are [22] direct mixing and micro emulsion. These two physical methods can lower the viscosity of vegetable oil, but they can not solve the problem of carbon deposits and lube pollution, and the high temperature pyrolysis cracking is hard to be controlled by its reactant at high temperature. The most relevant process parameters in these kinds of operation are reaction temperature, ratio of alcohol to vegetable oil, amount of catalyst, mixing intensity (RPM), catalyst, and the raw oils used [23].

In contrast, ester exchange is a more advanced method. The triglyceride can be transformed into monoester. Due to the transesterification in the ester exchange process, the viscosity of vegetable oil is reduced and heat values maintained. The Cetane number increases because the molecular chain is cut into 1/3.

Transesterification is the chemical reaction between triglycerides and short-chain alcohol in the presence of a catalyst to produce mono-esters. The long- and branched-chain triglyceride molecules are transformed to mono-esters and glycerin [24]. Commonly-used short-chain alcohols are methanol,
ethanol, propanol and butanol. Methanol is used commercially because of its low price [25]. The overall transesterification reaction can be shown by the reaction equation given in Fig. 2 [24-26].

Because this process is a reversible reaction, the output of biodiesel will be directly influenced by the proportion of reactants, the type and the dosage of the activator, and the reaction conditions.

From the principle of reversible reaction, it follows that a higher usage of carbinol leads to a higher output of biodiesel. However, the higher density of carbinol can cause a polycondensation reaction; as a result, it will reduce the effective concentration of carbinol, and cause difficulties for the separation of biodiesel. Furthermore, more carbinol is associated with higher costs. In the process of batch reaction or continuous reaction activated by an alkalescence catalyst, a 6:1 mol ratio has been used widely [27-30].

There are three common kinds of catalysts in the ester reaction: lipase catalysts, acid catalysts, and alkali catalysts. Each catalyst has its own advantages and disadvantages in the whole reaction process. As the catalyst, enzyme is restricted to rigorous reaction condition and activity lose of lipase etc, it can’t be used on the large commercial production until now.

Most of the commercial biodiesel is produced from plant oils using very effective homogeneous alkali catalysts such as such as sodium or potassium hydroxides, carbonates or alkoxides. [31-34]. The speed of the alkali catalyzing process is higher than that in the acid activating process. This, together with the good corrosion resistance properties, promoted the alkali catalysts to be widely used in industry. However, the alkali catalyzing process is very sensitive to the presence of water and free fatty acids and needs lots of carbinol, accompanied with a saponification reaction which leads to separation problems of biodiesel and glycerin. Moreover, since the alkali catalysts must be neutralized, giving rise to wastewaters they cannot be reutilized, and glycerol is obtained as an aqueous solution of relatively low purity [35-37].

These problems can be alleviated by using heterogeneous transesterification catalysts. Therefore, there is an increasing interest in the possibility of replacing the homogeneous alkaline hydroxides, carbonates or metal alkoxides by heterogeneous solid catalysts insoluble in methanol that could potentially lead to easier and more cost effective refining of the produced biodiesel and glycerol. These catalysts are reusable and lead to less amounts of toxic wastes. A comparison between homogeneous and heterogeneous catalysis is summarized in Table 5 [34].

4. Advantages of Emissions Produced by Biodiesel

Biodiesel can replace fossil fuel as a “clean energy source”. It can protect the environment by reducing CO₂, SO₂, CO, HC.

The carbon cycle of Biodiesel is dynamic through the photosynthesis process as shown in figure 3. Plants absorb CO₂, which is more than those discharged by the biodiesel combustion process. Thus, using biodiesel can more effectively reduce the emission of CO₂, protect the natural environment and maintain the ecological balance, compared to the use of fossil fuel [38].

The emission of SO₂ in the combustion process of biodiesel is much lower than normal diesel oil because of the low sulfur content in it [39]. Thus, the use of biodiesel instead of normal diesel oil will effectively reduce acid rain, which represents a serious threat to the environment and human infrastructure in forms of acidification of soil, surface and ground water forest and vegetation damage, and increased corrosion of buildings and historical monuments made from calcium containing stones. Furthermore, CO, HC and particulate matters will be less discharged, because ester compounds in biodiesel contains oxygen promoting clean burning.

Using biodiesel can also reduce air pollution. The use of biodiesel in a conventional diesel engine results in a substantial reduction of hydrocarbons, aromatic hydrocarbons, carbon monoxide, alkenes, aldehydes, ketones, and particulate matter [40]. Nitrogen oxide emissions are slightly increased if the engine management remains unchanged. However, this can be optimized using special software [41] and
biodiesel sensors [42]. Using biodiesel decreases solid carbon fraction particulate matter and eliminates the sulfate fraction. Increasing the percentage of biodiesel blended with petroleum diesel fuel progressively eliminates sulfates. Biodiesel works well with new technologies such as catalysts, particulate traps, and exhaust gas recirculation. Soy biodiesel reduces carbon dioxide by 78 percent on a life cycle basis. In addition, diesel engine exhaust from biodiesel was found to have a lower mutagenic potential than that from conventional diesel fuel [40, 43]. This effect is believed to result from a lower content of polycyclic aromatic hydrocarbons in the particle emission of biodiesel [40]. Biodiesel is the first alternative fuel that has fully completed the health effects testing requirements of the Clean Air Act.

5. Dynamic Property on Diesel Engines

The flammability of biodiesel is better than that of diesel oil because of its high cetane number which is an index of flammability. It also can be transported conveniently and more safely than diesel oil, due to its high flash point which enables it to be identified as safe goods. Biodiesel has a high viscosity and is composed of fatty acid methyl ester of high unsaturation [44]. It has a good lubricification which can lower the water rate of injection pump, cylinder and engine connecting, and extend the use-life-span of the engine. Biodiesel can be directly used in conventional existing diesel engines due to its similar combustion performance with diesel oil, and also be widely sold using restore and sales network of diesel oil.

All major U.S. manufacturers of diesel engines endorse the use of biodiesel. Biodiesel is not simple vegetable oil. Using unmodified vegetable oils in diesel engines can cause excessive carbon buildup in combustion chambers and reluctance to start. Biodiesel burns more cleanly than petroleum diesel and is a better lubricant and detergent. However, its high detergency can loosen debris in fuel systems that formerly used petroleum diesel and thus lead to a clogging of fuel filters. At higher concentrations, it can also degrade parts made of certain kinds of rubber commonly found in vehicles built before 1994. However, people usually use biodiesel as an additive in petroleum diesel at a 10 percent ratio (B10), at which level it causes few problems [45].

6. Challenges of Biodiesel Industry Development

Increased demand for vegetable oil as an biodiesel feedstock is altering world agricultural landscapes and the ecosystem services they provide, which will highlight a number of negative effects associated with its use.

Many countries’s biodiesel industry development has been motivated by their climate change mitigation target. Because biodiesel produced from biomass have the potential to be “carbon-neutral” over their life cycles as their combustion only returns to the atmosphere the carbon dioxide absorbed from the air by feedstock crops through photosynthesis. However, in order to grow the oil crops necessary to produce biodiesel, additional land must be brought into production. This has led to pristine rainforests being cleared for the sake of monoculture plantations. Worldwide, deforestation accounts for an estimated 20 percent of greenhouse gas emissions. And much of the forest now being cleared for palm oil is peatland, with marshy soils that are crucial holders of methane, a greenhouse gas even more potent than carbon dioxide. At the same time, landscapes with high levels of oil crops had low habitat diversity and significantly reduced biocontrol services in these fields [46,47].

On the other hand, the growing use of food crops as a feedstock of biodiesel has caused negative impacts on health and sanitation and reduced food availability and associated price effects. One major problem is diversion of traditional food and feed crops to biofuel production, as returns to biofuel production are often greater than the returns a farmer might get were the same crops sold for food, or for
non-biofuel crops. Such practices can reduce food availability and may consign food and feed production to less productive land, thus reducing yields and food security, and raising food prices [48,49].

7. The Biodiesel Policy

In recent years, incentives exist within energy-, climate- and agricultural policies in several countries to promote further progress in the use of biodiesel [50]. The policy and government incentives will directly influence the development of biodiesel industry. As a policymaker, government play an essential role in determining the course, and crucially, the scale, of biodiesel development, in particular by means of the proper incentives such as tax exemptions, price controls, targets and direct subsidies. Now, there are many incentives that can be offered by a government to spur the development of biodiesel industry and maintain its sustainability, they are given below [51,52]:

1) Crop plantation in abandoned and fallowed agricultural lands;
2) Subsidizing the cultivation of non-food crops or the usage of waste oil as feedstock;
3) Implementation of carbon tax;
4) Exemption from the oil tax;
5) Mandatory biodiesel blend use in gas station.

While governments are focusing on the ways to improve biodiesel production and consumption, they should give enough attention to unresolved issues like rainforest depletion, food prices increase. Without taking into account these, their policies might have detrimental effects on climate change.

8. The Prospect of the Application of Biodiesel

In conclusion, biodiesel production is set to rise drastically in the coming years. Biodiesel offers the promise of numerous benefits related to energy security, economics, expansion of the agriculture sector and reduction of pollutant emission. Despite its many advantages as a renewable alternative fuel, biodiesel presents a number of problems that must be resolved before it will be more attractive as an alternative to petroleum diesel.

1) These problems include improving the relatively poor low-temperature properties of biodiesel as well as monitoring and maintaining biodiesel quality against degradation during long-term storage (due to its unstable double bond). Maintaining fuel quality during long-term storage is a concern for biodiesel producers, marketers, and consumers. The most cost-effective means for improving oxidative stability of biodiesel is the treatment with antioxidant additives, e.g. the combination with hydrogen to reduce the double bond. This method will, make biodiesel more stable for storage, similar to the diesel oil. However, this method will consume a sheer bulk of hydrogen, so the resource of hydrogen and the rising cost could be a concern. At the same time, care must be exercised in cleaning storage tanks before filling them with biodiesel and in monitoring storage conditions inside the tanks such as temperature, moisture content, exposure to direct sunlight, and the atmosphere (nitrogen “blanket” is preferable) in which the fuel is stored. [24]

2) In spite of the impressive technological advances that have been made over the last decade in the field of biodiesel, a great deal of research remains to be accomplished to fully address technical deficiencies inherent in biodiesel. For example, biodiesel generally has higher density, viscosity, cloud point and cetane number, and lower volatility and heating value compared to commercial grades of diesel fuel. Long-run engine testing have shown that its fatty colloid will plug the fuel oil filter. The high viscosity will lead to a blocking of the fuel injector, and its unburned hydrocarbon also will deteriorate the tube when it leaks into crankcase. Furthermore, Biodiesel generally contains about 10 wt.% of oxygen and thus can be considered as a of oxygenated fuel. The high oxygen content in biodiesel results in the
improvement of its burning efficiency, reduction of PM, CO and other gaseous pollutants, but at the same time produces larger NOx formation, particularly under a high temperature burning environment.

Previous studies have shown that these drawbacks of biodiesel will be solved by mixing with diesel or ethanol. Research also has revealed that fuel blends are stable well below 0°C, and reduce the viscosity as well as NOx emissions. Fuel blends have shown equal or superior fuel properties to regular diesel fuel. [53-59]

As mentioned above, the primary market for biodiesel in the near to long-term future is likely to be as a blend component in petroleum diesel.

3) The cost of biodiesel, however, is the major hurdle to its commercialization in comparison to petroleum diesel (use of edible oil as biodiesel feedstock costs about 60–70% of raw material cost [60]). The high value of soybean oil or canola oil as a food product makes production of a cost-effective fuel very challenging. Use of such edible oil to produce biodiesel is not feasible in view of a big gap in the demand and supply of such oils in the producing countries for dietary consumption. In addition, food prices are expected to continue to rise over the next decade in response to biofuel consumption targets adopted in the world. Therefore, development of alternative feedstocks for biodiesel production is another important area of current and future research [61].

One way of reducing the biodiesel production costs is to use the less expensive feedstocks containing fatty acids such as non-edible oils, animal fats and oils, recycled or waste oil and byproducts of the refining vegetable oils, microalgae. These oils have great potential for supplementing other conventional feedstock. [25, 26, 62-70].

In addition, non-edible plants that contain oil can be cultivated on marginal lands where other crops, such as soybean, rape, palm and sunflower cannot be grown well. By this means, it would not only improve the utilization ratio of marginal lands, but also avoid major ethical and moral issues as would edible oil based biodiesel. Such projects must be well regulated. The governments need to establish regulations to assure that edible oil do not get into the drain; and rationally select the sites for biodiesel plants and other crops. If these precautions are missed, deforestation and intensive monoculture could become catastrophic, actually jeopardizing livelihoods in the long run rather than improving them.

To sum up the above points, biodiesel, rich in vast raw materials, excellent in dynamic properties, has received high attention from many countries, and is environmental-friendly. These benefits of biodiesel will continue to ensure that a substantial market exists for this attractive alternative to conventional petroleum diesel fuel. However, from a commercial standpoint, the traditional petroleum industry may be more comfortable with non-ester renewable diesel fuels than with biodiesel, which may present a substantial challenge to the widespread deployment of biodiesel as an alternative fuel in the future.

All of these evidences indicate that developing biodiesel industry is bound to gain great support from the governments. Now many countries are working to subsidize the biodiesel industry through fiscal and tax policy and set up national standards for the production process, product quality, and production safety in order to standardize the manufacturing. Meanwhile, governments should correctly understand and handle the relation between biofuel and unresolved issues, such food security, land use changes, forest protection.

If these issues mentioned above could be resolved properly, it would be reasonable to believe that in the near future, biodiesel will be widely applied in automobile industry, and bring us more convenience.

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References and Notes


Table 1 Properties of Biodiesel and Diesel (from Ref. 14).

<table>
<thead>
<tr>
<th>Fuel Properties</th>
<th>Biodiesel</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15°C, g/cm³</td>
<td>0.8834</td>
<td>0.8340</td>
</tr>
<tr>
<td>Viscosity at 40°C, mm²/s</td>
<td>4.47</td>
<td>2.83</td>
</tr>
<tr>
<td>Sulfur content, %</td>
<td>&lt; 0.005</td>
<td>0.034</td>
</tr>
<tr>
<td>Carbon, %</td>
<td>76.1</td>
<td>86.2</td>
</tr>
<tr>
<td>Hydrogen, %</td>
<td>11.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Oxygen, %</td>
<td>12.1</td>
<td>---</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>178</td>
<td>62</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>56</td>
<td>47</td>
</tr>
<tr>
<td>Net Calorie value, kJ/kg</td>
<td>37,243</td>
<td>42,588</td>
</tr>
</tbody>
</table>

Table 2 The typical chemical properties of vegetable oils (from Ref. 15).

<table>
<thead>
<tr>
<th>Vegetable oil</th>
<th>Fatty acid composition % by weight</th>
<th>Acid value</th>
<th>Phos (ppm)</th>
<th>Peroxide value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16:1</td>
<td>18:0</td>
<td>20:0</td>
<td>22:0</td>
</tr>
<tr>
<td>Corn</td>
<td>11.67</td>
<td>1.85</td>
<td>0.24</td>
<td>0.00</td>
</tr>
<tr>
<td>Cottonseed</td>
<td>28.33</td>
<td>0.89</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Crambe</td>
<td>20.7</td>
<td>0.70</td>
<td>2.09</td>
<td>0.80</td>
</tr>
<tr>
<td>Peanut</td>
<td>11.38</td>
<td>2.39</td>
<td>1.32</td>
<td>2.52</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>3.49</td>
<td>0.85</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Soybean</td>
<td>11.75</td>
<td>3.15</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sunflower</td>
<td>6.08</td>
<td>3.26</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 3 The typical fractions of fatty acids in different vegetable oils (from Ref. 15).

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Soybean</th>
<th>Cottonseed</th>
<th>Palm</th>
<th>Lard</th>
<th>Tallow</th>
<th>Coconut</th>
<th>Peanut</th>
<th>Rice bran</th>
<th>Sesame</th>
<th>Olive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lauric</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>46.5</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>Myristic</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>46.5</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>Palmitic</td>
<td>10.2</td>
<td>20.1</td>
<td>42.8</td>
<td>23.6</td>
<td>23.3</td>
<td>9.8</td>
<td>12.3</td>
<td>11.2</td>
<td>9.2</td>
<td>18.5</td>
</tr>
<tr>
<td>Stearic</td>
<td>3.7</td>
<td>2.6</td>
<td>4.5</td>
<td>14.2</td>
<td>19.4</td>
<td>3</td>
<td>4.6</td>
<td>1.6</td>
<td>4.8</td>
<td>4.5</td>
</tr>
<tr>
<td>Oleic</td>
<td>22.8</td>
<td>19.2</td>
<td>40.5</td>
<td>44.2</td>
<td>42.4</td>
<td>6.9</td>
<td>53.6</td>
<td>46.5</td>
<td>43.6</td>
<td>65.2</td>
</tr>
<tr>
<td>Linoleic</td>
<td>53.7</td>
<td>55.2</td>
<td>10.1</td>
<td>10.7</td>
<td>2.9</td>
<td>2.2</td>
<td>29</td>
<td>40</td>
<td>41.9</td>
<td>11.2</td>
</tr>
<tr>
<td>Linolenic</td>
<td>8.6</td>
<td>0.6</td>
<td>0.2</td>
<td>0.4</td>
<td>0.9</td>
<td>0</td>
<td>0.1</td>
<td>0.5</td>
<td>0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 4 Some fuel properties of biodiesel from deferent oils (from Ref. 18).

<table>
<thead>
<tr>
<th>Vegetable oil</th>
<th>Kinematics Viscosity (mm²/s)</th>
<th>Cetane number</th>
<th>Cloud point (°C)</th>
<th>Pour point (°C)</th>
<th>Flash point (°C)</th>
<th>Density (kg/l)</th>
<th>Lower Heating value (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peanut</td>
<td>4.9</td>
<td>54</td>
<td>5</td>
<td>---</td>
<td>176</td>
<td>0.883</td>
<td>33.6</td>
</tr>
<tr>
<td>Soya bean</td>
<td>4.5</td>
<td>45</td>
<td>1</td>
<td>-7</td>
<td>178</td>
<td>0.885</td>
<td>33.5</td>
</tr>
<tr>
<td>Babassu</td>
<td>3.5</td>
<td>63</td>
<td>4</td>
<td>---</td>
<td>127</td>
<td>0.875</td>
<td>31.8</td>
</tr>
<tr>
<td>Palm</td>
<td>5.7</td>
<td>62</td>
<td>13</td>
<td>---</td>
<td>164</td>
<td>0.880</td>
<td>33.5</td>
</tr>
<tr>
<td>Sunflower</td>
<td>4.6</td>
<td>49</td>
<td>1</td>
<td>---</td>
<td>183</td>
<td>0.870</td>
<td>33.5</td>
</tr>
<tr>
<td>Tallow</td>
<td>---</td>
<td>12</td>
<td>9</td>
<td>96</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Diesel</td>
<td>3.06</td>
<td>50</td>
<td>---</td>
<td>-16</td>
<td>76</td>
<td>0.855</td>
<td>43.8</td>
</tr>
<tr>
<td>20% biodiesel blend</td>
<td>3.2</td>
<td>51</td>
<td>---</td>
<td>-16</td>
<td>128</td>
<td>0.859</td>
<td>43.2</td>
</tr>
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Table 5: Comparison of homogeneously and heterogeneously catalyzed transesterification (from Ref. 34).

<table>
<thead>
<tr>
<th>Factors</th>
<th>Homogeneous catalysis</th>
<th>Heterogeneous catalysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction rate</td>
<td>Fast and high conversion</td>
<td>Moderate conversion</td>
</tr>
<tr>
<td>Post-treatment</td>
<td>Catalyst cannot be recovered, must be neutralized leading to waste chemical production</td>
<td>Catalyst can be recovered</td>
</tr>
<tr>
<td>Processing methodology</td>
<td>Limited used of</td>
<td>Continuous fix bed continuous methodology operation possible</td>
</tr>
<tr>
<td>Presence of water/ free fatty acids</td>
<td>Sensitive</td>
<td>Not sensitive</td>
</tr>
<tr>
<td>Catalyst reuse</td>
<td>Not possible</td>
<td>Possible</td>
</tr>
<tr>
<td>Cost</td>
<td>Comparatively costly</td>
<td>Potentially cheaper</td>
</tr>
</tbody>
</table>

Figure 1. FAME around the world [21]

Figure 2. Transesterification of triacylglycerols to yield fatty acid alkyl esters (biodiesel).
Figure 3. Closed Loop Cycle of Biodiesel