Chapter 6

Sustainable Waste-to-Energy Technologies: Transesterification

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6.1 INTRODUCTION

As a result of rising demand for energy from various industries and broad global modernization, the price of crude oil is steadily increasing and driving volatility in cost of finished fuel products such as gasoline and diesel. Prices of crude oil are influenced by short-term impacts of world supply and demand for petroleum and other liquids, and production decisions by OPEC (DoE/EIA, 2014). Alternative fuels could provide a means to decrease reliance on fossil fuels, while minimizing net greenhouse gas (GHG) emissions from fuel combustion, thus improving air and water quality. Due to the growing demand from the renewable energy sector and high crude oil prices, global biodiesel production has increased by 23% per year on average between 2005 and 2015 (Naylor and Higgins, 2017). Biodiesel can be produced from vegetable and plants oils, or animal fats, and is an excellent alternative renewable energy source to nonrenewable petroleum-derived diesel fuel.

In August 2017, the Energy Information Administration (EIA) estimated that the United States produces 149 million gallons (564 million liters) of biodiesel produced from 1140 million pounds (517 million kg) of feedstock (EIA, 2017). The U.S. Department of Energy Clean Cities Alternative Fuel Price Report (2014) stated that the average B20 (i.e., 20% biodiesel, 80% petroleum diesel) price at market nationwide was $3.81/gal, while the market price of B100 was $4.21/gal, and diesel $3.77/gal. Over the past 5 years, the cost of pure biodiesel (B100) has been approximately 1.2–1.5 times higher than petroleum diesel, depending on feedstock cost, plant size, and the value of by-product glycerol. Early adopters and environmentally minded consumers may be willing to pay a premium price for a renewable energy resource, but biodiesel production cost is high due to the generally low production volume of biodiesel relative to petroleum diesel. The National Renewable Energy Laboratory (NREL) reported that in 2018 there were 138 biodiesel plants across the United States, producing approximately 1 billion gallons of biodiesel per year (3.8 billion liters/year) from soybean, canola oil, corn oil, animal fats, yellow waste, and waste vegetable oils (NREL, 2018). This production volume is <2/3 of the total production capacity of nearly 2.5 billion gallons/year (9.5 billion liters/year).1 About 40% of production plants use multiple feedstocks and diversifying feedstock portfolio will reduce price volatility and dependency on a single product (Lim and Teong, 2010; Chai et al., 2014). Soybean oil is still the largest biodiesel feedstock, with 608 million pounds (276 million kg) consumed,2 and many biodiesel plants are located in close proximity to the centers of plant and animal feedstocks production in the Midwestern states (Fig. 6.1). However, waste cooking oil (WCO) and fats, oils, and grease (FOG) are common waste streams generated by many industrial, commercial and institutional food sector operations, and with appropriate pretreatment can also be suitable feedstocks for biodiesel production. These materials should be considered integral to the portfolio of resources available for sustainable food waste-to-energy conversion.

As an increase in global biodiesel production capacity has been observed, production of crude glycerol, a by-product of the transesterification reaction, is also expected to increase. However, the demand for crude glycerol has not kept pace, and because of its limited use, an oversupply of crude glycerol has had significant downward pressure on the market price. In 2008 crude glycerol from the rapidly growing biodiesel industry became the main player in the global glycerol market, which has driven some traditional glycerol production plants out of business (Gholami et al., 2014). As the value of crude glycerol has fallen to near zero, biodiesel producers are in many cases required to pay tipping fees to remove the material from their plants for disposal or incineration (Quispe et al., 2013). Efficient utilization of crude glycerol would potentially

help to lower the overall production cost of biodiesel, which is already high compared to diesel. But as the price of crude glycerol has fallen, the prices of alcohols and catalysts needed for purification and upcycling are generally unchanged (Mohammadshirazi et al., 2014). Crude glycerol from biodiesel production often contains a high level of contaminants, which further increases the purification cost. New applications for crude glycerol have been considered, and utilizing low-value crude glycerol in a community-based biodiesel production system is presented later in this chapter.

6.2 POTENTIAL FEEDSTOCKS FOR BIODIESEL PRODUCTION

It has been reported that >350 crops are available as feedstocks for biodiesel production (Atabani et al., 2013). Globally, 30% of biodiesel is produced from soybean oil, 25% from rapeseed oil, 18% from palm oil, 10% from recycled oils, 6% from animal fats, and 11% from other sources (Naylor and Higgins, 2017). In Europe, rapeseed oil is the primary source, while in the United States soybean oil accounts for 51% of total production on average, fluctuating between 40% and 60% of total feedstock used. Palm and coconut oils are widely used in Indonesia and Malaysia (Lim and Teong, 2010).

In many parts of the world, edible oils are considered essential to the daily diet as primary food resources. The demand for edible oils for biodiesel feedstock has been rising and that may create upward pressure on the price of the food commodity. The cost of raw material (vegetable oil or animal fat) is the primary factor driving the high biodiesel production cost, and biodiesel produced from virgin vegetable oil is often sold at a higher price than conventional petroleum diesel oil. Currently, the feedstock used for biodiesel production is primarily edible oils which account for 70%–95% of total production (Math et al., 2010).

The prospective feedstocks for biodiesel production can be categorized into three groups: edible, nonedible, and other sources, as summarized in Table 6.1. The cultivation of edible crops requires arable land which competes with food crops in agricultural land usage, and introduces associated environmental issues such as soil erosion, and pesticide leakage into the surface and groundwater (EEA, 2017). Nonedible biodiesel feedstocks such as jatropha, castor bean, and rubber seed do not directly compete for land needed for food production. Third-generation biofuels derived from alternative feedstocks such as algae seek to address the concerns associated with both edible and nonedible feedstocks. Algae have been considered as a viable feedstock to potentially replace soybean, rapeseed, and palm oils (Lim and Teong, 2010). However, despite high per acre productivity, fast growth rates, and ability to be grown on nonarable land areas, cultivation, harvesting, and valorization of algae biomass require high water use and high capital and operation cost, which make it economically challenging.
Nonetheless, utilization of algae for large-scale biodiesel production is under active research and development in many regions.

Approximately 8 million tons of coffee are produced per year and global coffee consumption is predicted to continue to increase (Vardon et al., 2013). A substantial quantity of spent coffee grounds (SCG) enters the global waste stream and in many regions is recognized as a major disposal challenge. Oil derived from spent coffee grounds (SCG) has been identified as a potential waste-based feedstock for biodiesel production due to its favorable oil content, which can be between 15 and 28 wt% depending on the coffee species, roasting and brewing processes, and extraction methods. One of the drawbacks to SCG as a biodiesel feedstock is that the sources can be widely dispersed, and transporting small quantities of SCG from multiple locations to a central biodiesel plant for further oil extraction is still a questionable economic proposition. Like other edible and nonedible feedstocks, oil from SCG can be extracted using n-hexane as a solvent which is only economically viable at relatively large production scale (Tuntiwattanapun et al., 2017).

The problem of high raw material cost can be addressed by using lower cost (or even “free”) feedstocks such as animal fat and waste vegetable oils. The production cost of biodiesel can be effectively reduced by 60%–70% by using waste cooking oil (WCO) instead of refined virgin oils (Math et al., 2010). Even when including the cost of pretreatment needed for refining relatively impure waste feedstocks, the overall production cost can still be reduced by 45% (de Araújo et al., 2013). The feedstock used for biodiesel production varies across countries depending on their geographical locations and agricultural practices (Lim and Teong, 2010), and the selection of raw material plays a significant role in effective biodiesel production depending on oil content, process chemistry, and economy of the process (Karmakar et al., 2010). For example, the composition of fatty acids in the raw feedstock influences the physiochemical properties of the final biodiesel product. Fig. 6.2 shows the diverse sources of feedstocks used for biodiesel production in the United States. Free fatty acid (FFA) content, moisture content, and other impurities from oils can inhibit the transesterification reaction (described in Section 6.3) and affect the purity and quality of both biodiesel and crude glycerol coproducts. Table 6.2 summarizes typical oil contents and estimated prices of select feedstocks for biodiesel production.

### Table 6.1 Summary of Feedstocks for Biodiesel Production

<table>
<thead>
<tr>
<th>Feedstock Type</th>
<th>Feedstocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edible (1st generation)</td>
<td>Canola, coconut, cottonseed, corn, soybean, sunflower, peanut, rapeseed, palm, mustard</td>
</tr>
<tr>
<td>Other sources (3rd generation)</td>
<td>Microalgae, spent coffee grounds (SCG), fats, oils and grease (FOG; including animal tallow, white grease, brown grease, yellow grease, fish oil), waste cooking oil (WCO)</td>
</tr>
</tbody>
</table>

Adapted and revised from Gui et al. (2008), Atabani et al. (2013), and Verma and Sharma (2016).

![FIG. 6.2 Production of biodiesel from different feedstocks in the United States (Brorsen, 2015).](https://example.com/fig62.png)
6.3 TRANSESTERIFICATION OF WASTE COOKING OIL (WCO)

Oils and Fats International has predicted that global total vegetable oil production in 2017/2018 will be 195 million tons (Lim, 2017). It is reasonable to expect that such large oil production levels will ultimately translate into availability of large volumes of WCO, also referred to as yellow grease, typically derived from edible oil that has been used for a certain period in a deep-frying process. Brown grease is often collected at grease traps in sink drains to prevent discharges of fats, oils, and grease (FOG) from entering and clogging sewer pipes. NREL has estimated that between 3 and 21 lbs (1.4 and 9.5 kg/person/year) of yellow grease from fast-food restaurants are produced in the metropolitan areas of the United States (Wiltsee, 1999). The average amount of grease discharged from each restaurant to sewage treatment plants ranged from 800 to 17,000 lbs/year (363 to 7718 kg/year). Similarly, Wiltsee (1999) reported total per capita production of 4.1 kg/year of yellow grease from fast-food restaurants are produced in the metropolitan areas of the United States (Wiltsee, 1999). The average amount of grease discharged from each restaurant to sewage treatment plants ranged from 800 to 17,000 lbs/year (363 to 7718 kg/year). Similarly, Wiltsee (1999) reported total per capita production of 4.1 kg/year of yellow grease from fast-food restaurants are produced in the metropolitan areas of the United States (Wiltsee, 1999).

### TABLE 6.2 Estimated Oil Content and Average International Crude Vegetable Oil Price of Different Feedstocks and the Corresponding Biodiesel Price

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Oil Concentration (%w/w)</th>
<th>Price of Crude Feedstock (US dollar/ton)</th>
<th>Price of B100 Biodiesel (US dollar/ton)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Edible oils</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>15–20</td>
<td>735</td>
<td>800–805</td>
<td>[1,2]</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>38–46</td>
<td>815–829</td>
<td>940–965</td>
<td>[1,2]</td>
</tr>
<tr>
<td>Palm oil</td>
<td>45–55</td>
<td>610</td>
<td>720–750</td>
<td>[1,2]</td>
</tr>
<tr>
<td><em>Nonedible oil</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Jatropha carcas</em></td>
<td>Seed 35–40 Kernel 50–60</td>
<td></td>
<td>400–500</td>
<td>[2,3]</td>
</tr>
<tr>
<td><em>Microalgae</em></td>
<td></td>
<td>26.3</td>
<td></td>
<td>[4]</td>
</tr>
<tr>
<td>Spent coffee ground</td>
<td>10–15</td>
<td>–</td>
<td></td>
<td>[6]</td>
</tr>
<tr>
<td>Animal tallow</td>
<td>245</td>
<td>500</td>
<td></td>
<td>[2]</td>
</tr>
<tr>
<td>Waste cooking oil</td>
<td>–</td>
<td>224–360</td>
<td>600</td>
<td>[2,7]</td>
</tr>
</tbody>
</table>


Waste cooking oil as a triglyceride supply from domestic and food service industries is the most economically viable feedstock because it is essentially “free” and potentially lowers the biodiesel production cost while also solving a serious waste disposal issue. However, the main disadvantages of waste cooking oil are the high free fatty acid (FFA), water and food residue content, depending on the cooking process and the storage type. Yellow grease (waste cooking oil) typically contains <15% FFA, while brown grease; fats, oils, and grease (FOGs) from grease traps or sewer systems often have >15% FFA. The content of FFA in the oil significantly increases during heating and frying processes over a long period. High FFA and water content and other impurities can present challenges to producing high-quality biodiesel (Wallace et al., 2017).
6.3.1 Basic Transesterification Process

Biodiesel production from vegetable oils and fats has been investigated for many years, and different production methods have been proposed to utilize triacylglycerol-containing materials (Knothe and Razon, 2017). Direct use and blending with petroleum-derived diesel fuel (petrodiesel), microemulsification, thermal cracking, and transesterification are the four basic production technologies. Among them, transesterification is the most economical technology, because of its low temperature and pressure conditions and relatively high yield. Biodiesel is chemically known as the mono-alkyl ester of fatty acids, or fatty acid (m)ethyl ester derived from triacylglycerol of vegetable/plant oils, and animal fats produced by transesterification (Knothe and Razon, 2017). During the transesterification process, also known as alcoholysis, triglycerides of fatty acids are reacted with alcohols in the presence of a catalyst to form monomethyl esters (biodiesel) and glycerol as coproducts, as shown in Fig. 6.3. The most commonly used low molecular weight, short-chain alcohols are methanol and ethanol, with methanol generally being less expensive with better reactivity.

Fundamentally, there are five main parameters that influence the biodiesel production process: free fatty acid (FFA) content of the feedstock, the type and amount of alcohol needed to support the reaction, type and amount of catalyst, molar ratio (alcohol:oil), and reaction time and temperature (Verma and Sharma, 2016). The stoichiometry of the reaction is 3:1 M ratio of alcohol to triglyceride in the oil; however, in practice the most recommended molar ratio is 6:1, in the temperature range of 50–60°C, with reaction time of 1 h with 1% w/w sodium hydroxide or potassium hydroxide since the reaction is reversible and excess methanol is required. <0.5 wt% of free fatty acid content is recommended with zero or low moisture content (Knothe and Razon, 2017). Type of feedstock, choice of catalyst, alcohol-to-oil ratio, reaction temperature, and time influence the transesterification and side reactions (Keera et al., 2011).

Transesterification processes can be categorized into catalytic and noncatalytic reactions. As expected, the presence of a catalyst should noticeably accelerate the reaction (Keera et al., 2011). Catalytic transesterification can be further divided into homogeneous acid and base catalytic reactions, heterogeneous acid and catalysts, and enzyme catalyst (organic in nature) to a lesser extent. The most common and simple noncatalyzed process uses supercritical methanol (MeOH), but it is still a very expensive process. The choice of catalyst for the transesterification reaction is mainly based on the free fatty acid (FFA) composition of the feedstock, and the type of catalyst influences the composition of the biodiesel product (Lam et al., 2010). All these methods have the ability to produce biodiesel from any triglyceride; however, they each have advantages and disadvantages, as summarized in Table 6.3.

6.3.2 Conversion of Institutional WCO

As described previously, heating conditions, FFA composition, and water content can significantly influence conversion of waste cooking oil to biodiesel. In general, waste cooking oils from restaurants and institutional food service operations such as cafeterias often contain large amount of free fatty acids and water. The free fatty acids can react with the alkaline catalyst to produce undesirable reaction by-products such as soap, and therefore the FFA value is expected to be <1 wt% prior to initiating the conversion process. A triglyceride contains a chain of three fatty acid molecules and one glyceride molecule. During the transesterification reaction, triglycerides (TG) are converted to diglycerides (DG) and then DG to monoglycerides (MG), and finally to glycerol. This three-stepwise reaction is reversible, and excess methanol is required to shift the equilibrium to the desired fatty product (Fig. 6.4).

When the raw WCO material contains a high percentage of free fatty acids and water, the water can hydrolyze with the triglyceride to produce diglycerides and form more long-chain free fatty acids while homogenous alkali catalyst (KOH) will react with the FFA to form soaps and water that reduces the ester yield. Strong acid catalysts like sulfuric acid (H$_2$SO$_4$) are often first used for the esterification reaction to reduce the FFA content to less than approximately 1% (Fig. 6.5), followed by methanol in alcoholysis to form biodiesel and glycerol.
<table>
<thead>
<tr>
<th>Chemical Process</th>
<th>Catalyst Materials</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Homogeneous acid catalyst        | • H₂SO₄  
• sulfonic acid  
• hydrochloric acid (HCL) | • high conversion yield  
• relatively less sensitivity to FFA and water than base catalyst  
• low cost | • slow reaction rate  
• high reaction temperature and pressure  
• difficult to separate and recover glycerol  
• H₂SO₄ is corrosive and can lead to corrosion of equipment |
| Homogeneous base catalyst        | • NaOH  
• KOH  
• Sodium methoxide  
• Potassium methoxide | • high conversion rate  
• high catalytic efficiency  
• faster mass transfer rate  
• short retention time  
• low reaction temperature and pressure  
• low cost | • high sensitivity to FFA and water  
• highly energy intensive  
• difficult to recover glycerol |
| Heterogeneous acid catalyst      | • Zirconium oxide (ZrO₂)  
• Titanium oxide (TiO₂)  
• Tin oxide (SnO₂)  
• Zeolites  
• Sulfonic ion-exchange resin  
• Sulfonated carbon-based catalyst  
• Heteropolyacids (HPAs) | • high conversion rate  
• insensitivity to FFA and water  
• catalyze esterification and transesterification simultaneously  
• easy to separate and reuse catalyst | • slow reaction time  
• high operation cost  
• energy intensive  
• high alcohol-to-oil molar ratio |
| Heterogeneous base catalyst      | • Basic zeolites  
• Alkaline earth metal oxides  
• Hydrotalcites (Mg/Al)  
• Calcium oxide (CaO) | • less sensitivity to FFA and water content  
• high glycerol purity  
• easy to separate and reuse catalyst from the product | • slow reaction time and high temperature  
• slow mass transfer rate  
• high alcohol-to-oil molar ratio |
| Enzyme (biocatalyst)             | • Mucor miehei (Lipozym IM60)  
• Pseudomonas cepacia (PS 30)  
• Rhizopus oryzae  
• Penicillium expansum | • high conversion yield  
• insensitivity to FFA and water  
• low operating temperature (lower than homogenous base catalyst)  
• absence of by-product  
• easier purification | • long reaction time (slower than acid-catalyzed transesterification) and slower reaction rate  
• sensitivity to alcohol (methanol deactivates the enzyme)  
• high cost of lipase  
• technology is still under development |
| Noncatalyzed (supercritical MeOH) | • High conversion yield  
• faster reaction rate and very short reaction time  
• absence of catalyst  
• eliminates FFA and water content issues  
• easy to separate by-products | • high reaction temperature and pressure  
• requires large amount of MeOH  
• high cost of operation  
• high alcohol-to-oil molar ratio  
• technology is still under development |

Adapted and revised from Lam et al. (2010), Leung et al. (2010), Gui et al. (2008), Tsoutsos et al. (2016), Gnanaprakasam et al. (2013), and Yaakob et al. (2013).
by base-catalyzed transesterification (Lam et al., 2010). NREL has recommended a recipe of reactants for the FFA pretreatment which is widely adopted by most biodiesel manufacturers: 2.25 g methanol and 0.05 g sulfuric acid for every gram of FFA in the WCO, equivalent to 19.8:1 methanol-to-FFA molar ratio and 5% acid-to-FFA weight percentage (Chai et al., 2014).

### 6.3.2.1 Determination of Acid Value/Fatty Acid Content

Free fatty acids content of waste cooking oil from institutional cafeterias has been determined to be lower than many other establishments (i.e., fast-food restaurants) as the cooking oil replacement rate should be faster. However, there are no specific guidelines or regulations on how often cooking oil should be replaced. Sanli et al. (2011) investigated the FFA content from different facilities; however, there are very limited data on free fatty acids values of WCO from institutions such as universities. Frank (2014) and Bruton (2014) measured FFA content of WCO from a university cafeteria, and measured 4.42 and 3.30 wt%, respectively. The acid value is defined as the amount of free fatty acid present in the oil requiring a computed mass of potassium hydroxide to neutralize it. This value is used to determine the amount of base catalyst to neutralize the acidity of a gram of raw material (Luque and Melero, 2012). The acid value (AV) is determined by applying Eq. (6.1) (Banani et al., 2015). A titration method is typically used to measure the FFA concentration and determine the fatty acid conversion during esterification. This method provides the amount of excess base catalyst required to neutralize the FFAs based on the initial concentration in the WCO. The extent of the acid esterification reaction can be determined by the acid value and the FFA conversion rate (Chai et al., 2014).

\[
AV \text{ (mg KOH/g)} = \frac{56.1 \times C_{\text{KOH}} \times V_{\text{KOH}}}{m}
\]  \hspace{1cm} (6.1)

where

- 56.1 = molecular weight of the solution employed for titration (g/mol)
- \( C_{\text{KOH}} \) = concentration of the titration KOH solution (g/mol)
- \( V_{\text{KOH}} \) = volume of solution employed for titration (mL).
- \( m \) = mass of the fatty acid sample (g)

The free fatty acid (FFA) conversion rate is calculated by Eq. (6.2):

\[
\text{FFA conversion} = \frac{(\text{Initial FFA} - \text{Final FFA})}{\text{Initial FFA}} \times 100\%
\]  \hspace{1cm} (6.2)

where

- Initial FFA = initial free fatty acid value (mg KOH/g)
- Final FFA = final free fatty acid value (mg KOH/g)
6.3.2.2 Two-Step Esterification/Transesterification

The conventional method of producing biodiesel from edible virgin oils today is homogeneous base-catalyzed transesterification on a larger production scale. In such systems, common base catalysts are sodium hydroxide (NaOH), sodium methoxide (CH₃NaO), potassium hydroxide (KOH), and potassium methoxide (CH₃KO). These catalysts are widely used because they provide fast reaction rate for a short process time (30–60 min), ability to run the process at lower temperature and atmospheric pressure, higher product yield and purity (Math et al., 2010). However, base catalysts are more effective with high purity reactants having <1 wt% free fatty acids and have generally performed better with virgin vegetable oils (Demirbas, 2009). When the waste cooking oil FFA content exceeds 1 wt%, a two-step catalyzed process is recommended. Acid catalysts are a better option if the initial feedstock oil has high FFA and/or water content. The most widely used acid catalysts are sulfuric acid, sulfonic acid, and hydrochloric acid. Unlike base catalysts, they are generally insensitive to FFA content and both oil and FFA can lead directly to the methyl ester (Chai et al., 2014). Longer reaction times, the requirement of a large amount of alcohol and lower yield makes acid-catalyzed reactions unattractive for large-scale biodiesel production. Fig. 6.6 shows the schematic flow diagram of two steps (esterification and transesterification process) biodiesel production from institutional waste cooking oil.

When the feedstock contains a significant amount of free fatty acids, the acid pretreatment step (acid esterification) is recommended to neutralize the free fatty acid content before proceeding to the “standard” transesterification reaction. As stated previously, many nonedible oils and low-quality feedstocks such as grease trap waste, animal fats, and waste cooking oils contain high free fatty acid content. Acceptable levels of FFA concentration in WCO should be lower than <5 wt% to achieve acceptable biodiesel yields (Lam et al., 2010). In the pretreatment process, free fatty acids in the oil are esterified to methyl ester with acid catalyst (H₂SO₄) in the presence of methanol while reducing the acid value (Fig. 6.5). Without this pretreatment step, excess free fatty acid in the raw oil would likely react with the alkali catalyst (KOH) through the saponification reaction to form alkali salts of fatty acids (soap) and water (Fig. 6.7). During this reaction, the catalyst is utilized by FFA and therefore water also inhibits the reaction which reduces the catalyst activity and leads to more difficulty in the separation process. Additionally, when there is water in the raw oil or it is generated during the saponification reaction, it will hydrolyze the triglycerides to form additional free fatty acid (Fig. 6.8).

As discussed in Section 6.2, feedstock characteristics have an important influence in determining the effectiveness of the biodiesel production process. Direct use of vegetable oils and animal fats as combustible fuel is generally not possible due to their high kinematic viscosity and low volatility compared to No. 2 diesel (Math et al., 2010). The reduction of viscosity can be achieved by transesterification of oil to produce biodiesel which has properties similar to diesel fuel. Furthermore, some feedstocks like jatropha, WCO, and animal fat have higher acid/FFA content which requires additional pretreatment process for biodiesel production. Table 6.4 shows typical physical and chemical properties of some common feedstocks. Generally, the reported properties of WCO, such as water, insolubles, unsaponifiables, phosphorous, and sulfur levels are all within acceptable ranges for biodiesel production and similar to the virgin oils. As shown in Table 6.5, the

**FIG. 6.6** Overall schematic process flow for biodiesel production using institutional WCO.
FIG. 6.7 Saponification reaction (Van Gerpen, 2005).

\[
\text{Fatty acid} + \text{Potassium hydroxide} \rightarrow \text{Potassium soap} + \text{Water}
\]

\[
\text{HO} - \text{C} - \text{R} + \text{KOH} \rightarrow \text{K} - \text{O} - \text{C} - \text{R} + \text{H}_2\text{O}
\]

FIG. 6.8 Hydrolysis of triglycerides (Van Gerpen et al., 2004).

\[
\text{Triglyceride} + \text{Water} \rightarrow \text{Diglyceride} + \text{Fatty acid}
\]

\[
\text{CH}_2 - \text{O} - \text{C} - \text{R}_1 + \text{H}_2\text{O} \rightarrow \text{CH}_3 - \text{O} - \text{C} - \text{R}_2 + \text{HO} - \text{C} - \text{R}_1
\]

TABLE 6.4 Comparison of Physiochemical Properties of Different Feedstocks for Biodiesel Production

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Soybean</th>
<th>Palm</th>
<th>Jatropha</th>
<th>Microalgae (Spirulina platensis)</th>
<th>Spent Coffee Oil</th>
<th>Waste Cooking Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating value</td>
<td>MJ/kg</td>
<td>39.6</td>
<td>39.3</td>
<td>37.01–38.73</td>
<td>41.36</td>
<td>23.10–38.22</td>
<td>41.40</td>
</tr>
<tr>
<td>Density (40°C)</td>
<td>kg/m³</td>
<td>890–913</td>
<td>881–919</td>
<td>919.5–932</td>
<td>860</td>
<td>925*</td>
<td>924**</td>
</tr>
<tr>
<td>Kinematic Viscosity (40°C)</td>
<td>mm²/s</td>
<td>28.08–32.6</td>
<td>39.4</td>
<td>35.62–51</td>
<td>5.66</td>
<td>42.65–49.64</td>
<td>36.4</td>
</tr>
<tr>
<td>Pour point</td>
<td>°C</td>
<td>–12.2</td>
<td>–</td>
<td>2</td>
<td>–18</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>254</td>
<td>252–267</td>
<td>242–274</td>
<td>130</td>
<td>&gt;200</td>
<td>212</td>
</tr>
<tr>
<td>Cloud point</td>
<td>°C</td>
<td>–3.9</td>
<td>31.0</td>
<td>–</td>
<td>–</td>
<td>11–12.2</td>
<td>–</td>
</tr>
<tr>
<td>Cetane Number</td>
<td></td>
<td>37.9</td>
<td>42.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>49</td>
</tr>
<tr>
<td>Acid value</td>
<td>mgKOH/g</td>
<td>0.709</td>
<td>0.1</td>
<td>42.78</td>
<td>0.45</td>
<td>9.85–11.27</td>
<td>43.46</td>
</tr>
<tr>
<td>Free fatty acid</td>
<td>%</td>
<td>0.3545</td>
<td>7.5</td>
<td>21.5</td>
<td>–</td>
<td>0.412</td>
<td>1.32–5</td>
</tr>
</tbody>
</table>

References
<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Method</th>
<th>Catalyst</th>
<th>Alcohol</th>
<th>Acid Catalyst (wt%)</th>
<th>Base Catalyst (wt%)</th>
<th>T (°C)</th>
<th>Reaction Time</th>
<th>Molar Ratio (Alcohol to Oil Ratio)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean oil [1]</td>
<td>Esterification</td>
<td>Homogeneous acid</td>
<td>Methanol</td>
<td>1</td>
<td>–</td>
<td>65</td>
<td>69h</td>
<td>–</td>
<td>&gt;90</td>
</tr>
<tr>
<td></td>
<td>Transesterification</td>
<td>Heterogeneous base</td>
<td>PbO</td>
<td>–</td>
<td>–</td>
<td>215</td>
<td>7:1</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heterogeneous acid</td>
<td>Al₂O₃/ZrO₂/WO₃</td>
<td>Methanol</td>
<td>–</td>
<td>250</td>
<td>40:1</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biocatalyst (enzyme)</td>
<td>Lipozyme RMIM</td>
<td>Methanol</td>
<td>7</td>
<td>50</td>
<td>3:1</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Rapeseed oil [2]</td>
<td>Transesterification</td>
<td>Homogeneous base</td>
<td>KOH</td>
<td>0.7</td>
<td>30</td>
<td>60 min</td>
<td>60 min</td>
<td>9:1</td>
<td>97–98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heterogeneous acid</td>
<td>ZnO</td>
<td>–</td>
<td>–</td>
<td>225–230</td>
<td>6h</td>
<td>20:1</td>
<td>94.3</td>
</tr>
<tr>
<td></td>
<td>Transesterification</td>
<td>Homogeneous base</td>
<td>KOH</td>
<td>1</td>
<td>60</td>
<td>60 min</td>
<td>6:1</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heterogeneous base</td>
<td>KNO₃/KL zeolite</td>
<td>Methanol</td>
<td>–</td>
<td>200</td>
<td>–</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heterogeneous base</td>
<td>Hydrotalcite particles with Mg/Al</td>
<td>Methanol</td>
<td>1</td>
<td>45</td>
<td>1.5 h</td>
<td>4:1</td>
<td>95.2</td>
</tr>
<tr>
<td>Microalgae oil</td>
<td>Supercritical transesterification</td>
<td>–</td>
<td>Methanol</td>
<td>270–350</td>
<td>–</td>
<td>10:1–42:1</td>
<td>90.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent coffee grounds [6]</td>
<td>In situ transesterification</td>
<td>–</td>
<td>H$_2$SO$_4$</td>
<td>Methanol</td>
<td>20</td>
<td>–</td>
<td>70</td>
<td>12 h</td>
<td>28.87 ml methanol/g oil</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------------------------</td>
<td>---</td>
<td>-------------</td>
<td>----------</td>
<td>----</td>
<td>---</td>
<td>---</td>
<td>----</td>
<td>-------------------</td>
</tr>
<tr>
<td>In situ transesterification</td>
<td>–</td>
<td>NaOH</td>
<td>Methanol</td>
<td>3:1 catalyst to oil mole ratio</td>
<td>60</td>
<td>90 min</td>
<td>400:1</td>
<td>96.0</td>
<td></td>
</tr>
<tr>
<td>Transesterification</td>
<td>1. Homogeneous acid 2. Homogeneous base</td>
<td>1. HCl 2. KOH</td>
<td>Methanol</td>
<td>10</td>
<td>1</td>
<td>54</td>
<td>90 min</td>
<td>20:1 9:1</td>
<td>82</td>
</tr>
<tr>
<td>Transesterification (used canola)</td>
<td>Homogenous base</td>
<td>NaOH</td>
<td>Methanol</td>
<td>–</td>
<td>0.08</td>
<td>60</td>
<td>20 min</td>
<td>28 mL per 100 mL of oil</td>
<td>94.5</td>
</tr>
<tr>
<td>Transesterification (used sunflower)</td>
<td>Homogenous base</td>
<td>KOH</td>
<td>Methanol</td>
<td>–</td>
<td>1</td>
<td>25</td>
<td>30 min</td>
<td>6:1</td>
<td>Maximum</td>
</tr>
<tr>
<td>Supercritical methanol transesterification</td>
<td></td>
<td></td>
<td>Methanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transesterification</td>
<td>Heterogeneous base</td>
<td>CaO</td>
<td>Methanol</td>
<td>0.85%</td>
<td>60–65</td>
<td>1 h</td>
<td>12:1</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>Transesterification</td>
<td>Heterogeneous acid</td>
<td>Zeolite Y (Y756)</td>
<td>Methanol</td>
<td>–</td>
<td>–</td>
<td>460</td>
<td>0.37 min</td>
<td>6:1</td>
<td>26.6</td>
</tr>
<tr>
<td>Transesterification</td>
<td>Biocatalyst (enzyme)</td>
<td>Novozyme 435</td>
<td>Methanol</td>
<td>–</td>
<td>4% based on oil mass</td>
<td>–</td>
<td>40</td>
<td>12 h</td>
<td>4:1</td>
</tr>
<tr>
<td>Microwave-assisted transesterification</td>
<td>Heterogeneous alkali on the carbonized coconut shell</td>
<td>KOH/CS</td>
<td>Methanol</td>
<td>–</td>
<td>5</td>
<td>80</td>
<td>40 min</td>
<td>12:1</td>
<td>91.3</td>
</tr>
</tbody>
</table>

TABLE 6.6 Physiochemical Properties of Biodiesel Produced From Different Feedstocks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Edible Oils</th>
<th>Nonedible Oils</th>
<th>Other Sources (Waste Based)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soybean</td>
<td>Rapeseed</td>
<td>Palm</td>
</tr>
<tr>
<td>HHV (MJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematic viscosity (mm²/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>–4</td>
<td>–10.8</td>
<td>12</td>
</tr>
<tr>
<td>Flash point (°C, min)</td>
<td>168–185</td>
<td>155</td>
<td>135</td>
</tr>
<tr>
<td>Cloud point (°C)</td>
<td>–0.5</td>
<td>–4</td>
<td>16</td>
</tr>
<tr>
<td>Cetane number (°C)</td>
<td>45–60.9</td>
<td>52.9</td>
<td>57.3</td>
</tr>
<tr>
<td>Acid value (mg KOH/g)</td>
<td>–</td>
<td>–</td>
<td>0.08</td>
</tr>
</tbody>
</table>


varying feedstock properties dictate the use of different transesterification processes and operating parameters, which in turn result in final biodiesel products with different ranges of critical properties such as density, viscosity, pour point, flash point, and cetane number (Table 6.6). Comparison between the data in Tables 6.4 and 6.6 indicates that the relatively high kinematic viscosity of vegetable oil feedstocks is reduced after transesterification.

6.4 USES OF BIODIESEL

Global demand for transportation fuels has been growing and is expected to increase from 124 billion liters in 2015 to 202 billion liters by 2024 (Verma and Sharma, 2016). The rise in crude oil demand, and the attendant GHG emissions, provide strong motivations to find alternative fuels. The U.S. Renewable Fuel Standard (RFS) mandates that renewable energy fuels in the U.S. transportation sector should provide a minimum use of 136 billion liters (36 billion gallons) by 2022. Biodiesel has been recognized as the best alternative to ultra-low sulfur diesel (ULSD) and provides many advantages over diesel fuel which include lower sulfur content, no aromatic content, biodegradability, and miscibility with petroleum-based diesel in all blend ratios. Also, the lack of significant modifications required for diesel engines or gen-sets makes biodiesel the most attractive renewable fuels over other available options, although there is an approximately 10% lower energy content compared to petroleum diesel fuel (Math et al., 2010). Global biodiesel production has continued to rise even as crude oil prices have dropped since mid-2014. As of 2015, the United States produced 4.8 billion liters (1.3 billion gallons) of biodiesel and contributed 15% of global production (Naylor and Higgins, 2017).

Biodiesel has largely developed as an alternative transportation fuel, although it has numerous potential uses which include space heating, and a small quantity of biodiesel is used in lubricants, plasticizers, high boiling absorbents for cleaning of gaseous industrial emissions, and other solvent applications (Knothe and Razon, 2017). Current utilization pathways for biodiesel are in automotive diesel engines for transportation and diesel generators for off-grid or stand-alone...
electricity generation, especially in developing countries. The most considerable constraint encountered in converting waste cooking oil to biodiesel for heating fuel is blending regulations to produce diesel-based heating oil (commonly referred to as No. 2 heating oil). In the United States, a mixture blend constraint exists for heating oil, because only 2–10% v/v biodiesel blend is required (EIA, 2017).

European standard EN 14214 and American standard ASTM D6751 specify quality metrics for biodiesel and have served as reference standards worldwide. These standards consider the variation of fuel quality influenced by pretreatment processes for feedstock oils, the transesterification reaction itself, and any posttreatment processes (Bart et al., 2010). For instance, density, kinematic viscosity, cetane number (CN), cold flow, and oxidative stability are all comprehended in the standards and are directly related to the composition of the input feedstock. Biodiesel (B20) can viably be used without the limitation of cloud point and pour point and may also be directly used in engines without further modifications. The disadvantages are cold flow issues at low temperatures and higher concentrations of oxides of nitrogen (NOx) during combustion. As shown in Table 6.7, reported properties of crude WCO, biodiesel from WCO, and commercial diesel fuel were in accordance with the ASTM standards.

### 6.5 UTILIZATION OF BY-PRODUCT GLYCEROL

Glycerol (1,2,3-propanetriol) is the simplest trihydric alcohol containing two primary and one secondary hydroxyl groups, and is the main component of triglycerides, usually found in vegetable oils and animal fats. It can be obtained from soap manufacturing, fatty acid production, fatty ester production, microbial fermentation and can be synthesized from propylene oxide (Crocker, 2010). Similar to petroleum fuel production, processing of biodiesel generates by-products, with glycerol being one of the main by-products generated from the homogeneous base-catalyzed transesterification reaction. Fundamentally, for every 3 mol of methyl esters, 1 mol of glycerol is produced, which is approximately 10–20 wt% of the total product (Gholami et al., 2014; Quispe et al., 2013). Every 100lbs (45 kg) of biodiesel produced generates approximately 10lbs (4.5 kg) of glycerol. Crude glycerol typically contains 65%–85% w/w glycerol content, with other constituents including
methanol, salt, and various impurities. One of the primary drawbacks of homogenous base-catalyzed transesterification is that glycerol separation is not efficient and requires significant secondary processing to achieve low levels of contamination.

6.5.1 Types of Glycerol and Their Uses

Glycerol generated as a by-product of the transesterification reaction can be categorized into three main groups: crude glycerol, technical glycerol, and purified glycerol (Fig. 6.9). In the current market, crude glycerol generated from biodiesel production is sold with methanol concentration of 0.3% (max) and glycerol concentration of 80%–88% purity (min) for lower grade applications. It has very little economic value because of various impurities, but can be further purified to achieve a higher market level. Technical grade glycerol is sold with methanol concentration of 0.1% (max) and glycerol concentration of 95% purity (min) for industrial applications. United States Pharmacopeia (USP) and Food Chemicals Codex (FCC) grade refined glycerol with 99.7% purity (min) is used in cosmetics, pharmaceuticals, and food (Gholami et al., 2014; Quispe et al., 2013).

Glycerol is used in many applications from energy bars to cough syrups to sealants for boat coatings (Gholami et al., 2014). However, the low-grade crude glycerol available directly from biodiesel production cannot be used for food, pharmaceutical, and cosmetic products because of its associated impurities. For large-scale biodiesel producers, crude glycerol can be purified by conventional methods in their manufacturing sites or sent to large refineries to produce a higher grade coproduct that can then be distributed in markets for other industries. Due to the current surplus of crude glycerol on the worldwide market, the capacity of refineries could well reach their production limits. The process of converting and refining crude glycerol into a pure form is usually cost prohibitive for small- and medium-sized scale biodiesel producers. Hence, the development of effective utilization strategies for crude glycerol might be a possible solution for producers in improving the economics of biodiesel manufacturing.

6.5.2 Process of Refining Crude Glycerol

Various kinds of glycerol purification methods and technologies are available in the market today, such as neutralization, acidification, ion exchange resins, vacuum distillation/evaporation, and membrane separation. The combination of more than one method can enhance the process and increase the purity level to as high as 99.2% (Wan Isahak et al., 2014). Distillation is the most common and mature technology, but the drawback is that it is highly energy intensive and consumes a large amount of water during condensation. Purification processes of crude glycerol generally require significant energy input, are high in chemical consumption, and have high production costs. The development of cheap and efficient purification processes that can be deployed at scale is essential to the biodiesel industry because they offer potential for additional economic benefits in generating secondary value-added products (Saifuddin et al., 2014).

Purification of crude glycerol generated by an institutional-scale biodiesel process developed in our laboratory was achieved by chemical treatment combined with vacuum distillation, as described by Hunsom et al. (2013) with additional modifications extracted from the literature (Tiangfen et al., 2013; Manosak et al., 2011; Kongjao et al., 2010; Marbun et al., 2014; Hajek and Skopal, 2010; Yang et al., 2013), following these steps:

1. Acidification
2. Neutralization
3. Vacuum distillation, and

![Fig. 6.9](image.png) Types of glycerol with their end applications.
Figs. 6.10 and 6.11 illustrate the overall process of converting crude glycerol to purified glycerol in an institutional-scale process. Crude glycerol from biodiesel production was acidified with \( \text{H}_3\text{PO}_4 \) and left for 12 h before phase separation. After complete separation, the upper phase consisted of free fatty acid, methanol, water, and acids, while the middle phase was a glycerol-rich layer with some methanol, water, and salt, and it had a dark brown color. The lower phase also had a small fraction of an inorganic salt-rich layer with a high concentration of potassium phosphate. The final purified glycerol by-product was obtained from the middle layer after adsorption with activated carbon. Each of these process steps is described in more detail as follows.

**Step 1: Acidification.**
A phosphorus acid solution (85% \( \text{H}_3\text{PO}_4 \), Sigma-Aldrich) was added to improve the acidity of crude glycerol. This produced three distinct layers: free fatty acid top layer (FFA), glycerol-rich middle layer, and inorganic salt-rich bottom layer. A filter funnel with pore size between 70 and 100 \( \mu \text{m} \) was used to remove the precipitated salt from the mixture and to separate the upper layer from the glycerol-rich middle layer. These two layers were then poured into the separation funnel to remove the glycerol-rich layer for further processing.

**Step 2: Neutralization.**
The glycerol layer was then neutralized by the addition of 12.5 M NaOH to achieve the required pH and remove the precipitated salts.

**Step 3: Vacuum distillation.**
The methanol and water from the glycerol were removed using two methods. In the first method, the glycerol solution was placed on a hot plate at 100°C for 2h to release both methanol and water in a chemical hood. In the second method, the glycerol solution was placed in a vacuum distillation unit to extract the excess methanol at 60°C for 50 to 60min at 95°C, and then to remove the water for 50–60min at a pressure of 3kPa. From an environmental standpoint, the latter method should perform better, as excess methanol can be recovered and reused in the biodiesel process.

**Step 4: Activated carbon adsorption.**
The glycerol solution obtained from the prior process steps was then passed through a column of commercially available activated carbon to remove odor, color, and other impurities and yield viscous, nearly colorless and odorless glycerol solution. Activated carbon can also be reused in the process at least a few times, provided the color and purity of the product glycerol are closely monitored.

### 6.5.3 Saponification
Soap is produced by the saponification of triglyceride from animal fat or vegetable oil (Fig. 6.12), wherein fatty acids react with NaOH or KOH to produce glycerol, fatty acid, and salts; 10%–15% of glycerol is produced during the saponification process. However, most commercial soap manufacturers remove and sell the glycerol, or convert it into more profitable beauty products. Glycerin serves as a humectant, attracting moisture from the environment to the surface layers of the skin and hair (Lodén and Maibach, 1999) and has cleansing, lubricating, and soothing properties. Glycerol by-product soap from biodiesel production would typically have more glycerin than traditional soap that has only 10%–20% glycerin content (Failor, 2000; Nicely, 2009). Different vegetable oils or animal fats, catalysts (NaOH/KOH), and glycerin grades can be used to produce soap (Fig. 6.13). The ingredients are chosen depending on the individual preference and the economic value of the desired product (Win et al., 2015).
FIG. 6.11  Schematic diagram of glycerol purification process flow.

FIG. 6.12  Basic reaction of the saponification process (Tan et al., 2013).
6.6 FUTURE PERSPECTIVE AND RESEARCH NEEDS

Waste cooking oil (WCO)-to-biodiesel conversion is not a new technology and has been implemented at the scale of individual WCO generating facilities, to community-scale plants, to large commercial enterprises. A wide diversity of research studies have been conducted in many different areas related to WCO-based biodiesel production. However, there are relatively few studies of WCO-to-biodiesel production in a constrained system at small scale (i.e., community scale), and few, if any, studies have considered the effect of utilizing by-product crude glycerol in saponification, to produce a secondary product that can enhance the economic and environmental performance of the overall system.

Crude glycerol from biodiesel production plants contains 80% glycerol in the best scenario and between 20% and 40% impurities. Purified through the costly refining process to cosmetic or pharmaceutical quality is generally not financially viable. Much research has been targeted on biodiesel production utilized for different applications, and other focused studies on conversion of low-value by-product crude glycerol into valued-added products. Many published papers have discussed ways to utilize crude glycerol from biodiesel production, and producing low-cost soap from edible or nonedible vegetable feedstocks in developing countries has already been implemented. Nonetheless, what has been minimally explored is the potential synergy between two waste products (WCO and crude glycerol) and converting the waste resources into two value-added products (biodiesel and soap), to determine the effect on economic development, resilience, energy independence, and waste for a constrained community-scale system.

Institutions generate waste cooking oil (WCO) from dining services and have few disposal options. The waste oil can properly be disposed at the facilities described previously, which can be costly, or sold for animal feed production for a small revenue. The development of a closed-loop biodiesel production system utilizing crude glycerol as an ingredient for soap production is compelling, especially in a constrained system where the WCO feedstock supply and biodiesel demand are in close proximity and controlled by a single entity. Biodiesel can be used in vehicles and other applications, while crude glycerol can be refined and used to produce soap. Potentially, the soap can be used in cafeterias and bathrooms across campus and dining services, to provide significant financial benefits beyond producing biodiesel fuel alone.

A case study of a community-based biodiesel production program in Atlanta, Georgia (GA) was conducted by Fyfe et al. (2006) to determine the opportunity to recycle yellow grease into biodiesel for urban fleets and other diesel users. The development of this yellow grease program in an urban area was likely to have potential based on the strong interest from the restaurant industry, with high grease volumes generated from nearby restaurants and Emory University, and diesel demand from the local public school buses. In another study, Skarlis et al. (2012) investigated the viability of a small-scale biodiesel production plant (10,000 ton/year) on the Greek island of Crete. They found that a small-scale plant would offer opportunities for decentralized rural development, which is important for the Greek economy. The investment of a small-scale project was found to be viable, as long as the biodiesel market value is consistently higher than the biodiesel production cost value. Schut et al. (2011) discussed the opportunities and constraints to implementing a sustainable community-based biofuel production and utilization in the Nhambita community in Mozambique. They developed three scenarios to understand how much jatropha oil production is needed to replace fossil fuels with pure plant oil (PPO) and to locally manufacture oil-based products such as soap. More rigorous economic and environment assessments should be

FIG. 6.13 General flowchart of the saponification process.
Conducted to determine the financial performance and environment impacts over the entire energy cycle, from WCO collection to biodiesel production and crude glycerol utilization. Table 6.8 provides a summary of universities in the United States that are currently producing biodiesel from waste cooking oil, and a few also have parallel soap production operations.

<table>
<thead>
<tr>
<th>University</th>
<th>Location</th>
<th>Feedstock Source</th>
<th>Biodiesel Production Capacity</th>
<th>Facilities</th>
<th>Utilization and Benefits</th>
<th>Crude Glycerol Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Arizona</td>
<td>Tucson, AZ</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Produce soap</td>
</tr>
<tr>
<td>Appalachian State University</td>
<td>Boone, NC</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>House heating systems and farm equipment</td>
<td>Produce soap and use in composting</td>
</tr>
<tr>
<td>Dickinson College</td>
<td>Carlisle, PA</td>
<td>WCO from dining services</td>
<td>5000 gal</td>
<td>Students manage production operation</td>
<td>NA</td>
<td>Produce soap</td>
</tr>
<tr>
<td>Loyola University</td>
<td>Chicago, IL</td>
<td>WCO from Loyola, Northwestern University, and donation from neighborhood</td>
<td>10,000 gal</td>
<td>Student-run enterprise. First and only university operation licensed to sell biodiesel in the U.S. and a certified green business with the Illinois Green Business Association.</td>
<td>B100 (55–500 gal) is available for sale and also utilized in campus shuttle buses and a boiler in the Institute of Environmental Sustainability</td>
<td>Produce soap (marketed as BioSoap)</td>
</tr>
<tr>
<td>Clemson University</td>
<td>Clemson, SC</td>
<td>WCO from dining halls and local businesses</td>
<td>3000 gal per year in 90 gal batches</td>
<td>Student-run enterprise. Produce 20%–33% mix (i.e., 20%–33% biodiesel and 67%–80% diesel), with some vehicles running 100% biodiesel</td>
<td>Diesel trucks within fleet of vehicles on campus, landscaping, and utility trucks</td>
<td>Produce soap</td>
</tr>
<tr>
<td>Santa Fe College</td>
<td>Gainesville, FL</td>
<td>WCO from cafeteria</td>
<td>NA</td>
<td>Conduct biodiesel courses and provide education opportunities for students</td>
<td>Two fleet vehicles running with biodiesel</td>
<td>NA</td>
</tr>
<tr>
<td>Rochester Institute of Technology</td>
<td>Rochester, NY</td>
<td>WCO from cafeteria</td>
<td>5000 gal per year</td>
<td>Researchers produced biodiesel that met ASTM standards for vehicle use and heating fuel blends.</td>
<td>Performance of biodiesel was tested using campus vehicles and space heating appliances</td>
<td>Crude glycerol purified to produce soap of varying quality</td>
</tr>
</tbody>
</table>
6.7 CONCLUSIONS

Today biodiesel offers one of the best substitutes for conventional transportation fuels because its physical and chemical properties are very similar to diesel fuel. The major disadvantages associated with biodiesel production are the high raw material cost and limited availability of vegetable oils resources that do not compete with food commodities. The high raw material cost is also due to high global biodiesel demand in blended mixtures with petroleum-based diesel, usually up to 20% in the U.S. (B20). In the future, vegetable oil prices are unlikely to be low enough for biodiesel produced from such feedstocks to compete with petroleum fuels, unless financial support from governments is made available (i.e., subsidies and tax credits). One of the widely accepted ways to reduce the raw material cost is the use of waste cooking oil (WCO) as a feedstock for biodiesel production.

Low-grade waste cooking oil is not as desirable as edible oils for biodiesel feedstock because of its generally high level of impurities. However, the growing volume of waste cooking oil generated by domestic and industrial operations due to the trend of increasing population growth has received a lot of attention. WCO has been facing serious disposal problems in many parts of the world, and proper management and utilization of this widely generated food supply chain waste material are urgently needed. Recycling of the waste cooking oil provides not only the benefit of producing a renewable energy resource that can displace high-GHG emitting transportation fuels, but also helps address a serious waste disposal problem. The importance of looking beyond the profitability and quality of oils for biodiesel production to address other benefits is essential. It has been shown that utilization of glycerol, widely considered a low-value output of the transesterification process, is essential to the economic viability of WCO-to-biodiesel conversion at small scale. The development of waste cooking oil-based biodiesel production in a community biorefinery system could contribute to sustainable waste management practices and also provide positive microeconomic outcomes for local populations.

REFERENCES


