Chapter 24: Economic Assessment for Biodiesel Production

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Abstract

Biodiesel production as well as consumption in the European nations are augmenting, taking into account the uncertainties connected to fossil fuel reserves and the related natural effects of their use. This biofuel can be generated from numerous oil-rich feedstocks and by using different processing technologies. Therefore, the techno-economic assessment for biodiesel production becomes of high relevance to make critical decisions under uncertainties that are essential for the successful implementation of the process on an industrial scale. The economic aspects of using different triglycerides and non-triglycerides based lipid biomass as well as the processing technologies for biodiesel production are thoroughly discussed and compared in this chapter.

24.1 Introduction

Energy is a basic requirement for human existence; and the demand for the same has been consistently gaining because of the increasing human population. According to the International Energy Outlook 2016 set by the U.S. Energy Information Administration, the total world energy consumption will grow by 48 % between 2012 and 2040. The energy consumption for the transportation sector increases at an annual rate of 1.4 %, tallying for 49 % growth from 2012 to 2040. Transportation energy demand growth occurs almost entirely in regions outside of the Organization for Economic Cooperation and Development (OECD). The fastest growth in the energy consumption per capita in the transportation sector occurs in China and India; however, the total transportation energy use per capita remains lower than in the OCED regions. In 2012, the OCED and non-OCED national accounted for 55 % and 45 % of the world's total transportation energy consumption, respectively. In 2020, the OECD and non-OECD shares of world transportation energy use are projected to be equal. In the non-OECD regions, where 80% of the world's population resides, transportation energy demand nearly doubles, with an average annual increase of 2.5 % (International Energy Outlook 2016). Among the different energy resources, fossil fuels continue to supply most of world's energy; liquid fuels, natural gas, and coal account for 78 % of total world energy consumption. The use of fossil fuel resources for the energy production has several hazardous impacts on the ecosystem, such as large greenhouse gas emissions, acid rain, and global warming. Furthermore, a consistent fear of dwindling reserves of crude oil and oscillating fuel prices have made todays necessity to find an alternative resources of energy which are sustainable, renewable, environmentally friendly, economically reasonable, and easily available (Avhad and Marchetti 2015). As part of the global response to the climate change, policies in several nations around the world have been introduced. The policies are formed to

safeguard the sustainable use of renewable energy. The European Union (EU) has been taking the initiative in establishing the renewable and sustainable energy prominence. The EU Renewable Energy Directive 2009/28/EC (RED) set a target of increasing the share of renewable energy use in the EU from 8.5 % in 2005 to 20 % by 2020 with the motive to promote cleaner transport, to limit the greenhouse gas emissions, and to stimulate innovation and the technological development. In addition to the overall target for renewables, all member states have to reach a target of 10 % share of renewable energy for transport (EU Directive 2009/28/EC 2009). The directive implemented in Norway, a country which is not a member of the EU, but part of the European Economic Area (EEA), sets a goal of increasing the share of renewable energy from 60.1 % in 2005 to 67.5 % by 2020 (Rosenberg, Lind, and Espegren 2013). Lund and Mathiesen (Lund and Mathiesen 2009) reported a study focused on the energy system analysis of Denmark. It was concluded that 50 % and 100 % renewable energy supply in Denmark by the year 2030 and 2050, respectively, from the domestic resources (biomass and combinations of wind, wave, and solar power) is physically possible. However, the challenges for the design of 100 % renewable energy systems in Denmark included the integration of high share of intermittent resources in the energy system, the involvement of the transportation sector in the strategies, and the balance between large consumption of biomass and large amounts of electricity for direct use, or for production of synthetic fuels (Lund and Mathiesen 2009). The above-mentioned strict targets for the utilization of renewable energy in transport has boosted the use of biofuels. The synthesis of transportation fuel from biomass is expected to minimize the entire dependency on the utilization of petroleum-derived fuel (Huber, Iborra, and Corma 2006). The ‘‘Roadmap for Biomass Technologies”, set by the U.S. Department of Energy, has predicted that by 2030, 20% of transportation fuel would be produced from biomass (U.S. Department of Energy 2002).

Among different biofuels, biodiesel has been gaining substantial relevance as a potential alternative or additive to current petroleum-derived diesel not only because this oxygenated fuel can be synthesized from oil-rich biomass but also for a reason that it offers minor environmental toxicity and is biodegradable in nature (Avhad and Marchetti 2016). According to the American Society for Testing and Materials (ASTM), biodiesel is defined as mono-alkyl esters derived from lipid feedstocks, such as vegetable oils and animal fats. The combustion of biodiesel offers net carbon dioxide emissions reduction of 78 % (based on lifecycle analysis), 48 % less carbon monoxide, 47 % less particulate matters, and 67 % less hydrocarbons, when compared with petroleum-based diesel (Poddar et al. 2016, Tsoutsos et al. 2016). Both biodiesel production and consumption have augmented considerably in the past decade in the European market; possibly, due to the previous mentioned benefits. The prime advantage of producing and utilizing biodiesel involves the reduction of foreign oil imports. The European biodiesel market is one of the largest in the world, accounting for approximately 80 % of the total biofuel production in the EU (Tsoutsos et al. 2016). The breakdown of total EU biofuel consumption, in energy content, in year 2014 for transport by biofuel type is shown in Figure 24.1. The share of biofuel types consumed in several EU countries in 2014 for transport is shown in Figure 24.2. The major biodiesel producers in Europe include Neste (Finland), Total, Avril (France), Marseglia Group, Eni (Italy), Petrotec, ADM Biodiesel, Verbio AG (Germany), Infinita (Spain), amongst others. The biodiesel consumption in the EU transport was registered to increase by 7.8 % in the year 2014, when compared to that of in 2013 (EurObserv'ER 2015). A graphical representation showing a comparison of biodiesel consumption in the EU countries between the year 2013 and 2014 is presented in Figure 24.3. According to the Spanish Institute for Diversification and Saving of Energy (IDAE), the biodiesel consumption in Spain raised from 825,026 tons in 2013 to 903,544

86 tons in 2014. Few southern European countries import high proportion of biodiesel from other
87 nations, such as Indonesia and Argentina. This is predicted due to low oil prices and economical
88 crisis. However, the consumption of biofuel in Spain has started to accelerate as the country's
89 economic situation is recovering with the associated increase in road fuel consumption. The
90 statistics presented by the Department of Energy and Climate Change (DECC) suggested that the
91 volume of biodiesel consumed in United Kingdom in 2014 was 1.24 times of that in 2013. While,
92 German biodiesel consumption increased slightly in 2014 than the previous year (EurObserv'ER
93 2015).

94 The available literature suggested that biodiesel presents high combustion efficiency, high cetane
95 number, minimal sulfur content, low particulate matters, high flashpoint, and improved
96 lubrication (Avhad and Marchetti 2015). However, the final fuel properties are heavily dependent
97 on the fatty acid composition of the lipid feedstock. On other side, the type of lipid feedstock
98 utilized for biodiesel production has a significant influence on the cost of this biofuel since it has
99 been reported that the price of raw material accounts for 60-80 % of the total production cost of
100 biodiesel (Helwani et al. 2013, Avhad and Marchetti 2015, Zheng et al. 2013). Consequently, a
101 wide range of edible, non-edible, and waste lipid feedstocks have been tested for biodiesel
102 production. The food-grade oils, such as rapeseed oil, sunflower oil, soybean oil, and palm oil are
103 utilized in a large-scale for biodiesel production in several countries, like the United States of
104 America, Argentina, Brazil, European nations, Malaysia, and Indonesia (Da Porto, Decorti, and
105 Tubaro 2012, Zheng et al. 2012). However, their application for biodiesel production resulted in
106 the rise of food prices, deforestation, land use change, agriculture of monoculture plants, and
107 biodiversity threatening concerns in some developing nations around the world. The sustainable
108 biodiesel production could be possible by the generation of lipid feedstock from the perennial

plants grown on degraded farmland. Since the recent few years, consistent scientific efforts are underway in finding a cost-effective and abundantly available non-edible oil-rich biomass for biodiesel production (Karmakar, Karmakar, and Mukherjee 2010, Balat 2011). As a next generation lipid feedstock, *jatropha* oil, karanja oil, mahua oil, linseed oil, amongst others have been employed for biodiesel production (Sánchez et al. 2015, Atabani 2013). India and Brazil have driven their attention towards the utilization of *jatropha*, castor bean, and karanja oil as a feedstock for biodiesel production (Rincón, Jaramillo, and Cardona 2014). Jojoba oil, which profoundly differs from other seed oils because of the absence of glycerol molecule in its chemical structure, is another non-edible lipid biomass that was rarely utilized but is gaining high relevance these days for the synthesis of value-added jojobyl alcohols and biodiesel (Sánchez et al. 2015, Avhad et al. 2016). The application of non-edible biomass for large-scale biodiesel production might be advantageous because the agriculture of such plants could be both profitable and trouble-free. These plants grows strong in soil even of marginal fertility, requires less water, needs less maintenance, survive under hot regional weather, and have a long life span (Avhad et al. 2016, Al-Widyan and Al-Muhtaseb 2010, Al-Hamamre and Rawajfeh 2013). Moreover, algal lipids are also considered as a promising alternative feedstock for biodiesel production. The available reports suggests that algae are capable of producing 250 times the oil quantity per acre as soybean, and up to 31 times higher oil than palm (Hossain and Salleh 2008). Microalgae are described to have higher oil content, when compared with macroalgae. The lipid content in microalgae can exceed 70 % of the dry cell mass depending on certain conditions, such as light intensity, organic carbon and nitrogen sources, temperature, pH, salinity, and dissolved oxygen level. While, microalgae can be cultivated using an open raceway, a photobioreactor, and a fermenter technology (Metting 1996, Sawangkeaw and Ngamprasertsith 2013). Despite the high lipid

productivity of microalgae, its usage on an industrial scale for biodiesel production faces serious challenges, such as its high cost, and the need for sustainable outdoor cultivation microalgal strain and effective lipid extraction technology (Halim, Danquah, and Webley 2012). In a standpoint of finding an additional low-cost feedstock, the capability of used cooking oil and waste animal fats for their transformation to biodiesel was also investigated (Lam, Lee, and Mohamed 2010). The available reports indicated that the exploitation of used cooking oil for biodiesel production resulted in 83-85 % carbon savings (Tsoutsos et al. 2016). The production of biodiesel from tallow oil was stated to have high cetane number, good stability, and low price (Rincón, Jaramillo, and Cardona 2014). The Finnish oil company, Neste, claimed to be world's largest biofuel producer from wastes and residues (frying oil, animal fats, fish oil, etc.) stating to produce 1.3 million tons of biodiesel in the year 2014 (EurObserv'ER 2015). The utilization of used cooking oils for biodiesel production was reported to be advantageous because: (i) it is a residue, and therefore, its generation requires no energy inputs, and (ii) its utilization for biodiesel production would eliminate the disposal concerns (Talebian-Kiakalaieh, Amin, and Mazaheri 2013, Nair et al. 2012). However, the occurrence of oxidation, hydrolysis, and the polymerization reactions while the frying process of vegetable oil results in the generation of impurities, free fatty acids (FFAs), and water components in oils (Banerjee and Chakraborty 2009). This in return would demand the additional treatment and purification steps for the used cooking oils before its application for biodiesel production. Secondly, the shortage of used cooking oils in European countries may require its import, which in consequence, might increase the cost of the raw material for biodiesel production (Tsoutsos et al. 2016).

Among different methodologies available for the transformation of lipid feedstock to biodiesel, the alcoholysis process has been extensively applied. The alcoholysis process is also known as

transesterification of triacylglycerols (TAGs) and esterification of FFAs. The stoichiometry of the transesterification reaction between the TAGs based plant oils and alcohol requires a mole of TAGs and three moles of alcohol to produce three moles of biodiesel and a mole of glycerol. This process consists of three sequential reversible reactions, where in a mole of biodiesel is released in each step, and monoaclyglycerols and diacylglycerols are the intermediate products (Avhad and Marchetti 2016). The general reaction and a sequence for the transesterification process is shown in Figure 24.4 and 24.5, respectively. In a stoichiometry of the alcoholysis reaction between the non-TAGs based oil (jojoba oil) and alcohol, one molecule of oil reacts with a molecule of alcohol to synthesize one molecule of biodiesel and a molecule of jojobyl alcohols (Avhad et al. 2016). The general schematic representation for the transesterification of non-TAGs based plant oils (jojoba oil) can be seen in Figure 24.6. The esterification reaction between FFAs and alcohol involves the formation of one mole of biodiesel and water after the reaction between one molecule of FFAs and a molecule of alcohol. A general esterification reaction is shown in Figure 24.7. The alcoholysis reactions are the reversible process, and therefore an excess of alcohol are required to shift the reaction equilibrium towards the formation of products. The types of alcohol that could be utilized for the alcoholysis reactions include short chain, long chain, and cyclic alcohols; however, low molecular weight alcohols (methanol and ethanol) are widely used for biodiesel production (Avhad and Marchetti 2015). Methanol is used because of its high reactivity, polarity, easy phase-separation, and low price (Sánchez, et al. 2015), while, the application of ethanol is advantageous from an ecological standpoint because it can be derived from the reasonable cost and abundantly available lignocellulosic biomass and due to its low toxicity (Limayem and Ricke 2012, Marchetti, Miguel, and Errazu 2007a).

178 The catalytic material is applied to the alcoholysis process to stimulate the reaction rate, modify
179 the reaction kinetics, reduce the process time, and increase the selectivity of the desired products.
180 The available literature suggested that several studies have been focused on finding an appropriate
181 catalytic material for biodiesel production (Avhad and Marchetti 2015, 2016, Chouhan and Sarma
182 2011, Lee et al. 2014). The ideal catalyst for biodiesel production should not only present superior
183 activity and selectivity towards the desired products but also be easily available, simple to prepare,
184 less expensive, and reusable. However, the selection of the type of catalytic material for biodiesel
185 production is heavily dependent on the nature of the feedstock. The base catalyzed-alcoholysis
186 reactions are faster than the acid ones; consequently, the synthesis of biodiesel is completed using
187 relatively low reaction time. The most commonly utilized base catalysts for the industrial-scale
188 biodiesel production include sodium hydroxide, and potassium hydroxide. However, the
189 applicability of homogeneous base catalysts is restricted to high quality lipid feedstocks
190 containing negligible amount of FFAs (1ess than 0.5 %) and moisture (Lukić et al. 2013, Jasen
191 and Marchetti 2012). The existence of high amount of FFAs in the lipid feedstocks directs the
192 saponification reaction, in the presence of soluble base catalyst, leading towards the formation of
193 undesired soap. The soap formation minimizes the biodiesel yield because of the generation of
194 esters-glycerol emulsion. Whereas, moisture in the reaction mixture promotes the hydrolysis of
195 the esters; thus, reducing the biodiesel yield (Avhad and Marchetti 2015). The operation of the
196 acid-catalyzed alcoholysis reaction could eliminate the above-mentioned technical hurdles
197 because the performance of acid catalysts is not affected by the presence of high amount of FFAs
198 and moisture in the lipid feedstock. Furthermore, the appliance of acid catalysts could be
199 advantageous because it can assist both transesterification and esterification reactions. The acid
200 catalysts, therefore, can possibly be utilized for biodiesel production from waste oils, animal fats,

and the industrial by-products. The frequently used acid catalysts are sulfuric acid, and hydrochloric acid. However, the acid-catalyzed alcoholysis reactions are extremely slow and could take around a day for the complete transformation of oil to biodiesel (Marchetti and Errazu 2008a, Soriano Jr, Venditti, and Argyropoulos 2009). The need of high reaction conditions have been a major reason of concern for its upscaling on an industrial platform. Additionally, the appliance of non-green catalyst also creates worries related to human safety and corrosion of the equipment (Lee et al. 2014). The possibility of catalyst reutilization could be ensured with the replacement of homogeneous catalysts with the heterogeneous catalytic system. The heterogenization of the alcoholysis process is possible if the catalyst is neither consumed nor dissolved in the reaction mixture. The heterogeneous catalytic materials can then be easily separated from the post-reaction mixture through the physical methods, such as the filtration and the centrifugation. The utilization of potential heterogeneous catalyst hold the capability of minimizing the separation and purification stages for biodiesel production, and decreasing the post-reaction wastewater and other contaminant content. The process intensification enabled because of the heterogenization biodiesel production could not only allow recycling of the catalyst but also increase the yield and the purity of biodiesel as well glycerol. The challenges associated with the utilization of heterogeneous catalysis for biodiesel production includes: (i) limited catalytic active sites in comparison to homogeneous catalysts, (ii) sometimes need of severe reaction conditions, (iii) generally, tri-phasic reaction systemic (liquid/liquid/solid) leading towards the occurrence of mass transfer resistance, (iv) complicated and time-consuming catalysts synthesis procedure, (v) poisoning of the catalyst because of the surrounding atmosphere, (vi) need of characterization of solid materials to determine physical as well as chemical properties (Avhad and Marchetti 2016). A wide range of solid catalysts have been tested for biodiesel

production, such as metal oxides, mixed metal oxides, hydrotalcites, heteropoly acids, ion-exchange resins, silica-, zirconia-based catalysts, amongst others. Among several options, calcium oxide catalysts has been gaining scientific as well as industrial relevance because of its low solubility in methanol, high basicity, high activity, low cost, and easy synthesis from natural resources (Avhad and Marchetti 2016).

The process parameters also play an important role in deciding the final cost of biodiesel. The process parameters, such as catalyst amount, alcohol-to-feedstock molar ratio, reaction temperature, reaction time, and stirring intensity are most frequently studied for the alcoholysis reactions performed in a conventional method to achieve maximum biodiesel yield using lowest possible energy input (Marchetti, Miguel, and Errazu 2007b). The change in reaction method has been also carried out to reduce the processing cost and achieve maximum biodiesel yield using milder reaction conditions. For instance, the alcoholysis reaction performed under the supercritical conditions possesses some advantages over the conventional process. The alcoholysis reactions performed under supercritical conditions results in the rapid transformation of the lipid feedstock to biodiesel without even using a catalyst. The supercritical reaction conditions enables a mutual solubility between the oil and the alcohol phase; thus, eliminating the concerns related to mass transfer. Furthermore, the non-requirement of catalysts for biodiesel production helps straightforward post-reaction separation and purification stages. This reaction method being unaffected by the presence of high content of FFAs and moisture in the reaction mixture, the low-quality lipid feedstocks, such as waste cooking oils and animal fats can be transformed to biodiesel using the supercritical reaction conditions. However, severe reaction parameters (high temperatures and high pressures) and large alcohol-to-oil molar ratio are required to perform the alcoholysis reaction under the supercritical conditions. The use of large

247 amount of alcohol would require supplementary energy for the pre-heating stages, and the
248 recycling process. The utilization of high reaction temperatures would not only increase the
249 capital cost of biodiesel but also deteriorate the quality of biofuel. The use of high temperatures
250 initiate the thermal cracking phenomenon; thus, reducing the biodiesel yield (Olivares-Carrillo
251 and Quesada-Medina 2011). Additionally, high temperatures and pressure conditions demand
252 both an expensive reactor and a safety management. The research studies focused on the reduction
253 of high reaction temperatures include the addition of liquid and gaseous co-solvents (Trentin et
254 al. 2011, Tsai, Lin, and Lee 2013), and the catalyst (Santana, Maçaira, and Larrayoz 2012, Shin
255 et al. 2013).

256 **24.2 Economical aspect of biodiesel production technologies**

257 As mentioned before, biodiesel can be produced by different technological approaches (Avhad
258 and Marchetti 2015, Marchetti, Miguel, and Errazu 2007b). However, this only shows the
259 potentiality of the technology to produce the desire fuel but has no comment on the liability of the
260 process to be actually commercialized. From a perspective to be able to establish a
261 commercialized process, the different economical aspects of different technologies will be
262 presented here and compared. There are several factors to be considered when comparing
263 processes, especially when they are different technologies involved. In order to have the more
264 reliable comparison, several general conditions were establish such as the production rate, cost of
265 the raw material, price of biodiesel, prices of the byproducts (this is based on their quality and
266 relevance), number of process equipment (this is related to the number of reactors used), among
267 others. We do know that these assumptions are arbitrarily, but are made by us to our processes in
268 order to compare each of them with other. Comparison with our technologies under other
269 economical scenarios is not recommendable due to the different considered assumptions.

Several researchers have been working on the economic evaluation of different technological solutions for biodiesel production from different sources. Among all of them, it can be found that the work reported by Nelson et al. (Nelson 1994) studied the production process of 100,000 ton per year of biodiesel from beef tallow and methanol, in the presence of an alkali catalyst. In this work, the comparison of the process and its evaluation was conducted using the total capital cost involved in the process. A similar work was carried out by Graboski and McCormick (Graboski and McCormick 1998) who studied a 38.8 million liter per year process. The authors studied and compared different raw materials and the process economic evaluation was done considering the credits of biodiesel, the credits of glycerol, and the cost of equipment as the selection criteria. A comparison among acid and base catalyst using waste cooking oil was done by (Zhang et al. 2003). Their process description was quite in detail, and the use of HYSYS was presented for a complete process flow diagram. The difference with the previous works is that the plant capacity being only 8000 ton per year in this case. Based on the commercialized software, Hass et al. (Haas et al. 2006) presented an economic analysis over an alkali catalyst for biodiesel production using soybean oil with a capacity of 37 million liter per year. The reported study presented a sensitivity analysis over the price of oil and biodiesel. Similar investigations were conducted by Marchetti et al. (Marchetti, Miguel, and Errazu 2008, Marchetti and Errazu 2008b), but using an acid oil as a feedstock and with a plant capacity of 36000 ton/year. In these works four technologies were compared: (i) pre-acid esterification followed by acid-catalyzed transesterification, (ii) acid catalytic process, (iii) heterogeneous solid ion-exchange resin catalyzed process, and (iv) supercritical process. In those reported studies, the direct and indirect cost for each technology as well as additional expenses involved in the process were taken into consideration. The performed comparison was based on the net present value (NPV) with an objective of investigating the

profitability of the technology and possibility for further study. The heterogeneous catalyzed process appeared as a promising approach, while, the supercritical showed a negative NPV with the period of the work. West et al. (West, Posarac, and Ellis 2008) studied a similar raw material (acid oil) but compared the after tax return rate and for only 8000 ton per year plant capacity. van Kasteren and Nisworo (van Kasteren and Nisworo 2007) compared the supercritical technology, achieving different result, when compared with those reported in some cases by Marchetti et al. (Marchetti and Errazu 2008b, Marchetti, Miguel, and Errazu 2008). This is because the main difference was based on the scale of the process as well as in the quality of the raw material; while Marchetti et al. (Marchetti and Errazu 2008b, Marchetti, Miguel, and Errazu 2008) used acid oil, van Kasteren and Niswoore (van Kasteren and Nisworo 2007) carried out their work with waste cooking oil, where the amount of fatty acid was higher.

Over the last few years, novel technological evaluation of different process have been considered. Even more life cycle analysis has been carried out and presented in order to have a broader picture of the biodiesel production scenario. Moreover, different sources of raw material such as algae or second-generation raw materials and non-edible oil have been tested and evaluated. Among other works, Seo et al. (Seo, Han, and Han 2014) have performed an evaluation of the production of algae oil while using algae residues as a food source for algae biomass. This oil-based biomass could then be transformed into biodiesel via different technologies and procedures. Rincón et al. (Rincón, Jaramillo, and Cardona 2014) have also studied the use of algae for biodiesel, in which the authors have compared different feedstocks such as edible oil (palm oil) and non-edible oils (*jatropha* oil, tallow oil, microalgae, and waste cooking oil). In their scenario, different reaction configurations for different raw materials was presented based on their need for purity and pre- and post-processing steps. Economic analysis was carried out in order to compare the future

316 prospective of each alternative. Based on their assumption and pricing, it was found out that the
317 total cost for producing biodiesel was the lowest when a basic catalyst is employed and *jatropha*
318 oil having low content of free fatty acids is used as feedstock, follow by a process in which waste
319 cooking oil with an acid catalyst is used for biodiesel production. As it was expected, the use of
320 refined oil gives the highest cost for production due to the high price of the raw material.
321 Researchers have also studied the use of waste cooking oil for the alcoholysis process, in the
322 presence of enzymatic catalyst. Lisboa et al. (Lisboa et al. 2014) presented a comparison of the
323 enzyme-catalyzed transesterification in the presence of supercritical carbon dioxide. To achieve
324 the latest mention scenario pressure is modify from atmospheric to 25 MPa. The authors presented
325 four study cases when different down streaming purification stages were required and unrequired
326 to achieve the desire purity in the final product. Based on their direct and indirect costs, as well
327 as the investment and production cost, the total biodiesel costs per liter were compared. The best
328 alternative is related to the scenario when the applied pressure and temperature for the separation
329 step are the lowest. Glisic and Orlovic (Glisic and Orlović 2014) also studied the effect of elevated
330 pressure and temperature on the process for biodiesel production. In their work, the authors
331 present a good comparison of the effect of these two variables over the economics of a
332 supercritical plant and conventional plant. After their comparison, it was concluded that the
333 breaking even price of biodiesel with the supercritical technology was better than with the
334 conventional technology. However, the operating cost of the process especially those related to
335 energy consumption and cost due to the high temperatures and pressure was not reported. The
336 item for utilities was considered, but there was no specification on what percentage of those
337 utilities is energy-based consumption. Moreover, with the purity of raw material having 5% FFAs
338 in within, the conventional technology with base catalyst is not recommended be for this quality

raw material (Freedman, Pryde, and Mounts 1984, Canakci, and van Gerpen 1999, Zheng et al. 2006, Marchetti 2010). Due to that the purification of the products gets more complicated or a pre-treatment step is required, making this technology more equipment dependent, and therefore, with a higher investment. Another approach is followed by El-Galad et al. (El-Galad, El-Khatib, and Zaher 2015), wherein the authors have performed an economic evaluation for the esterification of fatty acids into biodiesel. For their purpose, a technology to treat 2000 kg per hour of oleic acid in the presence of methanol and sulfuric acid was proposed. The capital cost were estimated based on market price in Egypt, making these values narrow to a one-market perspectives well as market dependent. The economic evaluation has shown that the technology is suitable for an economically attractive biodiesel process. However, it is not clear how from the soap and oil residues the authors purify this waste to produce 2000 kg per hour of oleic acid to be used in their technology.

As it could be seen from the previous selected worked, some of them use refined oil while other used non-edible oil, cooking oils, acid oil, or waste oils. All these feedstocks not only have different physico-chemical properties but also market and social value. As mentioned, refined oil are edible oil, and therefore must not be consumed for fuel production. Therefore, more and more work are relating in the use of waste and non-edible oil for biodiesel production. Even more, the general price for refine oil are so high that normally a process will not be economically attractive for investment if there are no governmental incentives. However, price of the major variables involve in the process, equipment, as well as market dependent such as the price of the oil and the selling price of the biodiesel have a major role in the economic analysis of each process. Due to that the prediction of price is not a simple, and the sensitivity studies are a crucial element in order to understand the effect of different aspect and its consequences in the long run of a plant. Due to

362 that, some result from different sensitivities studies and their effects over the biodiesel production
363 process will be compared and presented in the following write-up. As mentioned before, one of
364 the major variable is the quality of the oil, and associate to it its cost. It is worth mentioning that
365 not all the oils can grow all over the world. O'Brien (O'Brien 2008) presented a list of the different
366 types of oil and where they are being produce; this list can be seen in Table 24.1. The authors
367 have also included a column with the amount of oil that each seed can produce in each case. It is,
368 however, important to notice that the price range for one particular oil could vary considerable
369 from country to country.

370 Table 24.1: Major producer for several vegetable oils [Reprinted with permission from O'Brien et al. 2008]

Seed	Amount of oil (%)	Productive areas
Canola	40-45	Canada, China, India, France, Austria, United Kingdom, Germany, Poland, Denmark, Check Republic.
Corn	3.1-5.7	USA, Mexico, Russia, Belgium, France, Italy, Germany, Spain, United Kingdom.
Cotton	18-20	China, Russia, USA, India, Pakistan, Brazil, Egypt, Turkey.
Peanut	45-50	China, India, Nigeria, USA, Senegal, South Africa, Argentina
Crocus	30-35	China, USA, Spain, Portugal
Soybean	18-20	USA, Brazil, Argentina, China, India, Paraguay, Bolivia
Sunflower	35-45	Russia, Argentina, Austria, France, Italia, Germany, Spain, United Kingdom.
Coconut	65-68	Filipinas, Indonesia, India, México Sri Lanka, Thailand, Malaysia, Vietnam, Mozambique, New Guinea, Republic of Côte d'Ivoire
Olive	15-35	Spain, Italy, Italia, Greece, Tunes, Turkey, Morocco, Portugal, Syria, Algeria, Yugoslavia, Egypt, Israel, Libya, Jordan, Lebanon, Argentina, Chile, Mexico, Peru, USA, Australia.
Palm	45-50	Malaysia, Indonesia, China, Filipinas, Pakistan, México, Bangladesh, Colombia, Nigeria, Republic of Côte d'Ivoire
Palm kernel	44-53	Malaysia, Indonesia, China, Filipinas, Pakistan, México, Bangladesh, Colombia, Nigeria, Republic of Côte d'Ivoire

371

In order to make a sensitivity study of the major variables involved, it is important to know the process that is being considered because this has a great impact on the economic analysis. Marchetti (Marchetti 2013, Sánchez et al. 2015, Marchetti 2016) presented two sensitivities studies for three technologies to produce biodiesel, i) conventional alkali technology, and ii) supercritical technology. The two processes can be seen in Figure 24.8 and Figure 24.9. As it can be seen, the flow diagram is similar in both cases, allow us to make a better comparison. Sanchez et al. (Sánchez et al. 2015) presented a similar work with a process based on the transformation of jojoba oil into jojobyl alcohols and biodiesel. In this case, the main product is not the fuel, but the biochemical. This non-edible oil based process is also presented for comparison in order to present the difference when the process technology presented are different. This flow diagram can be seen in Figure 24.10. The major difference between these two technologies is based on the fact that their production capacity are different as well as that the conventional technology is not suitable for high impurity based raw material. Figure 24.11 shows a comparison of the effect of the oil price for both technologies. It can be seen that in Figure 24.11(a) the oil price affects linearly the internal return rate (IRR), this is because the supercritical technology not only transesterified the oil but also can carry on the esterification reaction. In Figure 24.11(b), it can be seen a very unusual tendency; this flatting tendency on the IRR values has a starting point for an oil price of $ 400 US per ton. Within these values, the amount of FFAs increase to a point where the saponification reaction is taking place in a considerable speed and a large amount of soap are being produce and therefore the biodiesel yield does not increase.

Both analysis presented in Figure 24.11 was done for the glycerol-based oil. However, a similar work was done by Sanchez et al. (Sánchez et al. 2015) where a biodiesel process was studied using a non-triglycerides based oil i.e. jojoba oil as raw material. In this case, as presented in

Figure 24.12, a similar effect as obtained where the lowest the price of the raw material the higher the IRR it goes. In this case, it was considered that when the price goes down almost half price the IRR value increases almost 40 times.

The other major variable that could affect considerable the profitability of the process is the selling price of the major product of the process. While in the cases studied by Marchetti (Marchetti 2013, 2011) the major product was biodiesel, in the work done by Sànchez et al. (Sánchez et al. 2015) the main product was jojoba alcohols being produced. The latest have been considered of high price due its difficulty of being produce with todays' technological possibilities. As it can be seen from Figure 24.13(a), the effect of biodiesel price on the conventional process makes the production technology more economically attractive, with a payback time of no more than 5 years when the process has the lowest price for biodiesel. Within that worst scenario, the IRR is close to 10 %. In the case of the supercritical technology, as presented in Figure 24.13(b), the price for biodiesel was slightly different, but the major tendency is that for the lowest price for the fuel, they payback time is over 16 years, making it less interest for investors. In Figure 24.13(c), it can be seen a similar effect when the price of the jojobyl alcohols is varied. In this case, the lowest cost estimated for selling the alcohols will produce a negative effect on the economics of the process given a payback time of 22 year, with a very low IRR. It was found in that work that the price of $ 513 US per kilograms of alcohols is the cutting price where the process became economically attractive.

Other researchers have also done similar sensitivity studies over those or even over other variables involved in the process. In the case of the supercritical technology, the energy inputs could become crucial for the technology to be profitable, while in the case of a conventional technology the use of cleaning water and waste treatment of the effluents will have a relevant role. Even more,

418 the price of glycerol is also a credit that could be beneficial for the process; however, its purity is
419 a strong conditional. Based on the purity and the amount being produce worldwide, this chemical
420 might become a new, promising, and cheap raw material for new chemicals (Marchetti 2012).
421 Based on the previous mentioned technical and economic aspects a comparison table is presented
422 in the Table 24.2.

423 Table 24.2. Comparison of different technologies for Biodiesel [Reprinted with permission from Marchetti 2012].

Variable	Basic	Enzyme	Supercritical	Monolithic	Resin	Acid
Temp. [°C]	60-70	30-50	200-350	50-180	60-180	50-80
Products from FFA	Soaps	Esters	Esters	Esters	Esters	Esters
Effect of Water*	↓	↓	——	——	— ↓	——
Yield to ester	Normal	High	High	Normal	Good	Normal
Purification of glycerol	Difficult	Simple	Simple	Simple	Simple	Difficult
Reaction time+	1-2 h	8-70 h	4-10 min	6 h	variable	4-70 h
Ester purification	Difficult	Simple	Simple	Simple	Simple	Difficult
Cost	Cheapest	Expensive	Expensive	Medium	Medium	Cheaper
Amount of equipment	High	Low	Low	Low	Low	High

424 ** in this case the down arrow mean that water is a draw back while the line means that the is not effect and the*
425 *system will be able to treat a raw material with some amount of water. For the Enzyme case, a down arrow has*
426 *been supply, in this case is important to say that is believe that some water is require for enzyme activation; however,*
427 *a lot of water will produce a deactivation of the catalyst. In the case of the resin, it could be seen a down arrow as*
428 *well as a line, this is because water has different effect over different solid catalyst. In the case of the monolithic*
429 *scenario, a line has been selected because leaching it is not causing by water per se but for a non-stability of the*
430 *catalyst.*

431 *+the reaction time set in this table is what it is most likely, however, it is important to point out that other times for*
432 *the same technology could be found in the open literature.*

433 As it can be seen from Table 24.2, the technical variables varies from technology to technology.
434 Some of them are more different from the others with temperature and reaction time, however the
435 combination of all of them plus the economic aspects are the key elements to select the best option.
436 The base-catalyzed technology is cheap and relative fast, but there is a lot of down streaming

equipment and purification required making the process less attractive. In the case of acid-catalyzed technology, the reaction time is considerable bigger; however, this technology is capable of dealing with more impurities in the raw material. In the schedule, there are other lower limits like the supercritical technology that could take care of the process in less than 5 minutes but with a high-energy demand, and therefore, energy cost involved. As mentioned before this technology is also capable of treating waste raw material and produce a high quality by product as well. In the case of the enzymatic technology, the process is simple as well as robust, and the enzyme will work under mild conditions that result in inexpensive operating cost in energy aspects. However, the price of the enzymes makes this technology less attractive for industrial scale.

As it has been presented from the technical and economic aspects, there are several points that needs to be considered in all the areas in order to establish a grading of priority for the technology to be used. This priority order is based on manmade decisions that are taken due to the market and social-political-economical situations of the location where the production plant will be built. Due to these external factors, is not possible to make a priority ranking that will be suitable for all possible scenarios at any possible location and a case-to-case study and evaluation is recommended.

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Caption:

Figure 24.1: Breakdown of total EU biofuel consumption in 2014 for transport by biofuel type [Modified with permission from EuroObserv'ER 2015].

Figure 24.2: Share of biofuel types consumed in the EU countries in 2014 for transport. ■-Biodiesel, ■-Bioethanol, ■-Biogas, ■-Others (Pure used vegetable oil and unspecified biofuel) [Reprinted with permission from EurObserv'ER 2015].

Figure 24.3: Biodiesel consumption for transport in the European Union. ■-2013, ■-2014 [Data source: EurObserv'ER 2015]. *For Denmark, biodiesel and bioethanol data is mixed due to confidentiality, so the figure contains both bioethanol and biodiesel. EU countries having no or insignificant consumption of biodiesel are not included in the figure.*

Figure 24.4: General transesterification reaction of TAGs based plant oils.

Figure 24.5: Stepwise transesterification reaction of TAGs based plant oils.

Figure 24.6: Stepwise transesterification reaction of non-TAGs based plant oils.

Figure 24.7: Generation esterification reaction of fatty acids.

Figure 24.8: Flow diagram for the conventional process [Reprinted with permission from Marchetti 2011].

Figure 24.9: Flow diagram for the supercritical process [Reprinted with permission from Marchetti 2013].

Figure 24.10: Biorefinery process for the production of jojobyl alcohols and biodiesel [Reprinted with permission from Sánchez et al. 2014].

Figure 24.11(a): Effect of the oil price over the supercritical process [Source Marchetti 2013].

Figure 24.11(b): Effect of the oil price over the conventional process [Source Marchetti 2011].

Figure 24.12: Effect of the oil price over jojoba oil based conventional process [Source Sánchez et al. 2015].

Figure 24.13(a): Effect of the biodiesel price in the process economy of conventional technology [Source Marchetti 2011].

Figure 24.13(b): Effect of the biodiesel price in the process economy of supercritical technology [Source Marchetti 2013].

Figure 24.13(c): Effect of the biodiesel price in the process economy of jojoba based conventional technology [Source Sánchez et al. 2015].

Table 24.1: Major producer for several vegetable oils [Reprinted with permission from O'Brien et al. 2008]

664 **Table 24.2**: Comparison of different technologies for Biodiesel [Reprinted with permission from
665 Marchetti 2012].

666

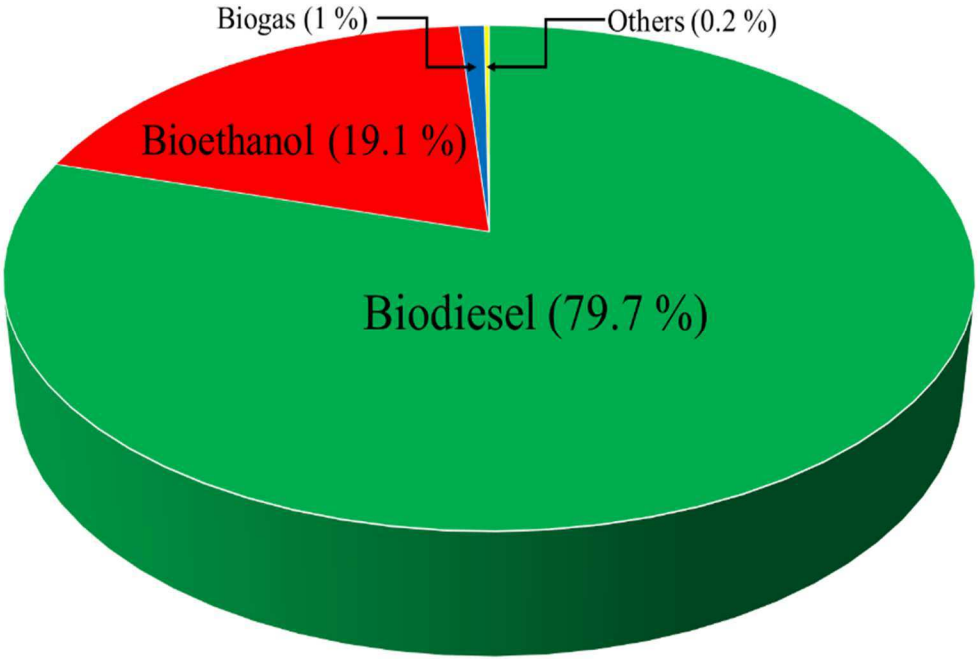


Figure 24.1: Breakdown of total EU biofuel consumption in 2014 for transport by biofuel type [Modified with permission from EuroObserv'ER 2015].

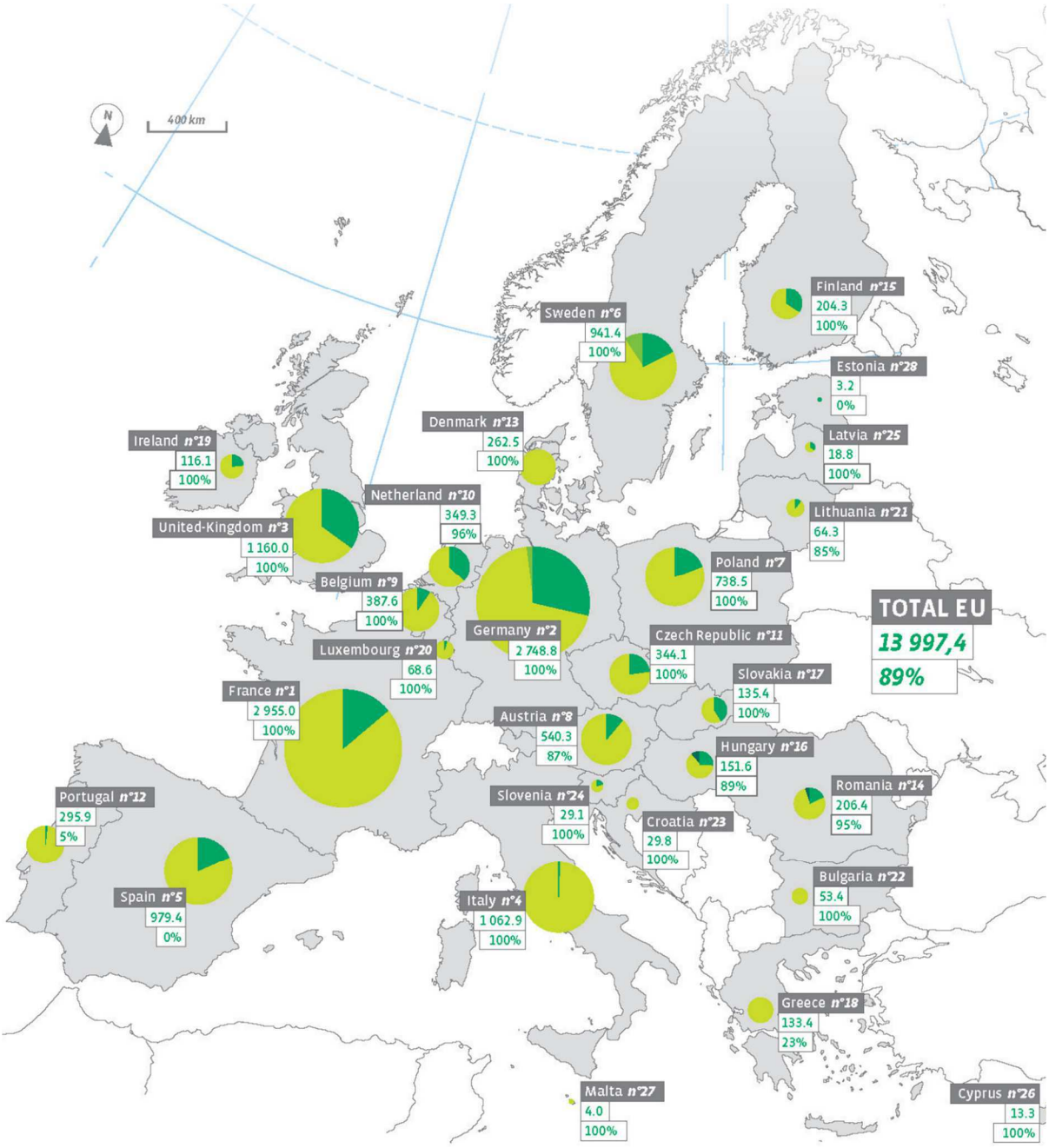


Figure 24.2: Share of biofuel types consumed in the EU countries in 2014 for transport. ■-Biodiesel, ■-Bioethanol, ■-Biogas, ■-Others (Pure used vegetable oil and unspecified biofuel) [Reprinted with permission from EurObserv'ER 2015].

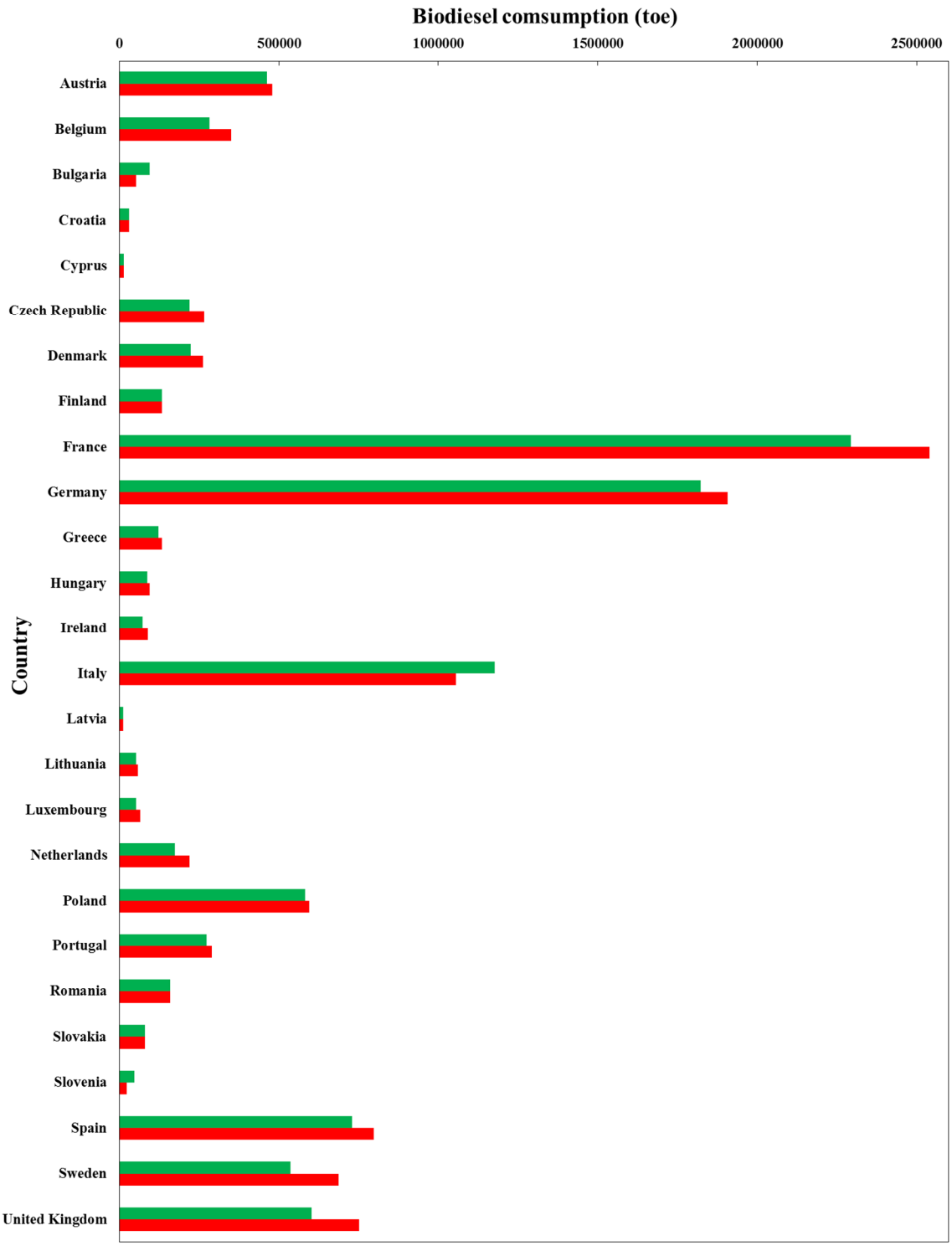


Figure 24.3: Biodiesel consumption for transport in the European Union. ■-2013, ■-2014 [Data source: EurObserv'ER 2015].

For Denmark, biodiesel and bioethanol data is mixed due to confidentiality, so the figure contains both bioethanol and biodiesel. EU countries having no or insignificant consumption of biodiesel are not included in the figure.

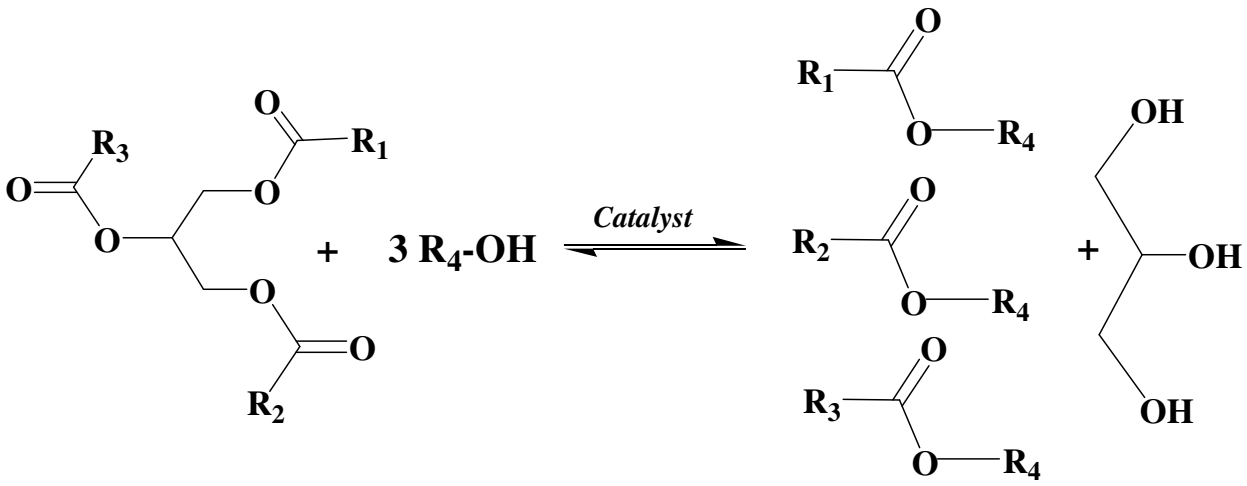
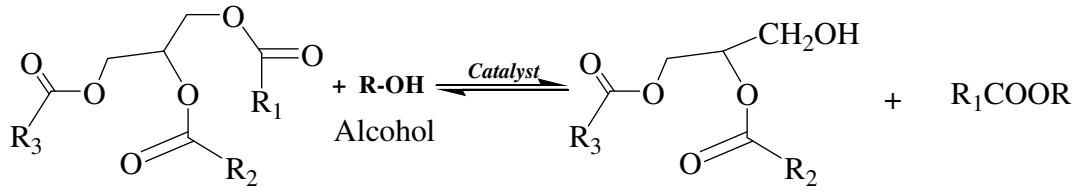


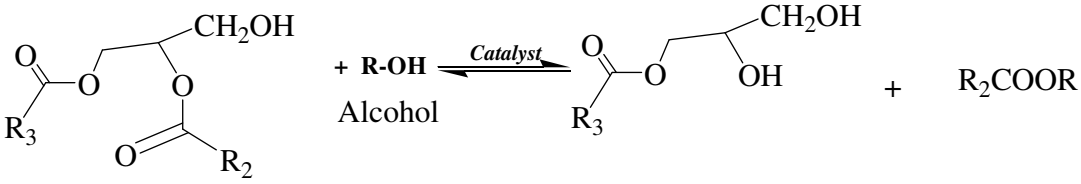
Figure 24.4: General transesterification reaction of TAGs based plant oils.

STEP-1



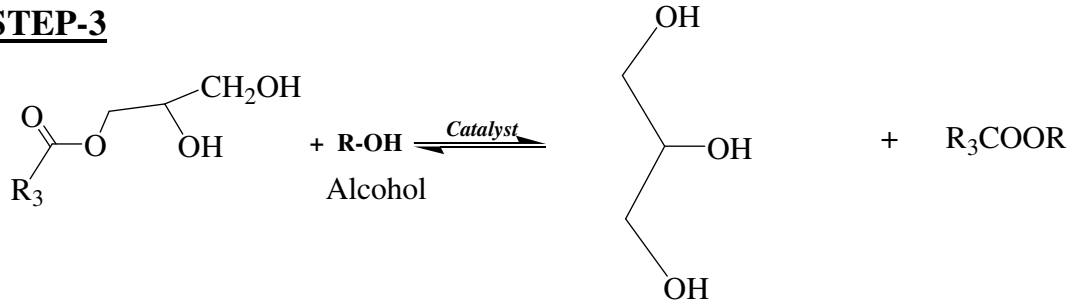
Triacylglycerols **Diacylglycerols**

STEP-2



Diacylglycerols **Monoacylglycerols**

STEP-3



Monoacylglycerols **Glycerol**

Figure 24.5: Stepwise transesterification reaction of TAGs based plant oils.

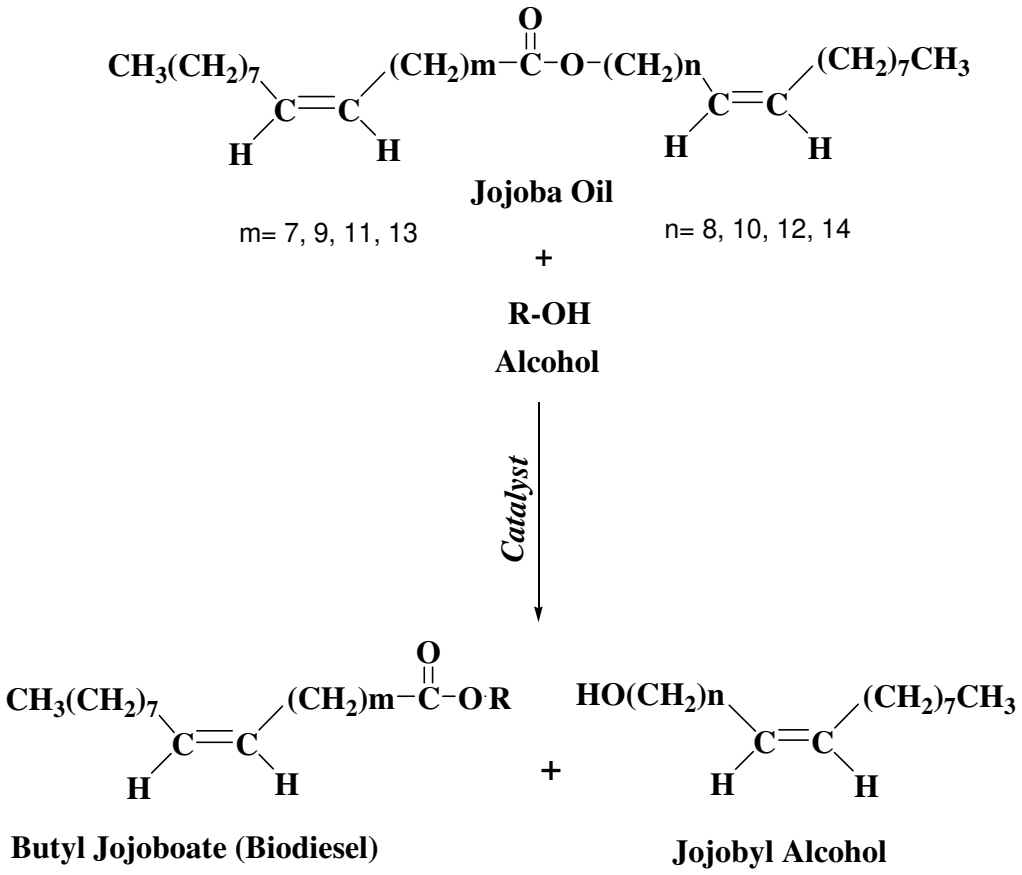


Figure 24.6: Stepwise transesterification reaction of non-TAGs based plant oils.

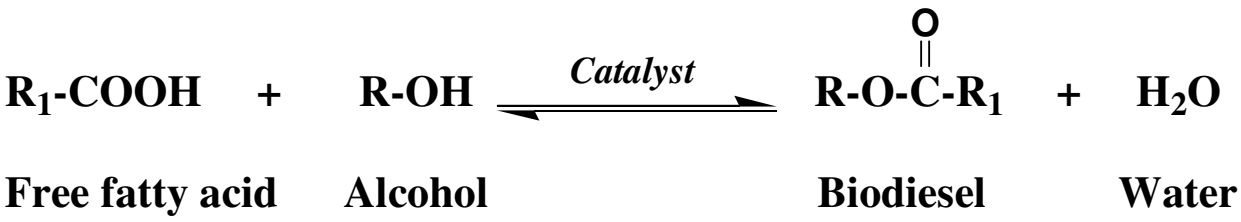


Figure 24.7: Generation esterification reaction of fatty acids.

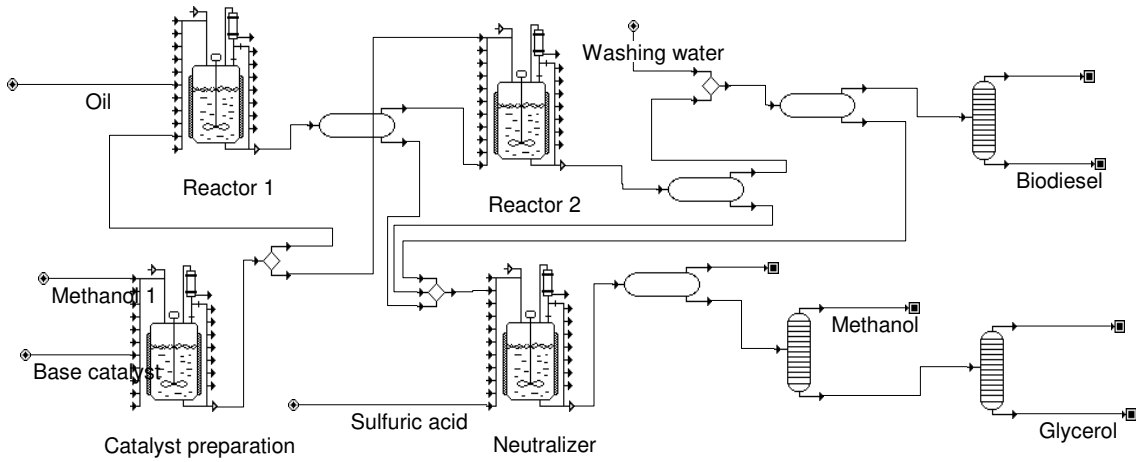


Figure 24.8: Flow diagram for the conventional process [Reprinted with permission from Marchetti 2011].

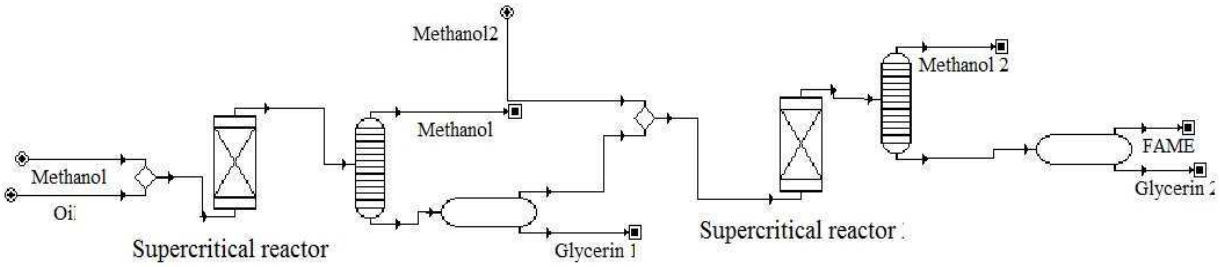


Figure 24.9: Flow diagram for the supercritical process [Reprinted with permission from Marchetti 2013].

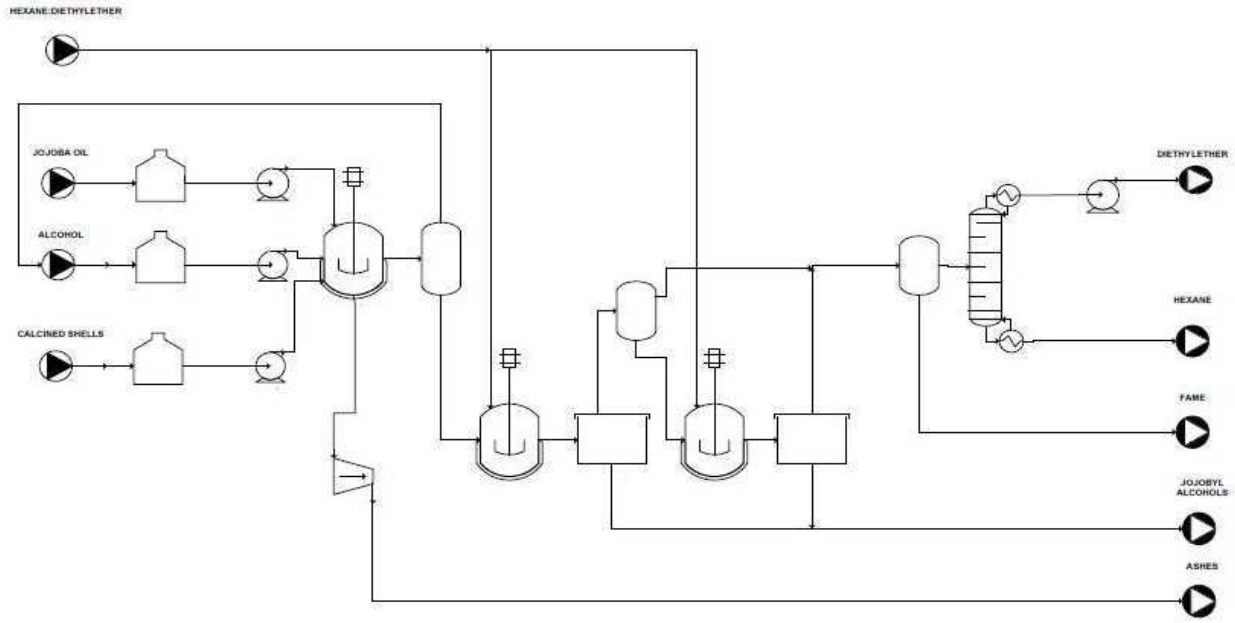


Figure 24.10: Biorefinery process for the production of jojobyl alcohols and biodiesel [Reprinted with permission from Sánchez et al. 2014].

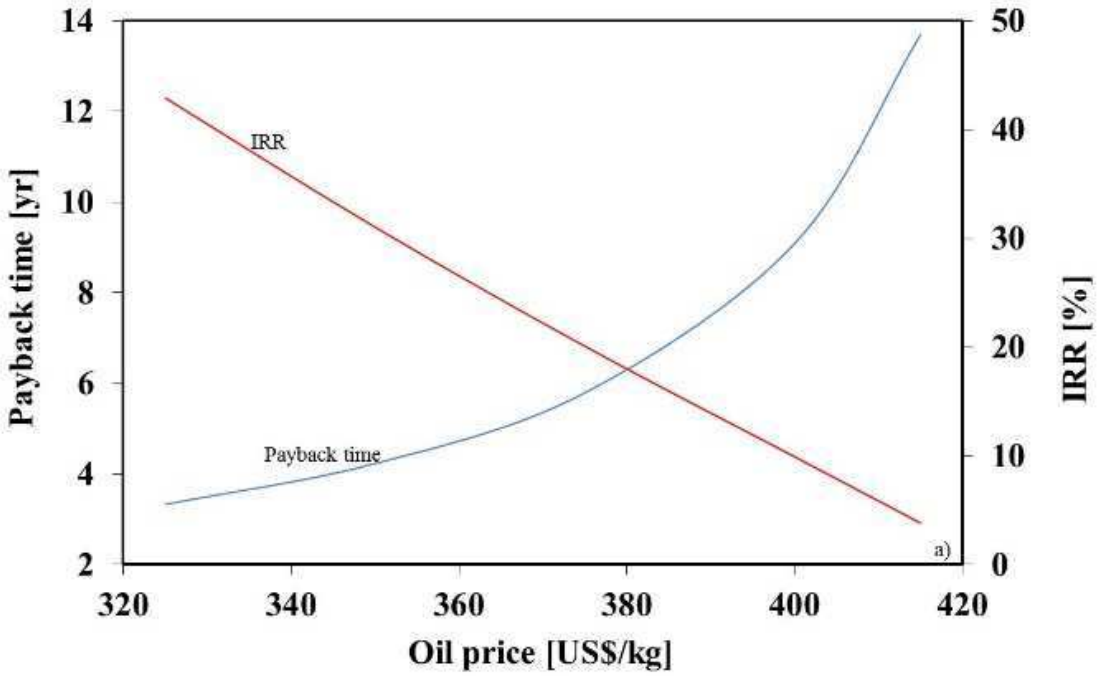


Figure 24.11(a): Effect of the oil price over the supercritical process [Source: Marchetti 2013].

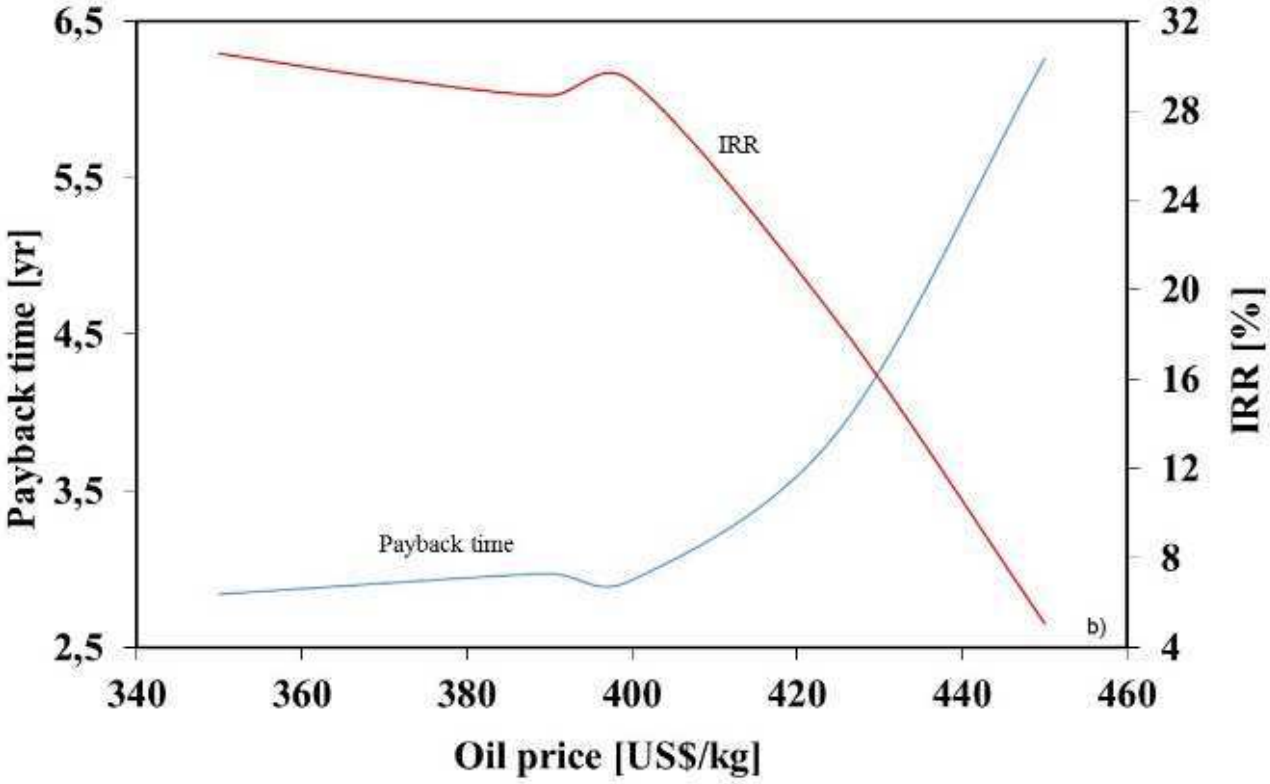


Figure 24.11(b): Effect of the oil price over the conventional process [Marchetti 2011].

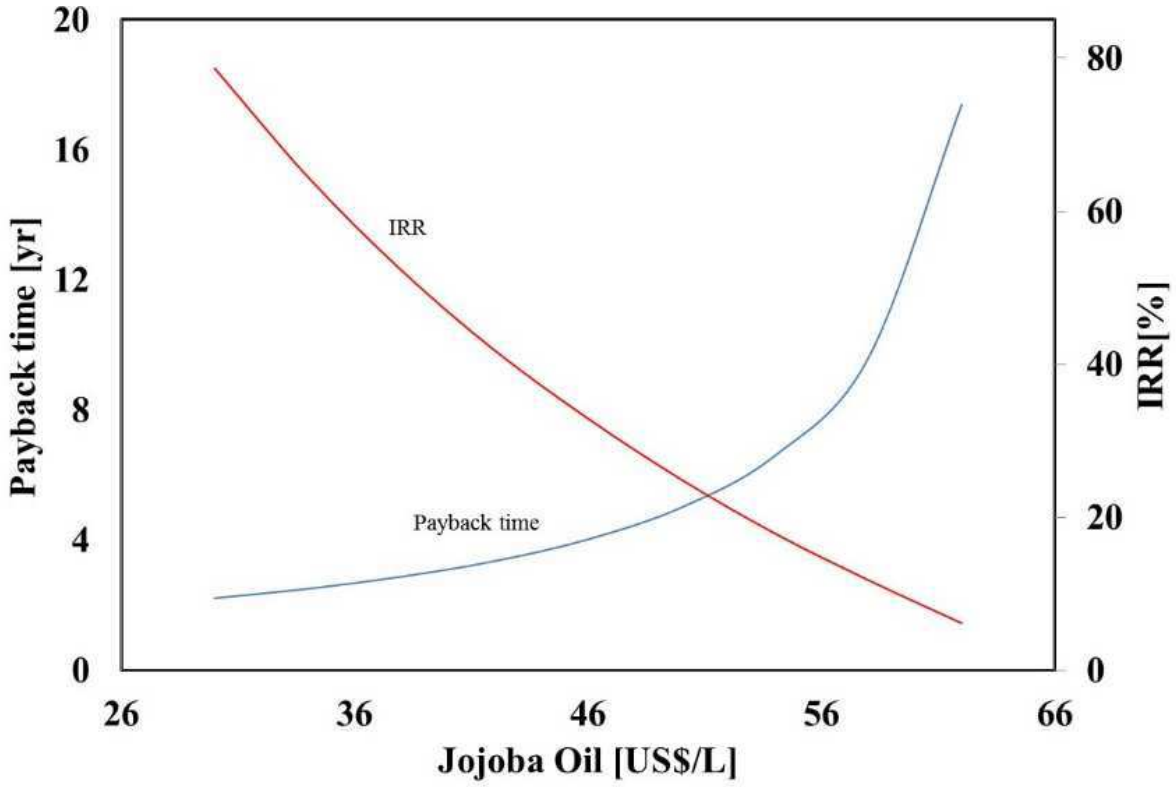


Figure 24.12: Effect of the oil price over jojoba oil based conventional process [Sánchez et al. 2015].

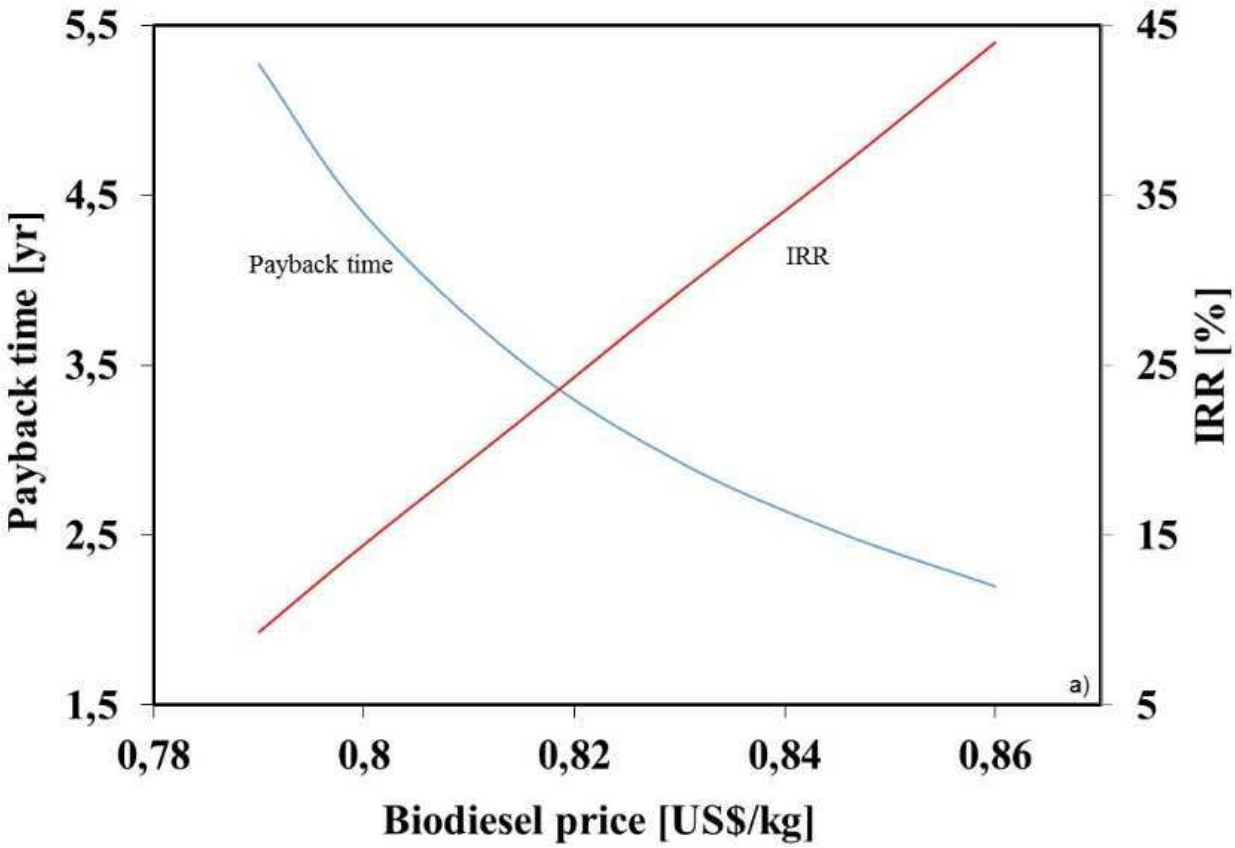


Figure 24.13(a): Effect of the biodiesel price in the process economy of conventional technology [Marchetti 2011].

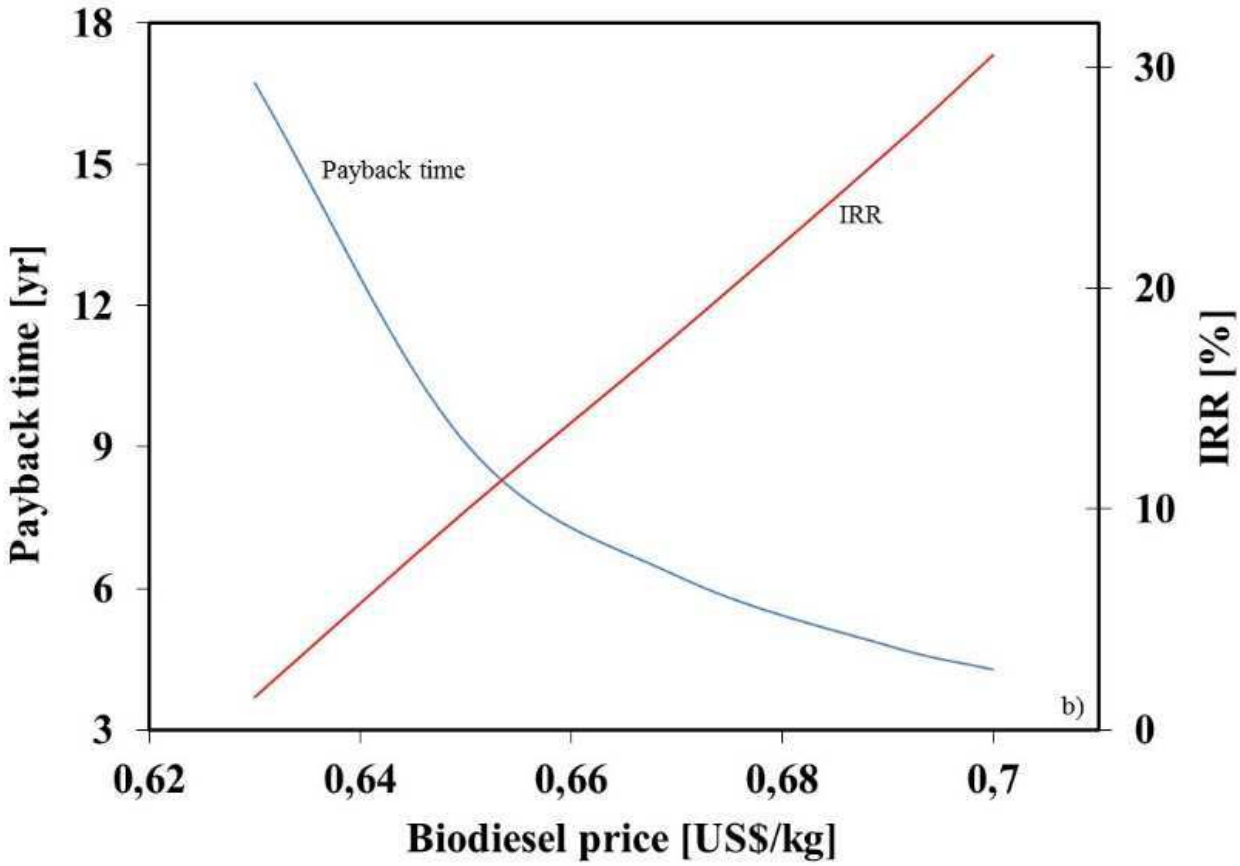


Figure 24.13(b): Effect of the biodiesel price in the process economy of supercritical technology [Marchetti 2013].

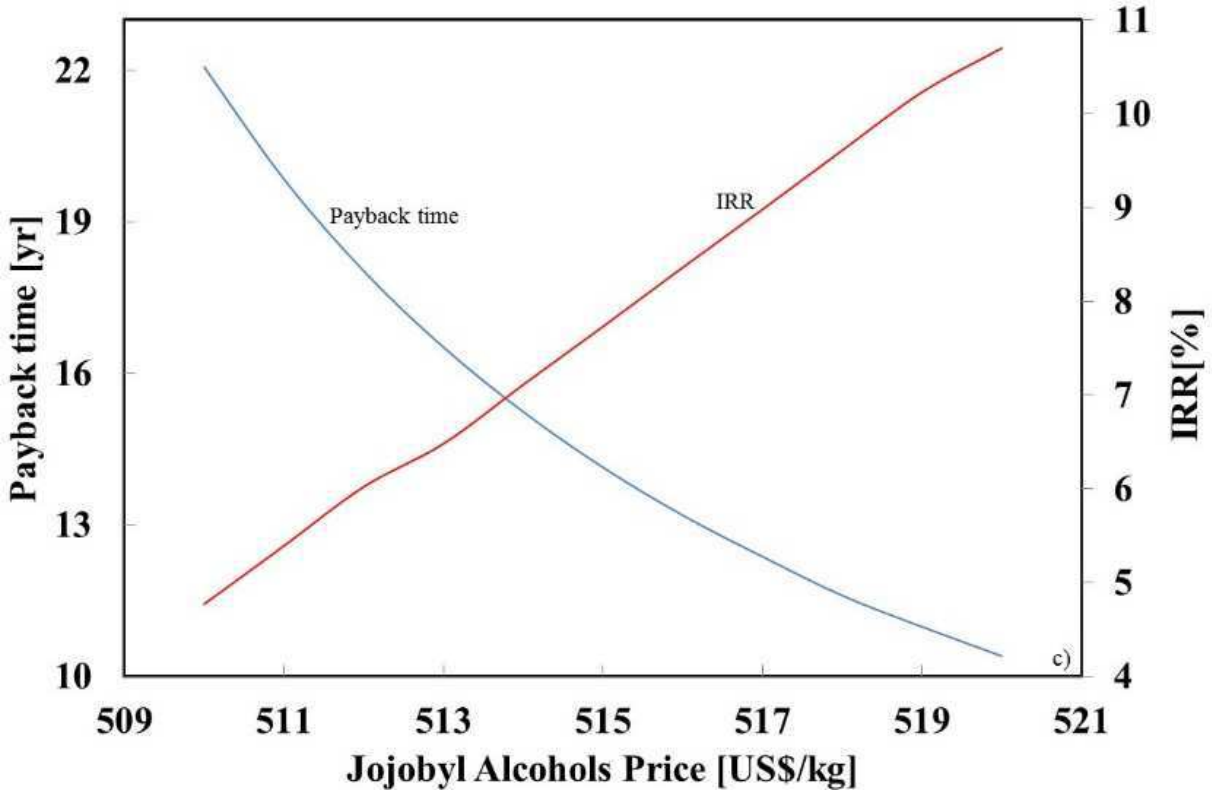


Figure 24.13(c): Effect of the biodiesel price in the process economy of jojoba based conventional technology [Sánchez et al. 2015].