The effect of economic variables on a bio-refinery for biodiesel production using calcium oxide catalyst

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Abstract: This study investigates the effect of market variables on biodiesel production and considers a calcium oxide catalyzed transesterification process. A conceptual process simulation of a plant using Super Pro software was used to vary the economic scenarios and to evaluate the effects of selected variables such as prices of biodiesel, glycerol, oil, alcohol, catalyst, equipment maintenance, labor, and tax variation. Changing the values of these variables led to large effects on the overall economics of the production process. Oil purchasing cost exerted a larger influence on the economic outcome, with an approximately 73% decrease in net present value (NPV) for a 22% increase in the oil purchasing cost. Under optimum conditions the process would be profitable for oil costs below 590US$ ton⁻¹. Varying the equipment maintenance costs produced a smaller effect, which could allow the amount of cost allocated for routine maintenance activities to be increased to sustain the productivity of the process. The study could also provide cutoff values for each variable for economic feasibility of the process at the given market scenario. © 2019 The Authors. Biofuels, Bioproducts, and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: biodiesel; calcium oxide; economic variables; sensitivity analysis

Introduction

Biodiesel is mono alkyl ester of long-chain fatty acids, which is produced through the transesterification of renewable feedstock like vegetable oil, animal fat, tallow, non-edible plant oil, and waste cooking oil. As a fuel, it has significant benefits over fossil diesel. Biodegradability, non-toxicity, lower pollution, and lower greenhouse gas (GHG) emissions are the main advantages.¹,² Lower emission of pollutants and GHGs is attributed to the existence of more free oxygen than is the case with conventional diesel. More free oxygen leads to complete combustion and reduced emissions.³,⁴ Moreover, biodiesel has better lubricity than fossil diesel.

Homogeneous base catalyzed transesterification is the conventional commercial way of producing biodiesel. It results in much higher catalytic activity in the transesterification reaction and causes less corrosion of equipment than acid catalysts.⁵ However, with this method it is a considerable challenge to make the overall biodiesel production economics competitive with fossil diesel. This is mainly because it requires high oil quality
with free fatty acid (FFA) content of less than 0.5%. Such high-quality feedstock is associated with high purchasing costs, thus making the final product expensive. Several studies have been conducted to investigate possible alternatives, which can suggest technical possibilities for producing biodiesel in an economically competitive manner. These include using cheaper feedstock and catalyst or using least-cost technological options. Particular interest has been directed towards heterogeneous alkaline catalyzed,
10–13 homogeneous and heterogeneous acid catalyzed,14–18 enzyme catalyzed,19–21 and supercritical22–24 transesterification of oil / fat feedstock with different FFA content. Some advanced technologies are also receiving attention as alternative technological options. Among them are nanocatalysts,25–27 nano-immobilized enzymes,28,29 and ionic liquid catalysts.30–32

Heterogeneous base catalyzed transesterification has shown great advantages over the rest and therefore it has been a focus of attention with the aim of reducing the overall cost involved when producing biodiesel.13,33 This particular method uses cheaper catalysts with relatively higher catalytic activity, and requires easy catalyst recovery, which enables repeated use of the catalysts.34–36

Calcium oxide is the most widely studied heterogeneous catalyst among the alkaline earth metal oxides, which could give a fatty acid methyl ester (FAME) yield up to 98%,35,37,38 The effective character of this catalyst is attributed to its nano-crystallized particle size and smaller defects, which give a higher surface area. Moreover, CaO presents higher basicity, lower solubility, and a lower price, and it is easier to handle than the conventional homogeneous alkaline catalysts such as NaOH and KOH.39 Ljupkovic et al.4 investigated the significance of the structural properties of a CaO catalyst in the production of biodiesel and discovered that the catalyst has benefits such as short contact time (up to 2 h), standard operating temperature (64 °C) and atmospheric pressure, a relatively low molar ratio (6:1), and small catalyst loading (1 wt.%). This study revealed that all the above factors could result in attaining a very high biodiesel yield with a high level of purity (> 95%).4 In another study, by Avhad et al.,10 it was reported that the optimum reaction conditions to obtain the maximum conversion within 2 h, for ethanolysis of avocado oil using glycerol enriched CaO catalyst, is 75 °C reaction temperature, 9:1 molar ratio of ethanol to oil, and 7% catalyst amount with respect to weight of the oil. A similar study by Sánchez et al.41 indicated that it took about 10 h to reach the maximum 93.3% conversion of Jojoba oil into biodiesel using a CaO catalyst prepared through calcination of mussel shells. The optimum reaction conditions for this process were taken to be 65 °C reaction temperature, the catalyst amount, respect to the oil mass is 8 wt%, and 9:1 methanol-to-oil ratio.41 Table 1 shows a summary of studies of the optimization of biodiesel production from different feedstocks using heterogeneous CaO catalysts.

Although some studies mentioned that CaO can be reused many times as a catalyst for transesterification,13,45,49 its reusability is usually compromised by a fast decrease in surface basicity, reducing its catalytic activity, because it adsorbs CO₂ and water from the atmosphere when exposed to air.50 However, one can simply wet the catalyst with methanol, oil, or biodiesel to prevent poisoning of the CaO by CO₂, because these liquids could occupy the pores of the catalyst and significantly minimize the CO₂ and water adsorption.51 For instance, if a biodiesel is added to activated CaO catalyst to form a catalyst paste, its catalytic activity could be maintained at least for 24 h because the formation of the paste prevents the diffusion of CO₂ and water.51

The immediate use of a recycled catalyst can be another option to avoid the poisoning of the catalyst due to the formation of a layer of CaCO₃ and Ca(OH)₂. Furthermore, the formation of calcium oxide glycerin complex, due to the presence of glycerin and the CaO catalyst, could make the catalyst tolerant to air exposure 52 and this complex could function as the main catalyst to accelerate the transesterification reaction.53–55 This can be considered as the other advantage of using CaO as a catalyst for the transesterification reaction.

There are some works where the economics or the effect of market variables for a biodiesel production plant using CaO have been studied. Sakai et al.56 conducted a feasibility study for producing biodiesel from waste cooking oil using four processes with four different catalysts. Among them, a heterogeneous CaO catalysis together with hot water purification process (CaO-W) and a heterogeneous CaO catalysis together with a vacuum FAME distillation process (CaO-D) were presented and analyzed. The authors studied the fixed and manufacturing costs for biodiesel production using each of the four processes at a different production capacity. They concluded that the manufacturing costs for CaO-W and CaO-D process were competitive in comparison to the two other homogeneous KOH catalyst alternatives. Moreover, the combined effect of the low cost of the CaO catalyst and the absence of the expensive distillation process gave the CaO-W process alternative the lowest manufacturing cost within the production range of 1452 ton year⁻¹ to 14 520 ton year⁻¹.56

The promising technical capability of the CaO catalyst for biodiesel production invites further investigation of the feasibility of using this catalyst in the production of
fuel-quality biodiesel. Accordingly, this work has analyzed the effect of a number of economic variables over biodiesel production plant using CaO as a catalyst. The analysis could help to understand how sensitive the selected production process might become towards the change in market values of most economic variables, which are more influential in the process of biodiesel production. The market variables considered were biodiesel price, glycerol price, oil feedstock price, alcohol price, catalyst price, labor cost, equipment maintenance cost, and variations in local taxes. The objective was to test how these variables could affect the feasibility of the business.

To perform this study, a complete simulation of the process flow was designed using both Super Pro and Aspen Plus software. The Aspen Plus design was used to recheck the accuracy of the simulation done by Super Pro, as it considers a wider choice of property methods and physical parameters. Even though there are wider differences between process simulation results and the actual process operation, it is possible to obtain reliable information on process operations when we use Super Pro software. This is because the Super Pro design considers specific chemical component properties and the application of advanced calculation techniques.

### Study case and process description

This study considered the production of biodiesel from acidic oil using CaO as a solid catalyst. The FFA content of the oil feedstock was taken to be 10% on a molar basis with respect to the oil. Acidic oil is considered to represent most of non-edible plant oil, which has higher FFA content and is usually cheaper. A conceptual process model with a biodiesel production capacity of 40,700 ton year$^{-1}$ was designed. The process flowsheet designed using Super Pro is as shown in Fig. 1. The entire process has four main unit procedures: transesterification, ethanol recovery, biodiesel, and glycerol separation and biodiesel purification.

#### Transesterification

The transesterification reaction considered in the process design is the typical CaO catalyzed reaction between ethanol and acidic oil. Acidic oil at 5177.23 kg h$^{-1}$ and ethanol at 2341.35 kg h$^{-1}$ are heated to 75 °C and simultaneously supplied to the fixed bed reactor (R-101) packed with 362.41 kg CaO catalyst. In the reactor both transesterification and saponification reactions are considered to happen. Transesterification takes place when triglyceride reacts with ethanol in the presence of the solid

| Feedstock       | Alcohol | Catalyst | Temperature (°C) | Alcohol to oil molar ratio | Reaction time (h) | Catalyst amount (%) | Conversion (%) | Yield (%) | Reusability | References |
|-----------------|---------|----------|------------------|---------------------------|-------------------|--------------------|----------------|-----------|-------------|------------|
| Fried vegetable oil | Methanol | CaO      | 65               | 6:1                       | 1.5               | 5                  | 92             | 92        | NA          | 42         |
| Jatropha curcas oil | Methanol | CaO in (NH$_4$)$_2$CO$_3$ | 70               | 2:1                       | 1.5               | 5                  | 96.45          | 93        | NA          | 43         |
| Sunflower oil   | Methanol | CaO      | 60               | 13:1                      | 1.67              | 3                  | 94             | 94        | NA          | 44         |
| Soybean oil     | Methanol | CaO      | 65               | 12:1                      | 1.5               | 8                  | 94             | 94        | 20 times    | 45         |
| Palm oil        | Methanol | CaO      | 65               | 12:1                      | 5                 | 6                  | 98.64          | 95        | 20 times    | 46         |
| Waste cooking oil | Methanol | CaO from waste crab shell | 65               | 11 times                 | 12.5              | 5                  | 98.7           | 98        | 17 times    | 47         |
| Palm oil        | Methanol | CaO      | 65               | 11 times                 | 12.5              | 5                  | 98.64          | 95        | >95 times   | 48         |
| Soybean oil     | Methanol | CaO      | 65               | 11 times                 | 12.5              | 5                  | 98.64          | 95        | >95 times   | 48         |
| Avocado oil     | Ethanol  | CaO enriched with glycerol | 75               | 9                  | 6                  | 91.82            | 97.58         | 40        | NA          | 41         |
| Jojoba oil      | Methanol | CaO from mussel shell | 65               | 9                  | 6                  | 91.82            | 97.58         | 40        | NA          | 41         |
catalyst CaO to produce biodiesel and glycerol, whereas saponification is between oleic acid and some amount of CaO catalyst to produce calcium oleate (calcium soap) and water. The reaction conditions in the reactor are set to 75 °C, 7% catalyst amount with respect to oil amount, and a 9:1 ethanol to oil molar ratio, based on the optimum reaction conditions indicated in the literature. Under these reaction conditions, the maximum conversion of triglyceride of 97.58% can be achieved within 2 h. Accordingly, 2 h of reaction time and 97.58% triglyceride conversion are taken during designing the reactor. The product is removed from the reactor at a rate equal to the rate of charging with reactants in such a manner as to give a residence time of 2 h in the reactor. The product from the reactor is then let into a distillation column to recover excess ethanol.

**Ethanol recovery**

The transesterification reaction is an equilibrium reaction with a stoichiometric molar ratio of alcohol to oil of 3:1. It is advisable to use excess alcohol to encourage a forward reaction and thus obtain more product. For this reason, in this particular process, the ethanol-to-oil molar ratio considered is 9:1 and thus excess ethanol after the reaction has to be recovered for reuse. To recover the excess ethanol, a distillation column (C-101) is designed with a 1.6 reflux ratio and working under vacuum at 0.25 bar to prevent thermal decomposition of biodiesel and glycerol during distillation. The heating agent is steam. The stage efficiency of the column is taken to be 80% resulting in six actual stages. The upper output from the distillation column is 99.3% pure ethanol, which can be reused or taken as credit in the economic calculations. The bottom output, mainly composed of ethyl ester, glycerol, and the calcium soap is further made to flow into a centrifugal separator (DC-101) where crude biodiesel is separated from glycerol.

**Biodiesel and glycerol separation**

The use of heterogeneous catalysts does have the advantage of making the biodiesel and glycerol separation and purification processes very easy. In this particular process model a simple centrifugal decanter (DC-101) is designed to separate the crude biodiesel from the glycerol. The decanting is based on oil removal – crude biodiesel with higher purity is separated. The crude biodiesel, from the upper outlet of the DC-101, is then let into the second distillation column (C-102) for further purification of the biodiesel product. The bottom outlet from the centrifugal decanter (DC-101) is mainly composed of glycerol byproduct with few impurities from the remaining biodiesel, water, and unreacted oil. The glycerol produced using heterogeneous catalysts like CaO is expected to be easily separated and have very high purity up to 98%.

**Biodiesel purification**

Biodiesel purification is mostly performed using wet and dry washing. Washing has some disadvantages, such as higher process costs, longer washing time, production of a large amount of wastewater, and emulsification because of continuous stirring to facilitate the washing. Moreover, when basic heterogeneous catalysts like CaO are used, soaps form, which cannot be removed easily and effectively through washing. In this study, a distillation column is designed to obtain the maximum possible pure biodiesel. The distillation column (C-102) is with three reflux ratio and seven number of stages, beyond which there would be no change in improving purity of the biodiesel. The upper output from this distillation column, the distillate, is the pure biodiesel at higher temperature. This has to be cooled to ambient temperature using a cooler. The bottom outlet from the distillation column, which mainly consists of unreacted oil and calcium soap, is considered to be waste, for safe disposal without further waste treatment. Table 2 shows a summary of operating conditions for each of the four main unit procedures required to complete the whole production process.

**Economic assessment**

This study considered eight groups of market variables known to affect the economic feasibility of chemical production processes. The downstream equipment and the unit procedures involved are well known for providing fuel-quality biodiesel. The simulation of the process used Aspen Plus and Super Pro, which is commercially available.
software. Aspen Plus was used for energy and material balance, as it has a wider choice of thermodynamic and property methods, depending on the type and properties of the chemicals and the chemical reactions involved. This could improve the accuracy of the design and the reliability of the results. The results from this process design could apply to most of the non-edible oil types, which have an FFA content of up to 10%.

A technical assessment indicated that this method is capable of producing biodiesel of the required quality and quantity. This is in agreement with similar studies. For instance, the yield before purification is about 92% biodiesel. This is also in agreement with the results reported in the literature which investigated production under similar reaction conditions. This encourages further assessment of the economic feasibility of the whole production process. However, not many studies have investigated the economic aspects of producing biodiesel from acidic oil using CaO as catalyst. In this study, the current best values of materials, equipment, utilities, and labor costs are used in the calculation of capital investment costs and operating costs using the process model that was designed.

### Estimation of capital costs

Total capital investment includes direct plant costs (equipment purchasing cost, installation, instrumentation, insulation, etc.), indirect plant costs (such as engineering and construction costs), working capital, and startup and validation costs. The equipment costs were calculated based on the Peters and Timmerhaus method and the latest Chemical Engineering Plant Cost Index used was 591.34. Based on the process flow diagram shown in Fig. 1 and the estimated cost of equipment, and the market price of input materials, labor and utilities, it was possible to calculate capital cost, production cost, and revenue. Table 3 summarizes the capital cost calculation.

A considerable amount of the plant's direct cost is for equipment purchase, and the reactor and the centrifuge have the largest cost of the process equipment considered in this design. Other components of the direct fixed capital cost are calculated based on the equipment purchasing cost following a percentage allocation from the literature as presented in Table 3. Engineering cost and construction cost are the two main indirect plant cost components. These costs are taken to be 25% and 35% of the direct cost respectively. The total plant cost, which is the sum of the plant direct costs and the plant indirect costs, is calculated to be US$1 526 000. The direct fixed capital cost includes the total plant cost, contractor’s fee, and contingency, and comes to US$1 756 000. Finally, by adding the working capital, validation cost, and the direct fixed capital cost, the total capital investment cost for the construction of the designed plant capacity is estimated to be US$4 646 000.

### Estimation of operating costs

The literature and current market prices from different suppliers have been used as main sources of cost estimation for raw materials, labor, and utilities. The cost of raw materials, labor, and utilities considered in this process design are indicated in Table 4. Raw materials include oil feedstock, ethanol, and CaO catalyst. The oil feedstock considered has a FFA content of 10% of the oil on a weight basis. The potential cheaper feedstock types do have a higher FFA value. According to some sources from the literature, the cost of such feedstocks can be placed in a range from US$478–684 ton$^{-1}$. For this study the

| Table 2. Summary of operating conditions in each main unit procedures. |
|-----------------------------|-----------------------------|
| **Transesterification reaction in R-101** |
| Reactor type | CSTR (22.85 m$^3$) |
| Temperature | 75°C |
| Pressure | 1.013 Bar |
| Catalyst | CaO |
| Alcohol-to-oil ratio | 9:1 |
| Conversion | 97.58% of triglyceride |
| **Ethanol recovery in C-101** |
| Stage efficiency | 80% |
| Number of actual stages | 6 |
| Reflux ratio | 1.6 |
| Column pressure | 0.25 bar |
| Distillate flow rate | 1579.5 kg h$^{-1}$ |
| Recovery | 67.46% |
| Distillate purity | 99.6% |
| **Biodiesel separation in DC-101** |
| Sedimentation efficiency | 30% |
| Equipment rating | Based on oil/fat removal |
| Oil concentration in oil stream | 870 g L$^{-1}$ |
| Purity of the biodiesel | 92% |
| Glycerol flow rate | 505 kg h$^{-1}$ |
| Glycerol purity | 99% |
| **Biodiesel purification in C-102** |
| Stage efficiency | 80% |
| Number of actual stages | 11 |
| Reflux ratio | 3 |
| Distillate flow rate | 5132 kg h$^{-1}$ |
| Distillate purity | 99.99% |
average value, 580US$ ton\(^{-1}\) or 0.58US$ kg\(^{-1}\), is taken as the cost of the acidic oil feedstock. The costs for alcohol, catalyst, and water are based on the current market price in Ethiopia. Table 4 summarizes operating / production cost categories considered in the design.

The labor cost calculation is carried out using the basic rate estimated according to the labor category. The current wage indicator in Ethiopia is the basis for estimation of the basic rate. Such a calculated labor cost is used as a minimum payment and then it is scaled up to a certain payment level. The utilities considered in this process model are steam, chilled water, and electricity. The market values for each of these utilities are estimated based on the literature and on current market prices in Ethiopia. Table 5 summarizes the operating cost categories.

The dominant cost category in the production cost calculation is that of raw materials. It accounts for 93% of the total production cost, and 81% of this material cost is due to cost of oil feedstock for biodiesel production. This agrees well with most similar studies using different catalysts and feedstock. The unit production cost is around 0.78 US$ kg\(^{-1}\) or 0.67 US$ L\(^{-1}\) biodiesel. This value is relatively lower than the value reported by Apostolakou et al. (1.15 US$ L\(^{-1}\) or 1.318 US$ kg\(^{-1}\)) and higher than the values reported by Marchetti et al. (0.5084 US$ kg\(^{-1}\) up to 0.5223 US$ kg\(^{-1}\)) and Haas et al. (0.53 US$ L\(^{-1}\)).

### Sensitivity analysis over some market variables

The cost of raw materials and prices of products in the chemical industry scheme are commonly dictated by the global economy. Similarly, in biodiesel production processes, the price of the biodiesel and the cost of raw materials in the market can sometimes make the business profitable. This kind of situation reduces the confidence of investors in such businesses. In line with this, it is always necessary to investigate how such market variables can affect the economic feasibility of the business, considering the possible ranges of prices. In this study, price ranges have been set for biodiesel, glycerol, acidic oil feedstock, ethanol, CaO catalyst, labor

### Table 3. Capital costs for the construction of a biodiesel production plant with 40 700 ton year\(^{-1}\) production capacity.

| Cost categories                                      | % allocation | Amount (US$000) |
|------------------------------------------------------|--------------|-----------------|
| **Direct plant cost (DC)**                           |              |                 |
| Equipment purchasing cost (PC)                       |              | 341             |
| Installation                                          | 20 x PC      | 68              |
| Process piping                                       | 20 x PC      | 68              |
| Instrumentation                                      | 10 x PC      | 34              |
| Insulation                                           | 3 x PC       | 10              |
| Electrical                                            | 15 x PC      | 51              |
| Building                                              | 15 x PC      | 51              |
| Yard improvement                                     | 10 x PC      | 34              |
| Auxiliary facilities                                 | 25 x PC      | 85              |
| Purchasing cost of unlisted equipment (UEPC)         | 20 x PC      | 68              |
| Installation cost of unlisted equipment               | 50 x UEPC    | 34              |
| **Total plant direct cost (DC)**                     |              | 844             |
| **Indirect plant cost (IC)**                         |              |                 |
| Engineering                                           | 25 x DC      | 211             |
| Construction                                          | 35 x DC      | 296             |
| Other indirect costs                                  |              | 175             |
| **Total Plant indirect cost (IC)**                   |              | 682             |
| Contractors’ fee                                      | 5 x (DC+IC)  | 76              |
| Contingency                                           | 10 x (DC+IC) | 153             |
| **Sum of Contractor’s fee and contingency (CFC)**     |              | 229             |
| **Total direct fixed capital cost (DC+IC+CFC)**       |              | 1756            |
| **Working capital (WC)**                             |              | 2764            |
| **Startup and validation cost (SVC)**                 |              | 87.8            |
| **Total capital investment cost (DC+IC+CFC+WC+SVC)**  |              | 4608            |

*Percentage allocation is based on Karmee et al.\(^8\)

### Table 4. Cost of raw materials, labor, and utilities for optimum production of biodiesel using the process models.

| Raw material            | Cost (US$) |
|-------------------------|------------|
| Oil                     | 0.58 kg\(^{-1}\) |
| Alcohol                 | 0.3 kg\(^{-1}\) |
| Catalyst                | 0.12 kg\(^{-1}\) |
| Water                   | 0.02 kg\(^{-1}\) |
| **Utilities**           |            |
| Electricity             | 0.09 kW-h  |
| Steam                   | 12 MT\(^{-1}\) |
| Chilled water           | 0.4 MT\(^{-1}\) |
| **Labor (basic rate)**  |            |
| Operator                | 20 h\(^{-1}\) |
| Reactor operator        | 25 h\(^{-1}\) |
| Supervisor              | 30 h\(^{-1}\) |
Effect of changes in biodiesel selling price

The selling price of biodiesel has a distinctive influence on the profitability of the biodiesel production business. This price, in turn, is governed by market demand and government policy interventions, like taxes and subsidies associated with services using the fuel. Thus, analyzing profitability of the business by considering different price scenarios would help to maintain confidence when attempting to sustain the business in the market. For this study the range of biodiesel selling prices has been taken as 0.77–0.84 US$ kg\(^{-1}\), considering all the above factors. This price range is in agreement with the current market price of biodiesel.\(^{72}\) Figure 2 shows the effect of the change in the price of biodiesel on payback time and NPV.

The NPV increases linearly as the biodiesel selling price increases. The payback time is decreasing in a non-straight manner as the selling price of the biodiesel is increasing. At the beginning, the increase in selling price causes a very large response in terms of the payback time, which tends to slow as the price becomes higher, above about 0.81 US$ kg\(^{-1}\). Figure 2 shows that a fraction increase in biodiesel selling price would bring about a considerable change in the NPV. With optimum production conditions, this analysis has indicated that selling the biodiesel with a price below 0.775 US$ kg\(^{-1}\) is not profitable.

Effect of changes in the glycerol selling price

As the main byproduct of the biodiesel production industry, glycerol can be a significant factor in the profitability of the

| Table 5. Summary of operating cost calculations for biodiesel production capacity of 40 700 ton per year. |
|---|
| Cost category | Calculation | Amount (US$000) | % |
| 1. Raw materials | From material balance | 29 373 | 93 |
| 2. Utilities cost | From material balance | 476 | 1.5 |
| **Variable costs (VC)** | (1) + (2) | **29 849** |
| 3. Maintenance | 6% x PC | 26 | 0.8 |
| 4. Operating labor | Manning estimates | 560 | 1.8 |
| 5. Laboratory cost | 30% x (4) | 168 | 0.5 |
| 6. Depreciation | 11.6 x DC | 98 | 0.3 |
| 7. Insurance | 2% x DFC | 35 | 0.1 |
| 8. Local tax | 35% x DFC | 615 | 1.8 |
| 9. Factory expense | 5% x DFC | 89 | 0.3 |
| 10. Miscellaneous | Fixed | 70 | 0.2 |
| **Fixed costs (FC)** | (3) + (4) + ...... + (9) | **1661** |
| **Annual operating cost** | (VC) + (FC) | **31 510** |
| **Unit production cost** | 31.51 M$/40.7MKg biodiesel = 0.775 US$ kg\(^{-1}\) = 0.67 US$ L |

| Table 6. Studied ranges for the market variables. |
|---|
| Market variables | Minimum value | Standard value | Maximum value |
| Biodiesel selling price (US$ kg\(^{-1}\)) | 0.77 | 0.78 | 0.84 |
| Glycerol selling price (US$ kg\(^{-1}\)) | 0.05 | 0.12 | 0.18 |
| Oil purchasing cost (US$ kg\(^{-1}\)) | 0.45 | 0.58 | 0.68 |
| Ethanol purchasing cost (US$ kg\(^{-1}\)) | 0.1 | 0.30 | 0.35 |
| CaO purchasing cost (US$ kg\(^{-1}\)) | 0.08 | 0.12 | 0.22 |
| Equipment maintenance (% of PC) | 3 | 6 | 40 |
| Local tax (% of DFC) | 15 | 30 | 45 |
| Labor cost (basic rate in US$ h\(^{-1}\)) | Operator 10 20 30 | Reactor operator 15 25 35 | Supervisor 20 30 40 |
| Total basic rate (US$ h\(^{-1}\)) | 45 75 105 |
biodiesel production process by increasing the total revenues of the business. However, its market value is mostly determined by its quality. The required quality of glycerol in the market can be as high as pharmaceutical quality or, on the other hand, as low as the quality of unrefined industrial glycerol. Pharmaceutical-quality glycerol (refined glycerol) has a higher price and, in the current US market, it can be sold for up to 960 US$ ton\(^{-1}\). The industrial-quality glycerol (unrefined glycerol), mainly from the biodiesel production process, may vary in quality depending on the technology involved. Consequently, these industrial glycerol products can be sold for up to 0.15 US$ kg\(^{-1}\).

In this particular study, the amount of glycerol produced with 87.8% purity is about 9.8% of the total production of biodiesel. It is therefore worth considering the glycerol for market. A price range of 0.05 up to 0.18 US$ kg\(^{-1}\) has been assumed in order to investigate how payback time and NPV could change.

Figure 3 indicates that the payback time changed inversely with the glycerol selling price whereas the NPV increased with an increasing glycerol price. A 0.05 US$ kg\(^{-1}\) increase in the glycerol price would make a US$1.21 million change in the NPV. However, the effect of the glycerol price on the payback time is less significant in comparison with the effect when the biodiesel price varies. An increase in price of glycerol by US$0.12 (three fold increment) could only decrease the payback time by 0.15 years but resulted in an increase in the NPV by about US$2 881 000 (an 11-fold increment). If glycerol is considered to have a zero value, the production process could become unprofitable.

### Effect of change of oil purchasing cost

The cost of feedstock takes a larger percentage of cost of biodiesel production. The highest share is when an oil with less free fatty acid content, like vegetable oil, is used. Feedstock with high free fatty acid content does have a relatively lower cost and this would provide opportunities to reduce the cost of production. This implies that the feedstock chosen could largely affect the profitability of biodiesel production business. In this study a cost range of 0.45–0.68 US$ kg\(^{-1}\) has been used. This cost range has been set based on the literature on the cost of acidic oil feedstock.

The feedstock type considered here is the same feedstock with the same FFA content within the stated cost range. However, it is also possible to consider feedstock with a range of costs based on its FFA content, to investigate the effect of the cost (due to the FFA content) on the profitability of the production process.

As it is depicted in Fig. 4, the NPV shows a strong response to a change in the cost of oil feedstock. Moreover, an increase in oil feedstock purchasing cost by about 0.1 US$ kg\(^{-1}\) (from 0.45 up to 0.55 US$ kg\(^{-1}\)) could result in a decrease in NPV of about US$24 502 000, whereas the payback time increment is only about 6 months. A feedstock cost of 0.59 US$ kg\(^{-1}\) and beyond made the business unprofitable, with a negative NPV. The effect of the change in price of oil shows very little effect on the payback time for low prices. However this tendency becomes more significant for oil prices above 0.5 US$ kg\(^{-1}\). Above 0.5 US$ kg\(^{-1}\) of oil feedstock price an increase in the oil price by 0.09 US$ kg\(^{-1}\) could increase the payback time by 3.32 years. In this case, one can say that the oil price can have a more profound effect on the profitability of the business than the other two market variables.

### Effect of change of alcohol purchasing cost

As an input, ethanol has the second highest cost after oil feedstock. This implies that the cost of alcohol does have
a meaningful impact on the profitability of the biodiesel production business. To investigate the effect of the ethanol market price on the process's profitability, a price range of 0.1 to 0.335 has been assumed considering the possible market fluctuations. As can be seen from Fig. 5, the change in the NPV due to the increase in the cost of ethanol is very high. An increase in the cost of ethanol by 0.05$ kg\(^{-1}\) could bring about a decrease in the NPV by US$5.54 million. The effect of the ethanol cost on the payback time is also very interesting. A strong effect is observed when the cost of ethanol increases beyond about 0.25US$ kg\(^{-1}\). The maximum cost of ethanol for profitable production process is about 0.31US$ kg\(^{-1}\). However, as the alcohol used in this process is much greater than the stoichiometric amount, the excess ethanol that is recovered in the process could be reused. This could help to reduce the effect of the alcohol purchasing cost on the profitability of the business over time.

**The effect of change of catalyst purchasing cost**

The effect of the cost of the catalyst on the economic feasibility of biodiesel production is expected to be less than that of oil and alcohol purchasing costs. This is more pronounced when a cheaper catalyst like CaO is used in the production process. However, to be more practical in comparing the economic effect of available market variables, the same test has been carried out on the effect of change of catalyst purchasing cost. Accordingly, for this study, a catalyst purchasing cost range of 0.08 up to 0.22 US$ kg\(^{-1}\) has been taken based on the average market price of 0.12US$ kg\(^{-1}\).

Figure 6 shows that the whole process could be insensitive to a considerable change in the cost of the catalyst because, even with a higher cost of the catalyst, the NPV from the project is in the positive range. However, this small effect for the change in catalyst purchasing cost is more profound on NPV than payback time. An increase in the cost of the catalyst by 0.1US$ kg\(^{-1}\) could result in a reduction of the NPV by about US$140 000. However, the effect of the change in cost of the catalyst on the payback time of the project is not very significant. A catalyst price change from 0.08 to 0.3$ kg\(^{-1}\) would not result in a considerable change in payback time.

**Effect of change of equipment maintenance cost**

Equipment maintenance in any kind of production process is crucial to sustain the process as effectively as possible up to the lifetime of the whole project. It involves actions necessary for retaining or refurbishing the equipment to a specified operable condition to achieve its maximum useful life. Such actions fundamentally include corrective maintenance and preventive maintenance. Similarly, any
equipment involved in the biodiesel production process should be subject to both corrective and preventive maintenance to sustain the production for a longer time and obtain the best possible economic advantage. In this study the maintenance cost has been estimated based on a percentage allocation of the purchasing cost of each item of equipment using recommended values from the literature.\textsuperscript{75} It is recommended that between 1% and 12% of the equipment purchasing cost should be used. Accordingly, the optimum value is set to be 6% of the purchasing cost of each item of equipment. Usually, half of this cost is for materials and the other half is for labor. However, to investigate the effect of the possible increment in the amount of maintenance cost, a percentage range of 3% up to 40% has been considered.

As shown in Fig. 7, even at a higher percentage equipment purchasing cost, about 45%, the business could still be feasible with around 1 200 000 US$ NPV and 1.5 years’ increment in payback time. So, the effect of equipment maintenance cost is insignificant. This indicates that enough money can be allocated for better equipment maintenance without compromising the profitability of the business to sustain the productivity of the project for a longer time.

**Effect of change in total required labor cost**

An estimation of the manufacturing cost for biodiesel production considers the cost of various labor categories – mainly professional workers. The basic payment rate for a given professional title might have varied substantially based on experience or level of education. The level of the basic payment rate can also be affected by the availability of skilled labor in the market. The probability of market fluctuations in the labor cost should thus be given due emphasis so that the effect of the variability of labor cost on the profitability of the business can be investigated. Accordingly, labor cost ranges have been set based on the basic payment rates for each labor category considered in the design, as shown in Table 6. In this case, only the basic payment rate is considered to fluctuate in the given range with respect to the labor type. However, the percentage of benefits factor, the operating supplies factor, the supervision factor, and the administration factor are kept the same in each labor category, and in each of the basic payment rate ranges. Figure 8 indicates the effect of variations in labor costs on NPV and on the payback time of the process.

Compared to the cost of materials and the prices of products, the labor cost have a medium effect on the feasibility of the business, which could manifest itself more in terms of NPV than payback time. The total basic rate (the sum of basic rates for supervisor, operator, and reactor operator) above 100US$ h\textsuperscript{-1} could make the business unprofitable. In other words, an increase of 15US$ h\textsuperscript{-1} in the basic rate of payment for labor could reduce the NPV by about US$982 000, resulting in a very insignificant addition to payback time.

**Effect of change in local tax amount**

As a production business, there might be a number of taxes applied to the biodiesel production process, which usually differ in type and amount from place to place. Due to the renewable nature of the biofuel, it is most common to have governmental subsidies for this type of process. However, we have considered the scenario where instead of having the tax deduction, the process will be considered as any other chemical industry process and therefore taxes could be higher. Such huge tax amounts involve an extra cost to the production process, jeopardizing the feasibility of the business. This requires an analysis of the sensitivity of the production process to variation in total local tax amounts set based on various possible tax considerations.
like corporate income tax, turnover tax, and value added tax, among others. In Super Pro software, the possible amount of the total local tax is considered in terms of the percentage of the direct fixed cost (DFC). Thus, a range of percentage of DFC of 15% up to 45% has been taken as the representative of the tax variations to investigate how the NPV and payback time would response to this variation. Figure 9 indicates the effect of the variation in local taxes on the NPV and the payback time of the process.

The effect of tax variation on the NPV is straightforward. An increase in the local tax amount by US$175,612 (10%DFC) could reduce the NPV by US$1,073,000 (a 35% decrease in NPV). This effect is reflected less in terms of the payback time because a 200% increment in the tax amount could only add about 0.2 years to the project payback time. In general, it is possible to see that the production process would not be feasible at higher tax amounts.

Conclusion

The economic effects of eight market variables for biodiesel production using a CaO catalyst were studied. Technically, the designed process route could provide fuel-quality biodiesel that could meet the American society for testing and materials (ASTM) standard. This is due to a combination of factors such as high reactivity and the heterogeneous character of the CaO catalyst as well as the efficiency of the selected downstream process equipment. Economically, the process can be feasible for feedstock costs lower than US$590 ton$^{-1}$.

The selected market variables exhibited various effects on the feasibility of the process. Obviously, their effect is largely dependent on their amount and relative market values. Feedstock purchasing costs had a pronounced effect on the feasibility of the business in comparison with the other market variables, with a very sharp decrease (US$24,502,000) in the NPV when the feedstock price is increased by 0.1 USD$ kg$^{-1}$. The second strongest market variable affecting the profitability of the business is the ethanol purchasing cost. This suggests a need for further investigation into the economic benefits of ethanol production from cheap renewable resources, which can be done side-by-side with the biodiesel production business.

For the selected production process, the minimum selling price of biodiesel for the business to be profitable is 0.775 USD$ kg$^{-1}$ (775 USD$ ton$^{-1}$). This price is broadly in agreement with the biodiesel selling price forecast in the Food and Agricultural Organization – Organization for Economic Co-operation and Development (FAO-OECD) Agricultural Outlook 2016–2025. The effect of the glycerol selling price is relatively less influential when compared with prices of oil feedstock and biodiesel. The labor cost and tax variations could also affect the viability of the business significantly. However, the effect in the change in equipment maintenance costs was found to be less, allowing for an increase in the amount allocated for routine maintenance activities to sustain the productivity of the process as much as possible.

This study is important because it included the eight most important market variables known to affect the economic feasibility of similar production processes. In this regard, the study could provide the cutoff values of the selected market variables at which the process could become profitable or not for a given market scenario. Moreover, this study can easily be extrapolated to other market scenarios, production capacities, and catalyst technologies if the process does not undergo major technical modifications.

Disclaimer

Any decision made using the results of the process design is not the responsibility of the authors. The process design is only for research purposes. The authors can be contacted for further information regarding the limitations and scope of the process design.

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References

1. Fazal M, Haseeb A and Masjuki H, Biodiesel feasibility study: An evaluation of material compatibility; performance; emission and engine durability. Renewable Sustainable Energy Rev 15:1314–1324 (2011).
2. Sillitonga A, Atabani A, Mahlia T, Masjuki H, Badruddin IA and Mekhilef S, A review on prospect of Jatropha curcas for biodiesel in Indonesia. Renewable Sustainable Energy Rev 15:3733–3756 (2011).

3. Shahid EMJ, Younis, production of biodiesel: A technical review. Renewable Sustainable Energy Rev 15:4732–4745 (2011).

4. Ljupkovic R, Micic R, Tomic M, Radulovic N, Bojic A and Zarubica A, Significance of the structural properties of CaO catalyst in the production of biodiesel: An effect on the reduction of greenhouse gases emission. Hem Ind 68:399–412 (2014).

5. Chen K-S, Lin Y-C, Hsu K-H and Wang H-K, Improving biodiesel yields from waste cooking oil by using sodium methoxide and a microwave heating system. Energy 38:151–156 (2012).

6. Demirbas A, Progress and recent trends in biodiesel fuels. Energy Convers Manage 50:14–34 (2009).

7. Zhang Y, Dube M, McLean D and Kates M, Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. Bioresearch Technol 90:229–240 (2003).

8. Karmee SK, Patria RD and Lin CSK, Techno-economic evaluation of biodiesel production from waste cooking oil—a case study of Hong Kong. Int J Mol Sci 16:4362–4371 (2015).

9. Marchetti JM, A summary of the available technologies for biodiesel production based on a comparison of different feedstock’s properties. Process Saf Environ Prot 90:157–163 (2012).

10. Bournay L, Casanave D, Delfort B, Hillion G and Chodorge JA, New heterogeneous process for biodiesel production: A way to improve the quality and the value of the crude glycerin produced by biodiesel plants. Catal Today 106:190–192 (2005).

11. Marinković DM, Stanković MV, Veličković AV, Avramović JM, Miladinović MR, Stamenković OO et al., Calcium oxide as a promising heterogeneous catalyst for biodiesel production: Current state and perspectives. Renewable Sustainable Energy Rev 56:1387–1408 (2016).

12. Semwali S, Arora AK, Badoni RP and Tuli DK, Biodiesel production using heterogeneous catalysts. Bioresearch Technol 102:2151–2161 (2011).

13. Reyero I, Arzamendi G and Gandía LM, Heterogenization of the biodiesel synthesis catalysis: CaO and novel calcium compounds as transesterification catalysts. Chem Eng Res Des 92:1519–1530 (2014).

14. Zheng S, Kates M, Dube MA and McLean DD, Acid-catalyzed production of biodiesel from waste frying oil. Biomass Bioenergy 30:267–272 (2006).

15. Soriano NU Jr, Venditti R and Argyropoulos DS, Biodiesel synthesis via homogeneous Lewis acid-catalyzed transesterification. Fuel 88:560–565 (2009).

16. Kulikarni MG, Gopinath R, Meher LC and Dalai AK, Solid acid catalyzed biodiesel production by simultaneous esterification and transesterification. Green Chem 8:1056–1062 (2006).

17. Miao X, Li R and Yao H, Effective acid-catalyzed transesterification for biodiesel production. Energy Convers Manage 50:2680–2684 (2009).

18. Farag HA, El-Maghrawy A and Taha NA, Optimization of factors affecting esterification of mixed oil with high percentage of free fatty acid. Fuel Process Technol 92:507–510 (2011).

19. Hama S and Kondo A, Enzymatic biodiesel production: An overview of potential feedstocks and process development. Bioresearch Technol 135:386–395 (2013).

20. Du W, Xu Y, Liu D and Zeng J, Comparative study on lipase-catalyzed transformation of soybean oil for biodiesel production with different acyl acceptors. J Mol Catal 30:125–129 (2004).

21. Ha SH, Lan MN, Lee SH, Hwang SM and Koo Y-M, Lipase-catalyzed biodiesel production from soybean oil in ionic liquids. Enzyme Microb Technol 41:480–483 (2007).

22. Marulanda VF, Anitescu G and Tavlarides LL, Investigations on supercritical transesterification of chicken fat for biodiesel production from low-cost lipid feedstocks. J Supercrit Fluids 54:53–60 (2010).

23. Anitescu G and Bruno TJ, Fluid properties needed in supercritical transesterification of triglyceride feedstocks to biodiesel fuels for efficient and clean combustion – A review. J Supercrit Fluids 63:133–149 (2012).

24. Shin H-Y, Lee S-H, Ryu J-H and Bae S-Y, Biodiesel production from waste lard using supercritical methanol. J Supercrit Fluid 61:134–138 (2012).

25. Hu S, Guan Y, Wang Y and Han H, Nano-magnetic catalyst KF/ CaO–Fe3O4 for biodiesel production. Appl Energy 88:2685–2690 (2011).

26. Tahvildari K, Anaraki YN, Fazaei R, Mirpanji S and Delirsh E, The study of CaO and MgO heterogenic nano-catalyst coupling on transesterification reaction efficacy in the production of biodiesel from recycled cooking oil. J Envir Health Sci Eng 13:73 (2015).

27. Rengasamy A, Anbalagan K, Sundaresan M and Velan P, Biodiesel production from Pongamia pinnata oil using synthesized iron nanocatalyst. Int J Chem Technol Res 6:4511–4516 (2014).

28. Ansari SA and Husain Q, Potential applications of enzymes immobilized on/in nano materials: A review. Biotechnol Adv 30:512–523 (2012).

29. Verma ML, Puri M and Barrow CJ, Recent trends in nanomaterials immobilised enzymes for biofuel production. Crit Rev Biotechnol 36:108–119 (2016).

30. Fan P, Xing S, Wang J, Fu J, Yang L, Yang G et al., Sulfonated imidazolium ionic liquid-catalyzed transesterification for biodiesel synthesis. Fuel 188:483–488 (2017).

31. Liu F, Wang L, Sun Q, Zhu L, Meng X and Xiao F-S, Transesterification catalyzed by ionic liquids on superhydrophobic mesoporous polymers: Heterogeneous catalysts that are faster than homogeneous catalysts. J Am Chem Soc 134:16948–16950 (2012).

32. Andreani L and Rocha JD, Use of ionic liquids in biodiesel production: A review. Braz J Chem Eng 29:1–13 (2012).

33. Sharma YC, Singh B and Korstad J, Latest developments on application of heterogenous basic catalysts for an efficient and eco friendly synthesis of biodiesel: A review. Fuel 90:1309–1324 (2011).

34. Lam MK, Lee KT and Mohamed AR, Homogeneous, heterogeneous and enzymatic catalysis for transesterification of high free fatty acid oil (waste cooking oil) to biodiesel: A review. Biotechnol Adv 28:500–518 (2010).

35. Colombo K, Ender L and Barros AAC, The study of biodiesel production using CaO as a heterogeneous catalytic reaction. Egypt J Pet 26:341–347 (2017).

36. Kouzu M and Hidaka J-S, Transesterification of vegetable oil into biodiesel catalyzed by CaO: A review. Fuel 93:1–12 (2012).

37. Velickovic A, Avramovic J, Stamenkovic O and Veljkovic V, Kinetics of the sunflower oil ethanolysis using CaO as catalyst. Chem Ind Chem Eng Q 22:409–418 (2016).

38. Boey P-L, Ganesan S, Maniam GP and Khairuddean M, Catalysts derived from waste sources in the production of
biodiesel using waste cooking oil. *Catal Today* **190**:117–121 (2012).
39. Chouhan APS and Sarma AK, Modern heterogeneous catalysts for biodiesel production: A comprehensive review. *Renewable Sustainable Energy Rev* **15**:4378–4399 (2011).
40. Avhad MR, Sánchez M, Bouaid A, Martínez M, Aracil J and Marchetti JM, Modeling chemical kinetics of avocado oil ethanolysis catalyzed by solid glycerol-enriched calcium oxide. *Energy Convers Manage* **126**:1168–1177 (2016).
41. Sánchez M, Marchetti JM, El Boulfli N, Aracil J and Martínez M, Kinetics of jojoba oil methanolysis using a waste from fish industry as catalyst. *Chem Eng J* **262**:640–647 (2014).
42. Viola E, Blasi A, Valerio V, Guidi I, Zimbardi F, Braccio G et al., Biodiesel from fried vegetable oils via transesterification by heterogeneous catalysts. *Catal Today* **179**:185–190 (2012).
43. Zhu H, Wu Z, Chen Y, Zhang P, Duan S, Liu X et al., Preparation of biodiesel catalyzed by solid super base of calcium oxide and its refining process. *Chin J Catal* **27**:391–396 (2006).
44. Granados ML, Poves MDZ, Alonso DM, Mariscal R, Galisteo FC, Moreno-Tost R et al., Biodiesel from sunflower oil by using activated calcium oxide. *Appl Catal B: Environ* **73**:317–326 (2007).
45. Liu X, He H, Wang Y, Zhu S and Piao X, Transesterification of soybean oil to biodiesel using CaO as a solid base catalyst. *Fuel* **87**:216–221 (2008).
46. Zabeti M, Daud WMAM and Aroua MK, Biodiesel production using alumina-supported calcium oxide: An optimization study. *Fuel Process Technol* **91**:243–248 (2010).
47. Boey PL, Maniam GP and Hamid SA, Biodiesel production via transesterification of palm olein using waste mud crab (Scylla serrata) shell as a heterogeneous catalyst. *Bioresour Technol* **100**:6362–6368 (2009).
48. Wei Z, Xu C and Li B, Application of waste eggshell as low-cost solid catalyst for biodiesel production. *Bioresour Technol* **100**:2883–2885 (2009).
49. Boey P-L, Maniam GP and Hamid SA, Performance of calcium oxide as a heterogeneous catalyst in biodiesel production: A review. *Chem Eng J* **168**:15–22 (2011).
50. Soares Dias AP, Puna J, Neiva Correia MJ, Nogueira I, Gomes J and Bordado J, Effect of the oil acidity on the methanolysis performances of lime catalyst biodiesel from waste frying oils (WFO). *Fuel Process Technol* **116**:94–100 (2013).
51. López GM, Martín Alonso D, Alba-Rubio AC, Mariscal R, Ojeda M and Brettas P, Transesterification of triglycerides by CaO: Increase of the reaction rate by biodiesel addition. *Energy Fuel* **23**:2259–2263 (2009).
52. Kouzu M, Tsunomori M, Yamanaka S and Hidaka J, Solid base catalysis of calcium oxide for a reaction to convert vegetable oil into biodiesel. *Adv Powder Technol* **21**:488–494 (2010).
53. Kawashima A, Matsubara K and Honda K, Acceleration of catalytic activity of calcium oxide for biodiesel production. *Bioresour Technol* **100**:696–700 (2009).
54. Suryaputra W, Winata I, Indraswati N and Ismadji S, Waste Capiz (Amusium cristatum) shell as a new heterogeneous catalyst for biodiesel production. *Renewable Energy* **50**:795–799 (2013).
55. Granados ML, Alba-Rubio AC, Vilà F, Martín Alonso D and Mariscal R, Surface chemical promotion of Ca oxide catalysts in biodiesel production reaction by the addition of monoglycerides, diglycerides and glycerol. *J Catal* **276**:229–236 (2010).
56. Sakai T, Kawashima A and Koshikawa T, Economic assessment of batch biodiesel production processes using homogeneous and heterogeneous alkali catalysts. *Bioresour Technol* **100**:3268–3276 (2009).
57. Avhad MR, Gangurde LS, Sánchez M, Bouaid A, Aracil J, Martínez M et al., Enhancing biodiesel production using green glycerol-enriched calcium oxide catalyst: An optimization study. *Catal Lett* **148**:1169 (2018).
58. Farooq M, Ramli A and Subbarao D, Biodiesel production from waste cooking oil using bifunctional heterogeneous solid catalysts. *J Cleaner Prod* **59**:131–140 (2013).
59. Santana GCS, Martins PF, de Lima da Silva N, Batistella CB, Maciel Filho R and Wolf Maciel MR, Simulation and cost estimate for biodiesel production using castor oil. *Chem Eng Res Des* **88**:652–632 (2010).
60. Atadashi IM, Aroua MK, Aziz ARA and Sulaiman NMN, Refining technologies for the purification of crude biodiesel. *Appl Energy* **88**:4239–4251 (2011).
61. Abbaszadeh A, Ghobadian B, Najafi G and Yusuf T, An experimental investigation of the effective parameters on wet washing of biodiesel purification. *Int J Automot Mech Eng* **9**:1525–1537 (2014).
62. Berrios M and Skelton RL, Comparison of purification methods for biodiesel. *Chem Eng J* **144**:459–465 (2008).
63. Alba-Rubio AC, Alonso Castillo ML, Albuquerque MCG, Mariscal R, Cavalcante CL and López Granados M, A new and efficient procedure for removing calcium soaps in biodiesel obtained using CaO as a heterogeneous catalyst. *Fuel* **95**:464–470 (2012).
64. Veljković VB, Banković-Ilić IB and Stamenković OS, Purification of crude biodiesel obtained by heterogeneously-catalyzed transesterification. *Renewable Sustainable Energy Rev* **49**:500–516 (2015).
65. Peters MS, Timmerhaus KD, West RE, Timmerhaus K and West R, *Plant Design and Economics for Chemical Engineers*, 4th edn. McGraw-Hill International, Singapore (1991).
66. Haas MJ, McAloon AJ, Yee WC and Foglia TA, A process model to estimate biodiesel production costs. *Bioresour Technol* **97**:671–676 (2007).
67. Marchetti J, Miguel V and Errazu A, Techno-economic study of different alternatives for biodiesel production. *Fuel Process Technol* **89**:740–748 (2008).
68. Kumar A and Sharma S, Potential non-edible oil resources as biodiesel feedstock: An Indian perspective. *Renewable Sustainable Energy Rev* **15**:1791–1800 (2011).
69. Gui MM, Lee KT and Bhatia S, Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. *Energy* **33**:1646–1653 (2008).
70. Wage Indicator Foundation, *Salary Scale in Ethiopian Public Sector*. [Online]. Available: https://mywage.org/ethiopia/home/salary/public-sector-wages [22 February 2019].
71. Apostoliakou AA, Kookos IK, Marazioti C and Angelopoulos KC, Techno-economic analysis of a biodiesel production process from vegetable oils. *Fuel Process Technol* **90**:1023–1031 (2009).
72. OECD/FAO, *OECD FAO Agricultural Outlook 2016–2025 Special Focus on Sub Saharan Africa*. OECD Publishing, Paris (2016).
73. Oleoline *Refined Glycerin Market Report*. [Online]. Available: http://www.hbint.com/datas/media/59020503077a6321e1a253/weekly-refined-lycerine.pdf [29 February 2019].
74. Yang F, Hanna MA and Sun R, Value-added uses for crude glycerol-a byproduct of biodiesel production. *Biotechnol Biofuels* **5**:13 (2012).
75. Perry RH, *Perry’s Chemical Engineers’ Handbook*, Vol. 1, 7th edn. McGraw-Hill International, New York, NY (1997).
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