Economics of Biodiesel Production: review

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Abstract:

Biodiesel is an alternative fuel similar to conventional diesel. It is usually produced from straight vegetable oil, animal fat, tallow, non-edible plant oil and waste cooking oil. Its biodegradability, non-toxicity and being free of sulfur and aromatics makes it advantageous over the conventional petrol diesel. It emits less air pollutants and greenhouse gases other than nitrogen oxides. In addition, it is safer to handle and has lubricity benefits than fossil diesel. However, with all these environmental benefits, biodiesel could not be extensively applied as a complete substitute fuel for conventional diesel. The main reason, repeatedly mentioned by many researchers, is its higher cost of production. Reduction of the cost of biodiesel production (unit cost of production) can be attained through improving productivity of the technologies to increase yield, reducing capital investment cost and reducing the cost of raw materials. These demand a thorough execution of economic analysis among the available possible technology alternatives, catalyst alternatives, as well as feedstock alternatives so that the best option, in economic terms, can be selected. With this respect, there are a number of researches done to investigate economically better way of producing biodiesel as a substitute fuel. Accordingly, this paper is meant to review the researches done on economics of biodiesel production, emphasizing on the methods of assessment and determination of total investment cost and operation cost, as well as on assessment of economically better technology, catalyst and feedstock alternatives. It also gives emphasis on profitability of biodiesel production and the major system variables affecting economic viability of biodiesel production.

Keywords: Biodiesel; Economics; Profitability; Production Cost; Total Investment Cost

Acronyms

AEC	Annualized Total Investment Cost
AOC	Annual Operational Cost
ARR	After-tax Rate of Return
ASTM	American Society for Testing and Materials
BBP	Biodiesel Break-even Price
BPC	Biodiesel Production Cost
CIC	Capital Investment Cost
CD	Catalytic Distillation
DCFR	Discounted Cash Flow Rate of return
FAME	Fatty Acid Methyl Ester
FCC	Fixed Capital Cost
FCI	Fixed Capital Investment
FOB	Fixed on Board
HCL	Hydrogen Chloride
IEA	International Energy Agency
IRR	Internal Rate of Return
ISBL	Inside Battery Limits
NNP	Net Annual Profit after Taxes
NPV	Net Present Value
NPW	Net Present Worth
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries
OSBL	Outside Battery Limits
PBP	Pay Back Period
PFR	Plug Flow Reactor
R&D	Research and Development
ROI	Return on Investment
SIC	Specific Investment Cost
TCC	Total Capital investment Cost
TEC	Total Equipment Cost
TMC	Total Manufacturing Cost
UPC	Unit Production Cost

1. Introduction

The world total energy consumption has been significantly increasing [1]. According to the International Energy Outlook 2016 (IEO2016) projection, the total world consumption of marketed energy expands by 48% from 2012 to 2040. The larger share of such growth in world energy use goes to countries outside of the Organization for Economic Cooperation and Development (OECD) [1]. In these countries, economic growth and population expansion are driving forces for energy consumption. In an economy experiencing considerable economic growth, living standards improve resulting in demand for more energy per capita. This together with population growth inevitably boost up the total energy consumption.

Currently the most dominant resources for world energy supply are crude oil, coal and gas [2]. However, the limited reserve of such fossil fuels prompts the consideration of alternative fuels from renewables. Most renewables do have environmental advantages over the conventional fuels, such as net greenhouse gas and pollution reduction [3]. These environmental advantages are additional points to strengthen the concept of replacing the fossil fuels with renewable energy sources. In line with this, the IEA Renewable Energy Medium Term Market Report 2016 indicated that the renewable energy share in the total world energy consumption is expected to have at least 39% increment by 2021 [4].

According to the Organization of the Petroleum Exporting Countries, OPEC [5], by 2040 world fuel oil demand will reach up to 109.4 million barrel per day from which, diesel fuel demand is expected to dominate by 5.7 million barrel per day as shown in Figure 1.

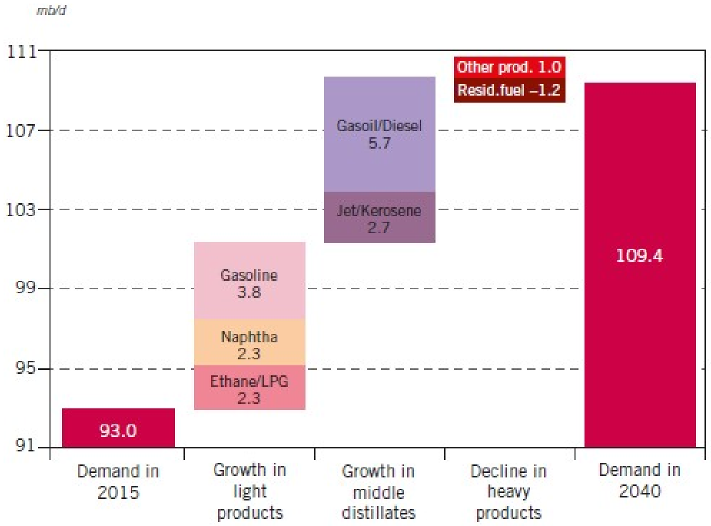

Figure 1: Oil demand growth by type from 2015 to 2040 [5]

However, this higher oil fuel demand is facing two major challenges, scarcity of the resource and negative environmental impact due to its use. These two challenges alone can impose an urge towards looking for better and long lasting substitute fuel. Accordingly, many researchers are becoming interested in investigating alternative energy resources. Among such alternatives, biodiesel is getting more emphasis for some reasons. It can be produced from a wide variety of resources including wastes like waste cooking oil, oily sludge from factories and waste animal fat [6, 7]. In addition, there are a number of technological choices to produce biodiesel based on the quality of the feedstock, giving possible alternatives to minimize overall production expenses [8].

When it is compared to conventional petrol diesel fuel, biodiesel has no sulfur. It also produces less carbon monoxide, particulate matters, smoke and hydrocarbons and has more free oxygen than the conventional petrol diesel [3, 9]. Having such more free oxygen results in complete combustion and reduced emission [10, 11]. Biodegradability, higher flashpoint and inherent lubricity are other worth mentioning advantages of biodiesel over the conventional petro diesel [12].

The major challenges associated with biodiesel as a fuel are, having higher cost of production, having relatively less energy content compared to fossil diesel and releasing nitrogen oxide emissions when it is burnt [13]. However, it is usually the higher cost of production that makes the fuel not to be extensively used [14-16]. Succinctly, there are three possible paths to attain unit cost reduction concerning biodiesel production processes such as improving the production technologies for better productivity/yield, reducing capital cost and reducing raw material cost for which feedstock cost is the most dominant [17, 18].

All of these possible paths demand economic analysis to be done among various alternative production technologies, catalysts, feedstock types as well as various biodiesel and glycerol purification technologies to pinpoint economically better ones. There are a number of worth mentioning investigations performed to test economics of biodiesel production processes.

Accordingly, in this paper more emphasis is given on reviewing the various studies done to investigate the economics of biodiesel production related to determination and comparison of total cost of investment, direct production costs as well as various system variables affecting profitability among different production technology types and production scales.

2. Methods to assess Total Investment Cost for Biodiesel Production

The total investment cost to produce biodiesel vary depending on a number of factors like the type of production technology chosen, the production scale (plant size), type and market price of raw materials used, among others. The total investment cost can be categorized in to fixed capital investment cost and operating (working capital investment) cost [19]. Fixed capital investment cost represents the capital necessary for the installed process equipment with all auxiliaries, which are desirable for comprehensive process operation whereas operating cost considers raw materials cost, utility cost, labor dependent costs, facility dependent costs and other similar variable expenses required for manufacturing of the biodiesel at a given rate.

A number of studies have been done on estimation of the total investment cost of biodiesel production, one different from the other in terms of cost considerations and the approach to calculate the required cost categories for a given production scale.

2.1. Capital Investment Cost

There are five known classifications of capital investment cost estimation ways in chemical processing industries[20]. These are order-of-magnitude estimates (class 5), study estimates (class 4), preliminary estimates (class 3), definitive estimates (class 2) and detailed estimates (class 1)

The capital cost estimates done using order-of-magnitude and study estimates are usually for preliminary feasibility analysis to compare process alternatives. The other two classes (preliminary estimates and definitive estimates) are employed to further carry out accurate estimation of the capital cost on the profitable process alternative screened using class 5 and/or class 4. Eventually, detailed estimates is usually applied as the final detail estimation of all the costs associated with the construction of the new plant so that a construction decision could be done based on the estimate[20].

Various researches that are done to estimate the capital investment cost for biodiesel production, make use of the study estimate approach, which is usually performed to give an overview on the economic feasibility of potential technological alternatives [18, 21, 22].

The major cost categories under capital investment cost are equipment purchasing cost and direct plant costs. Direct plant costs include those required for equipment installation, instrumentation, piping, electrical facilities, yard improvement, auxiliary facilities, among others. There are different techniques to calculate the fixed capital investment cost for biodiesel production processes. In all of these techniques, the primary activity demands estimation of total equipment cost for that the calculation of all other components of capital cost are based on total equipment cost, installed or purchased costs.

Furthermore, the accuracy of the estimation of total capital investment cost is mainly dependent on how the total equipment purchasing cost is precisely determined. Concerning calculation of capital investment cost for a given biodiesel production process, there are very crucial activities to be performed prior to doing the cost estimation. These include designing the complete process flow, selecting the equipment type, determining required equipment size, selecting type of construction material for the equipment in question and performing material and energy balances [19]. It is obvious that the most updated and accurate value of equipment purchased cost can be found from relevant vendors or from data of previously purchased similar equipment. If such cost data are for different plant capacity and at different purchasing time, it is necessary to adjust the equipment purchasing cost based on the capacity of the equipment and purchasing time differences[20]. While scaling up or scaling down the equipment purchasing cost based on unit capacity of the equipment, one can use cost relation like the six-tenth rule or the thirds power law described by Remer et al. [23]. Similarly, cost indexes, such as Chemical Engineering Plant Cost Index (CEPCI) and Marshall & Swift Process Industry Index (MSPII) are the two commonly used indexes to update the purchasing cost of equipment in time [20]. Such indexes are used to account for price changes due to inflation. For study estimates of equipment purchasing cost, however, cost summary graphs for various equipment can be used[20].

Different scholars follow different techniques for estimation of total equipment cost for specified production capacity. Apostolakou et al. [18] used a formula for each type of equipment considered in the design to calculate the Fixed on Board (FoB) cost of the equipment. For instance, the formula they used to estimate the purchasing cost of a reactor constructed from a stainless steel and having volume from 0.1 up to 20 m3, was $C_R^o = 15000\, V^{.55}$; where V stands for volume of the reactor. Accordingly, using its own formula for each equipment considered in the process, the total purchasing cost could easily be determined.

Another simple way to get estimates of equipment cost can be using a software such as Peters and Timmrhaus method [24] developed to calculate the estimated purchasing cost of equipment. This method requires specific design parameters for each equipment. Depending on the type of equipment, the parameters to be considered include the equipment size, material of construction, process method, power consumption, output capacity and process condition such as pressure. The approximate purchasing cost would then be determined when we enter the latest Chemical Engineering Plant Cost Index and its date to the software [24].

Haas et al. [21] used Richardson Construction Estimating Standards (now known as Cost Data Online) and Chemcost Capital Cost and Profitability Analysis Software for estimation of purchasing cost of all equipment included in the design. These softwares enable to calculate total installed costs using Installation Factors, to convert the supply cost of equipment into total installed costs. Total installed cost considers equipment purchasing cost plus costs for transport and associated insurance, cost of purchase tax, installation cost as well as electricity and pipping costs in some cases. For such calculation, the initial cost of equipment can be found from similar projects, suppliers, or from designer’s own files.

The total capital investment cost considers many cost categories in addition to the equipment purchasing cost. These include direct expenses such as cost of labor and materials for installation as well as indirect expenses such as transportation & associated insurance, purchase taxes, contingencies, contractor’s fee, construction overhead, auxiliary facilities among others.

For preliminary economic feasibility analysis of biodiesel production processes, the calculation of these additional cost categories is usually done based on the percentage allocation of the total equipment purchasing cost [25]. A number of available methods can be used for the estimation of capital investment cost through estimating the additional cost categories from the equipment cost. Among the methods are Peters and Timmrhaus method, Chilton method, and Holland method [26]. Peters and Timmrhaus method considers the purchasing cost of equipment including delivery costs from which the other cost categories can be calculated using the percentage allocation of the equipment purchasing cost as shown in Table 1, which indicates different values of percentages of equipment purchasing cost for calculation of other investment cost categories.

Table 1. Direct plant cost categories and their percentage allocation with respect to equipment purchasing cost for biodiesel production processes

	Percentage allocation with respect to equipment purchasing cost			
Direct Plant cost categories	Peters &Timmerhaus Method[a] [24]	Karmee et al. [27]	Marchetti [16]	Chilton Method [26]
Equipment cost	100	100	100	100[b]
Equipment delivery cost	-	10	-	-
Piping	66	20	35	60
Installation	47	20	-	47
Instrumentation	18	10	40	20
Insulation	-	-	3	-
Electrical facilities	11	15	10	-
Building	18	15	45	20
Yard improvement	10	10	15	-
Auxiliary/ Service facilities	70	25	40	2
Land acquisition	6	10	-	-
Unlisted equipment installation	-	-	50	-

[a] *The Peter and Timmerhaus method is for any fluid processing technology*

[b] *equipment cost includes delivery cost (it is delivered cost)*

Santana et al. [28] followed a different approach in the estimation of the capital investment cost required for construction of a give plant size. This method is usually applied for initial projects since it considers all possible physical structures required for construction of process plant. In this approach, fixed investment cost is divided into direct and indirect costs. The direct fixed investment cost considers financial resources allocated in development of installations. These are again subdivided into ISBL (Inside Battery Limits) and OSBL (Outside Battery Limits). ISBL include the financial resources required for equipment purchase, transportation, structural supports, insulation, paint, instruments, pipes, valves, electrical supplies and installation. All these expenses are directly related to the process. Whereas, the OSBL includes financial resources required for development of the facilities outside the main processing area.

These include investment for housing and auxiliary buildings, water treatment, land acquisition for building the process plant, among others. In this study done by Santana et al. [28], the authors took the value of OSBL to be equal to 45% of the value of the ISBL. But in another study, Van kasteren et al. [29] took OSBL to be 20% of ISBL.

For preliminary design and study cost estimates, the value of ISBL can be determined from the total equipment cost using Lang factor especially for major expansion of existing project [20]. Similarly, Van kasteren et al. [29], took a factor of 5 to get the ISBL from total equipment cost. The authors pointed out that the factor 5 was in agreement with the Lang factor 4.74 for predominantly fluid processing plant [29]

2.2. Operating Cost

Operating cost of biodiesel production process include the expenses associated with raw materials, utilities, labor, repairs, maintenance, and depreciation among others. Raw materials mainly comprising of oil feedstock, catalyst, alcohol, washing water, and the like. In all of the biodiesel production technologies, the cost of raw materials took the upper share of the operating cost [15, 27, 30]. This is more magnified when pure vegetable oil is considered as the feedstock in the process at any production scale. Skarlis et al. [31] shown that the most crucial parameter affecting the operating cost in a small scale biodiesel production process plant is the cost of the vegetable oil feedstock constituting a 77% of the total operating cost. The cost analysis for biodiesel production done in this particular study, indicated that raw materials and utilities together took 86% of operating cost whereas labor and maintenance cost, depreciation cost and other costs took 5%, 5%, 4% respectively [31].

The amount of raw materials required are dependent on the biodiesel production capacity of the process plant. Moreover, the material balance of the biodiesel production process is used as a reference to calculate the amount of raw materials needed to achieve the desired production capacity. Similarly, the utilities consumption are dependent on the type of process routes and type and size of equipment employed and it is usually estimated based on the energy balance of the process [27]. Table 2 shows typical methods to calculate operating cost categories for a biodiesel plant. During calculation of the total operating cost, the values for the cost of raw materials and utilities are typically based on latest market prices. The labor cost estimation is entirely dependent on the type and number of labor required as well as the payment rate allocated for each labor type. The labor required can be estimated based on the number of workers required for the given plant capacity. The other cost categories included in operating cost such as repair and maintenance costs are usually taken as percentages of the operating cost [32]. Whereas, depreciation cost is usually expressed in terms of percentage of equipment purchasing cost.

Many researchers argue that the expensiveness of the biodiesel production processes is largely attributed to the cost of the feedstock [17, 18, 21, 28]. In some cases, this cost contribution of the feedstock even increases as the production scale gets higher, making it less probable to scale up the production of biodiesel. According to the study done by Apostolakou et al. [18], the feedstock cost share of the total production cost can get as high as 75% for low production capacities and could get higher and higher up to 90% when the production capacities increase. In another study, Haas et al. [21] reaffirmed that, the higher contribution to cost of biodiesel production comes from cost of oil feedstock, scoring about 88% of the total production cost. In this study, it was indicated that the total production cost of biodiesel is linearly dependent on the cost of soy oil feedstock [21].

Table 2. Methods to calculate operating cost/annual production cost for a biodiesel plant [18].

No	Cost item	Calculation methods used
1	Raw material cost	From material balance
2	Miscellaneous materials	1% of FCI
3	Utility cost	From material balance
	Variable cost	(1) + (2) + (3)
4	Maintenance	10% FCI
5	Operating labor	Manning estimates
6	Labor cost	20% of operating labor
7	Supervision	20% of operating labor
8	Overheads	50% of operating labor
9	Capital charges	15% FCI
10	Insurance, local tax and royalties	4% FCI
	Fixed costs	(4) + (5) + (6) + (7)+ (8) + (9) + (10)
	Direct production cost	(Variable cost) + (Fixed cost)
11	General overheads + R&D	5% of the direct production costs
	Annual production costs	Direct production cost + (11)
	Unit production cost	Annual production cost/Plant capacity

The total cost of investment for biodiesel production is expected to be different for different technological routes. This is usually due to the difference in the amount and type of raw materials and equipment used in the processes. Thus, it seems logical to determine and compare the total cost of such technologies to find out the most cost effective technological option.

3. Alternatives to Economize Biodiesel Production

Higher cost of production is the major barrier for extensive use of biodiesel as a substitute fuel for petroleum diesel [33, 34]. In this regard, a number of possibilities have been studied and being under investigation to lower the cost of biodiesel production at least to the point to make it better competitive fuel. Among these possible ways are using cheaper catalyst alternatives [33, 35], as well as using technologies with minimum overall energy input and faster transesterification reaction [27, 36]. The other best viable option is using cheaper alternative feedstock material as it has the major share in cost of production [6, 37] .

3.1. Alternative Feedstock for economic advantages

As it has been repeatedly mentioned in this review, the higher percentage share of biodiesel production cost is from the feedstock. Thus, logically, using cheaper feedstock reduces the unit production cost [38, 39]. However, most of the cheaper feedstocks are waste oils or fats or non-edible oil crops, which are usually associated with higher FFA and water content [40, 41]. Obviously, as far as biodiesel production for fuel use is concerned, higher FFA and water content of the feedstock jeopardize the yield and quality of biodiesel as there are side reactions producing unwanted products and reducing the yield from the transesterification reaction [42, 43]. This, otherwise, demands the use of multiple chemical process steps or alternative approaches to produce biodiesel with better quality and yield, which in turn incur additional costs [44-46]. In addition, in economic terms, there is a wide variability on being profitable using these different low cost feedstock alternatives. With this respect, Olkiewicz et al. [6] studied the economic feasibility of producing biodiesel from liquid primary sludge. The study was done using scale up process model simulated using Aspen Hysys based on the data found from the laboratory scale experiment [6]. Due to using liquid primary sludge as feedstock, different lipid extraction steps were included in the process model incurring cost to the whole production process. However, the economic analysis of the different configuration of the lipid extraction steps indicated that the optimized extraction process could provide better breakeven price of biodiesel and make the biodiesel as cheap as fossil diesel. [6].

The alkali-catalyzed transesterification is the most economically viable process used at industrial scale to produce biodiesel from high quality oil [47-49]. However, when least cost feedstock types are considered, their high free fatty acid and water content make the alkali-catalyzed transesterification process unprofitable. This is because there should be additional cost incurring steps for feedstock pretreatment and product separation and purification [47]. Acid catalyzed transesterification can esterify the FFA into biodiesel. However, acid catalyzed transesterification reaction is very slow, requires more alcohol, requires larger reactor and the corrosiveness of the acid impose equipment deterioration [50]. All of these do have cost implications. The other alternative is supercritical transesterification reaction as it has some technical advantages. It does not use catalyst so there is no additional step for pretreatment of the feedstock to minimize the FFA, and removal of soap [51, 52]. In addition, it takes shorter time to complete. However, it requires high amount of alcohol and high reaction pressure and temperature [53-55], which incur considerable cost. Therefore, when we choose a certain configuration of feedstock and production technology for its low cost option, there should be a compromise between the cost reduction due to using the cheaper configuration option and the cost incurred due to additional steps and/or techniques for pretreatment of the low value feedstock, product separation and product quality improvement.

When large-scale production of biodiesel is considered, sustainable feedstock supply is the main issue [56]. Currently, edible oil crops produced through large-scale agricultural systems are considered as the main supply to produce more than 95% of the world biodiesel product [40]. However, enduring large-scale production of biodiesel from edible oil is not sustainable as there is clear controversy with crops for food, which also makes biodiesel an expensive fuel [57]. In this regard, potential substitutes are non-edible oil crops, which can be produced at large scale at relatively cheaper price.

The assessment done by Gui et al. [40] compared economic performances of production of edible and non-edible oil crops so that to indicate the cheapest feedstock. The comparison was done in terms of cost of plantation. The plantation cost considers costs for fertilizer, herbicides and insecticides among others. According to their assessment result, the cost per kg oil required for plantation of non-edible oil crops is lower than that for edible oil crops. However, among the non-edible oil crops, the plantation cost for palm oil was found to be higher, which could actually be balanced by high oil yield [40]. The higher plantation cost associated with most of the edible oil crops is clearly due to requirements of better soil nutrient and good irrigation system. The high yield from palm oil plantation can make the feedstock economically more attractive for profitable biodiesel production business. As main non-edible and relatively draught resistant oil crops, castor and Pongamia pinnata indicate low plantation cost as they require very minimum fertilizer and irrigation [40].

However, as far as alternative feedstock for a standard quality of biodiesel fuel are concerned, the price of the feedstock cannot be taken as the sole criterion to reduce the cost of biodiesel production. Rather, there should be a compromise between the price of the feedstock alternatives and the quality of the biodiesel produced from the alternatives in question. This is because the saturated free fatty acid content in such alternative feedstock may risk quality of the biodiesel produced [58]. One of the techniques to improve the quality of biodiesel produced from feedstock with high content of saturated fatty acid is using additives to improve the cold properties of the fuel [43]. However, such quality improvement measures do have cost implications. Thus, the economic advantages of the alternative feedstock can be seen from perspectives of its low price as well as the impurities of the feedstock that may jeopardize the quality of the biodiesel, requiring expensive feedstock pretreatment and/or product quality improvement processes.

Another possible feedstock alternative for reduced cost of biodiesel production is waste cooking oil [7, 29, 38, 39, 43]. Waste cooking oil practically contain more free fatty acids, water content and particulates as impurities. The higher contents of free fatty acid and water are the main reason why such feedstock types are not convenient for commercially known production process, which is alkali-catalyzed transesterification [59]. However, there are other possible technical alternatives such as acid catalyzed [59], enzyme catalyzed [60] and supercritical [61] transesterification reactions enabling production of fuel grade biodiesel from such low quality oil feedstock.

3.2. Alternatives Technologies for Economic Efficiency

The economics of biodiesel production can also be seen among different technologies using the same feedstock. Some of the technologies do have economic advantages over the others usually due to having less number of unit operations, which in turn reduce the overall energy input and number of equipment and thus minimize the required investment [62]. In another perspective, such economic advantages may also be due to the relative minimum cost of input materials usually catalysts [36, 63].

Using neat vegetable oil as feedstock, generally, the alkali catalyst technologies are most cost effective as there are less number of unit operations and less number of equipment and thus relatively less total investment compared to other potential alternatives [15, 64]. However, among the alkali catalyst technologies, heterogeneous ones are more cost effective due to reusability of the catalysts for a number of process cycles [65-67]. The cheapest of all possible heterogeneous alkali catalysts is calcium oxide, which can be prepared from waste materials at very low cost [68, 69].

In cases, where low value feedstock, those with higher FFA content, are to be used for biodiesel production, the cost effective alternatives are the acid catalyst technologies [70, 71]. This is because the acid catalysts can esterify the excess free fatty acids into additional biodiesel, which otherwise could be changed into soap in alkali catalyst technology by consuming considerable amount of the catalyst, which also incur extra investment for product separation and purification [72, 73]. Heterogeneous acid catalysts do have better economic performances among the acid catalyst technologies for that they can be easily separated and reused in the process cycle, are less corrosive, as well as have no washing steps required to purify the product [72]. In addition, the coproduct glycerol can be produced in better quality for higher market value [16, 70].

The other possible technologies tolerating high free fatty acid and water content of the feedstock for biodiesel production are, the enzyme catalyzed and supercritical transesterification methods. Both of them could not compute with acid catalyst options in economic terms [27, 74].

The study done by Jegannathan et al. [22] revealed that it is very cheaper to produce biodiesel from palm oil feedstock using alkali catalyst than biocatalysts. The authors compared economics of biodiesel production from palm oil feedstock among three catalyst alternatives; alkali catalyst, immobilized enzyme catalyst and soluble enzyme catalyst. The expensive way among the three alternatives was the soluble enzyme catalyst option. This is because, generally, the enzyme catalyzed transesterification reaction takes longer time [22, 75] and the expensive soluble enzyme cannot be reused. However, in the case of immobilized enzyme catalyst option, the catalyst can be reused a number of times reducing the additional cost required at least to some extent [22].

In this particular study by Jegannathan et al. [22], the authors also compared the total plant cost among the technological alternatives in producing 1000 tons of biodiesel from palm oil feedstock. According to their result, to produce the required product amount, with in equal batch process time, the immobilized enzyme catalyst process took higher plant cost than the two other options. The plant cost for the immobilized enzyme catalyst method was 57.18% higher than the alkali catalyst process and the plant cost difference between the two enzyme catalyst methods was about 0.40% [22]. This higher plant cost for the immobilized and soluble enzyme process alternatives was mainly due to additional reactor units required to achieve the same product amount with in the same batch process time. The plant cost variation between the soluble and immobilized enzyme options was also due to the additional operation unit for enzyme immobilization [22] .

In another study, Marchetti et al. [16] did techno-economic investigation of three possible alternative technologies to produce 36,036 metric ton biodiesel per year from spent oil with 5% FFA. The processes were homogeneous alkaline catalyst with acid pre-esterification, homogeneous acid catalyst and heterogeneous solid catalyst. According to their conclusion, the cheapest option was the homogeneous alkaline with acid pre-esterification process. Even though the total investment cost for this option was the higher among the three, its operating cost was estimated to be the lowest making the unitary production cost of biodiesel to be the minimum. However, the total investment cost was higher for both homogeneous scenarios. This was due to additional equipment required for product separation and purification in both homogeneous catalyst options as similarly indicated in [27]. The authors also argued that the heterogeneous alternative could also be the possible future technology for having lower amount of waste and high purity of the coproduct glycerol for its potential market value [16].

The study done by Zhang et al. [38] provide more insight into how technology and feedstock pairing could make the process profitable or not. They analyzed the economic feasibilities of biodiesel production through alkali and acid catalyzed processes using waste cooking oil and virgin vegetable oil as feedstock. The processes studied were; alkali catalyzed process using virgin vegetable oil, alkali catalyzed process using waste cooking oil with acid catalyzed pre-esterification, acid catalyzed process using waste cooking oil and acid-catalyzed process using waste cooking oil with hexane as an extraction solvent. The results of this study indicated that the alkali catalyzed option to produce biodiesel exhibited lowest fixed capital cost. However, the more economically feasible option was the acid catalyzed process using waste cooking oil as feedstock, indicating lower total production cost, better after tax return rate and lower biodiesel break-even price [38]. The smaller sizes of the equipment used and low cost of their construction material, which is carbon steel, could make the total capital cost of the alkali catalyzed process option the minimum of the others [38].

An economic comparison among the three possible homogeneous catalyst options was done by Karmee et al. [27]. The homogeneous catalysts studied were; acid, base and enzyme catalysts for transesterification of waste cooking oil for biodiesel production. For such feedstock character, the acid catalyst option was found to be the most cost effective due to absence of feedstock pre-treatment as well as less steps for product purification compared to the alkali catalyzed option [27]. Comparatively, the enzyme catalyst option was very expensive mainly due to higher cost of enzyme catalyst [27].

The economics of a production technology can be improved by making the byproducts and recovered materials valuable for market and/or recycling them in the process. With this respect, having recyclable catalyst, recovering excess alcohol and producing high quality glycerol are the most crucial entry points in biodiesel production processes. Accordingly, concerning the new feedstock type, which is algal biomass, being studied by various researchers, there is a possibility of recycling the coproduct glycerol for algal consumption so that to have more and cheap feedstock for biodiesel production.

Brunet et al. [76] studied how recycling the coproduct glycerol affect the economics of biodiesel production from microalgae through sulfuric acid catalyzed transesterification. The two technological alternatives studied were similar in all aspects except the second alternative considered glycerol produced in the transesterification process as a carbon source to grow the microalgae. In the second scenario, the glycerol produced was supposed to be absorbed by algae in photo bioreactor and then converted into triglycerides through metabolic processes. Then the produced triglyceride could be used as feedstock to continue the biodiesel production process. Summary of the economic performances of these two technological alternatives is shown in Table 3.

Table 3. Executive economic summary of the conventional and alternative biodiesel processes [76]

Economic parameters	Conventional biodiesel process	Alternative biodiesel process
Net Present Value [M$]	70.575	75.442
Total Capital Investment [M$]	7.456	12.756
Operating Cost [M$/year]	20.910	18.882
Production Rate [tones/ year]	23.700	33.700
Unit Production Cost [$/kg]	0.620	0.580
Unit Selling Price [$/kg]	0.820	0.820
Total revenues[M$]	28.919	28.919

The authors found out that the alternative scenario was better in its economic performance indicating less unit biodiesel production cost and higher net present value [76] . In terms of the total investment cost, the alternative scenario had 71% increment than the conventional. This was mainly due to additional bioreactor operating units for microalgae production. In another view, since there were no any feedstock purchase, the alternative scenario could have 10% less in its operating cost minimizing the unit production cost compared to the first scenario [76].

Most recently, Gaurav et al. [59] compared the economic performances of two different processes for biodiesel production from waste cooking oil; conventional reactor with separation process and Catalytic Distillation (CD) process. Both processes were heterogeneous acid catalyzed. The catalytic distillation process could reduce the number of required equipment by avoiding the plug flow reactor and flash separation unit, which are required in the conventional reactor plus separation arrangement. This actually led to significant reduction of capital and production costs making this technological option economically efficient [59]. Table 4 summarizes some studies done on cost of producing biodiesel using different technologies.

Table 4. Summary of studies on cost of biodiesel production using different technologies and feedstock types

Production technology type	Capacity	Feedstock	Production cost $/ton	Ref
KOH Catalyzed transesterification with methanol	8000 ton per year	Waste cooking oil	868,60	[27]
H_2SO_4 Catalyzed transesterification with methanol		Waste cooking oil	750,38	
Lipase (Novozym-435) Catalyzed transesterification		Waste cooking oil	1047,97	
Alkali catalyst process	Batch mode with a production capacity of 1000 tons	Palm oil	1166,67	[22]
Soluble lipase catalyst process		Palm oil	7821,37	
Immobilized lipase catalyst process		Palm oil	2414,63	
Homogeneous H_2SO_4 catalyzed and using purchased feedstock	Continuous reactor operating at 30 ºC	Microalgae oil	620	[76]
Homogeneous H_2SO_4 catalyzed and using self-produced feedstock from recycled glycerol		Microalgae oil	580	
Homogeneous KOH catalyst and hot water purification process	Batch mode with a production capacity of 1452 tons per year biodiesel	waste cooking oil	921	[77]
Homogeneous KOH catalyst and vacuum FAME distillation process		waste cooking oil	984	
Heterogeneous CaO catalyst and hot water purification process		waste cooking oil	911	
Heterogeneous CaO catalyst and vacuum FAME distillation process		waste cooking oil	969	
Homogeneous KOH catalyst and hot water purification process	Batch mode with a production capacity of 7260 tons per year biodiesel.	waste cooking oil	598	[77]
Homogeneous KOH catalyst and vacuum FAME distillation process		waste cooking oil	641	
Heterogeneous CaO catalyst and hot water purification process		waste cooking oil	584	
Heterogeneous CaO catalyst and vacuum FAME distillation process		waste cooking oil	622	

3.3. Alternative Catalysts for Economic Advantages

There are a number of alternative catalysts, with economic advantages, to catalyze transesterification reaction for biodiesel production. The economic advantages of such alternative catalysts can be seen at least from three perspectives: having lower price, reusability and acquiring higher catalytic activity. The lower price of the catalyst would bring a direct reduction in the overall production cost. The reusability of some alternative catalysts, like immobilized lipase catalysts [75, 78, 79] and heterogeneous solid catalysts [8, 73], could avoid considerable amount of money for repeated purchase of catalysts. Whereas the higher catalytic activity accelerates transesterification reaction and minimize the overall process cycle, which, in turn, would improve the process throughput per unit time [33].

However the main criteria to choose a catalyst for the transesterification is not primarily governed by economic terms like its price; rather the feedstock character, such as free fatty acid and water content, are the dominant factors determining the type of catalyst to be used [73, 80]. Low cost feedstocks for biodiesel production are usually associated with higher free fatty acid and water content, for which acid catalysts are found to be more convenient [64, 71, 81], especially; heterogeneous acid catalysts do have economic advantage of being easily and cheaply recovered for reuse [70]. Thus, this implies that heterogeneous acid catalysts are more efficient than other conventional catalyst technologies in terms of reducing unit cost of biodiesel production.

In general heterogeneous catalysts options do have more advantages than homogeneous ones in terms of reusability, having less process steps required for product separation and purification, producing high purity glycerol and enabling easy catalyst recoverability [8, 72, 82-84]. All of these advantages do have economic implications making heterogeneous catalysts better candidates to reduce unit cost of biodiesel production.

Even though there are considerable studies done on alternative catalysts for biodiesel production, only few investigate and analyze such catalysts for their direct economic advantages. Wei et al. [65] studied the application of waste eggshell as low-cost solid catalyst for biodiesel production. The preparation of solid catalyst from waste eggshells can simply be done by calcination of the eggshell at higher temperature [65]. In this study, the effect of calcination temperature on the structure and activity of the eggshell catalyst was investigated and the reusability of eggshell catalyst was examined. It is very understandable that utilizing eggshell as a catalyst could brought about economic and environmental benefits through recycling the waste to produce least cost catalyst. Accordingly, the authors concluded that the whole process could enable to reduce the price of biodiesel in a manner to make it competitive with petro diesel [65]. This economic advantage is mainly due to catalyst reusability as well as cheap cost of source material and catalyst preparation process.

In another study, Hidayat et al. [85] studied the possibility of catalyzing the esterification of palm fatty acid distillate with a cheap catalyst prepared from coconut shell bio-char. Sulfonating with concentrated H_2SO_4 was the method used to prepare the solid catalyst from coconut shell bio-char [85]. They argued that sulfonating coconut shell bio-char using H_2SO_4 could create sulfonic acid groups as well as additional week acid groups favoring the catalytic activity of the solid catalyst prepared. This in turn enable to esterify low value and very cheap feedstock for efficient production of fuel grade biodiesel. Table 5 shows some low cost catalyst alternatives from cheap sources.

Table 5. Catalyst alternatives from cheap sources

Source Material	Method of catalyst preparation	Catalyst	Reusability	Remarks	Ref.
Waste eggshell	Through Calcination under air	Solid catalyst with CaO the active phase	Reusable up to 13 times with no apparent loss of activity	Eggshell sample calcined above 800 ºC was the most active catalyst	[65]
Coconut shell biochar	Sulfonating the coconut shell biochar using concentrated H2SO4	Coconut shell char based catalyst	-	Sulfonation using H_2SO_4 significantly increased surface area and pore structure formed in the biochar.	[85]
Carbonaceous ash-like waste, a common residue from biomass gasification Processes.	Through Calcination at 800 ºC under air	A metal oxide (particularly CaO) rich catalyst	Reusable up to 4 times with little loss in activity	The activity of this waste material was lower as compared to similar pure metal oxides (Ca and MgO) in the Literature.	[86]
Mussel shells (*Mytilus galloprovincialis* species)	Through calcination at 800 ºC during 6 h	CaO	-	The catalyst should be used immediately after calcination process to avoid poisoning of catalyst by H_2O and CO_2	[87]
Scallop waste shell	Through Calcination at 1000 °C for 4 h	Solid catalyst mainly composed of CaO (97.53 wt.%)	-	The catalyst performed equally well as the laboratory-grade CaO	[88]
Crustacean shells	Through Calcination at 900 ºC for 1 h	Calcined calcium/chitosan spheres	-	Chitosan particles without calcium are not active for biodiesel production.	[89]
Incompletely carbonized sugar produced through pyrolysis	Sulfonating the incompletely carbonized sugar with H_2SO_4	solid sulfonated carbon catalyst	-	Solid Catalyst with a high density of active sites	[90]
Kraft lignin	Chemical activation with phosphoric acid, pyrolysis and H_2SO_4	High acid density Catalyst	Reusable 3 times with little deactivation	Simplify biodiesel production procedure and reduce costs	[91]

4. Profitability of Biodiesel Production

Profitability is the capacity to make a profit, which is a mathematical difference between income earned and all costs and expenses used to earn the income. Profitability is usually measured using a profitability ratio. One such important profitability ratio is Return on Assets (Return on Investment). It measures the efficiency of a firm in managing its investment in assets and using them to generate profit. Profitability of a production process can be improved through managing costs and boosting productivity. Cost management demands minimizing the expense as much as possible without compromising the quality and quantity of the product. In addition, increasing productivity requires production technologies, which are better in technical and economic efficiencies.

A number of other economic parameters can also be used to measure the profitability of a given biodiesel production process as well as to compare among a number of available technologies for their economic feasibility. Among them are Net Present value, Break-even Price of Biodiesel, after tax Internal Rate of Return, Gross Margin, and Payback time.

The profitability of biodiesel production process depends on various variables like the type of the technology in question, which determines the productivity, as well as the market values of inputs and outputs. The type of the technology determines the quantity and quality of the biodiesel product affecting the economic feasibility of the whole process. In another view, the economic feasibility of a given biodiesel production technology can also be affected by the production scale.

4.1. The effect of market variables over profitability of biodiesel production

Obviously, the effect of a given market variable might not be the same among two or more technological alternatives, because the amount and quality of the market variables, i.e. input materials and products, could not necessarily be the same for different technological options. Accordingly, a number of studies have been carried out to investigate which market variables affect profitability of biodiesel production using different technologies at different market scenarios with respective production capacities [38, 92-94].

A study done by Mulugetta [17] indicated that the major market variables, which could have strong effect on the profitability of biodiesel production business, include biodiesel selling price, raw feedstock purchasing cost, cost of oil extraction and selling price of the glycerol. The cost of oil feedstock, as considered by many authors, is the main dominant market variable affecting the economic feasibility of the business while using most of the possible technological alternatives [16, 18, 27, 30, 93]. This is mainly because this cost category took the larger share of the operating cost directly affecting the unit cost of production.

In another study done by Van Kasteren et al. [29], it was indicated that, when supercritical methanol method is used for producing biodiesel, the major market variables that could directly affect the economic feasibility include raw material price, plant capacity, glycerol price and capital cost. In this case, cost of raw materials comprise cost of oil feedstock (waste cooking oil) and cost of methanol. Most studies did not include more market variables other than the raw materials and the products to investigate their effect over economic feasibility of biodiesel production. Marchetti et al. [93] considered additional market variables such as advertisement and selling expenses, tax incentives, investment in research and development and product failure over profitability of biodiesel production using supercritical methanol method. The author indicated that, still the major effect on the economic feasibility of the biodiesel production process was due to the income (biodiesel and glycerol) and outcome (raw materials) variables.

As can be clearly understood, the effect of these market variables on the profitability of biodiesel production is not expected to be uniform and equal in any case. In this respect, Marchetti [92] studied how the possible market variables affect the profitability of biodiesel production using homogeneous alkali catalyzed process. It was concluded in this study that, the entire income variables (selling price of glycerol as well as biodiesel) have positive effect on the internal return rate and payback time, which was also showed by Haas et al. [21]. However, the outcome variables did the opposite by reducing the internal return rate and increasing the payback time and made the process less profitable [93]. Among the outcome variables considered, usually oil feedstock and alcohol have more effect on the profitability of the process as their required amounts are high. But the other outcome variables like catalyst, washing water, etc., are required relatively in small fractions, resulting in a relative smaller effect [93]. Summary of some studies done on the effect of system variables over economic viability of different biodiesel production technologies is shown in Table 6.

Table 6. Summary of studies done on system variables affecting economic viability of different biodiesel production technologies

Production technology	Production capacity	Variables affecting economic viability	Economic parameters	Explanations	Ref
Alkali-catalyzed process using sodium hydroxide catalyst Acid-catalyzed process using sulfuric acid catalyst	8000 tons per year	Plant Capacity Prices of Feedstock Oils and Price of Biodiesel	Internal Return Rate (IRR) and Break-even Price of Biodiesel	These were the major factors affecting the economic feasibility of the biodiesel production in both cases. Moreover, acid-catalyzed process was economically competitive alternative to the alkali process for biodiesel production.	[38]

Base, Acid and Lipase Catalyzed transesterification of WCO	8000 tons per year	Waste Cooking Oil Price Biodiesel Price	Internal Return Rate (IRR)	Production of biodiesel using acid and base as catalysts can withstand variations from the WCO and biodiesel price	[27]
Alkali Catalyzed transesterification of vegetable oil	10000 tons per year	Vegetable oil price for different CIC	Internal Return Rate (IRR)	For lower CIC values, the project's viability may be able to resist to higher oil feedstock price forcing.	[31]
Homogeneous base catalyzed transesterification of triglyceride with methanol	150480 tons per year	Biodiesel price Glycerol price Alcohol price Catalyst price Shipping distance Washing water price R&D Oil price	Internal Return Rate (IRR) Payback Time	Selling prices of glycerol & biodiesel have positive effect over the IRR & in reducing the payback time The outcome variables have the negative effect making the process less profitable. Even though their effect is dependent on their relative required amount	[92]
Supercritical technology with no catalyst and no co-solvent	39910.5 tons per year	Oil price Biodiesel price Glycerol price Alcohol price Advertisement and selling expenses Tax incentives Investment in research and development	Internal Return Rate (IRR) Payback Time	Selling prices of glycerol & biodiesel have positive effect over the IRR & in reducing the payback time The outcome variables have the negative effect making the process less profitable. Even though their effect is not the same as it is dependent on their relative required amounts.	[93]
NaOH catalyzed transesterification of soybean oil	Three plant capacities with 8000, 30000, and 100000 tons per year	Plant capacity, Price of feedstock oil and diesel, Yields of glycerin and biodiesel	Net annual profit after taxes (NNP), Internal Return Rate (IRR), and Biodiesel break-even price (BBP)	These system variables were found to be the most significant variables affecting the economic viability of biodiesel production	[94]
Homogeneous acid-catalyzed esterification	1000 tons per year	Price of Salmon oil	Net Present Value (NPV)	Feasibility of proposed plant was limited by the price of salmon oil	[95]

4.2. Production scale as a factor affecting economic viability of biodiesel production

Profitability of biodiesel production may also be dependent on the production scale because producing biodiesel using the same technology and the same feedstock at different scales could show variability in oil productivity, in terms of the rate of output per unit of input, thus either reducing or increasing unit cost of biodiesel production [18]. Very few have been studied to investigate how production scale affects the feasibility of biodiesel production processes. Van Kasteren et al. [29] did a comparative study among three scales of biodiesel production through supercritical method. The result of this study indicated that as the production scale gets higher the unitary cost of biodiesel production gets cheaper making the business more profitable. The same result was reported by Apostolakou et al. [18], which was done on a biodiesel production process from vegetable oil using homogeneous alkali catalyst. The result of this research indicated that, until about plant capacity of 60000 tons per year, an increase in the plant capacity would improve the feasibility of the process since the unit production cost could be significantly reduced. However, the higher the production scale it gets beyond about 60000 tons per year, the less would be its effect on reducing the unit production cost [18]. This effect of biodiesel production scale on the unit production cost is shown in Figure 2.

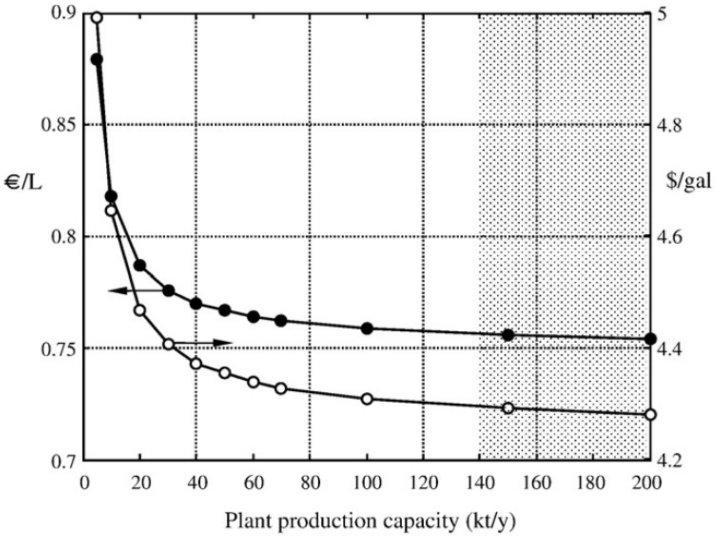

Figure 2. Unit production cost as a function of plant capacity [18]

In another study, You et al. [94] analyzed the effect of production scale on the feasibility of biodiesel production process using NaOH catalyzed transesterification of food grade soybean oil. The comparison was done among three production scales with 8000, 30000, and 100000 tons per year. It was concluded that the larger production scale was better in economic performances by providing a higher NNP and more attractive ARR with a lower BBP [94]. The authors also argued that increasing the plant capacity using a feedstock of soybean oil has the same economic effects as using waste cooking oil as feedstock.

Navarro-Pineda et al. [96] made an economic model for estimating the viability of biodiesel production from Jatropha curcas, starting from plantation to biodiesel production and pellet production from waste cakes found from oil extraction. The biodiesel production process considered was alkali-based transesterification reaction. The authors concluded that at production capacities over 10000 m^3 per year the production cost could remain constant and expenses always be greater than income. They also mentioned that this could only be reversed by higher Jatropha seed yields.

Most recently, Glisic et al. [97] did a study on process and techno-economic analysis of green diesel and ester type biodiesel production from waste vegetable oil. In this study, the authors investigated the influence of plant capacity (production scale) on the NPV of three biodiesel production processes. The processes investigated were catalytic hydrogenation, homogeneous alkali catalyzed transesterification and supercritical non-catalytic transesterification. They found out that, compared to feedstock cost, plant capacity showed less effect on NPV. However, there was considerable effect of the plant capacity on NPV, especially in catalytic hydrogenation process, for which an increase in plant capacity from 100,000 to 200,000 tons per year could increase NPV from 7.0 to 53.1 million US$. According to their conclusion, unit capacities of the investigated processes, which are below 100,000 tons per year, are likely to result in negative net present values after 10 years of project lifetime [97].

The study done by Kookos et al. [98] indicated that a biodiesel production plant producing fuel grade biodiesel from spent coffee grounds could be economically competitive (i.e. to have biodiesel selling price lower than the current market price) if the annual production capacity can be greater than 42000 tons per year. This capacity is lower than the normal medium level production capacities [99, 100]. However, the availability of the raw material (spent coffee grounds) limits the capacity that can be achieved, making the capacity of 42000 tons per year difficult to be attained in an economically feasible way due to higher logistics and collection costs of the spent coffee [98].

5. Summary/Conclusion

Cost of raw materials, especially cost of feedstock, accounts for most of the cost of biodiesel production, irrespective of the technology type. Thus, the economic feasibility of biodiesel production processes is mainly affected by the cost of feedstock. This demands looking for cheaper feedstock types such as non-edible oil plants, waste cooking oil and animal fats. The problem with these low cost feedstock types is their higher amount of impurities. The higher FFA and water content in such feedstock demands the use of additional pretreatment and product separation and purification units and process steps in order to produce quality biodiesel fuel, which complies with ASTM standards. This in turn incurs considerable amount of money to the total manufacturing cost. Therefore, to be profitable in biodiesel production, there should be a compromise between the cost reduction due to using cheaper feedstock and the cost incurred due to additional steps and/or techniques for pretreatment of the low value feedstock, product separation and product quality improvement.

Among the conventional technologies, the acid catalyzed transesterification reaction is the most cost effective to produce fuel grade biodiesel from cheaper feedstock with higher FFA content. Acid catalysts can catalyze both esterification and transesterification reactions without feedstock pretreatment steps. This economic feasibility is manifested by having lower total manufacturing cost, and lower biodiesel breakeven price.

Heterogeneous catalysts do have more advantages than homogeneous ones in terms of reusability, having less process steps required for product separation and purification, producing high purity glycerol and enabling easy catalyst recoverability. These advantages do have economic implications making heterogeneous catalysts good choice to reduce unit cost of biodiesel production. Again, among the heterogeneous catalysts, heterogeneous acid catalysts do have added economic advantage of catalyzing cheap feedstock types, those with higher FFA content.

There are a number of catalyst alternatives prepared from wastes and cheap materials. Such cheap materials include eggshell, scallop waste shell, crustacean shells, bio-char from coconut shell, Kraft lignin and pyrolyzed sugar. These type of catalysts are cheap and most of them are reusable. Least cost and reusable catalysts would bring considerable economic advantages through reducing manufacturing cost and improving throughput per unit time.

Among the different possible system variables that might have effect on the economic feasibility of biodiesel production plant; purchasing cost of feedstock, selling price of biodiesel, selling price of glycerol and plant capacity are the most significant.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

References

[1] EIA. International Energy Outlook 2016, With Projections to 2040. U.S. Eneregy Information Administration, Department of Energy, Washington, DC, May 2016.

[2] IEA. Medium term renewable energy market report 2015, Executive Summary: Market analysis and Forcasts to 2020. International Energy Agency2015.

[3] Ellabban O, Abu-Rub H, Blaabjerg F. Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews. 2014;39:748-64.

[4] IEA. Renewable Energy Medium Term Market Report 2016, Excutive Summary: Market Analysis and Forecasts to 2021. International Energy Agency 2016.

[5] OPEC. World Oil Outlook, October 2016. 10th ed. Organisation of the Petroleum Exporting Countries, OPEC, Vienna, Austria, 2016.

[6] Olkiewicz M, Torres CM, Jiménez L, Font J, Bengoa C. Scale-up and economic analysis of biodiesel production from municipal primary sewage sludge. Bioresourc technol. 2016;214:122-31.

[7] Mandolesi de Araújo CD, de Andrade CC, de Souza e Silva E, Dupas FA. Biodiesel production from used cooking oil: A review. Renewable and Sustainable Energy Reviews. 2013;27:445-52.

[8] Avhad MR, Marchetti JM. A review on recent advancement in catalytic materials for biodiesel production. Renew Sust Energ Rev 2015;50:696-718.

[9] Hasan MM, Rahman MM. Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review. Renewable and Sustainable Energy Reviews. 2017;74:938-48.

[10] Fazal M, Haseeb A, Masjuki H. Biodiesel feasibility study: an evaluation of material compatibility; performance; emission and engine durability. Renewable and Sustainable Energy Reviews. 2011;15:1314-24.

[11] Ouanji F, Kacimi M, Ziyad M, Puleo F, Liotta LF. Production of biodiesel at small-scale (10 L) for local power generation. Intl J of Hydrogen Energy. 2016.

[12] Knothe G. “Designer” Biodiesel: Optimizing Fatty Ester Composition to Improve Fuel Properties. Energy & Fuels. 2008;22:1358-64.

[13] Anuar MR, Abdullah AZ. Challenges in biodiesel industry with regards to feedstock, environmental, social and sustainability issues: A critical review. Renewable and Sustainable Energy Reviews. 2016;58:208-23.

[14] Lin L, Cunshan Z, Vittayapadung S, Xiangqian S, Mingdong D. Opportunities and challenges for biodiesel fuel. Appl Energy. 2011;88:1020-31.

[15] Kiss FE, Jovanović M, Bošković GC. Economic and ecological aspects of biodiesel production over homogeneous and heterogeneous catalysts. Fuel Proces Technol. 2010;91:1316-20.

[16] Marchetti J, Miguel V, Errazu A. Techno-economic study of different alternatives for biodiesel production. Fuel Proces Techno. 2008;89:740-8.

[17] Mulugetta Y. Evaluating the economics of biodiesel in Africa. Renew Sust Energ Rev 2009;13:1592-8.

[18] Apostolakou AA, Kookos IK, Marazioti C, Angelopoulos KC. Techno-economic analysis of a biodiesel production process from vegetable oils. Fuel Proces Technol. 2009;90:1023-31.

[19] Peters MS, Timmerhaus KD, West RE, Timmerhaus K, West R. plant design and economics for chemical engineers. 4th ed. McGraw-Hill International1991.

[20] R. Turton RCB, W.B. Whiting, J.A. Shaeiwitz. Analysis Synthesis and Design of Chemical Processes. Prentice Hall, New Jersey, USA, 2009.

[21] Haas MJ, McAloon AJ, Yee WC, Foglia TA. A process model to estimate biodiesel production costs. Bioresourc technol. 2006;97:671-8.

[22] Jegannathan KR, Eng-Seng C, Ravindra P. Economic assessment of biodiesel production: Comparison of alkali and biocatalyst processes. Renew Sust Energ Rev 2011;15:745-51.

[23] Remer DSaC, L. H. Process Plants, Costs of Scaled-up Units Chemical Engineering. 1990;97(4):138-75.

[24] Peters MS, Timmerhaus KD, West RE, Timmerhaus K, West R. Plant design and economics for chemical engineers. McGraw-Hill New York1991.

[25] Sinnott RK. Chemical Engineering Design in: C. Richardson, (Ed.). Chemical Engineering. Fourth ed. Elsevier Butterworth-Heinemann, 2005.

[26] Silla H. Chemical Process Engineering Design and Economics. Marcell Dekker, Inc. , New York Basel, 2003.

[27] Karmee SK, Patria RD, Lin CSK. Techno-economic evaluation of biodiesel production from waste cooking oil—a case study of Hong Kong. Intl j of molecul scienc. 2015;16:4362-71.

[28] Santana GCS, Martins PF, de Lima da Silva N, Batistella CB, Maciel Filho R, Wolf Maciel MR. Simulation and cost estimate for biodiesel production using castor oil. Chem Enging Resear and Design. 2010;88:626-32.

[29] Van Kasteren J, Nisworo A. A process model to estimate the cost of industrial scale biodiesel production from waste cooking oil by supercritical transesterification. Resourc, Conserv and Recycl. 2007;50:442-58.

[30] Nisworo AP. Biodiesel by Supercritical transesterification: process design and economic feasibility. Technische Universiteit Eindhoven, Eindhoven 2005. p. 62.

[31] Skarlis S, Kondili E, Kaldellis J. Small-scale biodiesel production economics: a case study focus on Crete Island. Journal of cleaner production. 2012;20:20-6.

[32] Benavides PT, Salazar J, Diwekar U. Economic Comparison of Continuous and Batch Production of Biodiesel Using Soybean Oil. Environmental Progress & Sustainable Energy. 2013;32:11-24.

[33] 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 and Sustainable Energy Reviews. 2016;56:1387-408.

[34] Bateni H, Saraeian A, Able C. A comprehensive review on biodiesel purification and upgrading. Biofuel Research Journal. 2017;4:668-90.

[35] Reyero I, Arzamendi G, Gandía LM. Heterogenization of the biodiesel synthesis catalysis: CaO and novel calcium compounds as transesterification catalysts. Chemical Engineering Research and Design. 2014;92:1519-30.

[36] Colombo K, Ender L, Barros AAC. The study of biodiesel production using CaO as a heterogeneous catalytic reaction. Egyptian Journal of Petroleum. 2017;26:341-9.

[37] Reşitoğlu İA, Keskin A, Gürü M. The Optimization of the Esterification Reaction in Biodiesel Production from Trap Grease. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2012;34:1238-48.

[38] Zhang Y, Dube M, McLean D, Kates M. Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. Bioresourc technol. 2003;90:229-40.

[39] Chhetri AB, Watts KC, Islam MR. Waste cooking oil as an alternate feedstock for biodiesel production. Energies. 2008;1:3-18.

[40] Gui MM, Lee KT, Bhatia S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy. 2008;33:1646-53.

[41] Kumar A, Sharma S. An evaluation of multipurpose oil seed crop for industrial uses (Jatropha curcas L.): A review. Industrial Crops and Products. 2008;28:1-10.

[42] Banković-Ilić IB, Stamenković OS, Veljković VB. Biodiesel production from non-edible plant oils. Renewable and Sustainable Energy Reviews. 2012;16:3621-47.

[43] Balat M. Potential alternatives to edible oils for biodiesel production – A review of current work. Energy Conversion and Management. 2011;52:1479-92.

[44] Sahoo P, Das L. Process optimization for biodiesel production from Jatropha, Karanja and Polanga oils. Fuel. 2009;88:1588-94.

[45] Patil PD, Deng S. Optimization of biodiesel production from edible and non-edible vegetable oils. Fuel. 2009;88:1302-6.

[46] Haas MJ. Improving the economics of biodiesel production through the use of low value lipids as feedstocks: vegetable oil soapstock. Fuel processing technology. 2005;86:1087-96.

[47] Chen K-S, Lin Y-C, Hsu K-H, Wang H-K. Improving biodiesel yields from waste cooking oil by using sodium methoxide and a microwave heating system. Energy. 2012;38:151-6.

[48] Meher L, Dharmagadda VS, Naik S. Optimization of alkali-catalyzed transesterification of Pongamia pinnata oil for production of biodiesel. Bioresou techno. 2006;97:1392-7.

[49] Keera ST, El Sabagh SM, Taman AR. Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst. Fuel. 2011;90:42-7.

[50] Canakci M, Sanli H. Biodiesel production from various feedstocks and their effects on the fuel properties. Journal of industrial microbiology & biotechnology. 2008;35:431-41.

[51] Lee J-S, Saka S. Biodiesel production by heterogeneous catalysts and supercritical technologies. Bioresour Technol. 2010;101:7191-200.

[52] Hawash S, Kamal N, Zaher F, Kenawi O, Diwani GE. Biodiesel fuel from Jatropha oil via non-catalytic supercritical methanol transesterification. Fuel. 2009;88:579-82.

[53] Shin H-Y, Lee S-H, Ryu J-H, Bae S-Y. Biodiesel production from waste lard using supercritical methanol. The J of Supercriti Fluids. 2012;61:134-8.

[54] Marulanda VF, Anitescu G, Tavlarides LL. Investigations on supercritical transesterification of chicken fat for biodiesel production from low-cost lipid feedstocks. The J of Supercriti Fluids. 2010;54:53-60.

[55] Demirbas A. Biodiesel from waste cooking oil via base-catalytic and supercritical methanol transesterification. Energ Conver and Manage. 2009;50:923-7.

[56] Price J, Nordblad M, Martel HH, Chrabas B, Wang H, Nielsen PM, et al. Scale-up of industrial biodiesel production to 40 m(3) using a liquid lipase formulation. Biotechnol Bioeng. 2016;113:1719-28.

[57] Fan X, Burton R. Recent development of biodiesel feedstocks and the applications of glycerol: a review. Open Fuels & Energy Science Journal. 2009;2:100-9.

[58] Shahid EMJ, Younis. Production of biodiesel: a technical review. Ren and Sust Energ Rev. 2011;15:4732-45.

[59] Gaurav A, Ng FT, Rempel GL. A new green process for biodiesel production from waste oils via catalytic distillation using a solid acid catalyst–Modeling, economic and environmental analysis. Green Energy & Environment. 2016;1:62-74.

[60] N. Saifuddin AZRaHNF. Production of biodeisel from high acid value waste cooking oil using an optimized lipase enzyme acid catalyzed hybrid process. E-J of Chem. 2009;6:S485-S95.

[61] Lee S, Posarac D, Ellis N. Process simulation and economic analysis of biodiesel production processes using fresh and waste vegetable oil and supercritical methanol. Chemical Engineering Research and Design. 2011;89:2626-42.

[62] Ojolo S.J. OBS, Adelaja A.O., Ogbonnaya M. Study of an Effective Technique for the Production of biodeseal. J of Emerg Trends in Enging and App Scienc 2011;2 (1): 79-86.

[63] Boey P-L, Ganesan S, Maniam GP, Khairuddean M. Catalysts derived from waste sources in the production of biodiesel using waste cooking oil. Catalysis Today. 2012;190:117-21.

[64] Atadashi IM, Aroua MK, Abdul Aziz AR, Sulaiman NMN. The effects of catalysts in biodiesel production: A review. J of Industal and Enging Chemis. 2013;19:14-26.

[65] Wei Z, Xu C, Li B. Application of waste eggshell as low-cost solid catalyst for biodiesel production. Bioresourc Technol. 2009;100:2883-5.

[66] Helwani Z, Othman MR, Aziz N, Kim J, Fernando WJN. Solid heterogeneous catalysts for transesterification of triglycerides with methanol: A review. Appl Cataly. 2009;363:1-10.

[67] Chouhan APS, Sarma AK. Modern heterogeneous catalysts for biodiesel production: A comprehensive review. Renew Sust Energ Rev 2011;15:4378-99.

[68] Kouzu M, Hidaka J-s. Transesterification of vegetable oil into biodiesel catalyzed by CaO: A review. Fuel. 2012;93:1-12.

[69] Boey P-L, Maniam GP, Hamid SA. Performance of calcium oxide as a heterogeneous catalyst in biodiesel production: A review. Chemi Enging J. 2011;168:15-22.

[70] Zheng S, Kates M, Dube MA, McLean DD. Acid-catalyzed production of biodiesel from waste frying oil. Biomass Bioenerg. 2006;30:267-72.

[71] Miao X, Li R, Yao H. Effective acid-catalyzed transesterification for biodiesel production. Energ Conver and Manage. 2009;50:2680-4.

[72] Lam MK, Lee KT, Mohamed AR. Homogeneous, heterogeneous and enzymatic catalysis for transesterification of high free fatty acid oil (waste cooking oil) to biodiesel: A review. Biotechnology Advances. 2010;28:500-18.

[73] Leung DY, Wu X, Leung M. A review on biodiesel production using catalyzed transesterification. Appl energy. 2010;87:1083-95.

[74] West AH, Posarac D, Ellis N. Assessment of four biodiesel production processes using HYSYS. Plant. Bioresource Technology. 2008;99:6587-601.

[75] Bajaj A, Lohan P, Jha PN, Mehrotra R. Biodiesel production through lipase catalyzed transesterification: an overview. J of Molecul Catalysis 2010;62:9-14.

[76] Brunet R, Carrasco D, Muñoz E, Guillén-Gosálbez G, Katakis I, Jiménez L. Economic and environmental evaluation of microalgae biodiesel production using process simulation tools. Symposium on Computer Aided Process Engineering2012. p. 20.

[77] Sakai T, Kawashima A, Koshikawa T. Economic assessment of batch biodiesel production processes using homogeneous and heterogeneous alkali catalysts. Bioresource Technology. 2009;100:3268-76.

[78] Marchetti J, Miguel V, Errazu A. Possible methods for biodiesel production. Ren and Sust Energ Rev. 2007;11:1300-11.

[79] Ranganathan SV, Narasimhan SL, Muthukumar K. An overview of enzymatic production of biodiesel. Bioresou techno. 2008;99:3975-81.

[80] Singh SS, Dipti. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review. Ren and Sust Energ Rev. 2010;14:200-16.

[81] Farag HA, El-Maghraby A, Taha NA. Optimization of factors affecting esterification of mixed oil with high percentage of free fatty acid. Fuel Proces Technolo. 2011;92:507-10.

[82] Janaun J, Ellis N. Perspectives on biodiesel as a sustainable fuel. Renewable and Sustainable Energy Reviews. 2010;14:1312-20.

[83] Bournay L, Casanave D, Delfort B, Hillion G, 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. Catalysis Today. 2005;106:190-2.

[84] Ting W-J, Huang C-M, Giridhar N, Wu W-T. An enzymatic/acid-catalyzed hybrid process for biodiesel production from soybean oil. J of the Chinese Inst of Chem Eng. 2008;39:203-10.

[85] Hidayat A, Rochmadi, Wijaya K, Nurdiawati A, Kurniawan W, Hinode H, et al. Esterification of Palm Fatty Acid Distillate with High Amount of Free Fatty Acids Using Coconut Shell Char Based Catalyst. Energy Procedia. 2015;75:969-74.

[86] Luque R, Pineda A, Colmenares JC, Campelo JM, Romero AA, Serrano-Riz JC, et al. Carbonaceous residues from biomass gasification as catalysts for biodiesel production. Journal of Natural Gas Chemistry. 2012;21:246-50.

[87] Sánchez M, Marchetti JM, El Boulifi N, Aracil J, Martínez M. Kinetics of Jojoba oil methanolysis using a waste from fish industry as catalyst. Chemical Engineering Journal. 2015;262:640-7.

[88] Buasri A, Worawanitchaphong P, Trongyong S, Loryuenyong V. Utilization of Scallop Waste Shell for Biodiesel Production from Palm Oil – Optimization Using Taguchi Method. APCBEE Procedia. 2014;8:216-21.

[89] Correia LM, Campelo NdS, Albuquerque RdF, Cavalcante CL, Cecilia JA, Rodríguez-Castellón E, et al. Calcium/chitosan spheres as catalyst for biodiesel production. Polymer International. 2015;64:242-9.

[90] Toda M, Takagaki A, Okamura M, Kondo JN, Hayashi S, Domen K, et al. Green chemistry: Biodiesel made with sugar catalyst. Nature. 2005;438:178-.

[91] Pua F-l, Fang Z, Zakaria S, Guo F, Chia C-h. Direct production of biodiesel from high-acid value Jatrophaoil with solid acid catalyst derived from lignin. Biotechnology for Biofuels. 2011;4:56.

[92] Marchetti J. The effect of economic variables over a biodiesel production plant. Energ Conver and Manage. 2011;52:3227-33.

[93] Marchetti JM. Influence of economical variables on a supercritical biodiesel production process. Energ Conver and Manage. 2013;75:658-63.

[94] You Y-D, Shie J-L, Chang C-Y, Huang S-H, Pai C-Y, Yu Y-H, et al. Economic Cost Analysis of Biodiesel Production: Case in Soybean Oil†. Energy & Fuels. 2008;22:182-9.

[95] Serrano M, Marchetti JM, Martínez M, Aracil J. Biodiesel production from waste salmon oil: kinetic modeling, properties of methyl esters, and economic feasibility of a low capacity plant. Biofuels, Bioproducts and Biorefining. 2015;9:516-28.

[96] Navarro-Pineda FS, Ponce-Marbán DV, Sacramento-Rivero JC, Barahona-Pérez LF. An economic model for estimating the viability of biodiesel production fromJatropha curcasL. Journal of Chemical Technology & Biotechnology. 2017;92:971-80.

[97] Glisic SB, Pajnik JM, Orlović AM. Process and techno-economic analysis of green diesel production from waste vegetable oil and the comparison with ester type biodiesel production. Appl Energy. 2016;170:176-85.

[98] Kookos IK. Technoeconomic and environmental assessment of a process for biodiesel production from spent coffee grounds (SCGs). Resources, Conservation and Recycling. 2018;134:156-64.

[99] Zhang Y, Dube M, McLean D, Kates M. Biodiesel production from waste cooking oil: 1. Process design and technological assessment. Bioresou techno. 2003;89:1-16.

[100] West AH, Posarac D, Ellis N. Assessment of four biodiesel production processes using HYSYS.Plant. Bioresourc Technol. 2008;99:6587-601.