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Techno-economic feasibility of producing biodiesel from acidic oil using sulfuric acid and calcium oxide as catalysts

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ABSTRACT

Biodiesel is becoming one of the best alternative fuels to substitute conventional diesel fuel for its environmental and fuel benefits. However, its full-fledged substitution to conventional diesel is hindered mainly due to its high cost of production. More than 85% of the production cost is attributed to feedstock cost. This forces to look for alternative feedstock at lower cost, which usually do have higher free fatty acid content. A number of investigations have been done to evaluate the technical and economic efficiency of biodiesel production from such acidic oil. Accordingly, in this study, three alternative production processes using two catalysts have been designed for techno-economic analysis. Sulfuric acid (H_2SO_4) catalyzed Transesterification and Esterification of Acidic oil; Calcium oxide (CaO) Catalyzed Transesterification of Acidic oil; and CaO catalyzed Transesterification with Pre-Esterification of Acidic oil with H_2SO_4.

Super Pro design and Aspen Plus softwares were used to perform the conceptual design and simulation of the different alternatives. The techno-economic competitiveness of three different scenarios were evaluated. The technical parameters were amount and quality of biodiesel and glycerol as well as the amount of biodiesel produced per feedstock used. The economic parameters considered were Total Investment Cost, Operating Cost, Unit Cost of Production, NPV, ROI and Payback time. The CaO catalyzed process could show better economic performances.

1. Introduction

Biodiesel is a mono alkyl ester of long chain fatty acids. It is a renewable fuel produced from oils and/or fats feedstock such as vegetable oil, animal fat, non-edible plant oil, and waste cooking oil, among others. As a fuel, biodiesel possesses a higher number of benefits than conventional petrol diesel. The most referred benefits are environmental ones such as its biodegradability, non-toxicity, emitting insignificant amount of sulfur, emitting less air pollutants and greenhouse gases other than nitrogen oxides. It also has worth mentioning use benefits as a fuel. These include better lubricity (reduce engine wear) and having higher oxygen content (encourage complete combustion).

The commercial practice to produce biodiesel involves homogeneous alkali catalysis of oil feedstock with free fatty acid content of less than 0.5% [1–3]. The higher the purity of the feedstock (lesser amount of FFA) the more expensive it would be, increasing the production cost to the point of making it a non-competitive alternative. Different investigations have been carried out to find alternative technologies for efficient and affordable production of biodiesel. Among such alternatives, the use of cheaper feedstock, cheaper catalyst and efficient production technologies have been considered. The most widely studied alternatives include heterogeneous and homogeneous acid catalyzed [4–9], heterogeneous alkali catalyzed [10–14], Enzyme catalyzed [15–18] and supercritical [19–22] transesterification reactions. There are also few promising but less studied alternative technologies. These include Nano Catalysts [23–25], Nano Immobilized Enzymes [26–28], Ionic Liquid Catalysts [29–31], and membrane reactors among others [32–34].

The studies so far done on the up supra mentioned biodiesel production technologies include those focusing on finding the optimum reaction conditions [2,35–38], determining the reaction kinetics [39–44], assessing technical efficiencies and evaluating economic performances [45–49] of selected technological alternatives. The technical and economic studies are usually done together as techno-economic analysis. Such studies are typically based on the stated reaction kinetics and optimum reaction conditions determined for max possible biodiesel yield.

Techno-economic study of biodiesel production technologies enable us to compare both technical and economic efficiencies of alternative technologies so that to choose the better performing option(s). The

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Nomenclature

ASTM	American Society for Testing and Materials
DG	Di-glyceride
DFC	Direct Fixed Cost
E	Ethanol
FAEE	Fatty Acid Ethyl Ester
FFA	Free Fatty Acid
G	Glycerol
IRR	Internal Rate of Return
MG	Mono-glyceride
NPV	Net Present Value
ROI	Return on Investment
TG	Triglyceride

technical performances are usually determined through energy and material balances of the whole production process. Karmee et al. [47] did a techno-economic study on three alternative technologies; base, acid and enzyme catalyzed transesterification for biodiesel production from waste cooking oil. The technical performances of these alternatives were made to be equal in terms of 100% biodiesel yield based on the optimum reaction conditions. This was then used to compare the cost effectiveness of the technologies. A more distinctive technical comparison was made by Marchetti et al. [50] on three biodiesel production alternatives, where the authors evaluated the technical performances based on material balances. The parameters used to compare the technical performances among the technologies were, biodiesel yield, total glycerol in biodiesel (referring the quality), amount of biodiesel produced per amount of raw materials used (referring performance), and yield of co-product glycerol.

In another way, the technological assessment can also be done through evaluating the technical benefits and limitations of the alternatives while attaining a given quantity and/or quality of biodiesel. These can include the number of process steps and the number of equipment required to achieve a given quantity and/or quality. This depicts how complex or how simple the whole production process of the alternative technology might be. Zhang et al. [51] assessed the technological performances of four alternative technologies for biodiesel production from waste cooking oil and vegetable oil. The authors used the size and number of equipment used in each process scenario to evaluate their technical performances and found out that the homogeneous alkali catalyzed process using virgin oil was the least sophisticated option requiring less number of process steps and equipment. They also found out that the acid-catalyzed process using waste cooking oil was less complex (requiring less process steps and less number of equipment) than the alkali-catalyzed process using the same oil character [51].

The economic performance evaluations should be done based on the results of the technological assessments. There are a number of economic parameters to test if technically efficient production alternative is cost effective or not, given a specified market scenario. Different researchers used different economic indicators. Zhang et al. [52] used total manufacturing cost, fixed capital cost, after tax rate of return and biodiesel break-even price to evaluate the economic performances of four process alternatives. Total investment cost and manufacturing cost are the most widely used economic parameters to have a clue on which technology option is cost effective. West et al. [53] used after tax rate of return as a parameter in addition to total capital investment and total manufacturing cost. However, it is realistic to consider more economic indicators to get deep insight into the profitability and sustainability of the technological options. Marchetti et al. [50] took a number of economic indicators to compare the economic feasibility of three proposed technological options to produce biodiesel from spent oil with 5% free fatty acid. The main parameters were total capital investment cost, total operating cost, NPV, unit cost of biodiesel, IRR, Gross Margin, and ROI.

It is obvious that the uncertain parameters (market variables) associated with biodiesel production could have considerably different effect on the techno-economic feasibility of the production process. Zhang-Chun et al. [54] investigated the effects of some parameters in the techno-economic assessments of biodiesel production. These include capital cost, interest rate, feedstock price, maintenance rate, biodiesel conversion efficiency, glycerol price and operating cost. The global sensitivity analysis done to quantify the contribution of each parameter to Life Cycle Cost and Unit Cost revealed that the feedstock price and the interest rate indicated considerable effects on the techno-economic assessment. In another study, Zhang-Chun et al. [55] also indicated that price of biodiesel, price of feedstock, and cost of operating can considerably affect techno-economic assessment of biodiesel production

The studies so far done on techno-economic assessment could cover only a limited type of technological alternatives. This triggers a need to investigate the techno-economic performances of more potential technologies for biodiesel production. Therefore, this study was aimed at assessing and comparing the techno-economic performances of biodiesel production from acidic oil using three process alternatives; H_2SO_4 catalyzed transesterification, CaO catalyzed transesterification, as well as CaO catalyzed transesterification with H_2SO_4 catalyzed pre-esterification.

A conceptual simulation of the processes were designed using Super Pro design software from Intelligen, Inc. [56] and Aspen Plus software from Aspentech [57]. Using the process flow sheets, a material balance for the total capacity of 41 thousand tons feedstock per year was done. Accordingly, the technical performances were evaluated in terms of the quantity and quality of biodiesel produced, amount and quality of glycerol produced, and the amount of biodiesel produced per raw material consumed. The economic competitiveness of three different scenarios were compared based on the economic parameters such as Total Investment Cost, Capital Investment Cost, Operating Cost, Unit Production Cost, NPV, ROI, and Gross Margin. The economic effects of change of oil cost and biodiesel selling price were also analyzed using NPV as the main economic indicator.

2. Reaction model

The dominant process in the production of biodiesel is the transesterification of the triglycerides. This reaction takes place in three steps sequentially as shown in Fig. 1. There are also some side reactions that could take place, depending on the quality of the feedstock considered and the technology employed. The dominant side reactions that can take place, due to the presence of acidic feedstock, are saponification in the presence of base catalyst and esterification in the presence of an acid catalyst. However, the hydrolysis of triglycerides can also take place depending on the water content of the feedstock as well as the amount of water produced during the esterification reaction.

In this study, two main catalysts were investigated separately and in combination to find out the most efficient and affordable option(s). Sulfuric acid as homogeneous and calcium oxide as the heterogeneous catalyst. Sulfuric acid was considered because it is the most

$$TG + E \xleftrightarrow{Catalyst} FAEE + DG$$

$$DG + E \xleftrightarrow{Catalyst} FAEE + MG$$

$$MG + E \xleftrightarrow{Catalyst} FAEE + G$$

Fig. 1. The three major reaction steps in catalyzed transesterification of triglycerides with ethanol.