Techno-economic study of the production of biodiesel from frying oil

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Received: 23/10/2021 Accepted: 23/02/2022 Published online: 15/03/2022

Abstract

Biodiesel is a clean and renewable fuel produced from a fatty biomass source such as vegetable oils or animal fats. The use of waste frying oil, instead of virgin oil, to produce biodiesel is an effective way to reduce the raw material cost and respect green chemistry principles. The main objective of this work is to valorise this frying waste by producing energy and eliminating a pollution source to preserve the environment. In this context, a techno-economic study was carried out for the synthesis of biodiesel from frying oils collected in the restaurants of the university on our campus. Firstly, an experiment optimizing the operating conditions was carried out, and the results obtained were exploited on a semi-industrial scale for an economic study using the SuperPro Designer V9 software. In this work, we investigated the effect of varying the amount of used oil to convert to biodiesel on the results of the cost analysis. The objective is to estimate the quantity from which the production process will be profitable. The collected oils were first characterized before proceeding with experiments using the Surface Response Methodology (RSM) to determine the optimal conditions for biodiesel production. A transesterification process with methanol and a potassium hydroxide catalyst was used. The results of the RSM design showed that the optimal conditions were 45 °C, 1.4 wt% of KOH, a methanol/oil molar ratio of 6: 1 and a reaction time of 30 minutes. These optimum values are in good agreement with literature values for transesterification of soybean oil. In the modeling part, the experimental protocol followed with all its stages is transformed into a set of operations for a semi-industrial process. This flowsheet is represented under SupePro Designer and material and energy balances as well as economic calculations were then made. The results of the study showed that the process becomes profitable when the amount to be treated is greater than 200 kg/batch. Variation in the quantities of waste oil was carried out and its influence on key parameters of the economic study is presented.

***Keywords**: Biodiesel; transesterification, economic evaluation, superpro designer, renewable energy.*

I. Introduction

The technological development of human society is highly dependent on fossil fuels for different activities. However, fossil fuels are non-renewable resources and there use in engines with internal combustion causes environmental problems. The depletion of global crude oil reserves and the climate change associated with the use of fossil fuels has stimulated, in recent years, the research of an alternative and efficient fuel to keep the environment clean and maintain sustainability renewable and environmentally friendly fuels. Biofuels are defined as liquid fuels produced from the biomass of different agricultural and forestry products and the biodegradable part of industrial waste [1]. Biodiesel, bioethanol, bio-methane and waste biomass or hydrogen have become renewable energy sources of great interest [2].

Biodiesel which is mainly derived from animal fats and vegetable oils is composed of long chain fatty acids e.g., mono-alkyl. Because of its biodegradability and non-toxicity, it has great potential as an alternative fuel. In addition, it can be directly used or blended with commonly available petrodiesel for the unmodified diesel engines. Biodiesel seems to be a good candidate in reducing the particulate matter, the emission of CO_2 and other greenhouse gases into the environment [3].

A variety of different types of reaction configurations can be employed in biodiesel synthesis, and may involve inorganic acid, inorganic base or enzymatic catalysis, biphasic or monophasic reaction systems, and ambient or elevated pressures and temperatures. The choice of chemical technology to employ in a production plant depends on the feedstock and its quality [4].

Due to the interest of the subject, several experimental works have been carried out on different vegetable oils such as cottonseed oil, rapeseed oil, soybean oil, etc. Also, the effect of different parameters on the yield and recovery of biodiesel from waste vegetable oil was studied. The parameters investigated include, catalyst %, temperature and oil to methanol molar ratio [5,6,7].

In the other hand, economical studies based on experimental investigation were performed on biodiesel processes such as in [8] or using softwares such Aspen plus [4] or Superprodesigner [9].

In this work, the technico-economic modelling of biodiesel production from waste frying soybean oil study was performed using SuperPro Designer, Version 9.0, a software tool for process simulation and flowsheet development that performs mass and energy balances, equipment sizing, batch scheduling/debottlenecking, capital investment and operating cost analysis, and profitability analysis [10]

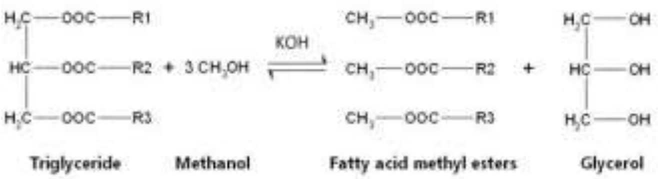
SuperPro Designer was chosen because it has built-in process models and an equipment cost database for typical unit operations used in this process.

As part of an eco-campus project at our university, cooking oil from restaurants of the residences was recovered and experimentally studied by performing transesterification with methanol and KOH as a catalyst. The parametric study resulted in optimal operating conditions of temperature, catalyst percentage and methanol/oil ratio. These experimental results were exploited for a semi-industrial scale modelling of a process for the transformation of cooking oil into biodiesel and the use of the Superpro Designer for the technico-economic study

II. MATERIAL AND METHODS

A. *Experimental study*

The frying oil samples were collected in the university residence restaurant Ain El Bey3 [11]. The experimental study was carried out in our research laboratory, were the samples where the samples were first tested before conducting an experimental study using the surface response methodology (RSM) to determine the optimal operating conditions for their conversion to biodiesel. A transesterification process with methanol and potassium hydroxide as a catalyst was used in this study which the reaction mechanism is as follows:



The results showed that the used frying oil studied have an acid value of 3.18 mg KOH/g oil, which is close to that for pure oil and is then good value to perform a transestererification [12]. This is because the oil is used in frying only once The RSM results showed that the optimum conditions are 45°C, 1.4 wt % of KOH catalyst, 6:1 feed methanol/oil molar ratio and 30mn as time reaction [11]. These optimum values agree well with the literature values for methanol basic transesterification of soybean oil [3, 13, 14].

B. *Process Modelling*

In the modelling part, we have transposed the experimental protocol followed in the realization of the first part of the work, with all its stages into a set of operations in the form of a semi-industrial process. This process is represented under SupePro Designer as follows:

First, the frying oil is filtered (NFD-101) to remove impurities and then introduced into the reactor (R-101) with the methanol-KOH mixture (V-101). In the stirred reactor (R-101) several operations take place: the transesterification reaction, the vaporization of the methanol, a cooling and a decantation-extraction, which makes it possible to recover the glycerol at the bottom of the reactor (R-101). The biodiesel obtained then passes into another vessel (R-102) for water washing and biodiesel-water separation. The washing water is recovered after decantation-extraction down the vessel (R-102) and finally a distillation removes the remaining water from biodiesel. The produced biodiesel is stored in a receiver Tank (V-102) and the by-product glycerol in (V-103) as shown in figure1.

After completion of the Superpro flowsheet and initialization of all the streams and operations of the process, the mass and energy balances are successfully completed.

C. *Economic evaluation*

When mass energy balances calculation is carried out with success, results of streams flowrates, composition, temperature and equipment sizing, energy consumption,...etc are then used by the software to perform economic evaluation.

In this work, the SuperproDesigner databank was used for purchasing prices (raw materials) and selling prices (revenue products) of materials and equipment cost, [15] was also used for filter equipment cost. For used frying oil cost, we assumed a cost of one fifth the price of pure soybean oil as it is assumed as a waste. Process economics included the recovery of by-product glycerol generated during biodiesel production, and its sale into the commercial glycerol market [4].

The software calculated most of the key economic indices: Total Capital Investment, Operating Cost, Revenues, Unit Production/Processing Cost, Unit Production/Processing Revenue, Return On Investment (ROI), Payback Time etc.

III. RESULTS AND DISCUSSION

A scale up of the experimental protocol and optimal operating conditions was carried out. At first, 50 kg of frying soybean oil was used to perform mass and energy balances and then the economic evaluation. Then, the frying soybean oil flowrate was varied to estimate its effect on process key economic indices.

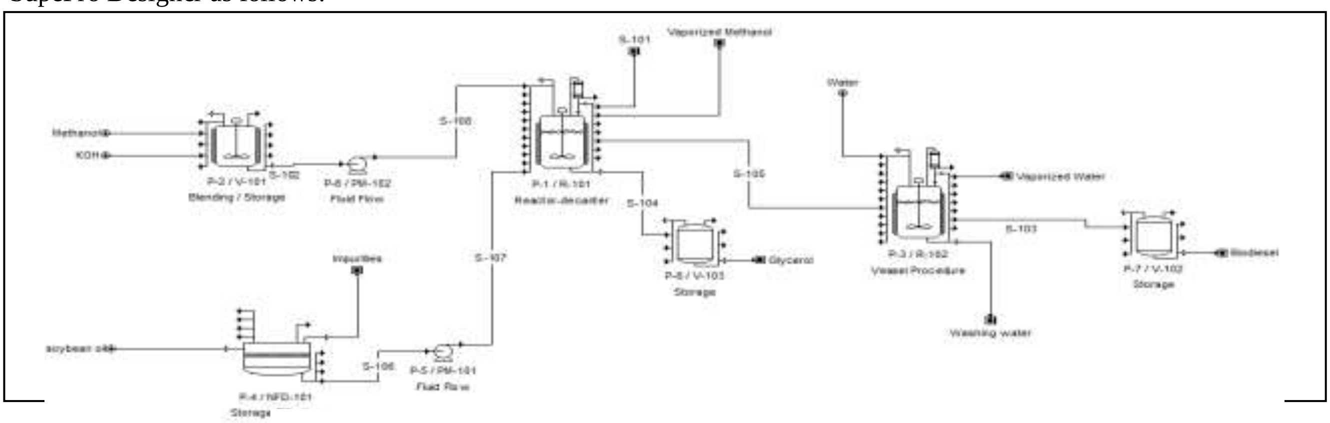


Fig. 1 Superprodesigner Process diagram for biodiesel production from waste cooking oil

A ***Streams and equipment results for 50 kg oil transformation***

First, we consider the modelling and economic evaluation study for a soybean oil feedstock of 50 kg. Methanol and KOH quantities were adjusted to this capacity according to the optimal experimental results cited above. Streams component flowrates (kg/batch) results obtained by performing mass and energy balances are summarized in the table below:

TABLE I
STREAMS COMPONENT FLOWRATES FOR 50 KG OIL FEEDSTOCK

Stream Name	**Soybeanoil**	**Methanol**	**KOH**	**water**
Source	**INPUT**	**INPUT**	**INPUT**	**INPUT**
Destination	**P-4**	**P-2**	**P-2**	**P-3**
Impuretes	0.10	0.00	0.00	0.00
Methanol	0.00	10.12	0.00	0.00
Sybean oil	50.00	0.00	0.00	0.00
KOH	0.00	0.00	0.70	0.00
Water	0.00	0.00	0.00	10.00
Stream Name	**Glycerol**	**Methanol**	**Washing water**	**Biodiesel**
Source	**P-1**	**P-1**	**P-3**	**P-3**
Destination	**OUTPUT**	**OUTPUT**	**OUTPUT**	**OUTPUT**
Glycerol	5.14	0.00	0.05	0.00
Methanol	0.06	4.40	0.23	0.00
KOH	0.14	0.00	0.56	0.00
Biodiesel	0.50	0.00	0.50	49.17
Water	0.00	0.00	9.99	0.00005

Also, all the equipments of the process were sized and the results are showed in table II:

TABLE III EQUIPMENT SIZING FOR 50 KG OIL

R-101 (Stirred Reactor)	
Volume	104.72 L
Diameter	0.38 m
Height	0.94 m
V-101 (Blending /Storage)	
Volume	14.65 L
Diameter	0.18 m
Height	0.55 m
NFD-101 (Storage/Filtration)	
Filter area	0.278 m^2
R-102 (Vessel procedure)	
Volume	75.03 L
Diameter	0.34 m
Height	0.84 m
Fractionation column is attached to vessel	
Number of fractionation column trays	5.00
PM-101 (Centrifugal Pump)	
Power	4.41 watt
PM-102 (Centrifugal Pump)	
Power	1.26 Watt
V-102 (Storage)	
Volume	62.54 L
Diameter	0.30 m
Height	0.89 m
V-103 (Storage)	
Volume	5.34 L
Diameter	0.13 m
Height	0.31 m

B ***STREAMS AND EQUIPMENT RESULTS FOR 50KG OIL TRANSFORMATION***

The results of the economic evaluation calculation are summarized in figure2. For 50 kg of frying soybean oil, the unit production cost is almost double the unit production revenue of pure soybean oil and all the economic project indices indicated that for this capacity of production, the project is not profitable.

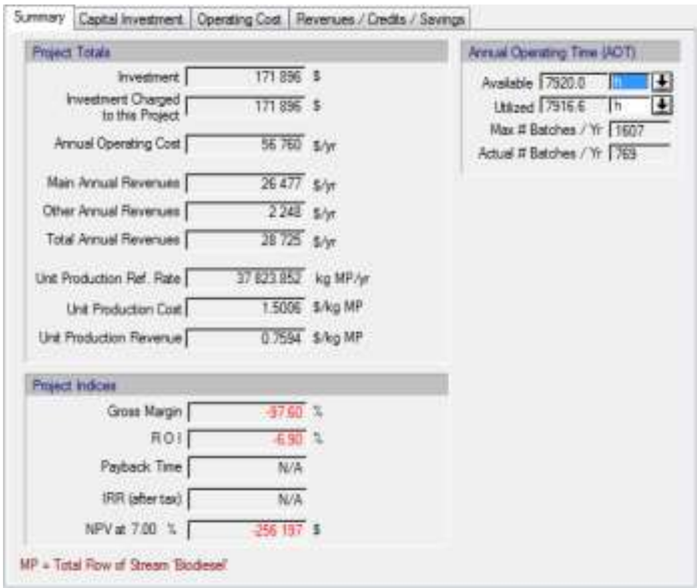


Fig. 2 Executive summary of economic evaluation for 50 kg oil transformation

C ***Effect of frying oil flowrate on economic key indices***

We decide to increase the frying soybean oil feedstock from 50 kg to 1000 kg in order to determine the optimal value from which the project become profitable. This increase will lead to an increase in equipment size, energy consumption, etc. Superpro Designer will take into account automatically these changes and adjust the prices using a locally defined cost model for which the parameters were used from SuperPro example file for the biodiesel process (BioDiesel9_0.spf) in SuperPro's "EXAMPLES\BioDiesel" sub-directory.

The results reported in table III shows that the project economic indices improve by increasing soybean oil feedstock flowrates. The project gross margin becomes positive for flowrates greater than 200 kg/batch.

TABLE IIIII

ECONOMIC KEY INDICES VARIATION WITH USED SOYBEAN OIL FLOWRATES

Used Soybean oil (kg)	Unit Production Cost ($/kg MP)	Unit Production Revenue ($/kg MP)	Gross Margin %	Return On Investment %	Payback Time (Year)
50	1.5	0.76	-97.60	-6.90	N/A
100	1.07	0.76	-41.07	0.61	163.17
200	0.78	0.76	-3.56	8.42	11.87
300	0.66	0.76	12.86	13.84	7.23
400	0.6	0.76	20.36	17.08	5.85
500	0.56	0.76	26.19	20.17	4.96
600	0.53	0.76	30.32	22.75	4.39
700	0.5	0.76	34.03	25.47	3.93
800	0.48	0.76	36.12	27.14	3.69
900	0.466	0.76	38.64	29.44	3.40
1000	0.45	0.76	40.53	31.33	3.19

Figure3 shows the exact flowrate value from which the unit production cost is equal to unit production revenue and which is estimated graphically to be 222.55 kg/batch.

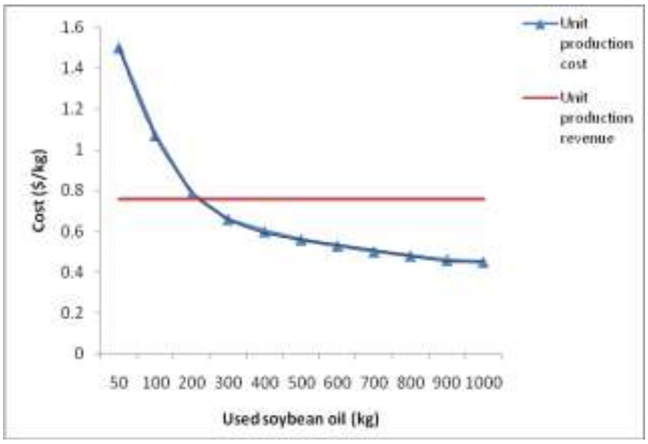


Fig3. Unit production and revenue costs variation with soybean oil flowrates

The economic evaluation calculations for the optimal flowrate give the results summarized in figure4.

Fig4. Executive summary of economic evaluation for 222.55 kg soybean oil feedstock

However, this optimal value has project indices which can be improved such the payback time estimated at 10.59 years while the shorter the payback time, the more attractive the project appears to be. The economic evaluation results showed from table III that for a payback time lower than 4 years the frying soybean oil flowrate must be greater than 600 kg/batch.

IV. CONCLUSION

From this work results we can conclude that frying oil used in university residence restaurant is a good feedstock to obtain a biodiesel. Data analysis of process economic evaluation study showed that the production of biodiesel from this feedstock become profitable from a flowrate of 222.55 kg/batch. However, the project profitability can be improved by increasing the oil flowrate to achieve lower payback time and higher gross margin and ROI.

The model is flexible in that it can be modified to carry out economic evaluation and also mass balances and equipment sizing by changing feedstock and equipment cost or even the process chemistry and technology.

Acknowledgment

The authors thank the university residence Ain El Bey3 at Constantine3 University to have provided the frying oil samples to perform this study.

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