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Techno-economic Assessment of Bio-based Lubricant Production Process from Waste Frying Oil: A Case Study of Egypt

Reda Z.K. Hussein[1]; N.K. Attia[2], M. Fouad[1]; Shakinaz T. ElSheltawy[1]
[1]Chemical Engineering Department, Cairo University, Giza-Egypt
[2]Chemical Engineering and Pilot Plant Department, National Research Centre, Giza-Egypt

Corresponding Author:- Reda Z.K. Hussein[1]; Orcid ID: 0000-0003-2210-3441

Abstract:- Biolubricants are promising substitutes to mineral oils or petroleum-based lubricants in many industrial applications. In the present study, a techno-economic analysis is carried out for evaluating the production of Ethylene glycol dioleoyl (EGD) biolubricant produced from waste cooking oil (WCO) and from biodiesel directly. Two scenarios of the process were studied. Scenario I was that the production process is comprised of two parts: (1) biodiesel production from WCO; (2) biolubricant production from biodiesel, while scenario II was only the second part (biolubricant production from biodiesel). The economic assessment for the process in Egypt (for both scenarios) was performed based on the results of process simulations and design calculations. The process showed positive after-tax rate of return (ROI %) and a very low payback period (PBP) for both scenarios with biolubricant selling price equal to the petroleum-based lubricant for same purposes. In addition, it was found that the biolubricant could be sold with a very challenging prices and the process would still be economically feasible and profitable. Despite, both scenarios are promising, scenario I showed a much lower cost of manufacturing, selling price and thus, break-even time. The main reason of this result is that big biodiesel price compared to WCO price.

Keywords:- *Biolubricants; waste Cooking Oil (WCO); Economic Assessment; Rate of Return on Investment (ROI%); Payback Period (PBP).*

I. INTRODUCTION

The main reasons for the incremental world need of lubricants are mainly the increased usage of motor vehicles, agriculture mechanization, building new constructions, mining, improved oil and gas production and the growth of many industrial sectors. It is expected that some regions will have the highest share in demands namely, Asia especially China followed by South America then the Middle East especially Egypt and Africa. Some studies stated that Asia-Pacific along with Africa and the Middle East especially Egypt account for more than half the global lubricants market [1, 2, 3].

Lately, developed countries have been implementing firm rules on the use and disposal of lubricants owing to the fact that petroleum depletion is expected soon, and the world energy need is expected to increase by more than 50 % by 2030, as reported by the International Energy Agency (IEA), 2007.

In addition, the European commission reported that the world energy consumption is expected to rise by 120 % by the year 2050 compared to 2017 [4]. Therefore, researchers have been lately focus on the usage of biomass in the production of valuable products and fossil fuel substitutes. The sustainability of biomass as a raw material for these products is a key advantage. In addition, such products are biodegradable and emissions free and hence are environmentally benign.

In general, biolubricants were first used in the early eighties in two stroke engines. They are a promising substitute to conventional petroleum lubricants as they could help reduce environmental problems due to their promising physical properties. Such properties are low volatility, non-toxicity, biodegradability, sustainability or being renewable, high lubricity, high viscosity index, high flash point and high solvency for additives. Bio-lubricants obtained from chemical modification of vegetable oil form a polymeric protective film on the lubricated surfaces and thus, give about 23 % lower coefficient of friction compared to synthetic lubricants [4, 5].

Egypt is one of the countries that have been recently interested in finding alternatives for petroleum-based products. Egyptian researchers have been performing studies on biomass-based products such as biolubricants. One of the main reasons for this recent trend is that in the last few years Egypt crude oil consumption has highly exceeded its production. Whereas the Egyptian yearly crude oil production is decreased from about 760 to 550 Barrels per day while, the consumption increased from about 540 to 770 Barrels per day from 2000 till 2022 [6]. Besides, Egypt is annually producing more than 500,000 tons of WCO from different resources and recently, there are many WCO collection companies in Egypt [7].

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In the present study, techno-economic analysis and assessment are conducted for the production process of Ethylene glycol dioleoyl (EGD) biolubricant produced from biodiesel coming from waste cooking oil (WCO) (Scenario I). The feasibility study of the project in Egypt was carried out. Where the economic feasibility study; is a measure of the effectiveness and profitability of the project. Assessment was also performed for the production process starting from biodiesel (Scenario II). Finally, the results of the two scenarios were compared.

II. METHODS

A. Process Description

Figure 1 is the flow diagram from the process simulation of the studied biolubricant production process. This simulation was carried out using the Aspen HYSYS (version 9). The flow diagram is composed of two main sections: (1) Biodiesel Production Section and (2) Biolubricant Production Section. In each section, there is diverse unit operations and process equipment. The whole process simulation along with an experimental parametric study were performed in a previous work Hussein et al. (2021) [8].

➤ *Biodiesel Production*

In the biodiesel production section, waste-cooking oil, methanol, and potassium hydroxide are fed to the process. First, fresh methanol is mixed with recycled methanol stream along with potassium hydroxide catalyst (1 %wt. of the oil) in MIX-100 and then the mixed stream enters reactor R-100 along with the preheated waste cooking oil in exchanger E-100. The molar ratio of methanol to oil is 6: 1. The reaction conditions were 65 o C temperature, 100 kPa pressure to achieve 98 % conversion. The reactor effluent stream was used to preheat the waste cooking oil inlet stream in exchanger E-100 then head to the distillation tower T-100 to remove methanol that is unreacted and in excess. Pure methanol from the distillation top was recycled back to MIX-100. Then, the distillation bottom product pumped and fed to a liquid-liquid gravity separator V-100 (component splitter) to separate glycerol layer from biodiesel (with potassium hydroxide catalyst dissolved in it). The heavy liquid (glycerol) went to a neutralization reactor R-200. Where, phosphoric acid (H_3PO_4) used to neutralize potassium hydroxide giving potassium phosphate by product that removed from glycerol in a sedimentation centrifugal separator V-200 (simulated as three phase separator). The light liquid stream from V-100 then sent to a vacuum distillation T-200 after the reduction of its pressure in throttling valve VLV-100. The tower T-200 was working under vacuum to prevent biodiesel degradation. Finally, the bottom of T-200 is the produced biodiesel.

➤ *Biolubricant Production*

While in the EGD biolubricant production section, biodiesel from previous section is cooled from 320 o C to 130 o C in air cooler AC-100. Then pumped and directed to the last reactor R-300. In addition, the ethylene glycol pressure reduced in VLV- 200 and then ethylene glycol heated in low-pressure steam heater E- 300. Hence, ethylene glycol entered the reactors at 130 o C and 85 kPa. A recycle stream (mainly biodiesel) entered reactor R-300 after raising its pressure to 85 kPa and the reaction time was taken 90 minutes based on the experimental work by Hussein et al. (2021). The exit stream from reactor R- 300 is then directed to distillation tower T-300. Unreacted biodiesel and small amount of ethylene glycol were removed (biodiesel recycle stream). Bio-lubricants product obtained as bottom product with recovery of 99.98% of bio-lubricant along with the remaining biodiesel. In the reboiler, superheated high-pressure steam was the heating medium. Finally, biolubricant product pumped to atmospheric pressure using P-600 and sent to storage tanks.

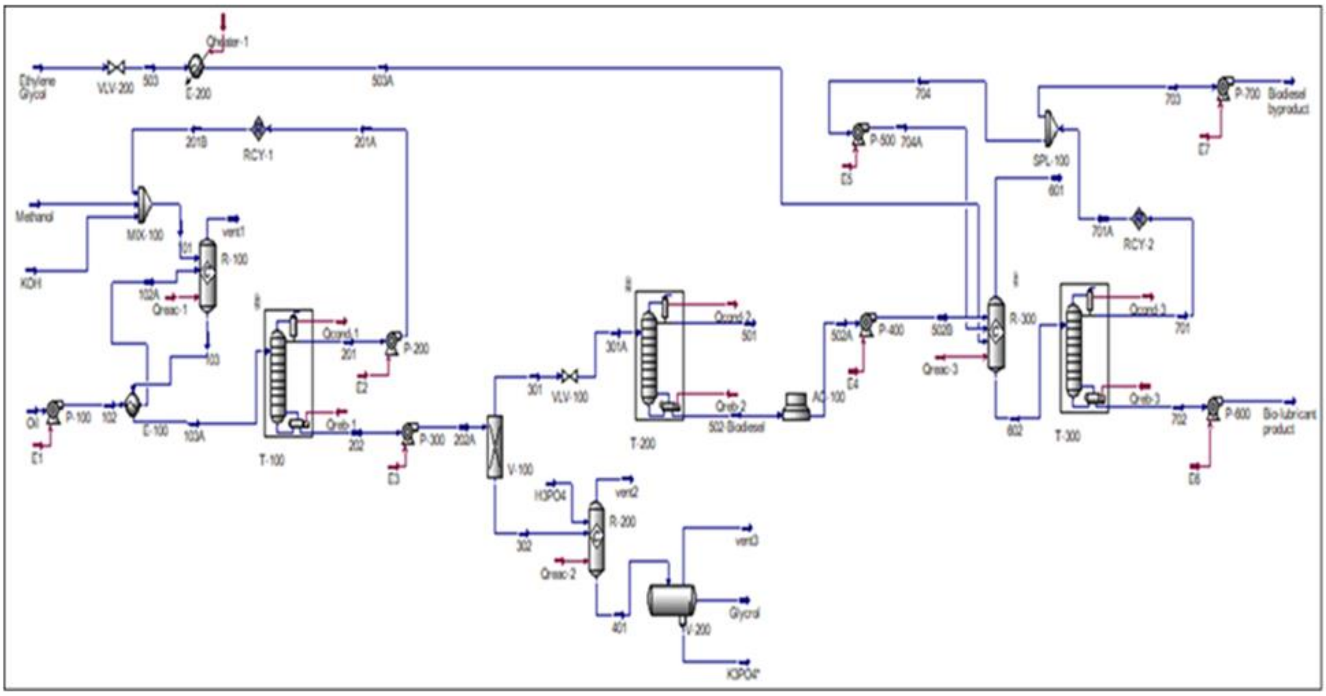

Fig 1 Process ASpen HYSYS Flow Diagram for Bio-Lubricant Productio

B. Process Design Calculations

Chemical design calculations of all process equipment were performed. Where, the target was to obtain the data needed for the costing of equipment in the studied biolubricant production process. Design calculations such as equipment sizing were performed according to principles outlined in the literature [9, 10, 11]. Residence times for vessels were obtained from experiments and common practice. Material and energy balances, along with operating conditions (from the previous study [6]) were taken from Aspen HYSYS process simulation. Equipment included in the process are listed in table 1.

- *Process Reactors*

The process includes three jacketed continuous stirred tank reactors (CSTR). The design of each reactor is composed of three steps: vessel design, mixer design and heating or cooling jacket design. The three reactor mixers were designed according to mixing principles in literature [11, 12, 13]. While, jackets design was performed according to Freeman, (2008) and Guest, (2010) [14, 15]. The design of the methanol mixer MIX-100 was performed using the same method used for the design of mixers of the three reactors.

- *Distillation Towers*

Tray sizing tool in Aspen HYSYS software was used to size the distillation towers. It must specify the tower type whether packed or tray column then enables the tool. Then the program calculates the column size after checking its performance e.g., weeping and channeling.

- *Heat Exchangers*

The process contains different types of heat exchange equipment; heat exchangers, heaters, coolers, and condensers and reboilers of the distillation columns. Heat exchangers, coolers, heaters, and condensers of the distillation columns were designed as shell and tube heat exchanger type while, reboilers were designed as kettle reboilers. The heat exchangers, reboilers and air coolers were designed using Aspen HYSYS software design tool (TEMA HEX). This is performed by enabling Aspen Process Economic Analyzer, then choosing the equipment and enabling interactive sizing tab.

- *Pumps*

The pumps used in the process are continuous centrifugal pumps. The necessary pump shaft power (P) was calculated using equation (1) where, Q is the feed volumetric flow rate, ρ is the density of pump feed, h is the pump total head, g is the acceleration due to gravity and η is the pump efficiency (typically taken 70%). The pump head was taken from Aspen HYSYS process model [12].

$$P = \frac{\rho g h Q}{\eta} \quad (1)$$

- *Separators*

Three separating unit operations are used in the current bio-lubricant production process starting from waste cooking. Those units are a gravity separator, sedimentation centrifuge and filter press.

The bottom product from the first distillation tower T-100 contains the produced biodiesel and glycerol in which the homogeneous catalyst potassium hydroxide (KOH) is dissolved. This mixture is separated using a gravity separator due to the large difference in densities. The light liquid phase is mainly biodiesel, and the heavy phase is glycerol with the dissolved catalyst. Design for the required gravity separated according to Arnold and Stewart (2008) [16].

The outlet from the neutralization reactor R-200 is mainly glycerol and potassium phosphate with a concentration of about 10.66 % (w/w) [5.5 % V/V]. It is required to separate glycerol from the salt to be able to sell it as a byproduct and selling potassium phosphate as a fertilizer. Many factors are considered in the selection of a suitable separation technique mainly; the solids content, flow rate to be treated, difference in density between liquid and solid, liquid viscosity and the size and nature of solids in the mixture. Therefore, sedimentation centrifuge was founded to be suitable for such separation. Design for the required centrifuge was performed according to literature and industrial cited data [9, 16, 17].

The outlet stream from the bio-lubricant production reactor R-300 contains the heterogeneous catalyst calcium oxide (CaO) with a concentration of 1.24 % (w/w). Although the leaf filter is the suitable filter however it is only used for small capacities. The capacity of the stream needed to be separated is 18.9 ton/h and thus the amount of solid to be separated is about 237.5 kg/h. Therefore, leaf filter will not be applicable for this large solid capacity. Plate and frame filter press could be used with a polypropylene filter medium. Filter press was designed according to common practice and cited design parameters [18].

Table 1 Process Equipment Included in the Biolubricant Production Process

Equipment	
Storage facilities	WCO tank
	Methanol tank
	EG tank
	Phosphoric acid tank
	KOH silo
	Intermediate biodiesel tank
	CaO silo

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Reactors (CSTR)	Oil transesterification reactor (R-100)
	Neutralization reactor (R-200)
	Biodiesel transesterification reactor (R-300).
Mixers	Static mixer
	MIX-100
Separators	Gravity separator
	Sedimentation centrifuge
	Filter Press
Distillation towers	T-100, T-200 and T-300
Heat exchange equipment	Preheater
	E-100
	Condenser of T-100
	Reboiler of T-100
	Condenser of T-200
	Reboiler of T-200
	AC-100
	E-200
	Condenser of T-300
	Reboiler of T-300
Pumps	P-100, P-200, P-300, P-400, P-500, P-600, P-700

C. Economic Assessment

The economic profitability assessment of the project requires the calculation of the total capital investment and total manufacturing cost based on the process design and simulation. Thus, for the process under study, it is important to know the plant capacity, raw materials, chemicals prices and cost of the main equipment in the process flowsheet. In addition, it is important to decide the place of the plant to get the land price taking into consideration that the land should be close to a WCO collection Company. All chemical costs including raw materials, catalysts, and products were used according to recent Egyptian local market prices see Table. Process economics calculations was based on a plant capacity of 100,000 tonnes bio-lubricants/year.

The economic assessment for the biolubricant production process in the present work was developed using the literature stated by Turton et al. (2012) [19].

➢ *The following Typically used Assumptions were Assumed [20, 21]:*

- 8000 operating hours/year.
- All costs used were in US$.
- Equipment prices from Turton et al. (2012) were updated from mid-2006 to July-2022 and equipment prices from matche.com were updated from mid-2014 to July-2022 using the Chemical Engineering Plant Cost Index (CEPCI), where IMid-2006 = 500, IMid-2014 = 575.7 and IJuly-2022 = 829.9 [19].

The capital cost estimation definition was provided by Turton et al. (2012), and it states that a study estimate for the process capital cost could be performed based on the sizing of the main equipment in the process flow sheet without the need for layout or piping and instrumentation diagrams (P&ID's). One of the most used techniques for cost estimation of a new chemical plant is the module costing technique that was used in the present study. This technique relates all costs back to the purchased cost of equipment which is evaluated at a base case where the equipment is at atmospheric pressure and made of carbon steel [19].

Table 2 Costs of raw materials, catalysts, chemicals and products that were used in the process.

Item	**Specification**	**Price ($/ton)**	**Source**
	Raw materials		
WCO	Free of FFAs	655	Egyptian Market Price 2023
Methanol	99.90%	600	[22]
KOH	Anhydrous	750	[23]
H_3PO_4	85% tech.	800	[24]
Ethylene Glycol	99.80%	650	[25]
CaO	99.90%	450	[26]
	Products		
Bio-lubricant	Compatible with ISO VG68 lubricant	3352	[27]
Biodiesel	89%	1560	[28]
Glycerol	85%	700	[29]
K_3PO_4	98%	1400	[30]
	Utilities		

Low press. Steam (LPS)	2 barg & 134 °C	\$8.62	[19]
Mid press. Steam (MPS)	9 barg & 180 °C	\$8.82	[19]
High press. Steam (HPS)	40 barg & 250 °C	\$8. 91	[19]
Superheated (HPS)	41 barg & 600 °C	\$12.26	[19]
Cooling water	30 °C to 40 °C	\$ 0.53/ m^3	Egyptian Market Price 2023
Electricity	220 V/50Hz	\$ 0.067/kw.hr	Egyptian Market Price 2023
Natural gas	Industrial	\$ 0.19/ m^3	Egyptian Market Price 2023
Waste disposal (solid & liquid)			
Hazardous	N/A	1826	[19]
Non-hazardous	N/A	59.8	[19]
Note that: USD=30.55 0EGP (@Feb 2023)			

➢ *Total Capital Investment*

The total capital investment C_{TCI} is calculated by summing up the fixed capital investment C_{FC}, the working capital investment C_{WC} and land price C_L. Where, C_{FC} is the amount of money paid to build up a plant and make it ready for startup while C_{WC} is the additional amount of money needed to start and operate the plant until revenue is earned (around 1-3 months).

C_{FC} was calculated using equation (2), where, C_{BM_T} is the total bare module cost of process equipment, C_{CF} is the contingency and fee costs (taken as 18 % C_{BM_T}) and C_{AFC} is the auxiliary facilities costs (it is 20-100 % C_{BM_T} and taken as 30 % C_{BM_T}). C_{CF} is added to the economic evaluation to account for errors and faulty information while, C_{AFC} is the expenses related to site development, auxiliary buildings and off-sites and utilities. The sum of the terms C_{BM_T} and C_{CF} give the total module cost C_{TM}. The working capital investment C_{WC} was calculated using equation (3) where, it is usually taken as 5-30 % C_{FC} and typically it was assumed to be 15 % C_{FC} [9, 19].

C_L is calculated by multiplying the price in dollars of one square meter of the selected industrial plant area according to market price by the plant estimated area. The plant estimated area is calculated by calculating the needed process area for the plant then adding 50 % administrations buildings and utilities along with 50 % expected future expansion. The process area was calculated by adding the area of every piece of equipment along with the minimum safe area around this equipment required for safety, maintenance and materials handling. Where, the choice of suitable spacing between equipment is crucial to be able to run and control the process in a better way. The equipment spacing or required safe area between equipment was assumed according to common practice [31]

$$C_{FC} = C_{BM_T} + C_{CF} + C_{AFC} \quad (2)$$

$$C_{WC} = 0.15 \times C_{FC} \quad (3)$$

➢ *The Cost of Manufacturing*

Cost of manufacturing COM is the total expenses of the day-to-day operation of the chemical plant. The major constituents of COM are raw materials, utilities, and waste treatment. COM was calculated by summing up three main terms: direct manufacturing costs DMC, fixed manufacturing costs FMC and general expenses GE. The calculation of COM depends mainly on the following costs: Fixed capital investment (C_{FC}), Cost of operating labor (C_{OL}), Cost of utilities (C_{UT}), Cost of waste treatment (C_{WT}) and Cost of raw materials (C_{RM}). The three costs; C_{UT}, C_{WT} and C_{RM} were calculated by multiplying their yearly flow rates from HYSYS by the corresponding prices from Table 2. C_{OL} was calculated using the method stated by Turton et al. (2012), which calculates the total number of required operating labor for a chemical plant. If each operator worked on average 49 weeks/year (assuming three weeks for vacations and sick leave) and there were three shifts a day for a continuously running plant. Then, the total number of operating labor is multiplied by the recent average salary of a chemical plant operator in Egypt in \$/year [19].

The direct manufacturing costs DMC refers to the expenses related to the operation and thus, it depends on the production rate. The expenses included in DMC are listed in table 3 along with the multiplication factors used in its calculation. The fixed manufacturing costs FMC include the expenses that are independent of the production rate. The expenses included in it along with the multiplication factors used in the calculations are listed in table 3 Table. Finally, the general expenses GE are the expenses that are rarely affected by the production rate like management, sales, financing, and research and development. The terms included in it along with the multiplication factors used in the calculations are presented in table 3 [19].

Table 3 Multiplication Factors for Estimating Cost of Manufacturing [19]

Item	**Multiplication Factors**	**Multiply by**
Direct Manufacturing Costs (DMC)		
Direct supervisory and clerical labor	18%	Operating labors (C_{OL})
Maintenance and repairs	6%	Fixed capital investment (C_{FC})
Operating supplies	15%	Maintenance and repairs ($C_{M\&R}$)
Laboratory charges	15%	Operating labors (C_{OL})
Patents and royalties	3%	Cost of manufacturing (COM)

Fixed Manufacturing Costs (FMC)		
Depreciation	10%	Fixed capital investment (C_{FC})
Plant overheads	60%	[Operating labors (C_{OL}) + Direct supervisory (SUP) + Maintenance and repairs ($C_{M\&R}$)]
Local Taxes and insurance	3.2%	Fixed capital investment (C_{FC})
General Expenses (GE)		
Administrative	15%	[Operating labors (C_{OL}) + Direct supervisory (C_{SUP}) + Maintenance and repairs ($C_{M\&R}$)]
Distribution and selling	11%	Cost of manufacturing (COM)
Research and development	5%	Cost of manufacturing (COM)

- *Process Profitability Assessment*

Commonly, there are three commonly used techniques to evaluate the economic profitability of a process or a project: payback analysis, rate of return on investment and net present value. The net present value is usually used to compare profitability of different project alternatives, and this is not the case in the present work. Therefore, the used techniques in this work were the payback period analysis and rate of return on investment along with break-even price of the produced bio-lubricant compared to the price of the petroleum based standard lubricant used in the same applications.

The values of the payback period and rate of return on investment will differ if the starting material was biodiesel not the waste cooking oil. Therefore, two scenarios for the biolubricant production process were studied and compared from the economics point of view. Scenario (I) is biolubricant production from WCO (Figure 1) and scenario (II) is biolubricant production from biodiesel (the second part from Figure 1).

- *Payback Period (PBP)*

The payback period (PBP) is the time that the process takes after startup to recover all the fixed capital investment (C_{FC}) and the cost of land C_L. The shorter the payback period, the more profitable and promising is the project. Typically for large projects the payback period is 4-5 years and for medium project it is 2-3 years. Equations (4), (5) and (6) are used to calculate the PBP. Where, A_{NNP} is the after tax net profit, A_{NP} is the annual net profit, A_R is the annual revenue. The annual revenue is calculated from the selling of bio-lubricant product and byproducts produced (biodiesel, glycerol and potassium phosphate). A_{IT} is the tax on income and it is calculated as a percent of the annual net profit A_{NP}. This percent is called tax rate and it differs from one country to another according to the national laws and regulations. This tax rate in Egypt is 22.5 % for the year 2020 [19].

$$\mathrm{PBP} = \frac{C_{FC} + C_L}{A_{NNP}} \quad (4)$$

$$A_{NNP} = A_{NP} - A_{IT} \quad (5)$$

$$A_{NP} = A_R - \mathrm{COM} \quad (6)$$

- *Rate of Return on Investment (ROI)*

The rate of return on investment is the rate at which money is earned from the fixed capital investment and represents the real financial value of an investment. It is usually represented in percentage (ROI %). The larger the value of ROI %, the more profitable and promising will be the project. It is the percent of payback period PBP reciprocal. It is also called after tax rate of return as the profit value used is the after tax net profit (A_{NNP}) [19].

III. RESULTS AND DISCUSSION

A. *Process Design*

The equipment design data required for process equipment costing were determined. Table 4 and table 5 contain the design data for the main process equipment, referring to figure 1.

Table 4 Bio-Lubricant Production Process Equipment Design Data (1st Zone)

Parameter	Biodiesel Production (Step1)
Methanol mixer (MIX- 100)	
Mixed stream temp. (°C)	43.64
Mixed stream Press. (kpa)	125
Residence time (min)	10
Size (V, m^3)	1.30
Agitator type	Propeller
Transesterification I (R- 100)	
Catalyst	KOH
Catalyst Phase	homogeneous
Temp. (°C)	65
Press. (kpa)	100
Methanol : Oil (mole ratio)	6: 1

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Reaction time (min.)	60
Conversion %	98
Size (V, m^3)	35.66
Agitator type	Propeller
Methanol recovery column(T- 100)	
Temp. (°C)	63.82
Press. (kpa)	90
Condenser duty (MJ/hr)	4543.77
Reboiler duty (MJ/hr)	7174.02
Reflux ratio	1.5
Size (D × H, m)	1.5 x 8.8
Glycerol separation (V- 100)	
Final biodiesel purity (% (w/w))	95.06
Size (D × H, m)	1.72 x 3.02
Catalyst neutralization (R- 200)	
Temp. (°C)	25
Press. (kpa)	100
Reaction time (min.)	10
Conversion %	100
Size (V, m^3)	0.382
Agitator type	Pitched 6-blade turbine
Biodiesel purification column (T- 200)	
Temp. (°C)	134
Press. (kpa)	50
Condenser duty (MJ/hr)	185.77
Reboiler duty (MJ/hr)	6293.4
Reflux ratio	2
Size (D × H, m)	3 x 6.7
Potassium Phosphate separation (V- 200)	(Sedimentation disc centrifuge)
Temp. (°C)	25
Solids in feed (% (w/w))	10.66
Capacity (lit./h)	1143.56
Σ value (m^2)	796.31
Size (D, mm)	230

Table 5 Bio-Lubricant Production Process Equipment Design Data (2nd Zone)

Parameter	**Bio-lubricant Production (Step 2)**
Transesterification II (R- 300)	
Catalyst	CaO
Catalyst Phase	Heterogeneous
Temp. (°C)	130
Press. (kpa)	60
FAME: EG (mole ratio)	3.5: 1
Reaction time (min.)	90
Conversion %	94
Size (V, m^3)	42.36
Agitator type	Pitched 6-blade turbine
Calcium oxide separation	Plate and frame filter press
Temp. (°C)	130
Solids in feed (% (w/w))	1.24
Number of filter plates	116
Size (V, m^3)	7.21
Filter area (A, m^2)	450
Bio-lubricant purification column(T-300)	
Temp. (°C)	130
Press. (kpa)	60
Condenser duty (MJ/hr)	10387.9
Reboiler duty (MJ/hr)	20093
Reflux ratio	0.9

Size (D × H, m)	2.3 x 5.5

B. *Economic Assessment Results*

The process economic feasibility evaluation was determined based on the equipment design calculations.

➢ *Total Capital Investment*

Fixed capital investment, working capital investment, land price and total capital investment for the bio-lubricant production process were calculated, and their values are $32,039,610, $4,805,941, $2,683,087, and $39,528,638, respectively for the first scenario. While the values for the second scenario are $15,330,174, $2,299,526, $1,831,772, and $19,461,472. Tables 6 and 7 show the items used for those calculations and the cost of all process equipment for each scenario.

Total capital investment for scenario II is half that of scenario I. This result is because almost half of the process is omitted and therefore, the fixed cost and land price were remarkably affected.

Table 6 Total capital investment for the process (Senario I)

Item	Values
Reactors	
Oil Transesterification (R-100)	
Size (D × H, m)	3.6 x 3.6
Cost ($)	0.5576
Neutralization (R-200)	
Size (D × H, m)	0.79 x 0.79
Cost ($)	0.0498
Biodiesel Transesterification (R-300) [2 parallel reactors]	
Size (D × H, m)	3.8 x 3.8
Cost ($)	1.8667
Columns	
Methanol recovery (T-100)	
Size (D × H, m)	1.5 x 8.8
Cost ($)	0.201
Biodiesel purification (T-200)	
Size (D × H, m)	3 x 6.7
Cost ($)	0.509
Bio-lubricant purification (T-300)	
Size (D × H, m)	2.3 x 5.5
Cost ($)	0.263
Other	
Pumps	0.1226
Heat Exchangers	6.1628
Mixers	0.0758
Separators	2.5125
Storage tanks	9.3276
Total bare module cost, C_{BM}	21.6484
Contingency fee, $C_{CF}=0.18C_{BM}$	3.8967
Total module cost, $C_{TM}=C_{BM}+C_{CF}$	25.5451
Auxiliary facility cost, $C_{AC}=0.3C_{BM}$	6.4945
Fixed capital cost, $C_{FC}=C_{TM}+C_{AC}$	32.0396
Working capital cost, $C_{WC}=0.15C_{FC}$	4.8059
Land price, C_L	2.6831
Total capital investment, $C_{TCI}=C_{FC}+C_{WC}+C_L$	39.5286
Note that: Costs are reported as $ millions.	

Table 7 Total Capital Investment For The Process (Senario II)

Item	Values
Reactors	
Biodiesel Tranesterification (R-300)	
Size (D × H, m)	3.8 x 3.8
Cost ($)	1.8667
Columns	
Biolubricant purification (T-300)	

Size (D × H, m)	2.3 x 5.5
Cost ($)	0.2630
Other	
Pumps	0.0785
Heat Exchangers	0.7600
Mixers	0.0483
Separators	2.3553
Storage tanks	4.9864
Total bare module cost, C_{BM}	10.3582
Contingency fee, $C_{CF}=0.18C_{BM}$	1.8645
Total module cost, $C_{TM}=C_{BM}+C_{CF}$	12.2227
Auxiliary facility cost, $C_{AC}=0.3C_{BM}$	3.1075
Fixed capital cost, $C_{FC}=C_{TM}+C_{AC}$	15.3302
Working capital cost, $C_{WC}=0.15C_{FC}$	2.2995
Land Price	1.8318
Total capital investment, $C_{TCI}=C_{FC}+CL+C_{WC}$	19.4615
* Costs are reported as $ millions.	

➢ *Cost of Manufacturing*

As previously stated, the cost of manufacturing (COM) for the process is calculated by summing up three main terms; direct manufacturing costs (DMC), fixed manufacturing costs (FMC) and general expenses (GE). The annual cost of operating labor for the two scenarios were determined to be $138,650 for scenario I and $73,249 for scenario II. The salary used was taken as average salary for chemical plant operator in Egypt (2022). This reduction was because the total number of operators was estimated to be 28 operator in scenario II while it is 53 operator for scenario I.

The detailed calculations of the total cost of manufacturing are shown in Tables 8 and 9. The annual cost of manufacturing for the two scenarios was found to be $94,496,299 for scenario I and $213,931,664 for scenario II.

Annual direct manufacturing costs equal $73,376,577 for scenario I and $176,783,285 for scenario II, and it represents about 77.7 % and 82.6 % of the total cost of manufacturing. The reason of this huge percentage is that the price of the raw material (WCO in scenario I and biodiesel in scenario II) is big. The market price of waste cooking oil (WCO) is in the range of $(420-700)/ton and thus, about 68 % of the direct manufacturing cost is the cost of feed waste cooking oil (WCO) which represents about 53 % of the total cost of manufacturing for scenario I. The market price of the biodiesel is in the range $(1000-1800) /ton and thus, about 90 % of the direct manufacturing cost is the cost of biodiesel which represents about 75 % of the total cost of manufacturing for scenario II. Annual fixed manufacturing costs and annual general expenses represent minor ratios for both scenarios.

Figures 2 and 3 shows the distributions of total direct manufacturing cost for both scenarios. It shows that a huge percentage of the direct manufacturing cost is for raw materials especially WCO for scenario I and biodiesel for scenario II. The ratio is bigger in scenario II due to the high price of biodiesel.

Finally, it was found that the cost of manufacturing of one ton of EGD biolubricant in Egypt is about $977 for scenario I and $2,212 for scenario II. Those values could be considered the break-even bio-lubricant prices for the process. Therefore, scenario I is favored as it has a lower cost of manufacturing for the biolubricant.

Table 8 Cost of Manufacturing for the Process (Scenario I)

Item	**Cost ($/year)**
Direct manufacturing cost	
Raw materials C_{RM}	
WCO oil	50,101,874
Methanol	6,852,643
KOH	765,306
H_3PO_4	475,258
Ethylene Glycol	6,132,417
CaO	854,975
Utilities C_{UT}	
Electricity	24,873
L.P.S	4,087
M.P.S	487,176
Superheated H.P.S	1,519,446
Cooling water	130,580
Waste disposal C_{WD}	

Non-hazardous	612,784
Hazardous	-
Operating labors C_{OL}	138,650
Direct supervisory and clerical labors, *18% of* C_{OL}	24,957
Maintenance and repairs, *6% of* C_{FC}	2,083,362
Operating supplies, *15% of* $C_{M\&R}$	312,504
Laboratory charges, *15% of* C_{OL}	20,798
Patents and royalties, *3% of COM*	2,834,889
Subtotal (I)	73,376,577
Fixed manufacturing costs	
Depreciation A_{DEP},*10% of* C_{FC}	3,203,961
Plant overhead costs, *60% of* $(C_{OL} + C_{SUP} + C_{M\&R})$	1,348,181
Local taxes and insurance, *3.2% of* C_{FC}	1,111,126
Subtotal (II)	5,663,269
General manufacturing expenses	
Administrative costs, *15% of* $(C_{OL} + C_{SUP} + C_{M\&R})$	337,045
Distribution and selling cost, *11% of COM*	10,394,593
Research and development, *5% of COM*	4,724,815
Subtotal (III)	15,456,453
Total cost of manufacturing (COM)	**94,496,299**
Cost of manufacturing/ton of bio-lubricant	**$977**

Table 9 Cost of Manufacturing for the Process (Scenario II)

Item		Cost ($)
Direct manufacturing cost		
Raw materials, C_{RM}		
Biodiesel		159,884,711
Ethylene Glycol		6,132,417
CaO		854,975
Utilities, C_{UT}		
Electricity		23,512
M.P.S		248,303
Superheated H.P.S		1,239,575
Cooling water		87,462
Waste disposal C_{WD}		
Non-hazardous		612,784
Hazardous		-
Operating labors, COL		73,249
Direct supervisory and clerical labors, 18% of COL		21,448
Maintenance and repairs, 6% of CFC		1,029,717
Operating supplies, 15% of CM&R		154,458
Laboratory charges, 15% of COL		10,987
Patents and royalities, 3% of COM		6,417,950
Subtotal		176,783,285
Fixed manufacturing costs		
Depreciation A_{DEP},*10% of* C_{FC}		1,533,017
Plant overhead costs, *60% of* $(C_{OL} + C_{SUP} + C_{M\&R})$		633,344
Local taxes and insurance, *3.2% of* C_{FC}		549,182
Subtotal		2,751,890
General manufacturing expenses		
Administrative costs, *15% of* $(C_{OL} + C_{SUP} + C_{M\&R})$		167,423
Distribution and selling cost, *11% of COM*		23,532,483
Research and development, *5% of COM*		10,696,583
Subtotal		34,396,489
Total cost of manufacturing (COM)		**213,931,664**
Cost of manufacturing/ton of bio-lubricant		**$2,212**

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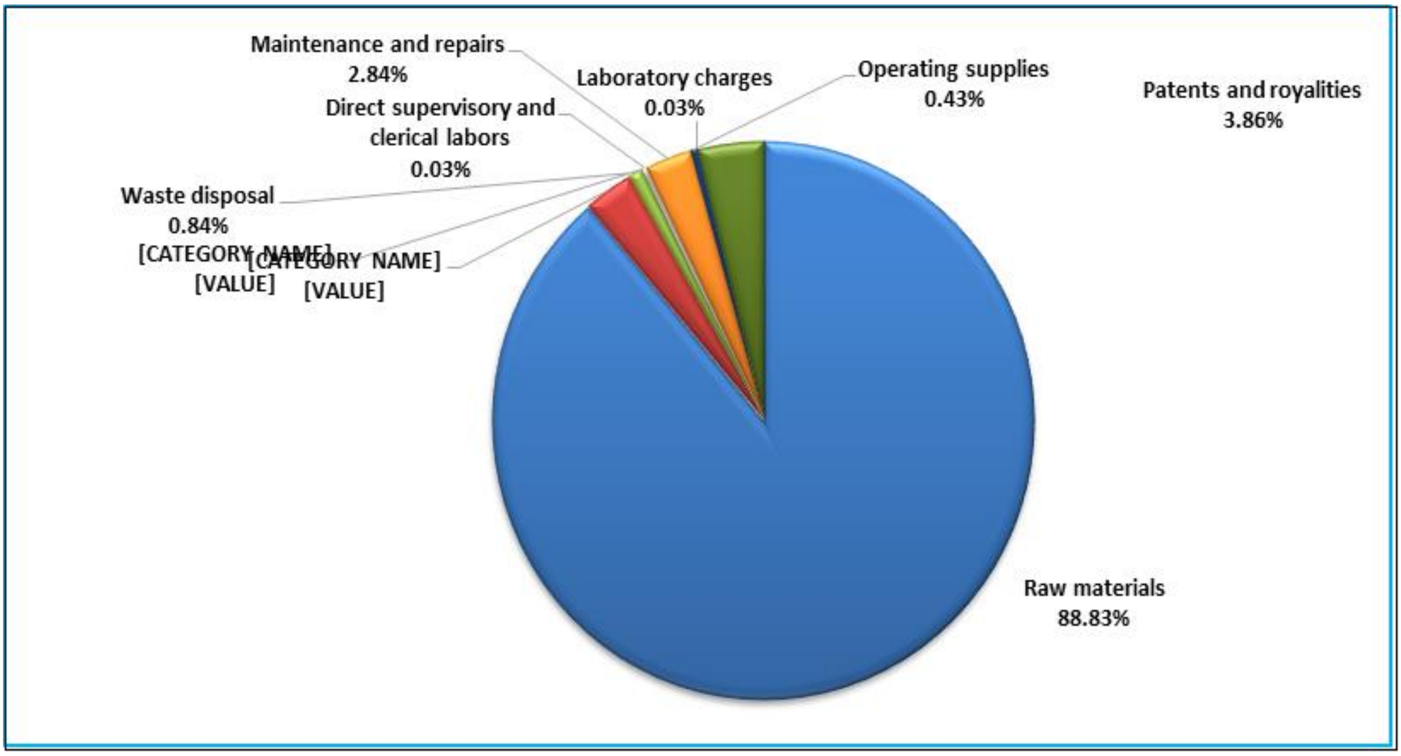

Fig 2 The Distributions of Total Direct Manufacturing Cost (Scenario I)

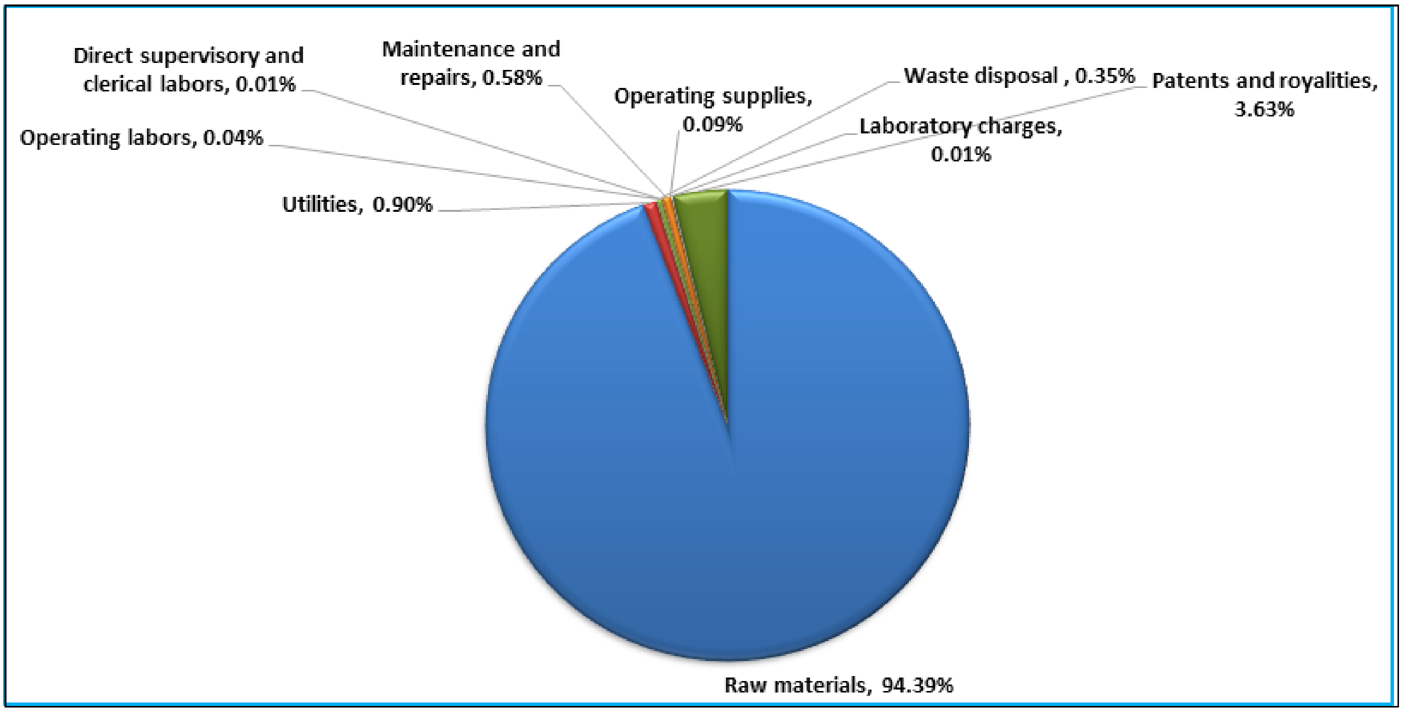

Fig 3 The Distributions of Total Direct Manufacturing Cost (Scenario II)

The price of the produced EGD biolubricant is not available as it is a novel product and thus, was taken equal to the price of the standard ISO grade lubricant ISO VG68 it complies with, which is equal to $3352/ton [27]. The total revenue was calculated based on selling the produced biolubricant and byproducts (only in scenario I) and it was equal to $356,970,778 for scenario I and $339,145,451 for scenario II. The annual net profit was then calculated by subtracting cost of manufacturing from total revenue and it was equal to $262,474,479 for scenario I and $125,213,787 for scenario II. The net profit after tax (22.5% tax) was calculated and was equal to $203,417,721 for scenario I and $97,040,685 for scenario II. Tables 10 and 11 presents all those calculations for the two scenarios.

The net profit for scenario II is less than that of scenario I with about 106 million dollars, this is because of the high cost of manufacturing and that there is no side product in scenario II that increase in the income.

After tax rate of return on investment (ROI %) was equal to 586 % for scenario I and 565 % for scenario II. ROI % with a positive and large value for both scenarios indicating that the studied biolubricant production process is profitable from the point of view of rate of return-on-investment criteria for each scenario.

The PBP was about 3 months for both scenarios. This period is very short, thus, the project is profitable and very promising for both scenarios. This also means that if the selling price of the biolubricant is reduced, the project will still be profitable. Thus, the produced biolubricant will be a challenging alternative to petroleum-based lubricant (ISO VG68) in price beside being eco-friendly and sustainable.

Different selling prices for the produced biolubricant were studied for both scenarios. Figure 4 shows the proposed prices and its corresponding price reduction percent versus PBP. It is shown that the price could be reduced to $2200/ton that give reduction percent of 34 % in scenario II. The PBP for this price was about 2.6 years while the ROI % is still positive. On the other hand, the price could be reduced to a much lower price of $1000 that gives a reduction percent of 70 % in scenario I. This price gives a PBP of about 1.8 years, while the ROI % is still positive and bigger than that of scenario II. It is also clear that the break-even time for the process is much lower for scenario I than scenario II. Table 12 shows all proposed prices and their effect on PBP and ROI % along with their price reduction percent for both scenarios. It is also clear from the table that the ROI % of scenario I is always lower than the corresponding values for scenario II.

Table 10 Profitability Checks Calculation (Scenario I)

Item	Cost ($)
Product	
Bio-lubricant	339,145,450.77
Byproducts Biodiesel	8,475,293
Glycerol	7,548,302
K_3PO_4	1,801,733
Total Revenue, A_R	356,970,778
Annual net profit, $A_{NP}= A_R\text{-}COM$	262,474,479
Income taxes, $A_{IT} = 22.5\%\ of\ A_{NP}$	59056758
After tax net profit, $A_{NNP}=A_{NP}\text{-}A_{IT}$	203,417,721
After tax rate of return on investment, $ROI\% = A_{NNP}/C_{FC}*100$	585.84
Payback period (years), $PBP = C_{FC}/A_{NNP}$	0.17

Table 11 Profitability Checks Calculation (Scenario II)

Item	Cost ($)
Product	
Bio-lubricant	339,145,451
Total Revenue, A_R	339,145,451
Annual net profit, $A_{NP}= A_R\text{-}COM$	125,213,787
Income taxes, $A_{IT} = 22.5\%\ of\ A_{NP}$	28,173,102
After tax net profit, $A_{NNP}=A_{NP}\text{-}A_{IT}$	97,040,685
After tax rate of return on investment, $ROI\% = A_{NNP}/C_{FC}*100$	565
Payback period (years), $PBP = C_{FC}/A_{NNP}$	0.18

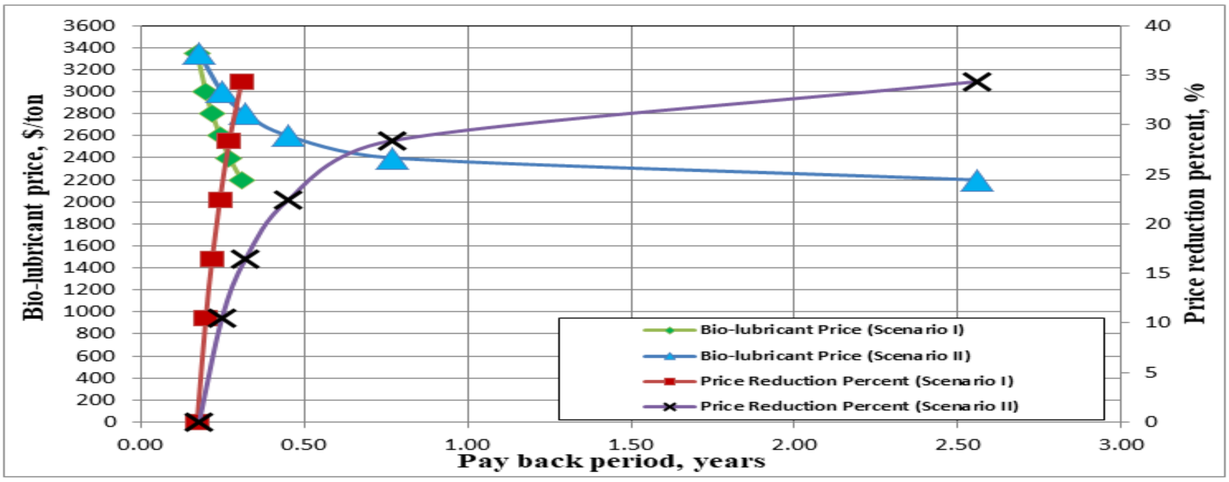

Fig 4 Bio-Lubricant Different Prices and Price Reduction Percent Versus Payback Period (PBP) for the Two Process Scenarios

Table 12 Proposed Prices for Both Scenarios Along with their Effect on PBP and ROI % and the Price Reduction Percent

Scenario I						
ROI%	586	506	461	416	371	326
Payback period, (years)	0.17	0.20	0.22	0.24	0.27	0.31
Price of Bio-lubricant ($/ton)	3352	3000	2800	2600	2400	2200
Price reduction percent	0	11	16	22	28	34
ROI%	281	168	77	72	55	
Payback period, (years)	0.36	0.60	1.29	1.38	1.83	
Price of Bio-lubricant ($/ton)	2000	1500	1100	1078	1000	
Price reduction %	40	55	67	68	70	
Scenario II						
ROI%	565	405	313	222	130	39
Payback period, (years)	0.18	0.25	0.32	0.45	0.77	2.56
Price of Bio-lubricant ($/ton)	3352	3000	2800	2600	2400	2200
Price reduction %	0	11	16	22	28	34

IV. CONCLUSION

In the ongoing work, production of eco-friendly lubricant using two scenarios; the first scenario was starting from waste cooking oil (WCO) and the second scenario was starting from biodiesel had been studied. The simulation results were used in the design of process equipment and design data were used in performing economic assessment for the project in Egypt. Total capital investment (C_{TCI}), fixed capital investment (C_{FC}), working capital investment C_{WC} and land price C_L for the studied process were calculated and founded to be $32,039,610, $4,805,941, $2,683,087, and $39,528,638, respectively for the first scenario. While the values for the second scenario are $15,330,174, $2,299,526, $1,831,772, and $19,461,472. The total cost of manufacturing (COM) was estimated to be equal $94,496,299 for scenario I and $213,931,664 for scenario II. The cost of waste cooking oil (WCO) is about 68 % of the direct manufacturing cost is the cost of feed waste cooking oil (WCO) which represents about 53 % of the total cost of manufacturing for scenario I. The cost of the biodiesel represents 90 % of the direct manufacturing cost is the cost of biodiesel which represents about 75 % of the total cost of manufacturing for scenario II. It was found that the cost of manufacturing of one ton of the produced biolubricant in Egypt is about $977 for scenario I and $2,212 for scenario II. This makes scenario I is favorable to scenario II.

The PBP for the process was found to be about 3 months for both scenarios. This period is very short; thus, the project is profitable and very promising for both scenarios with selling price equal to the petroleum-based lubricant. Also, it was found that if the selling price is reduced by up to 70 % ($1000/ton) for scenario I and to 34 % ($2200/ton) for scenario II. The ROI % was found to be positive for the process for each scenario with a very good PBP. Thus, it was concluded that the studied biolubricant production process is economically feasible and that it is applicable in Egypt with both process scenarios. Besides, scenario I is much favorable than scenario II because of big price of biodiesel and the added value of byproducts exists in scenario I.

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DECLARATIONS

- *Ethical Approval:* not applicable)
- *Competing Interests:* The authors declare no conflict of interest.
- *Authors' Contributions:* preparation, conceptualization, methodology, investigation, writing original draft preparation, performing calculations and data analysis, Reda Z.K. Hussein; review and editing, N.K. Attia; review, M. Fouad1; supervision, Shakinaz T. ElSheltawy1) All authors have read and agreed to the published version of the manuscript.
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