

1 **Biodiesel production through sulfuric acid catalyzed transesterification of acidic oil:**
2 **Techno economic feasibility of different process alternatives**

3 S. N. Gebremariam and J. M. Marchetti*

4 *Faculty of Science and Technology, Norwegian University of Life Sciences, Drøbakveien 31,*
5 *1432, Ås, Norway.*

6
7 * *Corresponding author.*

8 *Email address: Jorge.mario.marchetti@nmbu.no (J. M. Marchetti)*

9 *Tel: +47-67231647.*

10
11 **Abstract**

12 Biodiesel is renewable fuel produced from fats and oils. When compared to conventional
13 diesel fuel, it has considerable environmental benefits. However, its extensive use is hindered by
14 high cost of production, mainly due to cost of feedstock. Among the different biodiesel
15 production routes, acid catalyzed transesterification enables to use feedstock with higher free
16 fatty acid content (cheaper feedstock). The absence of soap formation while using acid as a
17 catalyst also simplifies the downstream separation and purification processes. In this study, a
18 homogeneous sulfuric acid catalyzed transesterification of acidic oil is designed into four process
19 scenarios based on four different downstream process routes.

20 The conceptual design and simulation of these process alternatives have been carried out
21 using Super Pro and Aspen Plus software. These process models were used to evaluate the
22 techno economic competitiveness of the four different scenarios. In the four process scenarios,
23 all reactors for biodiesel production have been designed to have the same reaction conditions and
24 the same amount of oil feedstock input. The difference of the scenarios was only on the
25 arrangements and type of downstream process equipment required to get fuel grade biodiesel.
26 The technical performances have been evaluated based on quality and quantity of products as
27 well as the amount of biodiesel produced per feedstock consumed. The specific economic
28 parameters considered were Unit Production Cost, NPV, IRR (after tax), and Payback time. The
29 process scenario with ethanol recovery after catalyst neutralization and glycerol separation using
30 decanting just before biodiesel purification has better technical and economic performances.
31 Whereas the double reactor scenario shows much better technical performances with very low
32 economic feasibility.

33 **Keywords:** Biodiesel, sulfuric acid catalyst, techno economics, sensitivity analysis

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36 **Nomenclature**

37 ASTM American Society of Testing and Materials

38 CSTR Continuous Stirred Tank Reactor

39 DG Di-glyceride

40 DFC Direct Fixed Cost

41 E Ethanol

42 FAEE Fatty Acid Ethyl Ester

43 FFA Free Fatty Acid

44 G Glycerol

45 GHG Greenhouse Gas

46 IRR Internal Rate of Return

47 MG Mono-glyceride

48 NPV Net Present Value

49 PC Purchasing Cost

50 PCUE Purchasing Cost of Unlisted Equipment

51 ROI Return on Investment

52 TLC Total Labor Cost

53 TG Triglyceride

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67 **1. Introduction**

68 The world energy demand is skyrocketing mainly due to economic growth and population
69 expansion [1]. Such high demand together with the negative global environmental impacts of
70 using fossil fuel for generations brings a question on dependability of the fossil fuel for
71 sustainable economic growth. As a way out, the world is tending to depend more on renewables
72 to secure the energy supply for extensive demands because of economic growth, improved
73 standard of living and population expansion [2, 3]. Among the promising renewable energy
74 resources for substitution of fossil fuels are biofuels [4]. Biodiesel is one of these biofuels with
75 significant advantages over its counterpart fossil diesel. It is produced from renewable resources
76 like edible and non-edible oils, animal fats, and waste cooking oil. When compared to fossil
77 diesel production, the process technologies usually employed to produce biodiesel are simpler
78 and can easily be implemented in decentralized manner from small scale to large scale levels.
79 The other major advantages are associated with its environmental and ecological benefits
80 compared to the fossil diesel. It is biodegradable, non-toxic and free from sulfur and aromatics
81 [5]. Combustion of biodiesel for energy releases less GHG, less air pollutants, and less
82 particulate matters compared to the conventional fossil diesel, because it has relatively high
83 amount of oxygen required for complete combustion of the fuel [6].

84 Biodiesel is a mono alkyl ester of long chain fatty acids produced mainly through the
85 process of transesterification reaction. There are a number of possible process alternatives to
86 accomplish transesterification reaction. Transesterification might be catalyzed or non-catalyzed.
87 The catalyzed options are heterogeneous and homogeneous acid catalyzed, heterogeneous and
88 homogeneous alkali catalyzed, and enzyme catalyzed transesterification reactions. The non-
89 catalyzed option is usually supercritical methanol transesterification reaction taking place at
90 higher pressure and temperature.

91 Depending on the characteristics of the feedstock used for biodiesel production, each
92 method has its own advantages and disadvantages. However, the commercially known
93 technological route for biodiesel production is the homogeneous alkali catalyzed alternative [7-
94 10]. This technology requires a feedstock with minimum FFA content, less than 0.5% [7, 11, 12].
95 Such oil feedstock are high quality oil like edible oil, which are usually expensive for biodiesel
96 production.

97 The cost of biodiesel feedstock usually took the higher percentage share of the total
98 manufacturing cost, affecting the unit cost of biodiesel production. In most cases, this cost share

99 is greater than 80% [13, 14]. Consequently, the unit cost of biodiesel production can directly be
100 reduced while using the least cost feedstock alternatives [15, 16]. Technically possible options to
101 produce fuel grade biodiesel from such low quality feedstock types are acid catalyzed, enzyme
102 catalyzed and supercritical transesterification routes [17-19]. Among them, supercritical route
103 could give the least cost of materials as there is no any catalyst considered in the process.
104 However, its higher pressure and temperature requirements result in bigger utility cost, making
105 the alternative expensive [20, 21]. The other alternative, enzyme catalyzed technology, is usually
106 taken as a better choice for production of fuel grade biodiesel from low value feedstock [19].
107 However, the expensiveness of the catalyst is mentioned as the main drawback to use this option
108 at industrial scale for production of biodiesel in economically competitive manner with that of
109 fossil diesel [22].

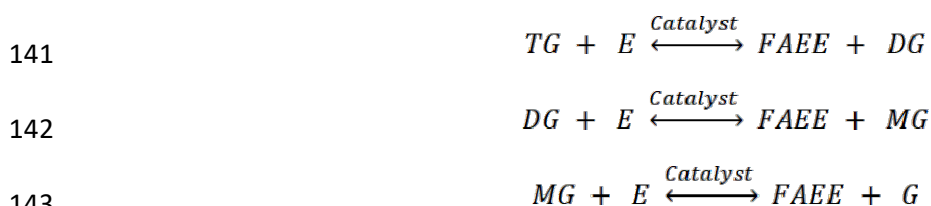
110 One of the most viable options to produce biodiesel from low cost feedstock is the acid
111 catalyzed transesterification reaction [23, 24]. This is mainly because there is no additional
112 pretreatment step required to reduce FFA, and the product separation and purification can be
113 done with simple process steps as there is no soap formation [25, 26]. Among the different
114 possible types of acid catalysts for biodiesel production, sulfuric acid is the most studied one. It
115 can catalyze the transesterification reaction at atmospheric pressure and relatively medium
116 temperature range, from 55°C up to 88°C [27-29].

117 The study done by Michael et al. [29] evaluated alcoholysis of soybean oil using sulfuric,
118 hydrochloric, formic, acetic, and nitric acids at different loading rates and found out that the
119 sulfuric acid catalyst was the most effective. Their result showed that at 100°C reaction
120 temperature, 99% conversion of TG in soybean oil could be achieved in 8 h, when 0.5% sulfuric
121 acid catalyst, and nine times methanol stoichiometry are used [29].

122 Farag et al. [30] studied the factors affecting production of methyl ester from mixed oil
123 formed from 50% sunflower and 50% soybean oil using sulfuric acid as the catalyst. They found
124 out that the optimum reaction conditions for the best conversion efficiency of 96.6%, was 6:1
125 molar ratio of methanol to oil, 60°C reaction temperature and, 2.5% wt. of H₂SO₄ with respect to
126 the oil feedstock [30].

127 In another study, Marchetti et al. [31], indicated that a conversion of 96% of acidic oil, with
128 10.684 % FFA content, could be reached with an optimum reaction conditions of sulfuric acid
129 amount of 2.5%, ethanol molar ratio of 6.1:1 and reaction temperature of 55°C. However, while
130 using sulfuric acid as a catalyst, excess amount of alcohol is usually recommended to get higher
131 final conversion percentage [9, 32, 33].

132 The maximum conversion in an optimized transesterification reaction catalyzed by sulfuric
133 acid could reach up to 96% - 99% [27, 30, 33]. Practically there are two main reactions taking
134 place when acidic catalyst like sulfuric acid is used to catalyze the biodiesel production process
135 using oil with higher FFA content. These are transesterification and esterification reactions.
136 Transesterification is a reversible reaction between one mole of the triglyceride of the oil and
137 three moles of alcohol in the presence of the catalyst to produce one mole of glycerol and three
138 moles of ester. This happens in three consecutive reaction steps as depicted in Figure 1.
139 Esterification reaction takes place when one mole of FFA reacts with one mole of alcohol to
140 produce one mole of ester and one mole of water as shown in Figure 2.



144 **Figure 1.** Steps in transesterification reaction



146 **Figure 2.** Esterification reaction

147 However, there might also be hydrolysis, depending on the amount of water in the feedstock
148 and the amount of water formed during esterification.

149 A number of studies have been done to show how sulfuric acid catalyzed process is cost
150 effective for biodiesel production from feedstock with high free fatty acid content [9, 15, 34].
151 Karmee et al. [15] compared the techno-economic performances of acid, base and enzyme
152 catalysts for the production of fuel grade biodiesel from waste cooking oil. They found out that,
153 the acid catalyst technology was the cost effective option by indicating better IRR compared to
154 the two other options [15]. In another study Zhang et al. [34] compared the economic
155 performances of producing biodiesel from waste cooking oil using alkali catalyzed and acid
156 catalyzed processes and found out that the sulfuric acid catalyzed process was the most
157 economically feasible alternative.

158 The techno-economic feasibility of the whole process of biodiesel production through
159 sulfuric acid catalyzed transesterification can be further improved by using the most cost
160 effective arrangement of equipment and selection of operation units for the major process steps.
161 In this respect, there are a number of possible arrangement of alternative equipment for
162 separation of the biodiesel from the glycerol as well as for purification of both the biodiesel

163 product and the glycerol byproduct. Accordingly, this study is specifically targeted to sort out the
164 most cost effective, technically efficient and economically sustainable biodiesel production route
165 using sulfuric acid as homogeneous catalyst. To do so four different scenarios of sulfuric acid
166 catalyzed biodiesel production processes have been simulated based on four different
167 arrangement of operation units for major downstream processes. Eventually, the technical
168 performances of the scenarios have been compared in terms of the amount and quality of
169 biodiesel and glycerol produced as well as the amount of product produced per unit of feedstock
170 consumed. The economic evaluations, among the four scenarios, were also done based on total
171 investment cost, unit cost of biodiesel production, IRR, NPV and payback time. The economic
172 sustainability of the alternatives has been tested through sensitivity analysis over selected market
173 variables. The sensitivity analysis was done to investigate how NPV and Payback time could be
174 affected by change in market values of biodiesel selling price and oil purchasing cost so that to
175 identify the most tolerant alternative to the global market fluctuations of the variables.

176 **2. Process Descriptions and Methods**

177 This study has been done on four process alternatives to produce biodiesel from acidic oil
178 using homogeneous sulfuric acid as a catalyst. In all of the scenarios, since the amount of water
179 in the biomass and amount of water produced during esterification is insignificant, hydrolysis has
180 been neglected and the only dominant reactions considered are transesterification and
181 esterification. Continuous stirred tank reactor is considered as the main reactor in all of the
182 scenarios, for which the reaction temperature is set to be 55°C. This is the optimum temperature
183 for better biodiesel production from acidic oil using sulfuric acid catalyst [30, 31, 35].

184 *2.1. Specifications of raw materials*

185 The raw materials used in all process scenarios are the same in amount and quality. These
186 include acidic oil feedstock, sulfuric acid catalyst, ethanol and calcium oxide. The oil feedstock
187 is with 10% FFA content. This could represent most of second generation oil feedstock types
188 from non-edible plants [36, 37], which can have up to 14% FFA. The alcohol considered in the
189 process designs is ethanol, which can be produced from renewable resources and which is also
190 less toxic and safe to use. In all of the process scenarios, the ethanol is taken to be in 6.1:1 molar
191 ratio with the oil feedstock amount to encourage the forward reaction and get more conversion
192 [30, 31, 35]. The acid catalyst used is sulfuric acid, with up to 98% concentration, as it is the
193 most studied and effective acidic catalyst available for biodiesel production [23, 38]. The relative
194 optimum amount of sulfuric acid catalyst taken in all the processes is 2.1% wt. of the oil
195 feedstock [35]. The calcium oxide is included to totally neutralize the catalyst after the

196 transesterification reaction. Calcium oxide is selected because it can be cheaply produced from
197 waste materials like eggshells, mud scrap shells, and cockleshells among others. Eventually, the
198 amount of each raw material has been determined based on their optimum allocations with
199 respect to oil feedstock amount required for maximum conversion.

200 2.2. Design assumptions

201 The major assumptions considered for reasonable designing of the process scenarios are as
202 follows:

- 203 • Oil feedstock capacities in all the scenarios are the same and equal to 41 million kg per
204 year.
- 205 • The oil feedstock is assumed to be 100% free from solid particle.
- 206 • Oil feedstock input is assumed to be supplied throughout the whole year.
- 207 • Working hours per year is taken to be 7920 (330 working days per year).
- 208 • Pressure drop in all the process equipment is neglected.
- 209 • Moisture content of the feedstock is assumed to be very low and the water formed
210 during esterification reaction is also considered negligible. Thus, the hydrolysis process is
211 not considered in all of the scenarios.
- 212 • Transesterification and esterification are the only dominant reactions considered in all
213 of the scenarios.
- 214 • Triolien represents the acidic oil with oil density of 907.8 kg/m^3 , oleic acid represents
215 the fatty acid with density of 895 kg/m^3 and ethylolate represents biodiesel with density
216 of 873.9 kg/m^3 .
- 217 • As the property package for calculation of activity coefficient of the liquid phase in the
218 simulations, the non-random two liquid (NRTL) thermodynamic model is selected due to
219 the presence of polar compounds such as ethanol and glycerol in the process.
- 220 • Life time of the project is assumed to be 15 years
- 221 • The whole production processes are assumed to be run by own money without loan

222 2.3. Process alternative scenarios

223 Four possible process scenarios have been designed to investigate their techno economic
224 feasibility so as to identify the most cost effective, technically efficient and economically reliable

225 option(s) in producing biodiesel from low value oil feedstock using sulfuric acid as a catalyst.
 226 The scenarios are designed based on the various possible configurations of the six main
 227 downstream processes. These six main downstream processes are separation of biodiesel and
 228 glycerol, biodiesel purification, glycerol purification, excess ethanol recovery, catalyst
 229 neutralization, and separation of calcium sulfate. A number of possible unit procedures with
 230 different equipment types can be used to accomplish the six major downstream processes for
 231 production of fuel grade biodiesel. Accordingly, the four scenarios are designed by configuring
 232 technically viable as well as least cost equipment options as much as possible. The four process
 233 scenarios with their unit procedures and equipment types used for each process step are shown in
 234 Table 1.

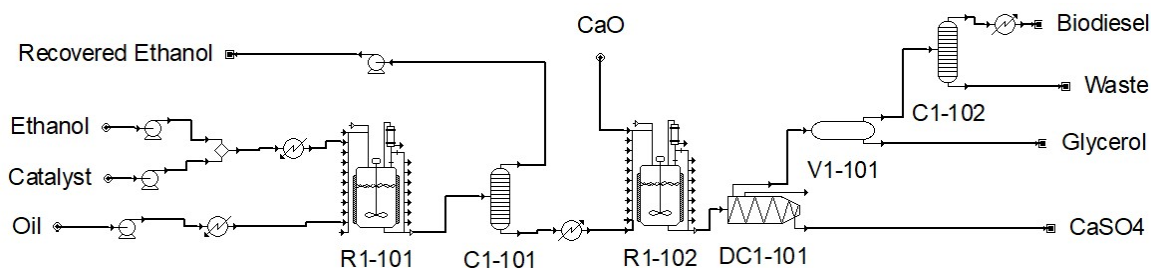
Table 1. Process scenarios with required equipment for each process step				
Process steps	Scenarios with unit procedures and equipment in each step			
	Scenario - I	Scenario - II	Scenario - III	Scenario - IV
1	Reaction (<i>CSTR - Single</i>)	Reaction (<i>CSTR - Single</i>)	Reaction (<i>CSTR - double</i>)	Reaction (<i>CSTR - Single</i>)
2	Ethanol recovery (<i>Distillation</i>)	Catalyst neutralization (<i>CSTR</i>)	Catalyst neutralization (<i>CSTR</i>)	Catalyst neutralization (<i>CSTR</i>)
3	Catalyst neutralization (<i>CSTR</i>)	CaSO ₄ separation (<i>Centrifuge</i>)	CaSO ₄ separation (<i>Centrifuge</i>)	CaSO ₄ separation (<i>Centrifuge</i>)
4	CaSO ₄ separation (<i>Centrifuge</i>)	Ethanol recovery (<i>Distillation</i>)	Ethanol recovery (<i>Distillation</i>)	Ethanol recovery (<i>Distillation</i>)
5	Glycerol separation (<i>Decanter</i>)	Glycerol separation (<i>Decanter</i>)	Glycerol separation (<i>Decanter</i>)	Biodiesel and glycerol purification (<i>Distillation</i>)
6	Biodiesel purification (<i>Distillation</i>)	Biodiesel purification (<i>Distillation</i>)	Biodiesel purification (<i>Distillation</i>)	Biodiesel and Glycerol separation (<i>Decanter</i>)

235 Each process has been designed with a capacity of 41 million kg feedstock per year. Acidic
 236 oil with 10% FFA content is heated up to 55°C and feed into the continuous stirred tank reactor
 237 at a rate of 5177.23 kg/h. At the same time, ethanol (1645.69 kg/h) and sulfuric acid catalyst
 238 (108.7kg/h) are mixed in a simple two-way mixer, heated up to 55°C and pumped into the
 239 continuous stirred tank reactor. The reaction condition in the stirred tank reactor is set to be
 240 isothermal at 55°C and 1.013 bar pressure. The isothermal condition could be achieved using
 241 steam as heat transfer agent. The rate at which the product leaves the reactor is in such a way to
 242 attain 21h residence time in the reactor. Because at the given reaction conditions (55°C
 243 temperature, 2.1 % wt. catalyst & 6.1:1 molar ratio of the alcohol to oil) the conversion could
 244 reach at about 97.57% in 21h [35]. All reaction conditions and everything else are made the same
 245 for all scenarios until this point

246 The product from the reactor is then passed through the different downstream
 247 configurations to get fuel grade biodiesel. In all of the scenarios, the calcium sulfate salt formed
 248 during the neutralization of the acidic catalyst is removed using centrifugal decanter just after
 249 neutralization reactor. The excess ethanol is recovered using distillation column in all of the
 250 scenarios. In scenarios II, III & IV, the excess ethanol is recovered just after the salt is removed.
 251 However, in scenario I the excess ethanol recovery is done before the catalyst is neutralized. In
 252 scenario III, the reaction is carried out in two consecutive CSTR where there is a decanter in
 253 between them to separate the glycerol part after the first reactor. This double reactor
 254 configuration is the main difference between scenario II and III. In scenario IV, the separation of
 255 biodiesel from the glycerol is considered at the end after the unreacted oil is separated using
 256 distillation column. Whereas in scenarios I, II & III the final step is purification of the biodiesel
 257 using distillation column. This is very effective in separating the biodiesel from the unreacted oil
 258 remaining in the product. The other similar situation in all scenarios is neutralization of the acid
 259 catalyst. This is done by using CaO in a CSTR just after the main reactor(s) for biodiesel
 260 production in scenarios II, III & IV, whereas in scenario I, neutralization of the catalyst is
 261 considered after the excess ethanol is recovered.

262 The process flow sheets shown in this study are performed using Super Pro design software
 263 from Intellegin Inc.[39]. In order to verify their correctness, each process model has also been
 264 redesigned using Aspen Plus software from AspenTech [40]. This is because Aspen Plus has a
 265 broader choice in physical parameters and physical property methods to select for each specific
 266 process taken in the design. This would help to increase the viability of the results. Figure 3 up to
 267 Figure 6 show the designed process flow sheets for each scenario.

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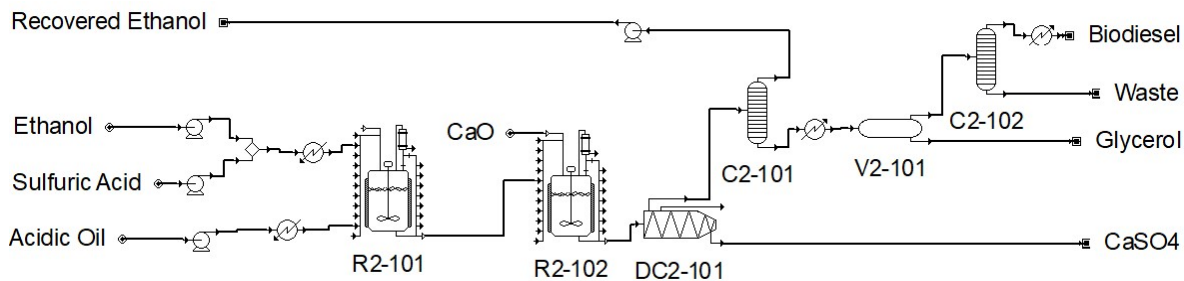


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Time Ref: h		Acidic Oil	Biodiesel	CaO	CaSO ₄	Ethanol	Glycerol	Recovered ethanol	Sulfuric Acid	Waste
Type		Raw Material	Revenue	Raw Material	Revenue	Raw Material	Revenue	Credit	Raw Material	
Total Mass Flow	kg	5177.2300	5151.3815	62.1700	155.8011	1645.6900	526.9222	866.4676	108.7200	293.3269
Temperature	°C	25.0	25.0	25.0	32.8	25.0	32.8	47.3	25.0	219.3
Pressure	bar	1.013	0.250	1.013	1.013	1.013	1.013	3.750	1.013	0.250

270

271 **Figure 3:** Scenario I: R1-101 CSTR for biodiesel production, C1-101 shortcut distillation column for ethanol
 272 recovery, R1-102 CSTR for catalyst neutralization, DC1-101 centrifuge decanter for CaSO₄ separation, V1-101
 273 decanting tank for glycerol separation and C1-102 shortcut distillation column for biodiesel purification

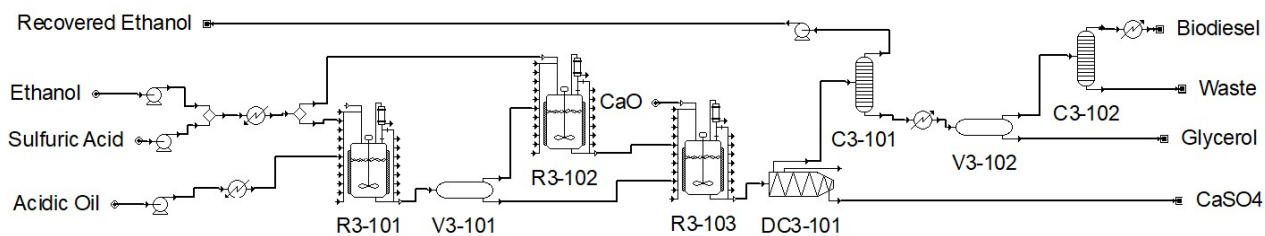


275

Time Ref: h		Acidic Oil	Biodiesel	CaO	CaSO ₄	Ethanol	Glycerol	Recovered Ethanol	Sulfuric Acid	Waste
Type		Raw Material	Revenue	Raw Material	Revenue	Raw Material	Revenue	Credit	Raw Material	
Total Mass Flow	kg	5177.2300	5282.1413	62.1700	155.7168	1645.6900	506.6240	885.9599	108.7200	163.4574
Temperature	°C	25.0	25.0	25.0	61.6	25.0	25.0	48.3	25.0	160.7
Pressure	bar	1.013	0.250	1.013	1.013	1.013	0.250	3.750	1.013	0.250

276

277 **Figure 4:** Scenario II: R2-101 CSTR for biodiesel production, R2-102 CSTR for catalyst neutralization, DC2-
 278 101 centrifuge decanter for CaSO₄ separation, C2-101 shortcut distillation column for ethanol recovery, V2-101
 279 decanting tank for glycerol separation and C2-102 shortcut distillation column for biodiesel purification
 280

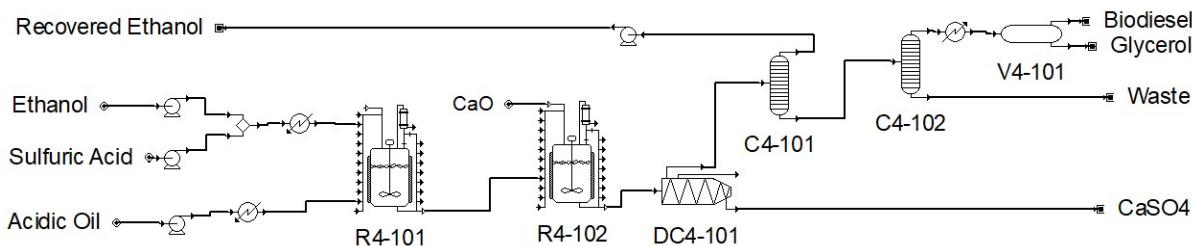


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Time Ref: h		Acidic Oil	Biodiesel	CaO	CaSO ₄	Ethanol	Glycerol	Recovered Ethanol	Sulfuric Acid	Waste
Type		Raw Material	Revenue	Raw Material	Revenue	Raw Material	Revenue	Credit	Raw Material	
Total Mass Flow	kg	5177.2300	5354.4722	62.1700	155.3394	1645.6900	513.0250	877.0671	108.7200	93.9966
Temperature	°C	25.0	25.0	25.0	61.5	25.0	25.0	48.3	25.0	179.2
Pressure	bar	1.013	0.250	1.013	1.013	1.013	0.250	3.750	1.013	0.250

282

283 **Figure 5:** Scenario III: R3-101 first CSTR for biodiesel production, V3-101 first decanter for glycerol
 284 separation, R3-102 second CSTR for additional biodiesel production, R3-103 CSTR for catalyst neutralization,
 285 DC3-101 centrifuge decanter for CaSO₄ separation, C3-101 shortcut distillation column for ethanol recovery, V3-
 286 102 second decanting tank for glycerol separation and C3-102 shortcut distillation column for biodiesel purification
 287



288

Time Ref: h		Acidic Oil	biodiesel	CaO	CaSO ₄	Ethanol	Glycerol	Recovered Ethanol	Sulfuric acid	Waste
Type		Raw Material	Revenue	Raw Material	Revenue	Raw Material	Revenue	Credit	Raw Material	
Total Mass Flow	kg	5177.2300	5012.8942	62.1700	155.4479	1645.6900	507.3237	885.9159	108.7200	432.3176
Temperature	°C	25.0	25.0	25.0	57.6	25.0	25.0	48.3	25.0	234.3
Pressure	bar	1.013	0.250	1.013	1.013	1.013	0.250	3.750	1.013	0.250

289

290 **Figure 6:** Scenario IV: R4-101 CSTR for biodiesel production, R4-102 CSTR for catalyst neutralization,
 291 DC4-101 centrifuge decanter for CaSO₄ separation, C4-101 shortcut distillation column for ethanol recovery, C4-
 292 102 short cut distillation column for biodiesel purification and V4-101 decanting tank for glycerol separation

293 2.4. *Economic Assessment*

294 The economic performance evaluation of the studied process scenarios has been done
 295 considering latest and estimated costs of raw materials, labor, utilities and equipment as well as
 296 associated costs of equipment installation, auxiliary facilities and depreciation cost among
 297 others. The oil feedstock considered in these processes is the cheapest from non-edible oil plants,
 298 and estimated to cost in a range of 478 - 684US\$/ton [41, 42]. We take the lower value
 299 478US\$/ton to be the estimated cost of oil feedstock. The cost of other raw materials such as
 300 catalyst, ethanol and calcium oxide are based on latest market prices from different suppliers in
 301 Ethiopia and relevant literatures [43, 44]. The labor cost is estimated based on the current wage
 302 indicator in Ethiopia [45], which is then extrapolated to scale it up to some amount. The
 303 calculation of the labor cost is based on detailed estimate using the basic rate allocated for each
 304 labor category. The other cost category included in the annual operating cost calculations is cost
 305 of utilities. The utilities considered in all of the studied scenarios are cooling water, steam, steam
 306 high and electricity, for which the cost estimations are entirely based on current market prices in
 307 Ethiopia and relevant literatures [46, 47]. Table 2 shows estimated costs of raw materials,
 308 utilities and labor considered in the process alternatives.

Table 2. Estimated costs of raw materials, utilities and labor considered in all process scenarios	
<i>Raw Material</i>	
Oil	0.478 US\$/kg
Ethanol	0.300 US\$/kg
Sulfuric Acid	0.275 US\$/kg
CaO	0.120 US\$/kg
<i>Utilities</i>	
Electricity	0.021 US\$/KW-h
Steam	6 US\$/MT
Steam high	10 US\$/MT
Cooling water	0.025 US\$/MT
<i>Labor (Basic rate)</i>	
Operator	10 US\$/h
Reactor Operator	15 US\$/h
Supervisor	15 US\$/h

309 The purchasing cost of each equipment designed in each process scenario is estimated using
 310 Peter and Timmerhaus method [48], where Chemical Engineering plant cost index of 591.335 for
 311 January 2018 is used [49]. This index denotes changes in the value of money due to inflation and
 312 deflation so that it helps to estimate the average cost of each equipment for the year 2018 based
 313 on previous year costs. The other components of the capital investment cost, such as installation,

314 piping, electricity, instrumentation, and yard improvement are estimated based on the percentage
 315 allocation of the equipment purchasing cost for each cost item as shown in Table 3.

Table 3. Direct plant cost categories and their percentage allocations with equipment cost [15]	
Cost category	% allocation with equipment cost
Piping	20
Instrumentation	10
Electrical	15
Insulation	3
Building	15
Yard improvement	10
Auxiliary facilities	25
Unlisted equipment	20

316 The cost estimation interface in the Super Pro design software gives options to allocate
 317 estimated percentage share of such cost categories as well as other associated costs like
 318 maintenance cost, depreciation, insurance and tax, during designing the processes. The
 319 percentage allocation of these type of costs are indicated in Table 4.

320

Table 4. Cost estimation methods for components of capital investment and operating costs [50]	
Cost items	Estimation methods
<i>Capital Investment Cost Categories</i>	
Installation cost (for each equipment)	0.2 X PC
Maintenance cost (for each equipment)	0.1 X PC
Purchasing cost of unlisted equipment (PCUE)	0.2 X PC
Installation cost of unlisted equipment	0.5 X PCUE
<i>Operating Cost Categories</i>	
Insurance	2 X DFC
Local Tax	15 X DFC
Factory expense	5 X DFC
Laboratory and quality control	30 X TLC

321

322 **3. Results**

323 Having optimized process conditions and determined equipment sizes, the material and
 324 energy balances of the four process alternatives have been carried out. Based on the results of the
 325 material and energy balances of each scenario as well as market values of input materials, labor
 326 and utilities the techno economics of the processes have been analyzed and presented as follows.

327

328

329 *3.1. Technical performances*

330 All four process scenarios are found to be technically feasible ways to produce biodiesel at
331 required quality in accordance with ASTM standards. The technical performance results, such as
332 biodiesel purity, glycerol purity and amount of biodiesel and glycerol produced per amount of
333 feedstock used, are in agreement with those reported in other studies [15, 51]. However, there is
334 still a comparable difference among the scenarios in terms of these technical performances. For
335 instance, scenarios II & III show better performance regarding the amount of biodiesel produced
336 per amount of feedstock consumed. For scenario III, this is due to the double reactor
337 configuration designed to improve the overall conversion of the oil into biodiesel. Whereas for
338 scenario II, the higher performance might be due to arrangement of the downstream processes,
339 where ethanol recovery is done after catalyst neutralization as well as biodiesel purification is
340 done using distillation just after the glycerol separation by decanting. Such process arrangement
341 helps to minimize the amount of biodiesel lost during biodiesel purification and waste separation
342 through distillation. In contrary, the least performance is recorded in scenario IV, where, during
343 separating the unreacted oil from the biodiesel in the second distillation process, considerable
344 amount of the biodiesel could also be removed together with the unreacted oil. This might be due
345 to the higher temperature of the reboiler required to separate the mixture of biodiesel and
346 glycerol from the unreacted oil. Accordingly, the difference in amount of biodiesel produced
347 among the scenarios could range up to 341 kg/h. This value specially indicates the product
348 difference between scenario II and IV. In all of the scenarios, the biodiesel purity achieved is
349 about 99.99 %. This is mainly because of the fractional distillation employed to further purify the
350 biodiesel after different arrangement of glycerol and calcium sulfate separation processes. As the
351 main byproduct, glycerol could also be obtained at higher quality because a number of separation
352 processes are employed in each scenario. Apparently, the higher glycerol product is recorded in
353 scenario III, where two consecutive reactors are designed for higher conversion percentages. The
354 purity of ethanol recovered in each scenario is the same. However, the amount recovered in
355 scenario III is slightly less than the rest because a little more is consumed due to the second
356 reactor.

357 The other crucial point that might improve the productivity of the whole production process
358 is considering the production of more valuable byproducts for additional income generation.
359 With this respect, a good quality calcium sulfate could be produced from all the scenarios with
360 almost the same quantity. In all of the scenarios the separation of the calcium sulfate is done
361 using centrifugal decanter as it is efficient in separating the solid calcium sulfate from the rest of
362 the components. This is done just after the acid catalyst is neutralized so that to avoid the

363 interference of the solid calcium sulfate to the liquid flow downstream afterwards. Calcium
 364 sulfate, as the second byproduct, can be used as a soil conditioner and if further calcined at
 365 required temperature, it can also be used in making tiles, wallboard, and various plasters among
 366 others [52]. Table 5 shows summary of technical performances of the studied process scenarios.

Table 5. Summary of technical performances of the process scenarios				
Technical performance indicators	Process scenarios with respective technical performances			
	Scenario I	Scenario II	Scenario III	Scenario IV
Annual Biodiesel production (kg/year)	40,798,942	41,834,559	42,407,420	39,702,122
Annual Glycerol production (kg/year)	4,018,719	4,018,719	4,067,549	4,018,719
Annual CaSO ₄ production (kg/year)	1,195,301	1,195,301	1,195,301	1,195,301
Biodiesel purity (%)	99.998	99.990	99.990	99.990
Glycerol purity (%)	96.20	99.98	99.95	99.86
CaSO ₄ purity (%)	97	97	97	97
Biodiesel produced per oil feedstock consumed (wt./wt.)	0.995	1	1	0.968

367 **3.2. Economic performances**

368 Having determined plant size, optimized reaction conditions and estimated costs for goods
 369 and services, it has been possible to compare the performances of the process alternatives in
 370 terms of some selected economic parameters. The economic parameters used for comparison are
 371 total investment cost, total annual operating cost, unit production cost, payback time, NPV, ROI,
 372 and after tax IRR. Summary of the economic performances of the alternative process scenarios is
 373 indicated in Table 6.

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Table 6. Summary of the economic performances of the studied process scenarios				
Economic performance indicators	Scenario - I	Scenario - II	Scenario - III	Scenario - IV
Total capital investment cost (US\$)	22,359,405	21,865,163	31,542,376	21,869,629
Total equipment purchasing cost (US\$)	4,372,471	4,346,531	6,477,990	4,271,634
Direct Fixed Capital (US\$)	18,021,578	17,521,523	26,699,684	17,605,966
Working Capital (US\$)	3,436,748	3,467,564	3,507,708	3,383,365
Total Annual operating cost (US\$)	44,081,688	44,262,764	47,811,814	43,353,794
Total annual raw material cost (US\$)	23,805,788	23,805,788	23,805,788	23,805,788
Labor dependent cost (US\$)	469,543	475,200	627,943	463,886
Facility dependent cost (US\$)	6,026,595	5,867,002	8,928,640	5,887,610
Laboratory, Quality Control & Analysis (US\$)	140,863	142,560	188,383	139,166
Utility cost (US\$)	13,528,900	13,862,214	14,151,061	12,967,345
Annual revenue from Biodiesel (US\$/year)	46,917,850	48,090,537	48,752,243	45,641,805
Annual revenue from Glycerol (US\$/year)	417,323	417,323	422,206	417,323
Annual revenue from CaSO ₄ (US\$/year)	153,173	153,173	153,173	153,173
Total Annual Revenue (US\$/year)	47,488,346	48,661,033	49,327,622	46,212,301
Unit production cost (US\$/kg biodiesel)	1.0805	1.0580	1.1274	1.0920
NPV at 7% (US\$)	4,268,069	8,761,177	-7,556,647	3,076,566
ROI (%)	19.02	22.19	12.47	18.01
After tax IRR (%)	9.92	12.73	2.89	9.14
Gross Margin (%)	8.92	10.92	4.72	8.17
Payback time in years	5.26	4.51	8.02	5.55

380 As shown in Table 6, scenario III is the most expensive alternative. This is mainly because
381 of the double reactor scenario, which is supposed to improve the oil conversion efficiency and
382 get more biodiesel produced. Because as the number of equipment increased, there would be
383 associated increase in the total equipment cost, labor cost and utility cost. Even though this
384 double reactor scenario could provide more biodiesel and glycerol compared to others, the
385 overall economic performance indicated that it is not an economically feasible alternative. At
386 optimum market values of goods and services, scenario III provides a very high unit cost of
387 biodiesel production, negative NPV at 7% interest and higher payback time, implying that
388 biodiesel produced should be sold at high price to get some profit. This makes the alternative
389 economically unattractive.

390 Comparatively, scenario II is the least expensive alternative and the second scenario in
391 providing more biodiesel amount. Even though it has the same type and number of equipment
392 with scenario IV, the arrangement of the equipment in scenario II could provide more amount of
393 biodiesel, making the alternative better in its economic performances through increasing the

394 revenue. This might be due to the process arrangement where glycerol is decanted out before the
395 biodiesel is purified using distillation column and thus the amount of biodiesel lost during
396 glycerol separation is minimized. In addition, this process arrangement favors scenario II to have
397 relatively less utility requirement because the reboiler in the distillation column works at
398 relatively lower temperature compared to the one in scenario IV, which has the same type of
399 equipment as well as the same process arrangement until the separation of the calcium sulfate
400 byproduct. This decreases the over production cost. In terms of the economic terms, scenario II
401 indicates higher NPV, less payback time and minimum unit production cost. Scenarios I and IV
402 are the third and fourth alternatives respectively, in terms of their economic performances. Both
403 show positive NPV, signifying that they are still feasible in the given market values of products.

404 In terms of the total capital investment cost, scenario III is the highest again because of the
405 double reactor situation, which increases the equipment purchasing cost and the associated
406 utility, installation and instrumentation costs. Among the other scenarios, scenario I is the second
407 most expensive mainly due to larger volume of distillation column required to recover the excess
408 ethanol before glycerol and calcium sulfate separation. Similarly, such larger column volume
409 results in higher equipment, utility, instrumentation, and installation costs among others.

410 Because of the higher amount of biodiesel and glycerol produced, the superior revenue is
411 recorded in scenario III, whereas scenario II shows the second larger revenue. Having the lower
412 investment cost and second larger revenue, scenario II is the better alternative in terms of
413 achieving lower unit production cost, higher ROI, and lower payback time.

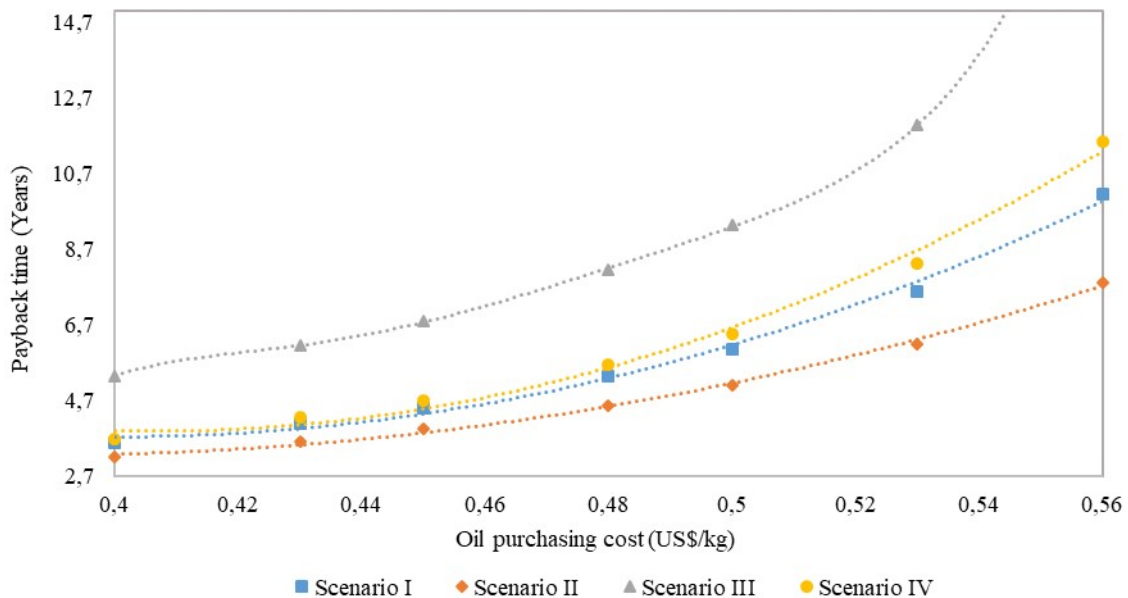
414 **3.3. Sensitivity analysis**

415 The economic feasibility of a biodiesel production process can be dependable when there is
416 a thorough analysis done on how fluctuation of values of market variables affect the profitability
417 of the business. This is because such study would identify the market variables, which affect the
418 profitability of the business more, so that we could take remedial measures, when necessary, to
419 keep the business profitable. In addition, when such analysis is done among a number of
420 alternative processes, it would help to identify the most reliable production alternative that could
421 tolerate market fluctuations of inputs and outputs. Accordingly, in this study, the effects of
422 change of market values of oil feedstock and biodiesel on profitability of the business have been
423 analyzed and the results have also been compared and presented as follows. The economic
424 indicators used to show the sensitivity of the business to changes in prices of the market
425 variables are NPV at 7% interest and payback time.

426 3.3.1. Effect of change of oil feedstock purchasing cost

427 The oil feedstock took the higher share of the annual operating cost in all of the studied
428 alternatives. This implies that a change in market price of the feedstock has a high probability in
429 affecting the profitability of the business. To investigate how NPV and payback time change
430 with change in feedstock cost among the studied scenarios, a price range of 0.45 up to
431 0.65US\$/kg of acidic oil feedstock was set. The effect of change of oil feedstock purchasing cost
432 on NPV is shown in Figure 5 and its effect on payback time is shown in Figure 6.

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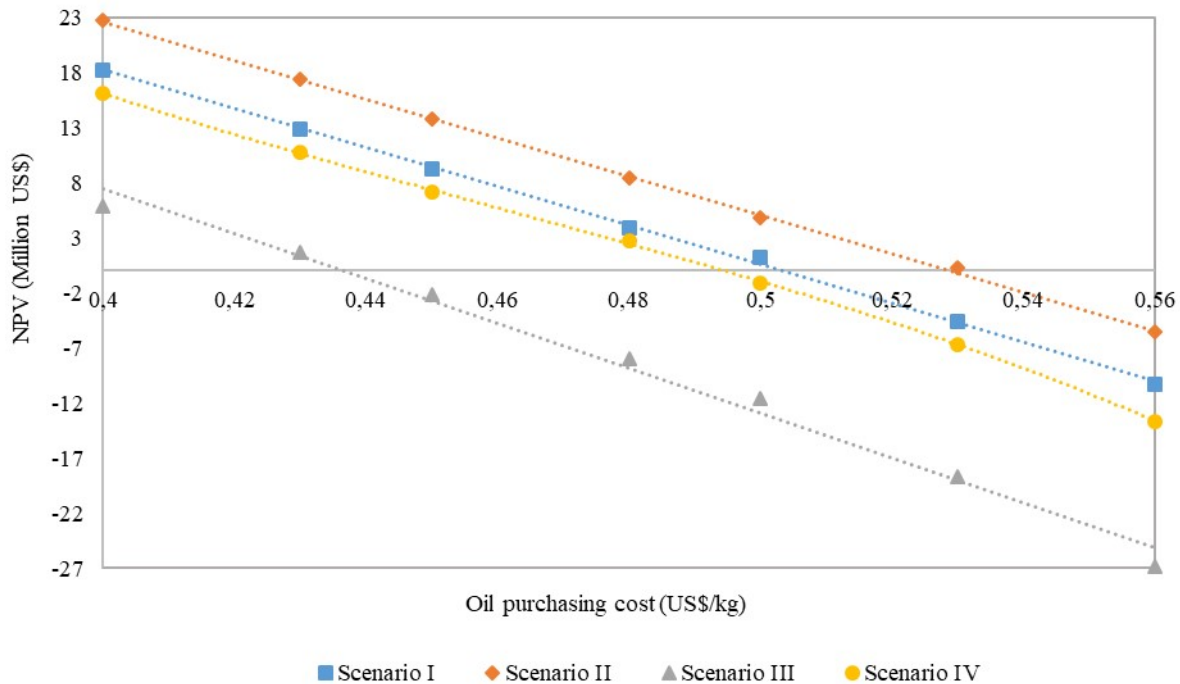
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435 **Figure 7:** Effect of change of oil purchasing cost on Payback time among the alternative scenarios

436 Scenario III is the least dependable alternative for sustainable biodiesel production business.
437 In this scenario, an increase in oil cost by 0.1US\$/kg could result in additional 4 years of
438 payback time. At higher oil purchasing cost, above 0.53US\$/kg, the payback time would be
439 beyond the lifetime of the project, making the alternative very sensitive to change to oil
440 purchasing cost. Comparatively, scenario II indicates more tolerance to change in oil purchasing
441 cost, in which the same price change (0.1US\$/kg) could increase the payback time by about 1.9
442 years.

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Figure 8: Effect of change of oil purchasing cost on NPV among the alternative scenarios

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The effect of change of oil feedstock purchasing cost on the profitability of biodiesel production business could be shown in a better way using NPV. Because NPV denotes the value of the investment calculated by adding the present value of expected future cash flows to the initial cost of the investment. Accordingly, the negative NPV attained in scenario III, as shown in Figure 6, clearly suggests that the alternative is not economically feasible at even medium cost of oil feedstock (above 0.435US\$/kg). Consequently, feedstock has to be purchased with very minimum cost (less than 0.43US\$/kg) in order to be profitable using scenario III. The other less dependable option is scenario IV. It is unprofitable at moderately higher cost of oil feedstock (above 0.49US\$/kg). Comparatively, scenario II could provide positive NPV at higher cost of oil feedstock (up to 0.535US\$/kg), making it more economically dependable alternative for sustainable biodiesel production business.

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3.3.2. Effect of change of biodiesel selling price

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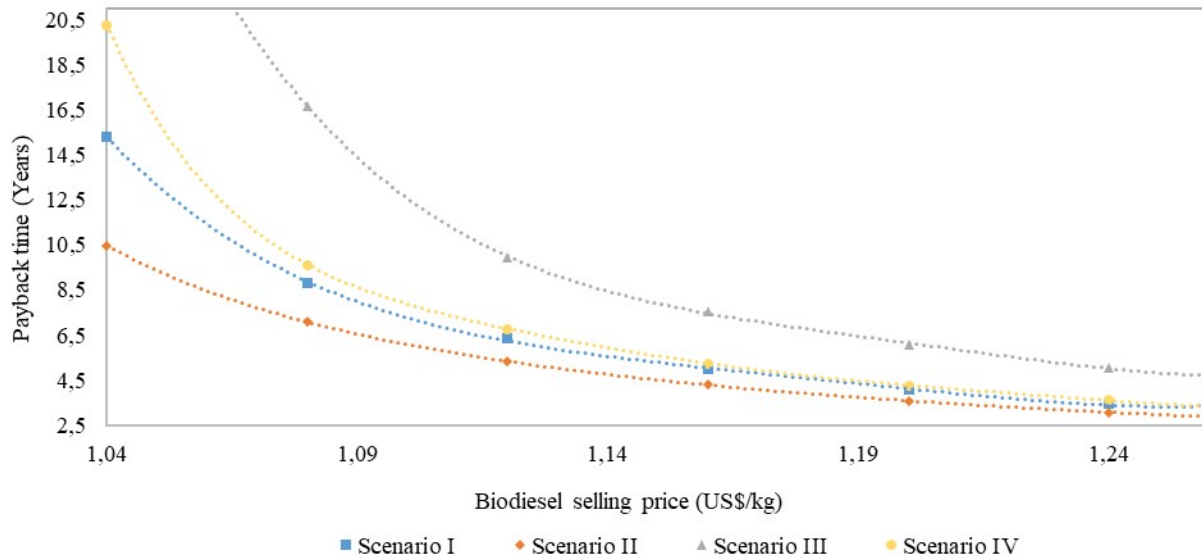
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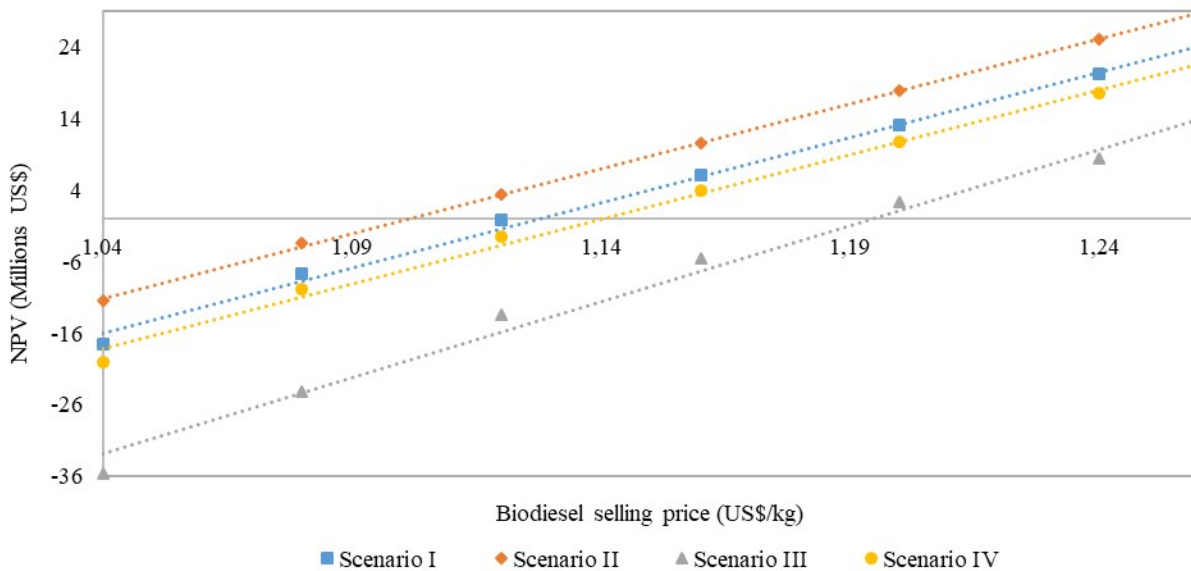
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The other market variable considered to have an effect on the profitability of the alternative scenarios is the biodiesel selling price. Since biodiesel is the main product, its market value could have significant effect on the profitability of the production business. Similarly, NPV and payback time are the two economic indicators used to show how each scenario respond to change in selling price of biodiesel. The biodiesel selling price range of 0.96 up to 1.24US\$/kg is taken for the analysis. The effect of change of biodiesel selling price on NPV is shown in Figure 7 and its effect on payback time is shown in Figure 8.



466
467 **Figure 9:** Effect of change of Biodiesel selling price on Payback time among the alternative scenarios

468 Here again it is indicated that scenario III is the most sensitive for change in biodiesel
469 selling price. Biodiesel price lower than 1.08 US\$/kg would make the project payback time to go
470 beyond its lifetime, making it less practical. The next sensitive alternative is scenario IV, which
471 also required a biodiesel selling price of more than 1.14US\$/kg for its feasibility. Comparatively,
472 scenario II is found to be the most tolerant to a considerable change in the market values of
473 biodiesel selling price, allowing to consider minimum biodiesel price (up to 1.1 US\$/kg) within
474 the feasibility domain.



475
476 **Figure 10:** Effect of change of Biodiesel selling price on NPV among the alternative scenarios

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479 As shown in Figure 8, the trend of change of NPV with change in biodiesel prices is the
480 same for all scenarios. However, among them scenario III is found to be more sensitive and get
481 no profit to the business even at higher prices of the biodiesel product. The next less dependable
482 alternative is scenario IV, which indicates negative NPV starting from medium values of the
483 biodiesel selling price (lower than 1.14US\$/kg). Scenario II is the better alternative in this
484 respect, providing positive NPV at 7% interest even at lower values of biodiesel selling price
485 (about 1.1US\$/kg).

486 **4. Conclusion**

487 Four process scenarios for biodiesel production from acidic oil using sulfuric acid as a
488 catalyst were designed, analyzed and evaluated for their techno-economic performances.
489 Accordingly, all scenarios are capable of producing fuel grade biodiesel and could also provide
490 high quality calcium sulfate and glycerol byproducts for additional income. Scenario III, with
491 double reactor, shows better technical performance with very low economic feasibility. In
492 addition, scenario III is found to be the most sensitive alternative to change in market values of
493 inputs and outputs.

494 Comparatively, scenario II is the cheapest alternative with less total investment cost, less
495 unit cost of production, higher NPV and minimum payback time. It also indicates good technical
496 performance and provides competitive amount of glycerol byproduct. In terms of sensitivity to
497 change in market values of inputs and outputs, scenarios II is found to be more tolerant than the
498 other scenarios.

499 Scenarios I and IV are relatively technically less efficient and scenario IV is the second
500 most expensive alternative for having higher cost of biodiesel production, and less NPV among
501 others. It is also the second most sensitive alternative to change in market values of inputs and
502 outputs.

503

504 **Disclaimer**

505 The authors do not have responsibility for a decision made based on the results of these
506 process alternatives. The process designs indicated in this work are solely for research purposes.
507 For specific applications, please contact the authors to get information about the limitations and
508 scope of the process designs.

509

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513 **Conflict of Interest**

514 All authors declare no conflicts of interest in this paper.
515

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