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Techno-Economic Study of Biodiesel Generation from *Sterculia foetid* Seeds

Bilqist Imeilia Az Zahra[1], H.C. Theofany[2,3]*, Teuku Meurah Indra Riayatsyah[4], H.B. Aditiya[1,3], Bidattul S Zainal[5]

[1]*Department of Mechanical Engineering, Faculty of Engineering and Technology, Sampoerna University, 12780, Jakarta, Indonesia*

[2]*Department of Metallurgical and Materials Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia*

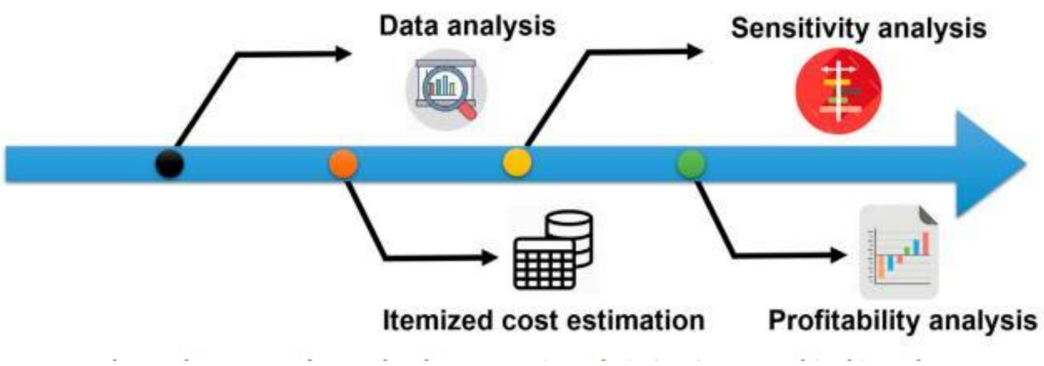
[3]*Energy Research Center, Faculty of Engineering and Technology, Sampoerna University, Jakarta, Indonesia.*

[4]*Program Study of Mechanical Engineering, Department of Production and Industrial Technology, Institut Teknologi Sumatera, 3536, South Lampung, Indonesia*

[5]*Department of Engineering, School of Engineering and Technology, Sunway University, Selangor Darul Ehsan, Malaysia*

*Corresponding Author: theofany.harley@office.ui.ac.id

Graphical Abstract



Highlights

- Sterculia foetida seeds, with 50–60% oil content, enable near-complete conversion to biodiesel, producing ~16.19 million kg of biodiesel annually with minimal mass balance error (0.001%).
- The project has a modest gross margin (3.48%) and a favorable ROI of 19.67%, with a payback period of 5.08 years, demonstrating economic viability at a biodiesel price of $1.00/L.
- Profitability is most sensitive to the biodiesel market price and feedstock cost, highlighting the importance of stable market conditions for ensuring long-term success.

ARTICLE INFO

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ABSTRACT

As fossil fuel reserves diminish and energy demand grows, biodiesel from non-edible oils has emerged as a promising renewable alternative. This study evaluates the feasibility of producing biodiesel from Sterculia foetida (Java olive) seeds, which contain 50–60 % oil. A second-generation biodiesel plant is designed and simulated using SuperPro Designer, covering oil extraction, transesterification, product purification, and by-product recovery. The plant processes 4,396 kg of seeds per hour in Lombok (Indonesia). Material and energy balances indicate nearly complete conversion to biodiesel, yielding ~16.19 million kg/year with a 0.001 % mass balance error. The total utility power demand is 6.2 million kWh/year, with the transesterification reactor consuming ~27 %. Economic evaluation (2021 USD) shows a capital investment of ~$3.82 million and annual operating cost of ~$20.72 million. At a biodiesel price of $1.00/L,

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annual revenue is ~$21.47 million, including ~$2.4 million from glycerol and co-products. Profitability metrics are positive: gross margin 3.48 %, ROI 19.67 %, payback period 5.08 years, IRR 9.14 %, and NPV ~$1.03 million. Sensitivity analysis shows profitability is most affected by biodiesel market price and feedstock cost. Overall, biodiesel production from Sterculia foetida is technically feasible and economically viable, diversifying Indonesia's biodiesel feedstocks.

1. Introduction

The rapid depletion of fossil fuel resources and rising energy demand have driven the search for sustainable biofuels. Biodiesel, a renewable fuel derived from biological lipids, is a viable substitute for diesel fuel that can reduce dependence on petroleum [1, 2]. Unlike first-generation biodiesel feedstocks (e.g. palm oil), which compete with food supply, second-generation feedstocks are non-edible and often underutilized. Sterculia foetida, a tropical tree native to Indonesia and other regions, produces seeds rich in oil (roughly half of the kernel weight). This high oil content and the tree's ability to grow on marginal land make Sterculia foetida a promising feedstock for biodiesel production in Indonesia [3, 4].

Biodiesel from *Sterculia foetida* has been studied in terms of its fuel properties and small-scale processing, but a comprehensive feasibility assessment for industrial-scale production remained incomplete [5, 6]. Indonesia's biodiesel industry has so far been dominated by palm oil; however, relying on a single feedstock poses sustainability and supply risks. Diversifying feedstocks with non-edible oils like *Sterculia* could enhance energy security and reduce competition with food crops. There is a need to evaluate not only the technical process of converting *Sterculia* oil into biodiesel, but also the economic viability of such a project under realistic conditions. Prior studies on second-generation biodiesel often lack a detailed techno-economic analysis combining process simulation with cost analysis [7, 8].

This study addresses that gap by designing a full-scale biodiesel production process from *Sterculia foetida* seeds and conducting a techno-economic analysis. The objectives are to develop a process flowsheet for *Sterculia* biodiesel production and assess its material and energy requirements, evaluate the technical feasibility and performance (yields, energy efficiency) of the process, and analyze the economics of the plant (capital costs, operating costs, and profitability metrics) to determine if the project can be competitive. By examining both technical and financial aspects, we aim to determine whether *Sterculia foetida* biodiesel can feasibly contribute to Indonesia's renewable energy mix. The findings will inform investors and policymakers about the potential of this novel feedstock and guide future improvements in biodiesel process design.

2. Materials and Methods

2. 1 Feedstock Preparation

Sterculia foetida seeds were chosen as the feedstock due to their high oil yield and availability in Indonesia. A supply analysis was performed to estimate the scale of cultivation needed to support a commercial biodiesel facility. Based on seed oil content and annual yield per tree, approximately 1.28 million *Sterculia* trees cultivated on ($0.034/kg from planting costs) but also additional farming expenses (fertilizer, irrigation, labor, etc.). This conservative feedstock price was used in the economic calculations to account for full agricultural supply chain costs. The plant is assumed to be located in Lombok, Nusa Tenggara Barat (Indonesia), where *Sterculia* grows well and land and labor are accessible.

2. 2 Process Design and Simulation

The input parameters for the process simulation utilising SuperPro Designer v10 software call for composition data from both Sterculia foetida seeds and crude oil. The necessary and appropriate biodiesel conversion methods would also be influenced by the input data from Sterculia foetida seeds and crude oil. A process flowsheet was developed to convert Sterculia seed oil into biodiesel fuel. The production process consists of five main sections arranged in sequence as shown in Figure 1.

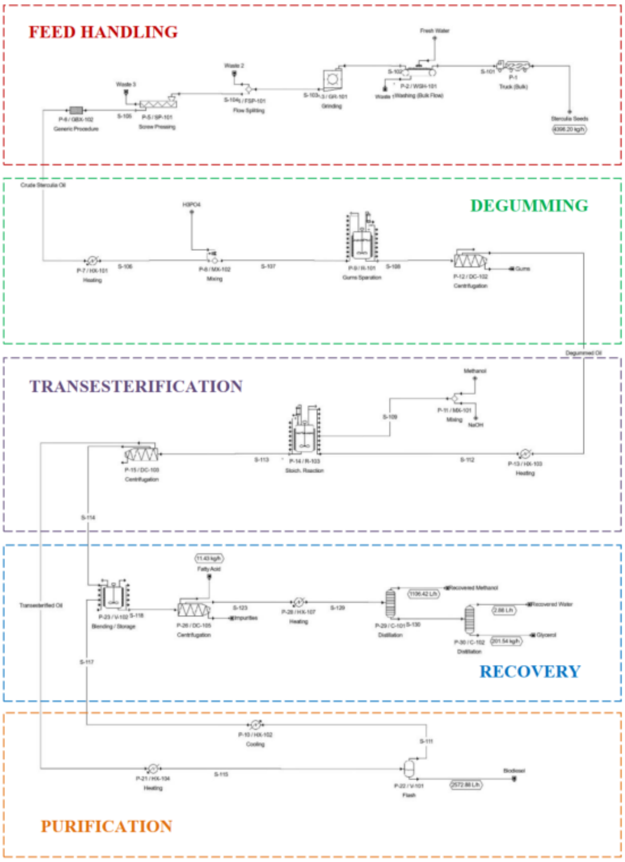

Figure 1 The Block Flow Operations

2.2.1 *Biodiesel Simulation*

In the simulation, the seeds are washed and then ground using industrial grinders to facilitate oil extraction. Next, a mechanical screw press expels crude oil from the ground kernels, while the defatted seed cake (containing proteins, fiber, etc.) exits as a by-product. The extracted crude oil is treated to remove gums (phospholipids and other impurities). A stirred-tank reactor (R-101) is used for degumming by adding phosphoric acid, which reacts with phospholipids to form a heavy phase that is separated. The core reaction step where fatty oils are converted to fatty acid methyl esters (biodiesel). In this section, the equipment used and parameters such as temperature, types of acid, conversion rate, methanol concentration, acid concentration, chemical reaction, and conversion rate are based and adjusted from some literature reviews [9-11].

The degummed oil is pumped into a series of three continuously stirred reactors (R-103 train) along with methanol and a catalyst (sodium hydroxide). In these reactors, the triglycerides in the oil react with methanol to form methyl esters (biodiesel) and glycerol. The reaction conditions and multiple stages ensure a high conversion of oil to biodiesel. The reaction mixture is subsequently sent to separation units to purify the biodiesel. Glycerol (the co-product) along with excess methanol, catalyst, soaps, and other impurities are separated from the methyl esters. This section includes decanter centrifuges (for phase separation of glycerol-rich vs. biodiesel-rich phases) and water washing units. Multiple washing steps (WSH-101 series) are employed to remove residual catalyst and soaps from the biodiesel, each handling ~880 kg/h of flow. The washed biodiesel is then dried and sent to storage as the final product. Unreacted methanol and other volatile components are recovered for reuse or sale. Two small distillation columns (C-101 and C-102) each of ~147 L volume are used to recover methanol from the glycerol and aqueous streams. The recovered methanol can be recycled back into the process, improving overall yield and reducing waste. Glycerol (about 80% purity) is collected as a valuable co-product, and any solid wastes (spent catalyst, seed cake) are sent to waste handling. SuperPro Designer offers a variety of complex and useful method modeling options. SuperPro Designer can calculate energy and mass balances, as well as cost accounting, using a comprehensive library of chemical elements and combinations, as well as instrumentality and resources [12, 13]. The entire process flowsheet was constructed and simulated in SuperPro Designer v11, which computed stream balances and equipment duties for the steady-state continuous operation.

2.2.2 *Equipment Simulation*

Each unit operation in the flowsheet was specified and sized based on the required throughput and processing time. Table 1 summarizes the major equipment in the plant and their design capacities. Two grinders (GR-101) are installed to handle the feed throughput, each rated at about 2,068 kg/h. The oil expeller (SP-101 screw press) can process ~4,136 kg of seed mash per hour to extract the oil. The degumming reactor (R-101) volume is ~1.56 m^3, sufficient for the acid pretreatment of the oil. Transesterification is carried out in three parallel stirred reactors (R-

103) of ~3.63 m^3 each, sized to ensure adequate residence time for nearly complete conversion of the oil. Downstream, several centrifugal separators (decanters labeled DC-102, DC-103, DC-105) handle flow rates of 1.3–3.2 m^3/h to continuously separate biodiesel, glycerol, and wash water streams. Five washing units are included, each processing ~879 kg/h, to meet biodiesel purity specifications. Heat exchangers (HX-101, 102, 103, etc.) of various sizes (0.2–2.4 m^2) provide heating or cooling where needed, though many heating/cooling duties are optimized via heat integration. A flash drum (V-101) and blending tank (V-102) are also used for vapor-liquid separation and final product blending, respectively. The equipment is constructed from compatible materials (carbon steel for non-corrosive service, stainless steel 316 for reactors and other units in contact with biodiesel or caustic). These equipment specifications were used to estimate the capital costs and to ensure the technical feasibility of assembling such a plant.

Table 1 Equipment specifications

Name	Type	Qty	Capacity	Units	Materials
GR-IOI	Grinder	2	2,068.19	kg/h	CS
FSP-IOI	Flow Splitter	1	4,136.39	kg/h	CS
SP-101	Screw Press	1	4,136.32	kg/h	SS316
GBX- 102	Generic Box	1	2,538.26	kg/h	CS
R-IOI	Stinted Reactor	1	1,561.61	L	SS316
HX-101	Heat Exchanger	1	0.49	m^2	CS
HX-103	Heat Exchanger	1	0.23	m^2	CS
DC-103	Decanter Centrifuge	1	3,217.13	L/h	SS316
V-101	Flash Drum	1	1,433.04	L	CS
HX-104	Decanter Centrifuge	1	0.74	m^2	CS
DC-105	Decanter Centrifuge	1	1,280.52	L/h	SS316
C-101	Distillation Column	1	147,26	L	CS
HX-107	Heat Exchanger	1	2.36	m^2	CS
C-102	Distillation Column	1	147.26	L	CS
R-103	Stirred Reactor	3	3,632.77	L	SS316
WSH-101	Washer	5	879.24	kg/h	CS
MX-102	Mixer	1	2.551.01	kg/h	CS
MX-101	Mixer	1	1,066.66	kg/h	CS
V-102	Blending Tank	1	1,422.80	L	SS316
DC-102	Decanter Centrifuge	1	2,806.33	L/h	SS316
HX-102	Heat Exchanger	1	0.22	m^2	CS

2.2.3 *Energy Integration and Utilities*

To improve energy efficiency, heat integration was applied in the design. Several operations in the process release heat (exothermic reactions or hot output streams) which can be used to preheat other streams [14]. A virtual energy recovery network was configured in the simulation to automatically match hot and cold streams, reducing the need for external utilities. As a result, the external heating and cooling duties are minimized, and utility consumption is lowered. The remaining utility demands (primarily electricity for drives and cooling water for condensers) were quantified. Electricity is needed for running motors (grinders, pumps, centrifuges, etc.) and the total power usage was calculated based on equipment load. The transesterification reactor mixers (which likely include heating elements or agitation) account for the largest portion of electricity usage (~27.1%), followed by the grinder motors (~23.2%). In contrast, the screw press is energy-efficient, using only ~2.6% of total power. The overall electricity usage of the plant is about 6.20×10^6 kWh per year (≈775 kW average load). This level of energy demand is moderate for a plant of this scale, and local grid supply or on-site biomass generators could meet the requirement. Other utilities include cooling water and low-pressure steam, mostly handled through the integrated heat exchange network, therefore their costs are relatively small (utilities contribute ~4.6% of operating cost).

2.2.4 *Economic Analysis*

A detailed economic evaluation was performed for the designed plant. All cost calculations were based on 2021 price data (US dollars). Capital expenditure (CAPEX) was estimated by summing the costs of all major equipment (including installation factors) and adding indirect costs (engineering, construction, contingencies). Equipment purchase costs were obtained from vendor quotes or literature for similar capacity units. For instance, each grinder was estimated at ~$20,000 and the screw press at ~$5,000, reflecting relatively low-cost items, whereas reactors and centrifuges were more costly. The total installed Total Capital Investment came out to ~$3.82 million. This capital is assumed to be expended before startup and depreciated straight-line over 10 years (a common practice for chemical plants). The plant's operational lifetime was taken as 20 years for the NPV analysis. Annual Operating Costs include raw materials (seeds, methanol, catalyst, acid, etc.), utilities (electric power, water), labor, maintenance, and other overhead. These were calculated using the simulation output for material and energy flows and standard cost factors. Notably, raw *Sterculia* seeds constitute the bulk of the operating cost given the large throughput (millions of kg per year at $0.315/kg). Raw materials are the dominant expense, while utilities (power, water) account for only ~4.6% ($0.96 M/yr) and transportation of products about 3.6% ($0.74 M/yr). By-products (glycerol, excess methanol, seed cake) yield some credits, which were accounted as other revenues. The economic model also assumed a corporate tax rate (not specified in the thesis excerpt, but IRR after taxes was reported, implying tax effects were included). Profitability metrics, including gross margin, ROI, IRR, payback, and NPV, were computed based on the net cash flows.

2.2.5 *Sensitivity Analysis*

The robustness of the economic outcome, a sensitivity analysis was conducted on key variables. Four parameters were varied by ±10%: the biodiesel selling price, the feedstock (seed) cost, the electricity cost, and the general inflation rate (which affects all costs uniformly). The impact of these changes on gross margin, ROI, and payback period was observed. This analysis helps identify which uncertainties have the greatest influence on project viability. The parameter uncertainties can considerably affect the sensitivity analysis assessments which neglecting the parameter uncertainties may lead to misleading results of the techno-economic assessments [15]. For each parameter, all other inputs were held at base values while the parameter was increased or decreased by 10%, and the profitability metrics were recalculated. Sensitivity results were presented in terms of percentage change in gross margin, ROI, and payback relative to the base case.

The slurry was subjected to microwave irradiation using a household microwave oven (Aqua AEM-S1112S model) as the heating source. Microwave power level and heating time were controlled according to the experimental design. The microwave power was set to either 200 W, 300 W, or 400 W (low, medium, high), and the irradiation time was set between 2 and 4 minutes. In each run, the 100 mL reaction mixture in a glass beaker was placed at the center of the microwave cavity. No external stirring was applied during irradiation. After the set time elapsed, the beaker was removed; at this stage, the mixture typically appeared more translucent, indicating starch gelatinization and solubilization. To separate the liquid hydrolysate from residual solids, the mixture was immediately transferred to centrifuge tubes and centrifuged at high speed (~4000 rpm) for 15 minutes. The supernatant – containing the dissolved sugars (and soluble organic matter) – was carefully decanted as the hydrolysate for analysis. Any gelatinized starch or insoluble residue remained as a pellet, which was discarded. The hydrolysate was yellow brown in colour due to the alkaline treatment.

3. Results and Discussion

3. 1 Feedstock Supply and Composition

The simulation confirmed that a feed rate of ~4.4 tonnes of *Sterculia foetida* seeds per hour is required to achieve the desired biodiesel output. Given the assumed oil content (~52% of seed mass) and process yields, this feed rate corresponds to roughly 2.2–2.3 tonnes of oil being processed per hour. The *Sterculia* supply scenario (1.28 million trees on 68 ha) is ambitious but feasible in parts of Indonesia where the tree is endemic. At the assumed yield per tree, this plantation could supply about 38,000 tonnes of seeds annually. The chosen feedstock cost of $0.315/kg reflects a scenario of organized cultivation; if seeds were collected from wild or waste sources, the cost could be lower, potentially improving economics. The seed composition from literature indicates ~51–58% fat, ~21–22% protein, and the rest fiber/carbohydrate. In the process, the protein and carbohydrate fractions exit in the pressed cake (which could be used as animal feed or fertilizer), while the oil (fat) enters the biodiesel production line. No insurmountable issues in feedstock handling were identified; the grinding and pressing operations are standard and the equipment specified (industrial grinder, screw press) can handle the seed characteristics. The plant location in Lombok provides a favorable setting with adequate labor and suitable climate for *Sterculia* cultivation. This suggests that steady feedstock supply at the required scale is attainable.

3. 2 Process Simulation and Performance

The SuperPro Designer simulation of the biodiesel plant ran successfully and generated detailed material and energy balances. Overall, the conversion of *Sterculia* oil to biodiesel was very high. The model indicates that out of ~16.21 million kg of oil (triglycerides) fed per year, about 16.19 million kg are converted to biodiesel (fatty acid methyl esters), implying a reaction yield of 99.9% on a mass basis. Glycerol production was ~1.68 million kg/yr, consistent with the stoichiometry of transesterification (roughly 10% of the oil mass ends up as glycerol). Small quantities of soap (saponified fats due to side reactions, ~0.39 million kg/yr) and unreacted free fatty acids (~0.04 million kg/yr of oleic acid) were noted as minor by-products. These losses are small (<0.3% of total mass) and occur due to the side reaction of free fatty acids with the base catalyst and incomplete conversions, respectively. The negligible overall mass balance error (0.001%) confirms that the process streams are well-accounted, and the simulation is consistent. The integrated heat exchange approach reduced external utility needs. Most heating of oil for reaction and most cooling of product streams were accomplished by energy recovery internally. The total external energy requirement was determined to be ~6.2×10^6 kWh per year of electricity.

The transesterification section (mixing and perhaps maintaining reaction temperature) is the largest consumer of power, followed by the grinding of seeds. Notably, mechanical oil extraction (screw pressing) is relatively low energy, and separation processes (centrifuges) together take about 11–12% of the total power. The seed to the solvent ratio was an important parameter with the maximum impact on the oil yield. Decreasing the volume of solvent minimises the oil yield, whereas using a high amount of the solvent increases the cost of the process. The extraction time was also optimised and minimised. The oil yield was also maximised which was another important biodiesel production [16]. These results highlight that the process is not extremely energy-intensive; the energy consumption per unit biodiesel produced is on the order of 0.38 kWh per kg biodiesel (i.e., ~0.38 MJ/kg, which is about 1.4 MJ per liter of biodiesel). This is a reasonable figure, suggesting that the energy payback (energy output vs. input) would be favorable since biodiesel contains roughly 37 MJ/kg heating value. The simulation results show that the designed plant can effectively convert *Sterculia foetida* seeds to biodiesel with high efficiency, and the equipment sizes chosen are adequate for the throughput. No major bottlenecks were observed in the material flow or energy usage that would impede scale-up.

3. 3 Product Quality and Yields

The biodiesel produced in the simulation meets the purity requirements after the washing and purification steps. The water wash units remove nearly all residual sodium (from NaOH catalyst) and any soap, bringing impurity levels down to acceptable ranges (the thesis mentions compliance with biodiesel standards was considered, although specific fuel properties are not detailed in the excerpt). The glycerol by-product is obtained at ~80% purity (typical crude glycerol from biodiesel process), which is assumed to be saleable to refining industries. The model did not explicitly report the purity of biodiesel, but given the process configuration, it is expected to be high (ester content >96.5% as per standards). The yield of biodiesel relative to seed input is approximately 34–36% by mass (since ~0.34 kg biodiesel is obtained per kg of whole seed processed, considering 50-60% oil in seed and ~90% recovery of that oil as biodiesel). This yield could potentially be improved with solvent extraction of the press cake to recover residual oil, but that would add complexity and cost (not included in this design).

3. 4 Economic Results

Techno-economic analysis (TEA) method includes calculation for life cycle cost, energy consumption, and payback period of the biodiesel production [17, 18]. The economic analysis of the *Sterculia* biodiesel plant indicates that the project is marginally profitable under the base case assumptions. Table 2 lists the annual operating cost distribution, while Table 3 summarizes the key financial figures. The annual revenue of ~$21.47million just exceeds the annual operating cost of ~$20.72 million, leaving a gross profit of about $0.75 million per year. This translates to a gross margin of only 3.48%, which is quite low for a manufacturing project. The low margin is largely a result of the biodiesel selling price being set to a competitive level ($1.00 per liter, or ~$1,000/ton) to encourage market adoption. At this price, there is little profit per unit of biodiesel sold. In essence, the plant is low-margin but high-turnover. The project's payback period is about 5.08 years, meaning it would take just over five years of operation for the cumulative net cash flow to recover the initial $3.8 M investment. This is within the 20-year project life and is generally acceptable for industrial projects (paybacks under 6–7 years are often considered reasonable). The internal rate of return (IRR) on the project (after taxes) is calculated at 9.14%. This IRR is above the assumed discount rate of 7% used for NPV, resulting in a net present value (NPV) of approximately +$1.03 million over 20 years. A positive NPV indicates that the project earns more than the minimum attractive rate of return (7% in this case), thus adding value. However, an IRR of 9.14% is not very high; it suggests that if the company's hurdle rate were higher (e.g., 10% or 15%), the project would not meet it.

Table 2 Annual Operating Cost

Component	Value ($)	%
Raw materials	14,399.00	69.49
Labor-Dependent	2.225.000	10.74
Facility-Dependent	2,065.00	9.96
Laboratory/QC/QA	334	1.61
Utilities	960	4.63
Transportation	739	3.56
Total	20,721.00	100

Table 3 Capital Cost Summary

Component	Value ($)
Direct Fixed Capital	1,955,000
Working Capital	1,583,000
Startup Cost	200,000
Up-Front R&D	38,000
Investment Charged to This Project	3,815,000

In summary, the base case economics show a slim profit, but the project is technically feasible and just economically viable, essentially breaking even with a slight profit over its lifespan. The largest contributor to operating cost is the feedstock itself (raw *Sterculia* seeds). If cheaper feedstock or higher biodiesel prices can be realized, the profitability would improve significantly. The co-products (glycerol, excess methanol, seed cake) contribute a small but notable fraction of revenue (~11% of total revenue), which helps the economics. For instance, selling crude glycerol at ~$250/ton and recovered methanol at ~$300/ton provides roughly $2.4 M extra income per year, which essentially makes the difference between profit and loss in this scenario. The results underscore the importance of market prices which the profitability is highly sensitive to how much the biodiesel can be sold for and how much must be paid for seeds.

3. 5 Sensitivity Analysis

The sensitivity analysis reveals that the economic viability of the *Sterculia* biodiesel plant is most sensitive to biodiesel selling price and feedstock cost. A ±10% change in the biodiesel price has a pronounced effect on gross margin: increasing the price by 10% (to $1.10/L) raises the gross margin from 3.5% to about 11.3%, whereas decreasing the price by 10% (to $0.90/L) drives the project into loss with a gross margin of –5.9%. This non-linear response is because revenue changes directly affect profit when costs are relatively fixed – at the base case, profit is small, so a 10% revenue drop wipes it out. Similarly, a 10% rise in the feedstock (seed) price (from \$0.315 to ~\$0.347/kg) causes gross margin to drop to –4.35%, meaning the project would operate at a loss if seeds were slightly more expensive than assumed. Conversely, a 10% reduction in feedstock cost boosts the margin dramatically (up to ~42.6%). This large swing indicates that raw material cost is the single largest determinant of operating cost (which it is, constituting ~80%+ of OPEX). As shown in Figure 2, the impact on ROI is analogous: a higher biodiesel price or lower feed cost significantly shortens the payback and increases ROI, whereas a lower price or higher feed cost can make the payback time effectively infinite (no payback within project life) [19]. In fact, the analysis noted that if biodiesel price dropped 10% or feed cost rose 10%, the SuperPro model yielded "N/A" for payback period, indicating the project would not recover its investment within 20 years, as shown in Figure 3. On the other hand, variations in electricity cost had a comparatively minor effect. Electricity constitutes only a small portion of total costs (as noted, ~4.6%), so even a 10% increase in power prices would only slightly erode margins. Inflation rate changes also had negligible influence on real profitability in the short term. Overall, the sensitivity results highlight that securing a low-cost supply of *Sterculia* seeds (for example, utilizing agricultural residues or intercropping to reduce cost) and maintaining a favorable biodiesel market price (possibly via incentives or mandates) will be critical for the success of production. The base case was somewhat optimistic on feedstock cost; if actual costs are higher, the study may need either a higher selling price or process optimizations to stay viable.

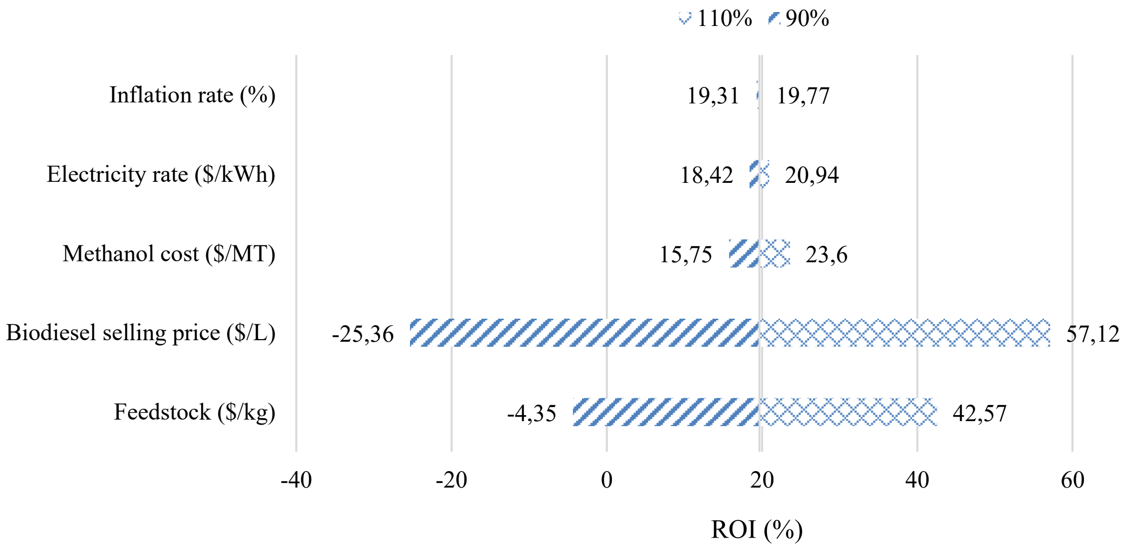

Figure 2 ROI Sensitivity to The Variation of Feedstock Price, Biodiesel and Methanol Selling Price, Electricity Price, And Inflation Rate

The techno-economic analysis of biodiesel from *Sterculia foetida* seeds demonstrates both the potential and the challenges of developing a new biofuel supply chain. From a process standpoint, the study shows that a biodiesel production plant using *Sterculia* oil can be designed with conventional equipment and known technologies. The process flow, that is mechanical extraction of oil followed by chemical transesterification, is analogous to those used for other oilseed biodiesel plants (e.g., *Jatropha*, soybean, palm) and did not reveal any unique technical hurdles. The high oil content of *Sterculia* seeds is a clear advantage, as it yields a large amount of biodiesel per unit of biomass processed. The near-quantitative conversion of oil to biodiesel achieved in simulation suggests that, under ideal conditions, *Sterculia* can produce biodiesel in yields comparable to traditional feedstocks. Key process parameters (reaction times, catalyst use, number of wash stages) were set to ensure fuel quality and yield, and these appear effective.

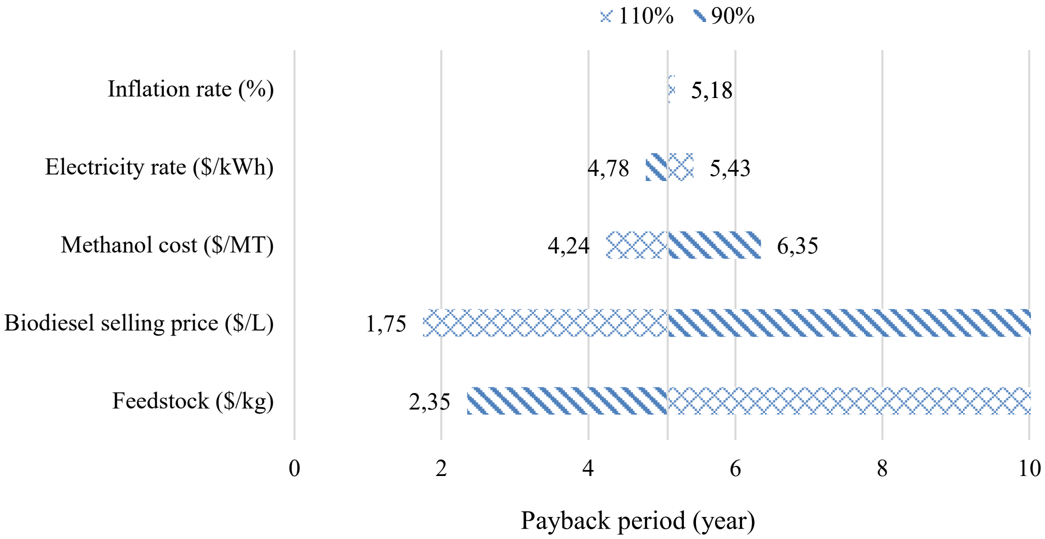

Figure 3 Payback Period Sensitivity to The Variation of Feedstock Price, Biodiesel and Methanol Selling Price, Electricity Price, and Inflation Rate

The energy consumption of the plant is moderate; in fact, the energy analysis implies an energy return on investment (EROI) well above 1, meaning the energy content of the biodiesel far exceeds the energy input required to produce it. This is crucial for the sustainability of the biofuel – a high EROI indicates a net energy gain. The integration of heat streams (energy recovery) further improves efficiency, a practice that could be implemented in real facilities to reduce utility costs. One technical aspect that might warrant further research is the handling of the *Sterculia* seed cake and by-products. While not the focus of this study, finding beneficial uses for the press cake (which is rich in protein and minerals) could improve the overall resource efficiency. Additionally, the presence of cyclopropene fatty acids in *Sterculia* oil (if any, as found in some related species) could affect biodiesel stability; this was not discussed in the thesis but would be important in a real application. Overall, the technical results give confidence that building and operating a *Sterculia* biodiesel plant is feasible with existing technology – in other words, from a technological standpoint, the plant is buildable and operable.

3. 6 Economic Viability

Economically, the project sits on a knife-edge between profit and loss. The base case scenario yielded a positive but modest profit, which indicates viability if conditions are as assumed. The results mirror the findings from some previous techno-economic studies on biodiesel from non-edible oils. For example, a techno-economic analysis of *Jatropha* biodiesel by Yusuf & Kamarudin (2013) found that profitability was contingent on feedstock cost and biodiesel price, and government incentives were often needed to ensure a reasonable return [20]. Similarly, Ziyai *et al.* (2019) reported that integrating value-add processes (like converting glycerol to more valuable products) could improve economics for biodiesel plants [21]. In the case of *Sterculia*, the co-product glycerol provides some revenue, but perhaps not enough to significantly alter the economics. The low gross margin observed (3.5%) is indicative of a commodity fuel market – biodiesel must be priced competitively with diesel (or receive subsidies) to be sold, which squeezes producers' margins. However, an ROI of ~20% is somewhat surprisingly high given the margin, and this is attributable to the low capital cost. The plant uses relatively simple, inexpensive equipment (e.g., mechanical presses instead of solvent extractors, small reactors, etc.), keeping the capital investment low. This is a positive finding – it means the financial risk (upfront cost) is not enormous, and even a small profit can be attractive relative to the investment. The payback period of ~5 years is quite reasonable, suggesting that if the project were started, investors could recoup capital in the mid-term. The IRR of 9.14% after taxes might be marginal for private investors (depending on their required rate of return), but as a national energy project it could be justifiable, especially if there are non-monetary benefits (job creation, energy security, emissions reduction). One way to improve the IRR would be to increase the scale of the plant to gain economies of scale, many costs (especially capital cost per unit output) would drop if the plant were larger, potentially improving margins. Another approach is to optimize the process for higher efficiency or lower cost: for instance, if a small amount of solvent extraction after pressing could boost oil recovery significantly, the additional biodiesel produced might outweigh the cost of solvent recovery. The sensitivity analysis highlighted that economic success is highly sensitive to market conditions. If diesel fuel prices fall or if *Sterculia* seed costs rise, the venture could quickly become unprofitable. This volatility is a common challenge in biofuel projects. It underlines the importance of supportive policies – such as biofuel blending mandates, feedstock supply agreements, or price support mechanisms – to buffer against market swings. For instance, if a floor price for biodiesel or a subsidy for using non-edible feedstocks were in place, it would reduce the downside risk. The analysis also showed that by keeping electricity and utility costs low (through energy integration), their impact is minor, which is good; the focus clearly should be on feedstock logistics and fuel market strategy. In conclusion, the economic analysis suggests that a *Sterculia* biodiesel plant can be viable, but with limited profitability, and it would greatly benefit from optimizations or external support to improve its economic robustness.

3. 7 Environmental and Social Considerations

Using *Sterculia foetida* as a feedstock has some potential advantages over conventional crops like palm or soybean. It is non-edible, so it avoids the food-vs-fuel conflict and can utilize marginal lands. If integrated into agroforestry systems, *Sterculia* cultivation could provide additional income to farmers without displacing food crops. The lifecycle greenhouse gas emissions of biodiesel from *Sterculia* were not calculated here, but since the process is similar to other vegetable oil biodiesels, significant reductions in CO_2 emissions (typically 50–80% lower than fossil diesel) can be expected, depending on land-use change considerations. The major environmental concern would be ensuring that natural forests are not cleared for *Sterculia* plantations – this must be managed via sustainable sourcing. The process itself will generate some wastes (seed cake, wash water with soaps, etc.), which require proper handling. The seed cake can be a useful co-product (e.g., organic fertilizer or animal feed if detoxified), and wash water can be treated biologically. These aspects were beyond the scope of the thesis but would be important for real-world implementation.

3. 8 Comparison with Other Feedstocks

The feasibility metrics obtained here can be compared to biodiesel from other feedstocks. For instance, palm oil biodiesel in Indonesia benefits from an established supply chain and often higher oil yields per hectare, thus typically showing better economics. However, palm biodiesel faces sustainability issues and often requires significant capital (since palm oil mills and transesterification plants are separate stages). *Sterculia* biodiesel, as proposed, could be smaller-scale and more modular. *Jatropha*, another non-edible oil crop pursued in Indonesia, had mixed results – many *Jatropha* projects failed due to lower-than-expected seed yields and high costs. *Sterculia* could avoid some of those pitfalls if its hardy nature and low maintenance are confirmed. The present study, being one of the first of its kind for *Sterculia*, provides a baseline for what to expect financially and technically. It suggests that *Sterculia* deserves further consideration and possibly pilot trials to firm up data on cultivation and processing.

4. Conclusion

The technical feasibility of producing biodiesel from *Sterculia* is affirmed – the process can be executed with standard technologies, achieving high oil-to-biodiesel conversion and manageable energy consumption. The designed plant (capacity ~4.4 ton seeds/hour) would incorporate units for grinding, pressing, reacting, and separating, and can operate continuously with an energy-efficient setup. The economic analysis indicates that the study is borderline profitable, yielding a small but positive net present value. Key financial metrics (ROI ~19.7%, IRR ~9.1%) suggest that while the project could attract investment under certain conditions, it is sensitive to feedstock and product pricing. The largest cost driver is the raw seed supply, and the success of such a biodiesel facility hinges on securing inexpensive *Sterculia* feedstock and obtaining a favorable market price for biodiesel (or policy support like subsidies). The sensitivity analysis showed that a slight adverse change in these parameters could tip the project into unprofitability, whereas improvements (cheaper seeds, higher biodiesel price) greatly enhance viability.

Sterculia foetida presents an interesting opportunity as a second-generation biodiesel resource for Indonesia. The plant can be built on a reasonable budget and, if operated under the assumed conditions, can contribute to renewable fuel production with a competitive product. The final fuel product would have a market value in line with existing biodiesel and could help diversify feedstock sources beyond palm oil. However, to fully realize the potential, further steps should be taken, including implementing pilot-scale operations to gather real performance data, exploring improvements like integrating utility systems (e.g., waste heat boilers, more complete energy integration) and waste treatment, and evaluating policy mechanisms to buffer economic risks.

5. Future Recommendation

Studies could expand the model to include upstream and downstream segments (plantation management, logistics, glycerol upgrading) to provide a more holistic assessment. Ultimately, the research here demonstrates that while converting a novel feedstock like *Sterculia foetida* into biodiesel is technically straightforward, ensuring it is economically sustainable will require careful optimization and likely supportive measures. With appropriate refinements and strategic planning, *Sterculia* biodiesel could become a viable contributor to Indonesia's renewable energy portfolio, helping to meet energy needs and fossil fuel substitution goals in an environmentally conscious way.

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CRediT Authorship Contribution Statement

Bilqist Imeilia Az Zahra: Writing – review & editing, Writing – original draft, Visualization, Validation, H.C. Theofany: Teuku Meurah Indra Riayatsyah: Visualization, Formal analysis, Methodology. H.B. Aditiya; Supervision, Methodology, Validation. Bidattul S Zainal: Validation, Methodology.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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