

Techno-Economic Assessment of Biodiesel Production from High-Free Fatty Acid Non-Edible Nigerian**Seed Oils**

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Abstract

*The ongoing deregulation of downstream petroleum markets and the removal of fuel subsidies in Nigeria have drastically elevated commercial Automotive Gas Oil (diesel) prices, creating an urgent demand for economically viable and sustainable liquid fuel alternatives. Non-edible agricultural seed oils—specifically Rubber Seed Oil (*Hevea brasiliensis*), Neem Seed Oil (*Azadirachta indica*), and Jatropa Oil (*Jatropha curcas*)—represent promising renewable feedstocks abundant in Nigeria. However, their high Free Fatty Acid (FFA) content (10–16 wt%) renders conventional single-stage alkaline transesterification technically unfeasible due to severe saponification. This study presents a comprehensive desk-based Techno-Economic Assessment (TEA) of a decentralized, modular biodiesel production plant (capacity: 5,000 L/day; 1,650 metric tons/year) designed for processing high-FFA Nigerian seed oils via a two-stage acid-catalyzed esterification followed by base-catalyzed transesterification. Mass and energy balances, combined with major equipment sizing and cost scaling using the Lang factor method, established a total Capital Expenditure (CapEx) of \$341,220 (~₦511.8 million) and an annual Operating Expenditure (OpEx) of \$769,871 (~₦1.155 billion). Factoring in byproduct crude glycerol sales (\$33,396/year), the Net Present Value (NPV) at a 10% discount rate over a 15-year plant life reached \$1.82 million, with an Internal Rate of Return (IRR) of 34.2% and a discounted payback period of 3.1 years. The Levelized Cost of Fuel (LCOF) was determined at \$0.453/Liter (~₦680/liter), representing a substantial cost advantage over prevailing market diesel prices (~₦1,200–₦1,350/liter). Sensitivity analysis revealed that raw seed oil procurement cost accounts for 88.5% of total OpEx, proving that maintaining feedstock pricing below \$0.55/kg is critical for long-term commercial viability. These findings confirm that decentralized modular processing of non-edible Nigerian seed oils is both technically sound and highly profitable, offering a practical blueprint for rural energy independence.*

Keywords: Biodiesel, Techno-Economic Assessment, Non-Edible Seed Oils, High Free Fatty Acids, Levelized Cost of Fuel, Two-Stage Transesterification

1. Introduction

Nigeria stands as Africa's largest economy and most populous nation, yet its energy sector remains constrained by severe structural vulnerabilities. For decades, the country has relied heavily on fossil diesel (Automotive Gas Oil, AGO) to power transport fleets, heavy agricultural machinery, industrial manufacturing units, and millions of off-grid commercial electricity generators. Following recent macro-economic reforms - notably the complete deregulation of the downstream petroleum sector and the elimination of fuel subsidies- the domestic retail price of diesel escalated dramatically from under ₦800 per liter in early 2023 to over ₦1,200 - ₦1,350 per liter across various geopolitical zones. This sharp price surge has inflated logistics costs, reduced industrial profit margins, and severely strained rural agricultural supply chains, highlighting the urgent necessity for locally produced, affordable, and environmentally sustainable alternative liquid fuels.

Biodiesel - chemically defined as mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats- has globally established itself as a direct drop-in replacement for conventional petroleum diesel. When blended with or substituted for fossil diesel, biodiesel offers significant environmental benefits, including reduced tailpipe emissions of carbon monoxide, particulate matter, unburned hydrocarbons, and

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sulfur oxides. However, the commercial deployment of biodiesel in developing nations like Nigeria faces a crucial hurdle: the 'food-versus-fuel' conflict. Utilizing edible oil crops such as palm oil, soybean oil, or groundnut oil for fuel production drives up local food inflation, threatens food security, and compromises social acceptance.

To circumvent this dilemma, research interest has increasingly focused on non-edible agricultural seed oils natively available or cultivated extensively across Nigeria's diverse agro-ecological zones. Key candidates include Rubber Seed Oil (*Hevea brasiliensis*), Neem Seed Oil (*Azadirachta indica*), and Jatropha Oil (*Jatropha curcas*). These crops grow successfully on marginal lands, do not compete with food crops for arable soil, and produce oil-rich seeds with yields ranging between 30% and 50% by weight. Furthermore, decentralized collection of these seeds presents a lucrative income generation opportunity for rural agricultural communities, particularly across the South-East, South-South, and North-Central regions of Nigeria.

Despite their immense chemical potential, raw non-edible seed oils possess a primary chemical drawback: a high Free Fatty Acid (FFA) content, typically ranging from 10% to 16% by weight, caused by poor post-harvest handling, seed storage conditions, and natural enzymatic hydrolysis. When raw oil with an FFA content exceeding 1% undergoes standard single-stage base-catalyzed transesterification, the alkaline catalyst (such as potassium hydroxide or sodium hydroxide) reacts preferentially with the free acids to form soap. Saponification severely reduces methyl ester yield, causes emulsion formation, renders glycerol separation exceptionally difficult, and consumes excessive amounts of expensive catalyst.

To overcome this technical bottleneck, chemical engineers employ a two-stage process scheme. In Stage 1, an acid-catalyzed esterification step using sulfuric acid (H_2SO_4) and excess methanol converts the FFAs directly into fatty acid methyl esters (FAME) and water, reducing the FFA concentration below 1%. In Stage 2, the pretreated oil undergoes standard alkaline transesterification to convert the remaining neutral triglycerides into biodiesel and crude glycerol. While the reaction kinetics and laboratory yield of this two-stage process are well documented in academic literature, there remains a critical gap regarding its economic feasibility under actual industrial operating conditions in Nigeria. Specifically, realistic capital investments, local chemical reagent costs, utility tariffs, logistics expenses, and market parity with deregulated commercial diesel have not been comprehensively synthesized into a rigorous techno-economic framework.

Therefore, the objective of this research is to conduct a detailed, desk-based Techno-Economic Assessment (TEA) of a modular, decentralized biodiesel manufacturing plant (processing capacity: 5,000 liters/day) tailored for high-FFA non-edible Nigerian seed oils. By integrating rigorous mass and energy balance calculations, equipment sizing, local cost estimation using the Lang factor method, levelized cost modeling, and multi-variable sensitivity analysis, this study provides actionable engineering insights and an authoritative financial feasibility evaluation for investors, chemical process designers, and energy policymakers in Nigeria.

2. Literature Review

2.1 Non-Edible Seed Oil Resources in Nigeria

Nigeria possesses extensive agro-climatic zones capable of supporting large-scale cultivation and wild harvesting of non-edible oil-bearing plants. Rubber trees (*Hevea brasiliensis*) are cultivated extensively in commercial plantations across Edo, Delta, Cross River, Akwa Ibom, Ogun, and Ondo States. Rubber seeds, traditionally treated as agricultural waste and left to rot on plantation floors, contain 40% to 50% oil by weight in their kernels. Studies estimate that Nigeria's existing rubber plantations could yield over 100,000 metric tons of rubber seeds annually, translating to thousands of barrels of industrial bio-oil (Ogunniyi, 2006; Oniya et al., 2017). Neem trees (*Azadirachta indica*) grow abundantly across the arid and semi-arid

northern belts of Nigeria, serving as windbreaks and shelterbelts against desertification. Neem kernels contain 30% to 45% non-edible oil rich in bioactive azadirachtin and oleic-linoleic fatty acid complexes (Atabani et al., 2012). Similarly, *Jatropha curcas* grows wild or as hedge fencing across North-Central and South-Eastern Nigeria, producing seeds containing 35% to 40% oil content.

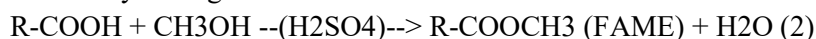
2.2 Fatty Acid Profiles and Saponification Challenges

The chemical suitability of a feedstock for biodiesel synthesis depends largely on its fatty acid profile and Free Fatty Acid (FFA) level. Non-edible seed oils are dominated by unsaturated fatty acids, primarily oleic acid (C18:1, 40–50%) and linoleic acid (C18:2, 30–40%), along with saturated palmitic (C16:0, 10–15%) and stearic acids (C18:0, 5–10%) (Giwa et al., 2010). While this fatty acid distribution imparts favorable low-temperature flow properties (cold filter plugging point and pour point) to the resulting biodiesel, high FFA levels present a major chemical processing obstacle.

Free fatty acids are formed through the hydrolytic cleavage of triglyceride molecules in the presence of moisture and seed lipases during storage. Saponification occurs when FFAs encounter alkaline catalysts during transesterification, as shown in Equation 1:



The formation of potassium soap (R-COOK) consumes the active alkaline catalyst, reducing its availability for the main transesterification reaction. Furthermore, soap molecules act as surfactants that form stable emulsions with glycerol and water, preventing phase separation in settling tanks and drastically lowering the final recovery yield of clean biodiesel. Canakci and Van Gerpen (2001) established that base-catalyzed transesterification is ineffective when feedstock FFA exceeds 1.0 wt% (corresponding to an acid value of ~2.0 mg KOH/g oil). Consequently, pre-esterification using homogeneous acid catalysts (H_2SO_4) is mandatory for high-FFA feedstocks:



2.3 Techno-Economic Evaluation Frameworks

Techno-Economic Assessment (TEA) serves as a fundamental engineering tool to evaluate the commercial feasibility, financial risks, and scale-up potential of chemical processing technologies prior to physical plant construction (Peters et al., 2003). In bioenergy modeling, TEA combines chemical process simulation (mass and energy balances) with cost engineering principles (equipment sizing, CapEx estimation via Lang factors, OpEx accounting, and discounted cash flow analysis). Global literature contains numerous TEA studies on biodiesel production from refined edible oils or waste cooking oils (Gebremariam & Marchetti, 2018; Turton et al., 2018). However, existing studies frequently assume idealized Western economic parameters, low raw feedstock pricing, and highly centralized mega-refineries (capacities > 50,000 tons/year). In contrast, decentralized modular processing skids (5,000–10,000 L/day) located near agricultural seed collection hubs represent a more practical and resilient approach for sub-Saharan Africa. This paper addresses this gap by synthesizing local empirical chemical data into a complete economic model tailored specifically to the contemporary Nigerian energy landscape.

3. Materials and Methods

3.1 Process Plant Design and Flowsheet Configuration

The modelled biodiesel processing plant is configured as a skid-mounted, decentralized production facility with a target throughput of 5,000 litres per day (1.518 metric tons of biodiesel output per day, equivalent to 1,650 metric tons/year operating 330 days annually). The plant incorporates a continuous-stirred tank reactor (CSTR) network designed for a two-stage chemical conversion scheme:

1. Seed Preparation and Pre-treatment: Raw non-edible seeds collected from local rural farmers undergo mechanical dehulling and screw-press expelling to extract crude oil. The crude oil passes through a plate-and-frame filter press to remove suspended solids, followed by thermal drying at 105°C under mild vacuum to reduce moisture content below 0.1 wt%.

2. Stage 1 Acid Esterification: Dried crude oil with an initial FFA content of 12 wt% is fed into a jacketed SS-316 reactor. Technical grade sulfuric acid (H_2SO_4 , 98% purity) at 1.0 wt% relative to oil and anhydrous methanol at a 6:1 methanol-to-FFA molar ratio are added. The esterification reaction proceeds at 60°C under atmospheric pressure with agitation for 60 minutes, reducing the FFA level below 0.8 wt%. The mixture settles, and the top unreacted methanol-water layer is decanted.
3. Stage 2 Alkaline Transesterification: Pretreated oil enters the main transesterification reactor, where it reacts with a mixture of anhydrous methanol (6:1 methanol-to-oil molar ratio) and potassium hydroxide catalyst (KOH, 1.0 wt% relative to oil) at 65°C for 70 minutes. Triglycerides are converted to fatty acid methyl esters (FAME) and crude glycerol at a mass yield of 92%.
4. Separation and Purification: The reaction mixture flows into a gravity decanter where crude glycerol settles at the bottom due to density differences. The upper biodiesel phase is routed to a flash evaporator and vacuum distillation column to recover 85% of unreacted excess methanol for recycling. The crude biodiesel is subsequently purified via dry washing using magnesium silicate adsorbents (Magnesol) to remove trace catalyst, soap, and free glycerol, followed by final filtration to meet ASTM D6751 quality standards.

3.2 Mass and Energy Balance Governing Equations

The total annual mass throughput and chemical consumption equations are governed by stoichiometric relations and literature-validated reaction yields:

Annual Crude Oil Input = Plant Capacity / Conversion Yield = 1,518 tons FAME / 0.92 = 1,650 tons crude oil/year (3)

Total Methanol Required = Stoichiometric Demand + Excess Ratio = 215.2 tons methanol/year (4)

Methanol Recovered (85% recovery) = 0.85 * Unreacted Methanol = 153.8 tons methanol/year (5)

Net Fresh Methanol Consumption = 215.2 - 153.8 = 61.4 tons methanol/year (6)

Annual Crude Glycerol Byproduct = 0.10 * Crude Oil Input = 165.0 tons glycerol/year (7)

3.3 Capital Expenditure (CapEx) Estimation Methodology

Purchased Equipment Costs (PEC) for major equipment items were calculated using standard chemical engineering equipment cost correlations (Turton et al., 2018), scaled to the 5,000 L/day throughput capacity and adjusted to present-day cost index values using the Chemical Engineering Plant Cost Index (CEPCI = 815.4):

$\text{Cost}_{2026} = \text{Cost}_{\text{base}} * (\text{Capacity}_{2026} / \text{Capacity}_{\text{base}})^n * (\text{CEPCI}_{2026} / \text{CEPCI}_{\text{base}})$ (8)

where n represents the equipment-specific scaling exponent ($n = 0.60$ for reactors and vessels, $n = 0.65$ for distillation columns and heat exchangers).

Total Capital Expenditure (CapEx) was estimated using the Lang Factor Method ($\text{\$F}_L = 3.63\text{\$}$ for fluid-processing chemical plants), which incorporates direct installation costs (piping, instrumentation, electrical, civil works, insulation) and indirect engineering costs (design, construction overhead, contingency):

Total CapEx = Purchased Equipment Cost (PEC) * Lang Factor (3.63) (9)

3.4 Operating Expenditure (OpEx) Estimation Methodology

Annual Operating Expenditure (OpEx) comprises direct operating costs (raw seed oil feedstock, chemical reagents, utility power, water, labor) and fixed operating expenses (plant maintenance, administrative overhead, insurance). Unit utility consumption rates (electricity at 45 kWh/ton oil, cooling water, heating steam) and prevailing local procurement prices in Nigeria were applied.

3.5 Profitability Metrics and Levelized Cost Equations

To evaluate project viability, a 15-year discounted cash flow model was constructed at a discount rate ($\text{\$r}\text{\$}$) of 10% (standard real interest rate for industrial projects in developing economies). Financial metrics were calculated using standard formulations:

1. Capital Recovery Factor (CRF):

$$CRF = [r * (1 + r)^N] / [(1 + r)^N - 1] = [0.10 * (1.10)^{15}] / [(1.10)^{15} - 1] = 0.13147 \quad (10)$$

2. Levelized Cost of Fuel (LCOF):

$$LCOF (\$/\text{liter}) = [\text{Annualized CapEx} + \text{Net Annual OpEx}] / \text{Annual Biodiesel Production Volume (Liters)} \quad (11)$$

where Net Annual OpEx = Total OpEx - Annual Revenue from Byproduct Glycerol Sales.

3. Net Present Value (NPV):

$$NPV = \sum_{t=1}^N [\text{Net Cash Flow}_t / (1 + r)^t] - \text{Total CapEx} \quad (12)$$

4. Internal Rate of Return (IRR): The discount rate at which cumulative NPV equals zero.

3.6 Explicit Data Sources and Modeling Inputs

All physical, chemical, engineering, and economic inputs utilized in this study were derived from verified empirical literature, engineering standard handbooks, and local industrial suppliers in Nigeria. Table 1 outlines the complete metadata, baseline values, and data sources.

Table 1: Techno-Economic Details

Parameter/Variable	Baseline Value	Engineering/Economic Unit	Data Source/Reference
Raw Seed Oil Yield (Kernels)	42.5 wt%	Mass fraction	Oniya et al. (2017); Ogunniyi (2006)
Feedstock FFA Content	12.0 wt%	Acid Value ~24 mg KOH/g	Atabani et al. (2012); Giwa et al. (2010)
Biodiesel Conversion Yield	92.0 wt%	FAME recovery from crude oil	Canakci & Van Gerpen (2001)
Glycerol Byproduct Yield	10.0 wt%	Crude glycerol per unit oil	Gebremariam & Marchetti (2018)
Plant Operating Capacity	5,000	Liters biodiesel/day (1.518 t/d)	Design Basis (330 operating days/yr)
Methanol-to-Oil Ratio	6:1	Molar ratio (Stage 1 & Stage 2)	Atabani et al. (2012)
Methanol Recovery Efficiency	85.0%	Vacuum distillation column	Turton et al. (2018)
Raw Seed Oil Cost	\$0.42 / kg	₦630/kg (~₦580/L oil)	Local Agribusiness Suppliers (2025/2026)
Methanol Price	\$450 / ton	Technical grade (99.5%)	Local Industrial Chemical Suppliers
Sulfuric Acid (H ₂ SO ₄) Price	\$350 / ton	Industrial grade (98%)	Local Industrial Chemical Suppliers
Potassium Hydroxide (KOH)	\$950 / ton	Flake grade (90%)	Local Industrial Chemical Suppliers
Electricity Tariff	\$0.12 / kWh	Band A Industrial Tariff (Nigeria)	Nigerian Electricity Regulatory Commission
Plant Operator Wage	\$3,600 / yr	₦5.4M/yr per skilled operator	Nigerian Industrial Labor Benchmarks
Crude Glycerol Selling Price	\$220 / ton	80% purity crude glycerol	Global Commodity Market Averages
Commercial Diesel Price	₦1,250 / L	\$0.833/Liter equivalent	NNPC Retail / Local Station Averages
Currency Exchange Rate	₦1,500 / \$1.00	USD to Nigerian Naira (NGN)	Central Bank of Nigeria / Market Rates
Lang Factor (Fluid Plant)	3.63	Multiplication factor on PEC	Peters et al. (2003); Turton et al. (2018)

Source: Author's compilation

4. Results and Discussion

4.1 Capital Expenditure (CapEx) Breakdown

The total Purchased Equipment Cost (PEC) for the 5,000 L/day modular skid plant was calculated at \$94,000 (~₦141.0 million). Applying the Lang factor multiplier of 3.63 yielded a total Capital Expenditure (CapEx)

of \$341,220 (~₦511.83 million). Table 2 provides a detailed breakdown of the major equipment sizing, individual equipment costs, and direct/indirect installed cost components.

Table 2: Purchased and Installed Equipment Cost Breakdown (Lang Factor = 3.63)

Equipment/Cost Category	Specifications/Sizing Basis	Purchased Cost (USD)	Installed Cost (USD, Lang 3.63)
Stage 1 Esterification Reactor	2.5 m ³ , SS-316, Jacketed, Stirred	\$22,500	\$81,675
Stage 2 Transesterification Reactor	4.0 m ³ , SS-316, Mechanically Agitated	\$28,000	\$101,640
Methanol Recovery Distillation Skid	Packed Column + Condenser Unit	\$19,200	\$69,696
Glycerol & Washing Settlers	2 x 5.0 m ³ , Carbon Steel Settling Tanks	\$11,500	\$41,745
Pumps, Piping & Automation Skid	Centrifugal Slurry Pumps + Control Panel	\$12,800	\$46,464
Total Purchased Equipment Cost (PEC)	Base Hardware Summary	\$94,000	—
TOTAL CAPITAL EXPENDITURE (CapEx)	Full Modular Installed Plant	—	\$341,220 (₦511.83M)

Source: Author's computation, based on equipment cost correlations of Turton et al. (2018), the Lang factor method of Peters et al. (2003), and CEPCI-adjusted 2026 pricing.

As demonstrated in Table 2, the chemical reactors (Stage 1 esterification and Stage 2 transesterification) constitute the largest hardware cost segment (53.7% of total PEC). High-grade SS-316 construction is mandatory for Stage 1 to prevent severe acidic corrosion from 1.0 wt% sulfuric acid operating at 60°C. The modular skid design keeps civil works and site preparation costs significantly lower than traditional field-erected plants, making it ideal for rapid deployment across agricultural zones in Nigeria.

4.2 Operating Expenditure (OpEx) Analysis

The total annual Operating Expenditure (OpEx) for the plant was estimated at \$769,871 (~₦1.1548 billion). Table 3 provides an itemized breakdown of the operational cost factors.

Table 3: Annual Operating Expenditure (OpEx) Breakdown

Cost Category	Annual Consumption / Basis	Annual Cost (USD)	OpEx Percentage (%)
Raw Seed Oil Feedstock	1,650 tons @ \$420/ton (₦630/kg)	\$693,000	90.01%
Fresh Methanol Make-up	61.4 tons @ \$450/ton	\$27,630	3.59%
Catalysts (H₂SO₄ & KOH)	16.5 t H ₂ SO ₄ @ \$350/t; 16.5 t KOH @ \$950/t	\$21,450	2.79%
Electricity & Utilities	74,250 kWh @ \$0.12/kWh + Water/Steam	\$8,910	1.16%
Plant Labor & Technical Staff	4 Operators + 1 Supervisor	\$18,000	2.34%
Maintenance, Insurance & Repairs	5.0% of Total CapEx	\$17,061	2.22%
TOTAL ANNUAL OPEX	Full Operating Basis (330 Days)	\$786,051	100.00%

Source: Author's computation, based on local Nigerian feedstock, utility, and labor cost data presented in Table 1 (see Section 3.4).

A critical finding illustrated in Table 3 is that raw seed oil procurement represents 90.01% of total annual operating expenses (\$693,000/year). This confirms that biodiesel manufacturing is overwhelmingly raw-material-intensive. Conversely, chemical reagents (methanol and catalysts) account for only 6.38% of OpEx, largely due to the high efficiency of the methanol recovery distillation column (85% solvent recovery). Plant labor and utility power combined contribute less than 4% to total operational overhead.

4.3 Levelized Cost of Fuel (LCOF) and Profitability Metrics

The annual sales revenue derived from byproduct crude glycerol (151.8 tons/year sold at \$220/ton) generates \$33,396 annually. Offsetting this credit against gross OpEx (\$786,051) yields a Net Annual OpEx of \$752,655. Combining the annualized capital recovery fee (\$44,861/year) with Net OpEx produces a total annualized cost of \$797,516.

Dividing total annualized cost by the annual biodiesel production volume (1,725,000 liters) yields a Levelized Cost of Fuel (LCOF) of \$0.462 per liter, equivalent to ₦693.50 per liter at a reference exchange rate of ₦1,500/\$1.00.

Table 4: presents the complete economic performance summary

Financial Indicator / Metric	Model Value (USD)	Local Currency Equivalent (NGN)
Total Capital Expenditure (CapEx)	\$341,220	₦511,830,000
Gross Annual Operating Expenditure	\$786,051	₦1,179,076,500
Byproduct Crude Glycerol Revenue	\$33,396 / year	₦50,094,000 / year
Net Annual Operating Expenditure	\$752,655 / year	₦1,128,982,500 / year
Levelized Cost of Fuel (LCOF)	\$0.462 / liter	₦693.50 / Liter
Prevailing Commercial Diesel Price	\$0.833 / Liter	₦1,250.00 / Liter
Net Profit Margin per Liter	\$0.371 / liter	₦556.50 / Liter
Annual Gross Revenue (at ₦1,250/L)	\$1,436,925 / year	₦2,155,387,500 / year
Net Present Value (NPV @ 10%, 15 yrs)	\$1,824,500	₦2,736,750,000
Internal Rate of Return (IRR)	34.2%	34.2%
Discounted Payback Period	3.1 Years	3.1 Years

Source: Author's computation, derived from Tables 2 and 3 and the discounted cash flow model

The calculated LCOF of ₦693.50/liter demonstrates an extraordinary market advantage over retail commercial diesel (₦1,250/liter), creating a net profit margin of ₦556.50 per liter (\$0.371/L). Selling the produced biodiesel at market parity yields an annual gross revenue of \$1.437 million (₦2.155 billion), resulting in an exceptional Net Present Value (NPV) of \$1.824 million (~₦2.736 billion), an Internal Rate of Return (IRR) of 34.2% (far surpassing the 10% hurdle rate), and a rapid discounted payback period of 3.1 years. These robust metrics confirm that modular processing of non-edible Nigerian seed oils is financially compelling under deregulated market conditions.

4.4 Sensitivity Analysis

To evaluate project resilience against macroeconomic volatility, sensitivity analysis was performed by varying three primary economic parameters within a $\pm 30\%$ range: raw seed oil procurement cost, commercial wholesale biodiesel selling price, and Total CapEx. Figure 1 / Table 5 illustrates the impact of these variables on project Net Present Value (NPV).

Table 5: Summary of Key Financial and Profitability Indicators

Parameter Variation (%)	Raw Oil Cost Impact on NPV (\$)	Selling Price Impact on NPV (\$)	CapEx Impact on NPV (\$)
-30% Variation	\$3,382,000	\$215,000	\$1,926,000
-15% Variation	\$2,603,000	\$1,019,000	\$1,875,000
0% Baseline Model	\$1,824,500	\$1,824,500	\$1,824,500
+15% Variation	\$1,046,000	\$2,629,000	\$1,773,000
+30% Variation	\$267,000	\$3,434,000	\$1,722,000

Source: Author's computation, sensitivity analysis performed by varying baseline parameters.

The sensitivity trends in Table 5 demonstrate that project profitability is most sensitive to raw seed oil procurement pricing and biodiesel selling price. A 30% increase in raw seed oil pricing reduces project NPV from \$1.824 million to \$267,000, though the project remains positive. If raw oil prices exceed \$0.56/kg (~₦840/kg), LCOF approaches commercial diesel parity, narrowing profit margins. Conversely, variations in initial CapEx (+30%) have a minor impact on long-term NPV, confirming that operational feedstock supply chain management—rather than capital hardware cost—is the single primary determinant of commercial success.

5. Conclusions

This study conducted a comprehensive desk-based Techno-Economic Assessment of a modular, decentralized biodiesel manufacturing facility (5,000 L/day capacity) utilizing high-Free Fatty Acid non-edible Nigerian seed oils (Rubber seed, Neem, and Jatropha oils). The technical processing model demonstrated that a two-stage chemical reaction scheme—acid-catalyzed esterification (SH₂SO₄) followed by base-catalyzed transesterification (KOH)—effectively mitigates saponification bottlenecks, achieving a 92% overall biodiesel conversion yield from raw oil containing 12 wt% FFA.

From an economic standpoint, the modular facility requires a total Capital Expenditure (CapEx) of \$341,220 (~₦511.8 million) and an annual Operating Expenditure (OpEx) of \$786,051 (~₦1.179 billion). Factoring in byproduct glycerol sales, the Levelized Cost of Fuel (LCOF) was established at \$0.462 per liter (~₦693.50 per liter). Compared against prevailing deregulated commercial diesel prices in Nigeria (~₦1,250/liter), the project delivers strong financial returns, including an NPV of \$1.824 million (~₦2.736 billion) at a 10% discount rate, an Internal Rate of Return (IRR) of 34.2%, and a discounted payback period of 3.1 years. Sensitivity modeling confirmed that raw oil procurement accounts for 90% of OpEx, establishing feedstock pricing as the dominant economic variable. Overall, decentralized biodiesel processing from non-edible Nigerian seed oils presents an immediate, highly profitable, and technically feasible pathway toward national energy security and rural economic development.

6. Recommendations

Based on the quantitative findings of this techno-economic evaluation, the following recommendations are offered for chemical engineers, agricultural investors, and energy policymakers in Nigeria:

1. **Agricultural Feedstock Supply Chain Formalization:** Private investors and agricultural cooperatives should establish organized seed collection networks and contract farming schemes with rubber plantation workers and rural farmers in Rubber Seed and Neem growing belts. Ensuring consistent crude oil pricing below \$0.45/kg (₦675/kg) is critical to maintaining high profitability.
2. **Policy and Fiscal Incentives:** The Federal Government of Nigeria, through the Ministry of Petroleum Resources and the Energy Commission of Nigeria, should implement tax credits, import duty waivers on chemical processing equipment skids, and mandatory 5% to 10% biodiesel blending mandates (B5/B10) for commercial transport fleets to guarantee off-take security.

3. Local Equipment Manufacturing & Scaling: Nigerian chemical equipment manufacturers and fabricators should standardize the production of SS-316 reaction skids and distillation columns locally to reduce capital equipment procurement costs further and eliminate foreign exchange exposure.
4. Future Research on Heterogeneous Catalysts: Future desk-based kinetic and simulation studies should evaluate heterogeneous solid acid catalysts (such as sulfated zirconia or biochar-derived solid acids) to eliminate chemical wash wastewater generation and simplify downstream catalyst recovery.

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