Jurnal IPTEK Bagi Masyarakat, Vol. 5, No. 3, (2026), 688-698 e-ISSN: 2807-7253
Doi: https://doi.org/10.55537/j-ibm.v5i3.1652 p-ISSN: 2807-7261

Integration of Energy Quality and Financial Feasibility in the Production of Oil Palm Frond Chips and Pellets

(Integrasi Kualitas Energi dan Kelayakan Finansial dalam Produksi Serpihan dan Pelet Daun Kelapa Sawit)

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Received: April 23, 2026 | Revised: April 29, 2026 | Accepted: April 30, 2026

Abstract: *Indonesia, as the world's largest palm oil producer, generates significant quantities of oil palm frond (OPF) biomass that remain underutilized. This study evaluates the technical characteristics and economic feasibility of converting OPF into energy products in the form of chips and pellets. Laboratory analyses including proximate, ultimate, and calorific value tests were conducted to assess fuel quality, followed by a techno-economic evaluation using a 15-year investment horizon and an 11% discount rate. Results show that pelletization improves fuel properties, particularly by reducing moisture content and increasing calorific value under actual conditions. The higher heating value (HHV) of pellets reached 3,962 kcal/kg under air-dry conditions, compared to 1,746 kcal/kg for chips. On a dry ash-free basis, the calorific values of both products were comparable, indicating that moisture content significantly influences actual energy performance. Economic analysis indicates that pellet production under coal price equivalence schemes does not achieve attractive financial returns, with internal rates of return (IRR) below the discount rate and payback periods exceeding project lifetime. Sensitivity analysis suggests that a selling price of Rp1,000,000 per ton or a calorific value above 5,300 kcal/kg is required to reach financial feasibility. In contrast, chip production with low calorific value is economically unviable; however, improving chip quality to 4,060 kcal/kg results in a financially feasible scenario, achieving an IRR of 32.3% and payback within four years. The findings highlight that product form, energy quality, and market pricing mechanisms critically determine the viability of OPF-based bioenergy development.*
Keywords: *Oil Palm Frond; Biomass Energy; Calorific Value; Coal Price Equivalence.*

Abstrak: *Indonesia sebagai produsen minyak sawit terbesar di dunia, menghasilkan biomassa daun kelapa sawit (OPF) dalam jumlah besar yang hingga kini belum dimanfaatkan secara optimal. Penelitian ini mengevaluasi karakteristik teknis dan kelayakan ekonomi pengolahan OPF menjadi produk energi berupa serpihan dan pelet. Analisis laboratorium termasuk uji proksimat, uji ultimate, dan uji nilai kalor dilakukan untuk menilai kualitas bahan bakar, diikuti dengan evaluasi tekno-ekonomi menggunakan cakrawala investasi 15 tahun dan tingkat diskonto 11%. Hasil menunjukkan bahwa proses peletisasi meningkatkan sifat bahan bakar, terutama dengan mengurangi kadar air dan meningkatkan nilai kalor pada kondisi aktual. Nilai kalor tinggi (HHV) pelet mencapai 3.962 kcal/kg pada kondisi kering udara, dibandingkan dengan 1.746 kcal/kg untuk serpihan. Pada basis kering bebas abu, nilai kalor kedua produk tersebut sebanding, menunjukkan bahwa kadar air secara signifikan memengaruhi kinerja energi aktual. Analisis ekonomi menunjukkan bahwa produksi pelet dalam skema kesetaraan harga batu bara tidak menghasilkan keuntungan finansial yang menarik, dengan tingkat pengembalian internal (IRR) di bawah tingkat diskonto dan masa pengembalian modal yang melebihi masa pakai proyek. Analisis sensitivitas*

menunjukkan bahwa harga jual sebesar Rp1.000.000 per ton atau nilai kalor di atas 5.300 kcal/kg diperlukan untuk mencapai kelayakan finansial. Sebaliknya, produksi serpihan dengan nilai kalor rendah tidak layak secara ekonomi; namun, peningkatan kualitas serpihan menjadi 4.060 kcal/kg menghasilkan skenario yang layak secara finansial, dengan mencapai IRR sebesar 32,3% dan masa pengembalian modal dalam waktu empat tahun. Temuan ini menyoroti bahwa bentuk produk, kualitas energi, dan mekanisme penetapan harga pasar sangat menentukan kelayakan pengembangan bioenergi berbasis OPF.
Kata kunci: *Daun Kelapa Sawit; Energi Biomassa; Nilai Kalor; Setara Harga Batu Bara.*

Introduction

Indonesia is the world's largest producer of oil palm, with a total plantation area reaching 16.38 million hectares (Directorate General of Plantations, 2023). The high production volume and vast plantation area result in a very large amount of biomass waste. One type of biomass waste that has not yet been optimally utilized is oil palm fronds. Oil palm frond waste is a by-product generated from the oil palm harvesting process and is often discarded or burned, which can cause environmental problems such as air pollution and a decline in soil quality (Sari et al., 2020).

Each hectare of oil palm plantation can produce around 10–13 tons of fresh fronds per year, equivalent to about 6.3 tons of dry fronds (Hambali et al., 2021). With a plantation area in North Sumatra reaching 1.6 million hectares, the potential of dry oil palm frond waste is around 10 million tons per year. With appropriate technology, this waste can be converted into a renewable energy source that helps reduce carbon emissions and provides a more environmentally friendly energy alternative. These efforts support the achievement of the Net Zero Emission (NZE) target and the Forest and Other Land Use (FOLU) Net Sink 2030 policy.

Oil palm fronds, as plantation waste, have the potential to be converted into fuels in the form of chips, sawdust, and pellets. Densifying biomass into pellets is one of the commonly applied strategies to improve the quality of solid fuels, particularly in terms of energy density, ease of storage, and transportation efficiency. Munawar and Subiyanto (2014) reported that oil palm fronds are easier to form into biopellets than other types of oil palm waste (such as empty fruit bunches, shells, and mesocarp), and that their calorific value increases when the pelleting temperature is raised to 250 °C. Another study by Sonjaya et al. (2025) showed that the calorific value of oil palm frond waste in the form of 40-mesh sawdust, which is 4220.84 kcal/kg, increases to 4229.72 kcal/kg after further processing into pellets. Although there is an increase in calorific value, the difference obtained is relatively small; therefore, the effectiveness of the densification process needs to be further analyzed not only from a technical perspective but also from the economic feasibility of the process.

The quality of the biomass pellets produced is strongly influenced by production process parameters, which ultimately determine the economic feasibility of their development. Research by Herzallah et al. (2025) shows that pellet production from oil palm waste has a reasonably viable economic prospect, with an estimated annual profit of around USD 41,000, a payback period of 2.4 years, and a return on investment of 36%. These findings are based on the assumption of pellet production from various oil palm wastes, including palm leaves, fronds, and empty fruit bunches. Operationally, pellet production from oil palm frond waste involves several stages, including raw material collection, drying, chipping, grinding, binder mixing, and pelletizing. Each stage requires energy input and operational costs that contribute to the overall production cost structure. The addition of a binder is also an important factor in improving the consistency of pellet density and mechanical strength, but it has implications for production costs and potential changes in combustion characteristics. Therefore, it is necessary to analyze how the choice of final product form affects the economic feasibility of developing bioenergy from oil palm waste.

Despite numerous studies on oil palm biomass utilization, most existing research predominantly focuses on either technical fuel characteristics or general economic performance, without explicitly integrating both aspects. In particular, limited studies evaluate how variations in energy quality parameters, such as calorific value (HHV), directly influence key financial indicators, including Internal Rate of Return (IRR) and payback period. This lack of integration creates a gap in understanding the techno-economic viability of specific biomass products derived from oil palm fronds.

Referring to the above explanation, this study addresses the research gap related to the integration between technical production parameters and economic feasibility analysis. This research specifically selects oil palm fronds as the main raw material and focuses on analyzing the fuel quality of oil palm fronds in the form of chips and pellets, as well as evaluating their implications for production feasibility. The objectives of this research are to compare the fuel quality of oil palm frond waste in the form of chips and pellets and to analyze the economic feasibility of developing a biomass energy business utilizing oil palm frond waste in these two forms.

Methods

The study area in this research is the potential utilization of oil palm frond waste in North Sumatra Province, which has an oil palm plantation area and crude palm oil production covering 1,357.23 thousand hectares, the fifth largest in Indonesia (BPS, 2025). The research began in January 2025, followed by sample collection, sample preparation, and analytical processes, which were carried out until December 2025. This study was conducted following the research procedure flow as presented in Figure 1.

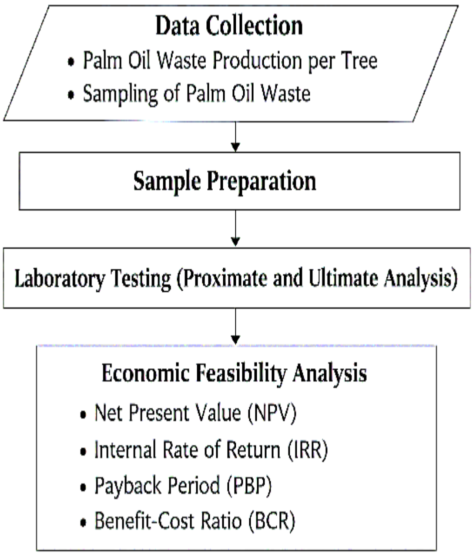

Figure 1. Research Workflow

Sample Preparation

The process begins with the collection of oil palm frond waste, which is then dried to reduce moisture content and improve fuel quality. Subsequently, the fronds are chipped into sizes of approximately 1–5 cm. Chipping is often performed before drying to enhance field operation efficiency. The dried oil palm fronds chips serve as Sample 1 for laboratory testing. The remaining chips are then ground into sawdust as a densification step. The sawdust is mixed with tapioca binder at varying compositions of 5–10% (w/w) and pressed to produce biomass pellets. The resulting pellets are used as Sample 2 for laboratory testing. Details of the sample preparation process are explained in Figure 2.

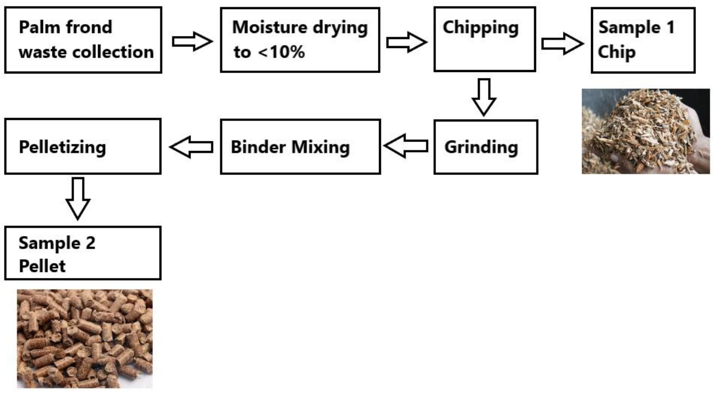

Figure 2. Sample Preparation Process

Laboratory Testing

In the context of the biomass energy supply chain, chips and biomass pellets are two distinct forms of solid fuels. In this study, biomass chips are the direct result of chipping oil palm frond waste without further densification, whereas biomass pellets are densified products produced through high-pressure compression, resulting in uniform cylindrical shapes (Rimantho et al., 2023).

Testing of the characteristics of the oil palm frond waste chip and pellet samples was conducted through proximate, ultimate, and calorific value analyses. Proximate analysis includes moisture content, volatile matter, ash content, and fixed carbon; ultimate analysis measures the elemental composition of C, H, O, N, and S; and thermal testing involves calorific value determination. The laboratory test results for both samples will be compared against Indonesian National Standard (SNI) specifications for biomass fuels, serving as the basis for economic analysis calculations.

Data validation was performed by calculating standard deviation for each measured parameter to assess the consistency of the results. The relative standard deviation (RSD) was maintained within an acceptable range (<5%), indicating good repeatability of the experimental measurements.

Economic Feasibility Analysis

This stage is a follow-up planning phase, where the analysis is conducted to estimate or predict the investment feasibility of utilizing oil palm frond waste as biomass energy. The data required for this analysis consist of primary and secondary data. Primary data include the productivity of available oil palm frond waste feedstock at the study location and the resulting fuel quality based on laboratory test results. Secondary data, used as basic assumptions for the economic analysis, will be obtained from literature studies.

Table 1. Technical Assumptions

Category	Parameter	Unit	Value	Source
Plantation	Oil palm plantation area	ha	1000	Primary Data
	Harvested frond area	ha day^{-1}	100	
	Tree density	trees ha^{-1}	140	
	Fronds per tree	fronds tree^{-1}	2	
	Frond weight	kg frond^{-1}	3	
	Frond waste production	ton day^{-1}	84	
Factory	Production capacity	ton h^{-1}	0.3	Estimate
	Operating hours	h day^{-1}	8	
	Number of shifts	shift day^{-1}	2	
	Pellet yield	%	80	Simangunsong et al. (2017)
	Chips yield	%	90	

Category	Parameter	Unit	Value	Source
	Electricity requirement	kWh ton^{-1}	100	
	Manpower Requirement			
	Manager	person shift^{-1}	1	
	Chips operator	person shift^{-1}	1	
	Pellet operator	person shift^{-1}	2	
	Packaging operator	person shift^{-1}	1	

Table 2. Financial Assumptions

Parameter	Unit	Value	Source
Factory investment costs			
Dryer/oven	Rp	467,291,500	
Pulverizing (0.3 ton h^{-1} capacity)	Rp	328,950,165	Simangunsong et al. (2017)
Cleaning (0.3 ton h^{-1} capacity)	Rp	13,795,854	
Pelleting, cooling, and packaging	Rp	678,781,942	
Inventory	Rp	6,645,327	
Building	Rp	300,529,409	
Production costs			
Electricity price	Rp kWh^{-1}	972	
Packaging	Rp ton^{-1} pellet	25,000	Simangunsong et al. (2017)
Raw material price	Rp ton^{-1} frond	202,355	Alamsyah & Supriatna (2018)
Binder	Rp ton^{-1} pellet	25,000	
Manager wages	Rp month^{-1}	4,000,000	Disnaker Sumut (2026)
Operator wages	Rp month^{-1}	3,000,000	
Administration wages	Rp month^{-1}	3,000,000	

The selling prices for oil palm frond chips and pellets in this study are set based on the domestic market approach, targeting use as co-firing fuel in coal-fired steam power plants (PLTU). Price determination references the maximum biomass price calculated by adjusting calorific value equivalence to the PLN Domestic Market Obligation (DMO) coal price limit of USD 70/ton at 6,322 kcal/kg (Katherine & Swastika, 2025).

Results

Fuel Characteristics

The proximate analysis results for oil palm frond chips and pellets are presented in Table 3, which includes moisture content, volatile matter, fixed carbon, and ash content as key indicators of biomass fuel quality.

Table 3. Proximate Test Results

Parameter	Unit	SNI 8675:2018	Air-Dry Basis	
			Pellet	Chip
Fixed carbon	wt%	≥ 14	13,7	7,8
Volatile matter	wt%	≤ 80	75,1	28,7
Ash content	wt%	≤ 3	1,2	1,3
Moisture content	wt%	≤ 12	10	62,2

The results show that pellets have better fuel characteristics than chips. The moisture content of pellets at 10% meets the SNI 8675:2018 standard (≤12%), whereas chips have a very high moisture content of 62.2%, far exceeding the standard limit. This indicates that the densification process is effective in reducing moisture content, which directly affects combustion efficiency. The fixed carbon content in pellets (13.7%) is higher than that in chips (7.8%) and approaches the minimum standard limit (≥14%), indicating the potential for more stable combustion. The volatile matter content in pellets (75.1%) remains within the standard range (≤80%), while chips have a significantly lower value (28.7%), indicating differences in thermal decomposition characteristics. The ash content in both samples is relatively low and meets the standard, namely 1.2% for pellets and 1.3% for wood chips, indicating minimal combustion residue potential.

The results of the ultimate analysis presented in Table 4 show the composition of the fuel's major elements.

Table 4. Ultimate Test Results

Parameter	Unit	Air-Dry Basis	
		Pellet	Chip
Carbon (C)	wt%	43,10	18,20
Hydrogen (H)	wt%	5,60	2,40
Nitrogen (N)	wt%	0,50	0,27
Oxygen (O)	wt%	39,49	15,49
Sulfur (S)	wt%	0,04	0,03
Chlorin (Cl)	wt%	0,01	0,16
Ash	wt%	1,20	1,30
Moisture content	wt%	10,00	62,20
Total	wt%	100	100

Pellets have a significantly higher carbon content (43.10%) compared to chips (18.20%), indicating an increase in energy density following the densification process. The hydrogen content in pellets (5.60%) is also higher than in chips (2.40%), contributing to the increased calorific value. The oxygen content in pellets (39.49%) is higher than in chips (15.49%), while the nitrogen and sulfur contents in both samples are relatively low (<0.5%), potentially resulting in lower exhaust gas emissions. A striking difference is seen in the chlorine content, where chips have a higher value (0.16%) compared to pellets (0.01%). The reduction in chlorine content in pellets indicates a lower potential for corrosion and fouling issues in combustion systems.

The calorific values of the fuels are presented in Table 5, including the Higher Heating Value (HHV) and Lower Heating Value (LHV) on an air-dry and dry ash-free basis.

Table 5. Calorific Value Test Results

Parameter	Unit	SNI 8675:2018	Air-Dry Basis		Dry Ash-Free	
			Pellet	Chip	Pellet	Chip
Higher Heating Value (HHV)	kcal/kg	-	3.962	1.746	4.200	4.060
Lower Heating Value (LHV)	MJ/kg	>16,5	16,59	7,31	17,58	17,00

On an air-dry basis, pellets have an HHV of 3,962 kcal/kg, which is significantly higher than that of wood chips at 1,746 kcal/kg. This difference is primarily due to the high moisture content in wood chips, which reduces their effective energy value. The LHV of pellets at 16.59 MJ/kg meets the SNI standard (>16.5 MJ/kg), whereas wood chips only reach 7.31 MJ/kg, thus failing to meet the standard for direct fuel use. However, under dry ash-free conditions, the HHV values between pellets (4,200 kcal/kg) and wood chips (4,060 kcal/kg) are relatively not significantly different. This indicates that the intrinsic energy content of the biomass is similar, and differences in energy performance are primarily influenced by moisture content and the densification process.

Economic Feasibility

The investment and operational cost components for chip and pellet production over a 15-year period are presented in Table 6.

Table 6. Oil Palm Frond Pellet and Chip Business Investment Cost Components (15-Year Period)

No.	Cost Components	Unit	Pellet	Chip
A	Initial Investment Costs			
A.1	Dryer/Oven	Rp	467.291.500	467.291.500
A.2	Pulverizing	Rp	328.950.165	328.950.165
A.3	Cleaning	Rp	13.795.854	13.795.854
A.4	Pelleting, cooling, and packaging	Rp	678.781.942	0
A.5	Inventory	Rp	6.645.327	6.645.327
A.6	Building	Rp	300.529.409	300.529.409
	Total Investment (A)	Rp	1.795.994.197	1.117.212.255
B.	Fixed Costs			
B.1	Depreciation	Rp	992.546.307	540.025.013
B.2	Maintenance (O&M)	Rp	359.198.839	223.442.451
B.3	Labor Wages	Rp	3.840.000.000	1.480.000.000
	Total Fixed Costs (B)	Rp	5.191.745.147	2.243.467.464
C.	Operating Costs			
C.1	Raw Materials	Rp	2.913.909.120	3.205.300.032
C.2	Electricity	Rp	1.399.680.000	1.399.680.000
C.3	Binder	Rp	360.000.000	0
	Total Operating Costs (C)	Rp	4.673.589.120	4.604.980.032
	Grand Total Costs (A+B+C)		11.661.328.464	7.965.659.751

The total initial investment for pellet production is Rp 1.79 billion, which is higher than that for chips at Rp 1.12 billion. This difference is primarily due to the need for additional equipment in the pelletization process. Fixed costs for pellet production are also higher (Rp 5.19 billion) compared to chips (Rp 2.24 billion), driven by higher labor costs and depreciation. Meanwhile, the operational costs of both systems are relatively comparable, at Rp 4.67 billion for pellets and Rp 4.60 billion for chips. Overall, the total production cost for pellets (Rp 11.66 billion) is higher than that for chips (Rp 7.97 billion), indicating that the pelletization process is more capital-intensive.

The results of the financial feasibility analysis are presented in Table 7, with key indicators including the Payback Period (PBP), Internal Rate of Return (IRR), Net Present Value (NPV), and Benefit-Cost Ratio (BCR).

Table 7. Financial Feasibility Results for Oil Palm Frond Pellet and Chip Business

Parameter	Unit	Pellet	Pellet	Chip	Chip
Calorific Value	kcal/kg	3.962	4.200	1.746	4.060
Selling Price	Rp/ton	739.759	784.197	326.002	758.057
Total Revenue	Million (Rp)	10.652	11.292	4.694	10.916
Total Revenue (Pre – Tax)	Million (Rp)	787	1.427	-2.154	4.067
Total Revenue (After – Tax) (10%)	Million (Rp)	708	1.284	-1.938	3.660
PBP	Year	25,4	14	Not Feasible	3,1
IRR	%	-5,9	0,9	Not Feasible	32,3

Parameter	Unit	Pellet	Pellet	Chip	Chip
NPV	Million (Rp)	509	923	Not Feasible	2.632
BCR		0,06	0,1	Not Feasible	0,48

For pellet production, the financial feasibility yields limited results. Under low calorific value conditions, the project is not viable with an IRR of −5.9% and a PBP of 25.4 years. Under higher calorific value conditions, financial performance improves with an IRR of 0.9% and a PBP of 14 years, though it remains relatively low. Conversely, chip production results are highly dependent on calorific value. Under low calorific value conditions, the project is not financially viable. However, under high calorific value conditions, chip production becomes highly profitable with an IRR of 32.3%, a PBP of 3.1 years, and a positive NPV of Rp 2.63 billion. These results indicate that economic viability is strongly influenced by the quality of the fuel, particularly the calorific value, which determines the selling price and revenue.

Discussion

Fuel Characteristics

Proximate analysis results for both samples indicate that oil palm frond waste biomass pellets have superior physical fuel characteristics compared to chips. This is due to particle size reduction and densification during pelleting, yielding more uniform and dense fuel. Table 3 provides a detailed comparison of proximate test results for chip and pellet samples against SNI standards.

On an Air-Dry Basis (ADB) which accounts for actual biomass moisture and better reflects real-world fuel performance oil palm frond chips exhibited very high moisture content at 62.2%. Additionally, fixed carbon at 7.8% was below the minimum standard threshold, indicating low solid carbon fraction for sustaining combustion. Volatile matter at 28.7% fell within standard range, though relatively low values suggest limited combustion reactivity (Kamga et al., 2024). Oil palm frond pellets showed improved fuel quality over chips, with moisture at 10.0%, ash at 1.2%, and volatiles at 75.1%, all meeting SNI requirements. However, fixed carbon at 13.7% remained slightly below the SNI minimum. Fixed carbon is a primary indicator of combustion duration and stability; lower values can lead to shorter burn times.

The low fixed carbon in both samples relates to the chemical characteristics of oil palm fronds as feedstock. Fixed carbon is influenced by lignin content, as lignin provides thermal stability and forms char during burning. This indicates that while pelleting enhances physical and proximate qualities, raw material chemistry limits fixed carbon achievement. Ultimate analysis results detailing chemical composition of pellets and chips are presented in Table 4.

Ultimate analysis results in Table 4 show that the chemical elemental composition of oil palm frond biomass pellets better supports fuel use compared to chips. This is evidenced by carbon (C) content in pellets reaching 43.10 wt%, significantly higher than chips at 18.20 wt%. Carbon is the primary contributor to heat energy formation during combustion, so higher carbon generally correlates with improved fuel energy quality.

Hydrogen (H) content in pellets (5.60 wt%) is also higher than in chips (2.40 wt%). Hydrogen boosts calorific value through oxidation reactions that generate additional energy during burning. Conversely, oxygen (O) content inversely correlates with calorific value, as intrinsic oxygen indicates pre-oxidized states that reduce combustion energy potential (Moreira et al., 2022). In this study, pellets had 39.49 wt% oxygen, higher than chips at 15.49 wt%. The differing C, H, and O ratios between pellets and chips reflect energy quality variations, confirmed by calorific value tests in Table 5. Overall, the higher carbon and hydrogen in pellets contribute to their superior calorific value over chips.

Nitrogen (N), sulfur (S), and chlorine (Cl) levels in both samples are relatively low. These elements are critical due to their potential to form polluting gas emissions during combustion. Low N and S concentrations indicate reduced NOx and SOx emissions, while low Cl minimizes corrosion risk in energy conversion equipment.

Oil palm fronds in pellet form exhibit better energy quality than chips, evidenced by higher calorific values on both Dry Ash-Free (DAF) and Air-Dry Basis (ADB). The difference is most pronounced on ADB, with a significant gap between pellets and chips. Pellets achieve a higher heating value (HHV) of 3,962 kcal/kg, while chips reach only 1,746 kcal/kg. Chips' low calorific value stems primarily from very high moisture content (62.2%), far exceeding SNI maximum limits. High moisture diverts combustion energy to evaporation, reducing net usable energy (Scott et al., 2025). On DAF basis—eliminating moisture and ash effects—calorific values rise, with a smaller gap: 4,200 kcal/kg for pellets and 4,060 kcal/kg for chips. This indicates similar organic energy content in both, derived from the same feedstock. Thus, actual energy quality differences are predominantly driven by moisture variation. These findings align with Ismail et al. (2023), who noted moisture's strong influence on biomass fuel calorific value.

Economic Feasibility

Field interviews revealed each oil palm tree yields ~3 kg wet frond biomass per harvest cycle. Assuming 50% drying yield, ~1.5 kg dry biomass per tree is available. This parameter underpins raw material needs for pellet and chip business scenarios. For pellet production at 0.3 ton/hour capacity and 16 hours/day operation, daily output targets 4.8 tons. With 80% pelleting yield, feedstock needs are ~6 tons dry biomass (equivalent to 12 tons wet) daily. At 140 trees/ha density, this equates to ~4,000 trees or ~29 ha plantation area..

For chip production, no densification occurs, so mass loss during processing is minimal. Analysis assumes 90% yield from dry biomass. With identical capacity (0.3 ton/hour, 16 hours/day), chips involve simpler flow and lower equipment investment than pellets. However, lower energy quality results in reduced selling price versus pellets. Table 6 compares investment cost components for pellet and chip production from frond waste over a 15-year project period.

Pellet selling price estimation uses an energy equivalence approach against coal fuel for power plants, via calorific value comparison (Katherine & Swastika, 2025). This proportionally ties product price to generated energy quality, so higher calorific value yields higher selling price. Based on test results, oil palm frond pellet prices are estimated at Rp 739,759 per ton on Air-Dry Basis (ADB) to Rp 784,197 per ton on Dry Ash-Free (DAF). Chips range from Rp 326,002 per ton (ADB) to Rp 758,057 per ton (DAF). The price range difference highlights how densification improves energy quality and economic value potential. Financial feasibility analysis for both scenarios, using these price assumptions and 11% annual discount rate, is presented in Table 7.

Financial feasibility analysis reveals that oil palm frond pellet production, even meeting SNI standards, does not yield attractive investment returns when sold to PLN via energy equivalence pricing against coal. At 3,962 kcal/kg calorific value, the venture fails feasibility criteria: IRR falls below the 11% discount rate, and payback exceeds the project life. Raising energy quality to 4,200 kcal/kg marginally improves financial performance. Under this condition, breakeven occurs at project end (year 15) with very low IRR (<1%). These results indicate that calorific improvements boost selling price and revenue but fail to offset high pellet production investment and operating costs. Findings align with Pantaleo et al. (2020), who identified investment costs and market prices as dominant factors in pellet production economics. Project profitability is highly sensitive to selling price fluctuations and input cost structures, even at relatively large scale.

Further sensitivity analysis shows that achieving more attractive feasibility requires higher pellet selling prices. At Rp 1,000,000 per ton, financial indicators improve markedly: payback in year 5, IRR of 21.5%, and positive NPV of Rp 2.9 billion. This scenario renders the pellet business financially viable if selling prices rise significantly above coal equivalence pricing. Two strategies could achieve this price level: (1) targeting non-PLN markets willing to pay premiums, such as industries needing premium biomass fuel or export markets; or (2) enhancing pellet energy quality to ~5,356 kcal/kg, equivalently yielding Rp 1,000,000 per ton under energy equivalence. This aligns with Ebadian et al. (2021), who emphasized that in advanced economy pellet supply chain studies, product price and energy quality critically determine profitability—especially relative to production and distribution costs.

For the oil palm frond chip production scenario with actual calorific value of 1,746 kcal/kg, selling price is very low under coal energy equivalence pricing. This results in revenue insufficient to cover operating costs. Despite lower initial investment than pellets, financial feasibility remains unachieved due to poor product selling price. However, improving chip quality to 4,060 kcal/kg significantly boosts selling price and business revenue. Under this condition, chip production becomes financially viable with IRR of 32.3%, positive NPV, and short payback period in year 4. These findings demonstrate that for low-investment biomass products like chips, energy quality enhancements yield greater economic feasibility impact.

Conclusion

This study confirms that integrating energy quality analysis with financial feasibility provides a more comprehensive assessment of oil palm frond potential as solid fuel. Under coal equivalence pricing, pellet production lacks attractive returns, while chips show viability potential at higher calorific values. Energy quality improvements via moisture control and market expansion beyond coal pricing schemes are needed for greater competitiveness and sustainability. Thus, renewable energy fuel development faces not only feedstock supply consistency challenges but also market support and pricing structure limitations that hinder investment sustainability.

Acknowledgments

The author would like to express gratitude to all parties who provided support for the conduct of this research, whether in the form of facilities, technical assistance, or contributions to data collection and processing. Special appreciation is extended to the institutions and laboratories that facilitated the testing process, as well as to those who provided the primary and secondary data supporting the analysis in this study, thereby enabling the entire research process to be successfully completed.

Conflict of Interests

The authors declare that there are no conflicts of interest in this study, whether financial or non-financial, that could influence the results, interpretations, or conclusions presented in this article. The entire research process was conducted independently and objectively.

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