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Renewable Energy from Various Oil Palm Varieties in Penajam Paser Utara Regency, Indonesia

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Abstract

Oil palm has the potential to serve as a strategic energy source for the national energy transition. This study evaluates the potential of four oil palm varieties Sain, Lonsum, Dumpy, and Marihat in Penajam Paser Utara (PPU) Regency as sources of biodiesel, edible oil, and solid biomass. The methods applied include fat content analysis, fatty acid profile evaluation, and utilization scenarios based on 2023 production data of Fresh Fruit Bunches (FFB) and Crude Palm Oil (CPO). The results showed that the Lonsum and Sain varieties, which have high fat content and are predicted to be dominated by saturated fatty acids (palmitic and stearic acids) based on literature-reported fatty acid profiles, are most suitable for biodiesel production. In contrast, the Dumpy and Marihat varieties exhibited lower fat content but are predicted to contain higher proportions of unsaturated fatty acids (oleic and linoleic acids), making them more suitable for edible oil applications. The Dumpy variety also has lower moisture content, making it favorable for solid biomass applications. With proportional allocation and conversion of FFB waste into briquettes, the production potential is approximately ±41,200 tons of biodiesel, ±26,159 tons of edible oil, and ±115,104 tons of solid biomass annually. The total energy potential reaches approximately ±3.49 million GJ per year. These findings indicate significant opportunities for the development of self-sufficient energy agroindustry based on oil palm to support energy security and sustainable development in the buffer zones of Indonesia's new capital city (IKN).

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1. Introduction

The increasing energy demand and global climate change have encouraged countries to transition towards sustainable and environmentally friendly renewable energy sources (Setyono & Kiono, 2021). Indonesia possesses unique and abundant natural resources that can drive its national development.

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The agricultural sector currently serves as one of the primary sectors and is naturally interconnected with other sectors such as transportation and households in fulfilling its energy needs (Rhofia, 2022).

In Indonesia, the agricultural sector plays a strategic role in supporting these efforts, particularly through the development of Energy Smart Agriculture (ESA). The ESA integrates technology and precision agriculture to optimize resource efficiency and reduce dependence on fossil energy (Seminar et al., 2023). This potential has become increasingly relevant considering that Indonesia is one of the world's leading producers of oil palm, which can be utilized as a key raw material for renewable energy, such as biodiesel and biomass (Hariyadi & Jelita, 2024).

The agricultural sector can produce food, building materials, clothing, and energy, thus supporting the development of self-sufficient agroindustrial zones (Prastowo). The preliminary design of the agroindustrial zone begins with an analysis of the energy potential of oil palm fruit. In addition to being an export and food commodity, palm oil plays a strategic role as a raw material for biodiesel and biomass production (Hariyadi & Jelita, 2024).

Chemical quality, particularly fatty acid composition, determines the potential use of palm oil as feedstock for energy or food applications. Oils with higher saturated fatty acid contents, such as palmitic and stearic acids, tend to exhibit greater oxidative stability and are more suitable for biodiesel production (Knothe, 2010), whereas oils rich in unsaturated fatty acids, such as oleic acid, are more appropriate for human consumption because of their better health effects (Atabani et al., 2012; Sujadi et al., 2016).

Understanding the fatty acid profile of each palm oil variety is essential to determine the most appropriate utilization pathway (Mekhilef et al., 2011). In addition to quality, production availability is a key factor in the development of palm-based energy. The allocation of Crude Palm Oil (CPO) utilization should be based on varietal and chemical characteristics to strategically differentiate its use between the energy and food sectors, including the optimization of biomass waste.

The Penajam Paser Utara (PPU) Regency, located in East Kalimantan, is a strategic region directly adjacent to Indonesia's new capital city (IKN) (Andita et al., 2023). PPU has the potential for agroindustrial development distributed across several districts, such as Sepaku, Penajam, Waru, and Babulu, which can be designed as self-sufficient agroindustrial zones (Pratiwi et al., 2020). According to data from the PPU Agriculture Agency, the total area of palm oil plantations in the region exceeds 46,409.32 hectares, with total Crude Palm Oil (CPO) production from six major mills, reaching more than 130,794.17 tons per year (PPU Agriculture Agency, 2023). This potential is highly relevant for supporting the projected energy demand in the new capital city area, which is expected to exceed 20 million GJ per year, particularly in the transportation and industrial sectors (Bappenas, 2022; ESDM, 2023). Palm oil can be processed into biodiesel as a substitute for fossil fuels while simultaneously strengthening the national green energy transition strategy based on local resources.

These figures reflect the significant potential of national food supply and renewable energy production (Rhofita, 2022). Previous studies have emphasized the need for integrative strategies to combine food and energy orientations in oil palm governance (Mekhilef et al., 2011). Therefore, future palm oil utilization requires a data-driven approach that considers chemical quality, productivity, site potential, and policy scenarios. Such an approach is essential to ensure that palm oil allocation accounts not only for economic aspects, but also for energy sustainability and food security.

In this context, this study examined fat content and fatty acid profile to determine whether oil palm fruit is more suitable for food or renewable energy production. In addition to quality assessment, this study also analyzed the production potential of oil palm in the study area based on actual productivity and land area data. Based on these results, utilization scenarios with specific allocation proportions were formulated for direct palm oil usage for biodiesel production, biomass fuel, and food consumption.

Through this integrated approach, the findings of this study are expected to provide practical contributions to strategic decision-making, particularly in designing self-sufficient energy agroindustrial zones that support both food security and national energy transition. In general, the objective of this study is to provide a more comprehensive understanding of the utilization potential of various oil palm varieties (Sain, Lonsum, Marihat, and Dumpy) cultivated in Penajam Paser Utara Regency.

2. Materials and Methods

2.1 Research Methodology

The research workflow, which includes oil palm fruit sampling, measurement of fat and moisture contents, formulation of CPO utilization scenarios, and estimation of the energy potential for biodiesel, edible oil, and solid biomass, is illustrated in Figure 1. Fresh fruit bunch (FFB) samples from four oil palm varieties Sain, Lonsum, Dumpy, and Marihat were collected from plantations in Penajam Paser Utara Regency. The samples were analyzed for moisture content (gravimetric method) and fat content (Soxhlet extraction using n-hexane). The data were analyzed using ANOVA and DMRT, along with descriptive analysis for fruit color and weight.

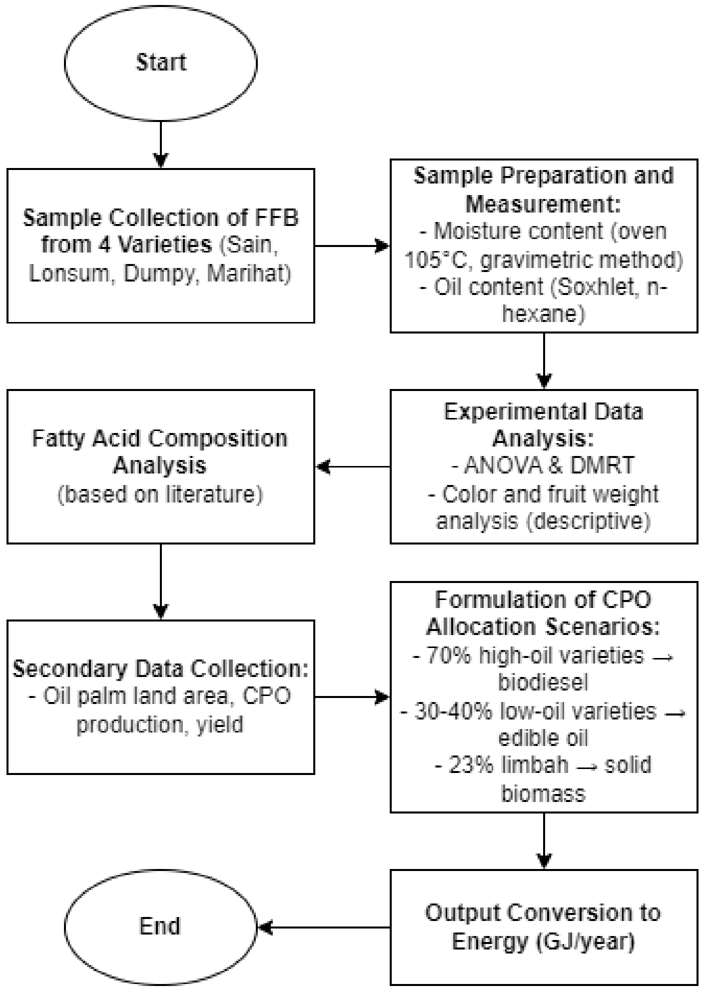

Figure 1. Flowchart of the research methodology and energy utilization scenarios.

The fatty acid composition was determined based on recent literature comparing the chemical profiles of oil palm varieties. These data were used to support the experimental fat content results and strengthen the justification for utilizing varieties dominated by saturated fatty acids (such as palmitic and stearic acids) as biodiesel feedstock. Secondary data, including plantation area, FFB production, and Crude Palm Oil (CPO) yield, were obtained from the local Agriculture Agency. Subsequently, CPO allocation scenarios were developed for biodiesel, edible oils, and solid biomass. The final energy potential was calculated and converted into Gigajoules per year.

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2.2 Experimental Design

This study employed a completely randomized design (CRD) without factorial treatment, consisting of four oil palm varieties (Yosephine et al., 2020): VS (Sain), VL (Lonsum), VM (Marihat), and VD (Dumpy). Each variety was tested in triplicate to improve the validity and reliability of the data. The research was conducted through both laboratory and field experiments, supported by secondary data from the Agriculture Agency and literature.

2.3 Scope of Research: Focus on CPO

The scope of this research is specifically limited to the analysis of crude palm oil (CPO) extracted from the mesocarp (pulp) of palm oil fruit. The kernel portion, which serves as the primary source of palm kernel oil (PKO), was not directly examined in this study because of significant differences in chemical characteristics, extraction processes, and utilization pathways.

The experimental focus on CPO is based on its practical relevance in the biodiesel and food industries, as it accounts for approximately 90% of the total palm oil output, whereas PKO represents only about 10% (Atabani et al., 2012). Furthermore, most national energy policies and food security studies emphasize the energy potential and economic value of CPO rather than PKO (Hariyadi & Jelita, 2024; Mekhilef et al., 2011).

Accordingly, all energy potential calculations, utilization scenarios, and energy unit conversions in this study refer exclusively to the content and characteristics of CPO.

2.4 Material and Equipment

2.4.1 Material

This study utilized fresh palm oil fruit collected from Penajam District, Penajam Paser Utara (PPU) Regency, East Kalimantan.

2.4.2 Equipment

Various tools were used to support the research activities, including an analytical balance for measuring the weight of the oil palm fruits and cutting tools such as cutters, scissors, knives, and machetes to detach the fruit from the bunches. Zip-lock plastic bags were used for sample storage and were then placed in cold boxes to maintain freshness during the research process.

Additionally, supplementary tools, such as burlap sacks and plastic crates, were used to facilitate sample transportation. Other supporting equipment included axes and harvesting poles (egreks) for cutting specific parts of the fresh fruit bunches. For fieldwork, safety measures were implemented by providing masks, gloves, helmets, and rubber boots. A camera was also used to visually document the oil palm fruit samples. All tools and materials were selected to ensure smooth research procedures and maintain the quality of the collected data.

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2.5 Research Variables

The parameters measured in this study are as follows:

1. Fat Content
2. Moisture Content
3. Whole Fruit Weight
4. Color

2.6 Sampling Procedure and Analysis Methods

One fresh fruit bunch (FFB) from each oil palm variety was collected from plantations in the Penajam District, Penajam Paser, and Utara Regency. Oil palm fruits were manually separated using knives and machines. Three samples were taken from each bunch, representing the upper, middle, and lower sections to ensure uniform representation.

Figure 2 shows the sampling locations of the four oil palm varieties in the Penajam Paser Utara Regency, specifically in the Buluminung and Sotek subdistricts. Administrative boundary data were obtained from GADM (2025).

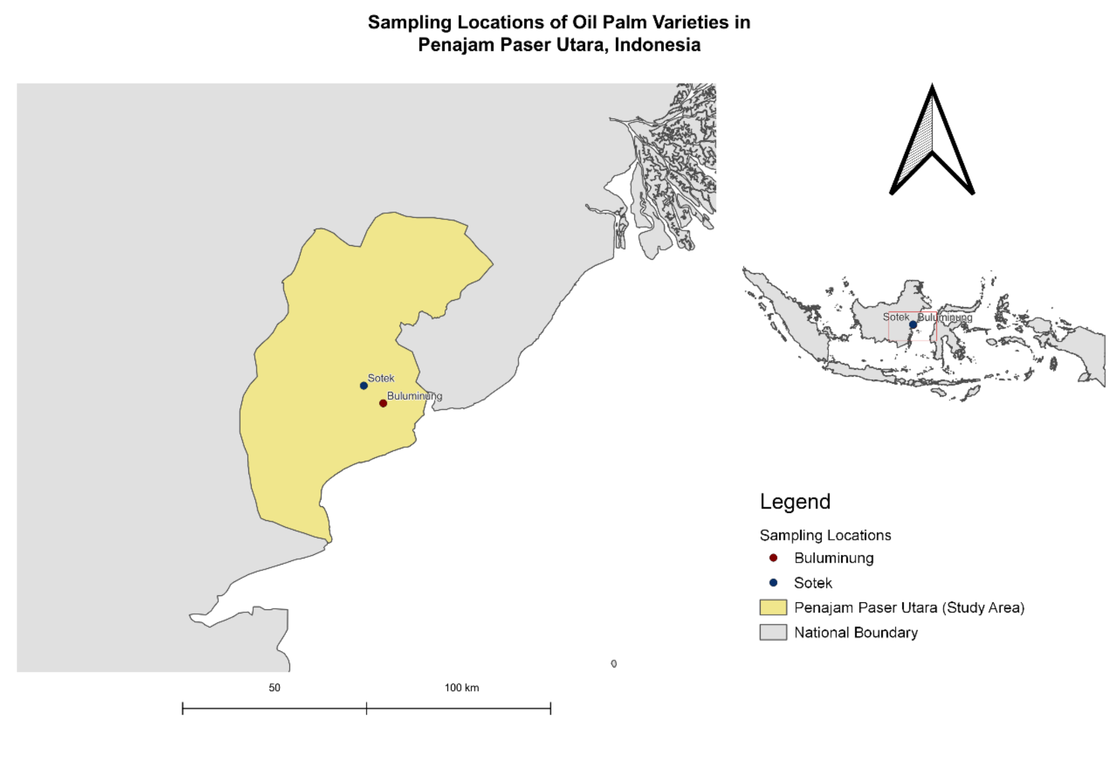

Figure 2. Sampling locations for oil palm varieties in Penajam Paser Utara, Indonesia. The inset map shows the location of the study area within Indonesian territory.

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The oil palm fruit samples were weighed using a digital analytical balance with a precision of 0.01 grams to determine the initial weight of each analysis unit. Moisture and fat content measurements were conducted based on the Indonesian National Standard (SNI), which refers to the official quality standards and methods published by the National Standardization Agency (BSN).

Moisture content was determined using the gravimetric method, in which the samples were dried in a drying oven at a constant temperature of 105°C for approximately 24 hours until a constant weight was achieved, following SNI 01-2891-1992. This step aimed to determine the moisture content as a key parameter for assessing raw material quality and energy efficiency.

The fat content was determined using the Soxhlet extraction method according to AOAC 920.39. Extraction was performed using n-hexane as the solvent, with two replications (duplicates) for each sample to ensure measurement accuracy. The extraction process was carried out for 6 hours of continuous distillation at a temperature range of 70–80°C (approaching the boiling point of n-hexane). The number of extraction cycles was not specifically counted but was controlled based on the total extraction time.

2.7 Data Analysis

The collected data were analyzed using the following approaches:

1. Statistical Analysis
   - Fat content, moisture content, and whole fruit weight parameters were analyzed using Analysis of Variance (ANOVA) to test for significant differences among varieties at a significance level of $p < 0.05$.
   - Post-hoc analysis was conducted using Duncan's Multiple Range Test (DMRT) at the 5% level to group varieties with statistically significant differences.
   - Prior to ANOVA, data were tested for normality and homogeneity of variance.
   - All statistical analyses were performed using SAS Studio based on the SAS 9.4 software and Microsoft Excel.
2. Descriptive Analysis
   - Descriptive analysis was conducted to interpret the fruit color data of each variety as an indicator of maturity.

2.8 Software

- Data processing was performed using Microsoft Excel and Statistical Analysis System (SAS) software to ensure accurate statistical analysis.

This study was designed using a comprehensive approach to ensure high data quality and valid results that can serve as a basis for the development of a self-sufficient energy agroindustry.

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2.9 Energi Potential Calculation Formula

The following formulas were used to calculate the production potential and energy content of the CPO and palm waste:

A. CPO allocation and conversion calculation

- CPO per variety = 25% × Total CPO
- Allocation for biodiesel = 70% × CPO from Lonsum & Sain varieties
- Allocation for food consumption = 40% × CPO from Dumpy & Marihat varieties
- Biodiesel production (tons) = CPO allocation (tons) × Conversion efficiency (90%)

A conversion efficiency of 90% represents the theoretical conversion of CPO into biodiesel, including the estimated losses during the transesterification process under optimal conditions (Saka & Kusdiana).

B. Waste and Biomass Estimation

- Solid waste from FFB = 23% × total FFB
- Solid biomass = Solid waste × Briquette conversion efficiency (75%)

The 75% efficiency refers to the study by Marieno et al. (2021), which reported an efficiency range of 70–80% in biomass briquette production.

C. Energy Conversion (Gigajoules)

Energy conversion was performed based on the assumption that 1 ton was equals to 1.000 kg.

- Biodiesel energy (GJ) = tons × 1.000 kg × 37.27 MJ/kg ÷ 1.000
- Biomass energy (GJ) = tons × 1.000 kg × 17 MJ/kg ÷ 1.000

The heating values used were approximately 38 GJ/ton for biodiesel (Eggleston, 2006) and approximately 17 GJ/ton for solid biomass (Basiron, 2017).

Throughout all the energy calculations, a standard conversion of 1 ton = 1.000 kg was applied. Decimal numbers were written following international standards using a period (.) as the decimal separator.

These three calculations were used to estimate the total energy potential from oil palm processing in the study area, serving as a basis for self-sufficient energy agroindustry planning.

3. Results and Discussion

3.1 Research Result

The measurement results for the four oil palm varieties are presented in Table 1, which shows the differences in fat content, moisture content, whole fruit weight, and fruit color.

Table 1. Oil palm fruit characteristics of different varieties.

Varieties	Fat Content (%)	Moisture Content (%)	Whole Weight (g)	Color
VS (Sain)	40.08^{CD}	34.12^{bcd}	2.935^{A}	Red
VL (Lonsum)	40.85^{CD}	33.46^{bcd}	4.690^{BC}	Reddish Purple
VM (Marihat)	26.05^{A}	36.39^{bcd}	6.625^{CD}	Reddish Purple
VD (Dumpy)	31.54^{B}	27.65^{a}	5.152^{BC}	Reddish Purple

Notes: Different superscripts within the same column indicate significant differences based on DMRT Analysis:
Uppercase letters A–D indicate highly significant differences at $p < 0.01$.
Lowercase letters a–d indicate significant differences at $p < 0.05$

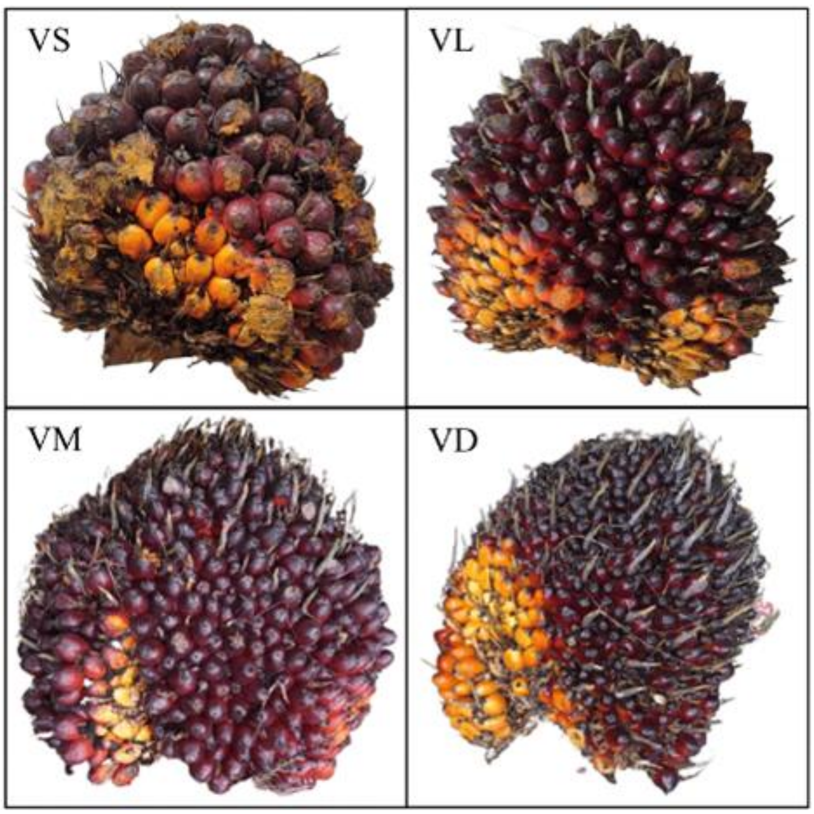

Figure 3. Oil palm fruits of different varieties.

The results showed that oil palm varieties had a significant effect on fat content, moisture content, whole fruit weight, and fruit color, with a significance level of $p < 0.05$, based on ANOVA. The following sections present the detailed results for each measured parameter.

3.1.1 Fat Content (%)

The Lonsum (40.85%) and Sain (40.08%) varieties exhibited the highest fat content, which was significantly different from that of the other varieties ($p < 0.01$). The high fat content of these two varieties makes them prime candidates for biodiesel production. The Dumpy variety (31.54%) was categorized as moderate, whereas the Marihat variety (26.05%) had the lowest fat content, indicating its limitations as a biodiesel feedstock.

3.1.2 Moisture Content (%)

The Marihat variety (36.39%) had the highest moisture content, followed by Sain (34.12%) and Lonsum (33.46%). The Dumpy variety (27.65%) exhibited the lowest moisture content, which was significantly different ($p < 0.05$) from that of the other varieties. This lower moisture content is one of the advantages of dumpy for dry biomass applications.

3.1.3 Whole Fruit Weight (g)

The Marihat variety (6.625 g) had the highest whole fruit weight, which was significantly different ($p < 0.01$) from that of the other varieties, indicating its high fruit productivity. The Dumpy (5.152 g) and Lonsum (4.690 g) varieties were categorized as moderate, whereas the Sain variety (2.935 g) had the lowest whole fruit weight, which is considered a limitation despite its high fat content.

3.1.4 Fruit Color

Fruit color varied among the different varieties. The Sain variety appeared red, whereas the Lonsum, Marihat, and Dumpy varieties exhibited reddish-purple colors. This color variation correlates strongly with fruit ripeness and oil content, as reported by Ishak et al. (2018) and Ritonga et al. (2023).

3.2 Discussion

3.2.1 Fat Content and Fatty Acid Composition

The results showed that The Lonsum variety had the highest fat content (40.85%), followed by Sain (40.08%), Dumpy (31.54%), and Marihat (26.05%). The high fat content in Lonsum and Sain supports their suitability as raw materials for biodiesel production, which requires feedstock with a high fat content to produce energy efficiently (Sujadi et al., 2016). The high fat content also indicates a greater energy potential from these varieties, as the fat content is directly proportional to the energy that can be extracted in the form of biodiesel (Knothe, 2010).

The findings further showed that the Lonsum and Sain varieties, with their high fat content and predominance of saturated fatty acids (palmitic and stearic acids), were the most suitable for biodiesel production. In accordance with the findings of Atabani et al., (2012) ,(Knothe, 2010), and (Sujadi et al., 2016), higher saturated fatty acid content enhances the oxidative stability of biodiesel, while unsaturated fatty acids (oleic and linoleic acids) are preferable for edible oil applications

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(Mardanawati et al., 2019). Although detailed fatty acid compositions of the Dumpy and Marihat varieties have not been extensively reported in the literature, field observations suggest that these varieties tend to produce oil with a relatively higher proportion of unsaturated fatty acids (particularly oleic and linoleic acids), making them more suitable for edible oil applications because of their health benefits and lighter physical properties.

3.2.2 Moisture Content and Whole Fruit Weight

Moisture content is an important indicator of the energy utilization efficiency. The Dumpy variety, which has the lowest moisture content (27.65%), is suitable as a raw material for dry biomass without requiring intensive drying processes. In contrast, the Marihat variety, which has the highest moisture content (36.39%), may reduce energy efficiency if utilized as biomass without further treatment (Radyanto et al., 2024).

The Marihat variety had an average whole fruit weight of 6.625 g, indicating a high fruit yield potential per bunch. A higher fruit weight is important for raw material productivity in both energy and food applications. However, owing to its low fat content, Marihat requires additional processing or selection for optimization as a biodiesel feedstock (Sijadi et al., 2016).

The high moisture content of the Marihat variety (36.39%) presents challenges for processing and storage, as excessive moisture can lead to material spoilage and reduce energy efficiency (Muarif et al., 2022). Conversely, the low moisture content of Dumpy (27.65%) offers a significant advantage ($p < 0.05$) in terms of drying efficiency and biomass processing, making it an ideal variety for dry biomass applications (Radyanto et al., 2024).

3.2.3 Fruit Productivity

The highest whole fruit weight observed in the Marihat variety (6.625 g) indicated high fruit productivity, which has the potential to generate a larger volume of raw material per fresh fruit bunch (FFB). However, according to Sujadi et al. (2016), the low fat content in Marihat meat requires additional processing steps before it can be optimally utilized for energy purposes. In contrast, the Sain variety (2.935 g), which had the lowest whole fruit weight, tended to be less productive in terms of raw material quantity, although it had a high fat content.

3.2.4 Color as a Maturity Indicator

Fruit color provides descriptive information regarding the physical characteristics and ripeness levels of palm oil fruits (Ritonga et al., 2023). The dominant reddish-purple color observed in the Lonsum, Marihat, and Dumpy varieties indicated optimal ripeness for high-quality palm oil processing. Conversely, the red color of the Sain variety reflects a simpler physical characteristic, although it remains suitable for biodiesel production (Sujadi et al., 2016).

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3.2.5 Production Potential at the Study Site

Secondary data from the PPU Agriculture Agency indicate that the oil palm plantation area in Penajam Paser Utara reached 17.377.75 ha in 2023. Based on estimated productivity of 12–15 tons FFB/ha/year and a CPO yield of approximately 20%, the projected CPO production potential in this region exceeds 190.000 tons per year. This estimate is indicative of uncertainty due to variability in plantation productivity, plant age, harvesting seasons, and processing efficiency at the mills. These findings demonstrate that the area is not only strategically located as a buffer zone for Indonesia's new capital city (IKN) but also holds significant potential in terms of natural resources to support renewable energy development (Rhofita, 2022).

3.2.6 Energy Utilization Scenarios for Palm Oil

This study not only evaluated the chemical quality and productivity of oil palm fruit, but also developed integrated energy utilization scenarios for various oil palm varieties (Sain, Lonsum, Dumpy, and Marihat) in the Penajam Paser Utara Regency. The scenario formulation was carried out by combining experimental data, secondary productivity data, and literature related to palm oil utilization pathways.

Based on the formulas described in the methods section, the following parameters and assumptions were applied to calculate the energy potential of biodiesel and biomass.

Table 2. Assumptions and Parameters Used.

Parameter	Value	Source/Note
Total CPO	130.794.17 ton	PPU Agriculture Agency (2023)
CPO distribution per variety	25% of total	PPU Agriculture Agency (2023)
Biodiesel conversion efficiency	90%	Equal allocation assumption (limited varietal data)
Biomass briquette efficiency	75%	Radyanto et al. (2024)
Solid waste to FFB ratio	23%	Mekhilef et al. (2011)
Biodiesel heating value	37.27 MJ/kg	Mekhilef et al. (2011)
Solid biomass heating value	17 MJ/kg	

3.2.6.1 Comparison Between Experimental Data and Literature

The experimental fat content data showed that the Lonsum and Sain varieties had high values (> 40 %), while their saturated fatty acid compositions were obtained from the dominant values reported in previous studies. These results are consistent with the findings of Sujadi et al. (2016) and Mikhilef et al. (2011), who stated that varieties with such characteristics exhibit better oxidative stability and are suitable as biodiesel feedstocks. In contrast, the Dumpy and Marihat varieties had lower fat

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content and higher levels of unsaturated fatty acids (oleic and linoleic acids), making them more suitable for edible oil consumption.

3.2.6.2 Annual CPO Production Estimate

Based on the most recent data obtained from the Penajam Paser Utara Agriculture Agency in 2023, from July to December, six oil palm companies operating in the region processed a total of 667.270.68 tons of Fresh Fruit Bunches (FFB). These six companies were PT companies. Waru Kaltim Plantation (WKP), PT. Sumber Bunga Sawit Lestari (SBSL), PT. Agro Indomas, PT. Kebun Mandiri Sejahtera (KMS), PT. Megah Hijau Lestari (MHL), and PT. Alam Permai Makmur Raya (APMR).
From this total, 130.794.17 tons of Crude Palm Oil (CPO), 2.028.18 tons of kernel, and 7.112.69 tons of Palm Kernel Oil (PKO) were produced. These figures indicate a CPO yield of approximately 19.6%, calculated by comparing the CPO volume with the total processed FFB.

3.2.6.3 Utilization Methods and Scenario

The allocation scenario of 70% CPO for biodiesel (Lonsum and Sain) and 30–40% for edible oil (Dumpy and Marihat) was determined based on a multidimensional assessment that included chemical properties, technical efficiency, and economic relevance. The three main considerations underlying this decision are as follows:

First, in terms of fat content, the Lonsum (40.85%) and Sain (40.08%) varieties exhibited significantly higher fat levels than Dumpy (31.54%) and Marihat (26.05%). A higher fat content is a key indicator of biodiesel production efficiency, as a greater fat content allows for a higher energy yield per unit weight of raw material. Thus, Lonsum and Sain are technically superior to biodiesel feedstocks because of their higher energy extraction potential.

Second, regarding fatty acid composition, Lonsum and Sain tend to have dominant proportions of saturated fatty acids, such as palmitic and stearic acids, which are more resistant to oxidation and stable during biodiesel transesterification (Atabani et al., 2012; Knothe, 2010). Oxidative stability is crucial for biofuel storage and distribution. Dumpy and Marihat contain higher levels of unsaturated fatty acids, such as oleic and linoleic acids, which are more suitable for human consumption because of their lighter properties, easier digestion, and health benefits (Mardawati et al., 2019).

Third, from an energy and economic efficiency perspective, varieties with lower fat content, such as Marihat, require a larger volume of fruit for biodiesel production, resulting in higher costs, energy consumption, and processing time. Moreover, Marihat's high moisture content (36.39%) presents an additional challenge in energy conversion efficiency, as it requires further drying. Conversely, Dumpy, which has a lower moisture content, is better suited for solid biomass but remains less optimal for biodiesel production because of its chemical composition.

Considering these three aspects—fat content, fatty acid composition, and technical-economic efficiency–a proportional allocation of 70% of CPO from Lonsum and Sain was directed to biodiesel,

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whereas 30–40% of CPO from Dumpy and Marihat was allocated for edible oil production. This scenario not only balances energy and food needs but also considers environmental sustainability and the economic resilience of palm oil-based regional development.

The CPO distribution among the varieties was assumed to be equal at 25% for each variety. This assumption was made because of the limited availability of varietal-specific production data at an industrial level. Therefore, an equal allocation approach was used as a conservative estimate to enable energy scenario calculations by integrating the laboratory results with secondary aggregate production data from the study area. Based on this assumption, CPO allocation per variety was calculated as follows:

- CPO per variety = 25% × 130.794.17 = 32.698.54 tons
- Total CPO from Lonsum and Sain = 2 × 32.698.54 = 65.397.08 tons
- Total CPO from Dumpy and Marihat = 2 × 32.698.54 = 65.397.08 tons

Based on the experimental results indicating that the Lonsum and Sain varieties have a high fat content (experimental data) and are dominated by saturated fatty acids (literature data), 70% of their CPO was allocated for biodiesel production. Meanwhile, 40% of the CPO from Dumpy and Marihat, with a lower fat content and higher unsaturated fatty acids, was allocated for edible oil consumption.

- CPO for biodiesel = 65.397.08 × 70% = 45.777.96 tons
- Converted to biodiesel (90% efficiency) = 45.777.96 × 90% = 41.200.17 tons
- CPO for edible oil = 65.397.08 × 40% = 26.158.83 tons

This scenario considers three main dimensions: (1) fat content efficiency, (2) chemical stability, and (3) technical-economic efficiency. Allocation proportions remain flexible to accommodate technological advancements, energy policy directions, and market dynamics.

With an estimated biodiesel production of approximately ±41,200 tons per year, which is equivalent to ±1.54 million GJ of energy, the energy contribution from palm oil may be utilized under several application scenarios in the IKN Nusantara area. First, biodiesel can be used as a blended fuel (B35–B50) for government service vehicles, public transportation, and logistics fleets operating within both the Penajam Paser Utara Regency and the IKN.

Second, biodiesel may be utilized as fuel for decentralized (off-grid) power generation systems to support distributed energy generation networks in IKN areas not fully connected to the main grid. Third, biodiesel production also has the potential to serve as a strategic biofuel reserve supporting IKN's clean energy mix target toward net-zero emissions by 2045. The integration of locally produced palm oil-based biofuels not only reduces dependence on fossil fuels but also strengthens domestic resource-based energy self-sufficiency for renewable energy development in PPU and IKN.

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3.2.6.4 Solid Waste Estimation and Biomass Potential

In addition to palm oil, FFB processing generates solid waste, such as empty fruit bunches, fibers, and shells. According to Mekhilef et al. (2011), the average solid waste from FFB processing is approximately 23% of the total FFB. Therefore:

- Solid waste = 667.270.68 × 23% = 153.472.26 tons/year
- Converted into biomass briquettes (75% efficiency) = 153.472.26 × 75% = 115.104.20 tons/year

This biomass has the potential to be used as a solid fuel to support local energy systems and environmentally friendly industries.

3.2.6.5 Annual Energy Estimation And Energy Conversion

To provide a more comprehensive overview of the potential energy that can be generated, the outputs of biodiesel and biomass were converted into energy units (GJ) based on their calorific values:

- Average calorific value of biodiesel: 37.27 MJ/kg (IEA, 2022)
- Calorific value of biomass briquettes: 17 MJ/kg (Radyanto et al., 2024).

Annual Energy Calculations

a. Energy from biodiesel

41.200.17 tons × 1.000 kg/ton × 37.27 MJ/kg = 1.535.524.332 MJ = 1,535,524.33 GJ

b. Energy from biomass

15.104.20 tons × 1.000 kg/ton × 17 MJ/kg = 1.956.771.400 MJ = 1,956,771.40 GJ

c. Total annual energy potential

1.535.524.33 GJ + 1.956.771.40 GJ = 3,492,295.73 GJ

Table 3. Estimated Annual Output and Energy Potential by Utilization Type.

Utilization Type	Volume (tons/year)	Energy (GJ/year)
Biodiesel (Lonsum & Sain)	41,200	1,535,524.33
Edible oil (Dumpy & Marihat)	26,159	-
Solid biomass (energy briquettes)	115,104	1,956,771.40
Total Energy		**3,492,295.73**

Note: Numerical formatting follows international standards using the period (.) as decimal separators.

Table 3 presents the estimated total energy derived from biodiesel and biomass based on the annual production conversion. Based on the estimation results, an energy potential of approximately ±3.49 million GJ per year demonstrates a significant capacity to support regional energy security, particularly in the buffer zone of Indonesia's new capital city (IKN).

Through a quantitative and comparative approach based on actual data and literature references, the energy utilization scenario for CPO in the study area shows that 65.397 tons of CPO from Lonsum

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and Sain varieties can be utilized, with 70% allocated for biodiesel production, yielding approximately ±41.200 tons of biodiesel per year.

Meanwhile, for the Dumpy and Marihat varieties, 40% of 65.397 tons of CPO is allocated for edible oil production, resulting in approximately ±26.159 tons of edible oil per year. In addition, the utilization of FFB waste from all varieties produces approximately ±115.104 tons of solid biomass (energy briquettes) per year. Overall, the total annual energy potential generated was approximately ±3.49 million GJ.

4. Conclusion

The Lonsum and Sain varieties, with high fat content (experimental results) and a predicted dominance of saturated fatty acids (according to literature references), demonstrate strong potential as biodiesel feedstocks. The allocation of 70% of the CPO from these two varieties for biodiesel-based energy is supported by their high energy conversion efficiency and oxidative stability.

Conversely, the Dumpy and Marihat varieties, which have a lower fat content and are predicted to contain higher levels of unsaturated fatty acids, are more suitable for edible oil production, with an allocation scenario of 30-40%. The Dumpy variety also has lower moisture content, supporting its utilization in solid biomass applications.

Considering the productivity data and oil palm plantation area in Penajam Paser Utara Regency, the estimated annual energy potential from CPO conversion into biodiesel and biomass reaches approximately ±3.49 million GJ per year.

These findings emphasize the importance of oil palm varietal selection based on chemical characteristics and productivity to support sustainable renewable energy policies without compromising national food security.

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