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The Potential for Utilizing Non-Productive Trunk of Sugar Palm (*Arenga pinnata* Merr) as Pulp and Wood Energy

The potential for utilizing non-productive trunk of sugar palm (*Arenga pinnata* Merr) as Pulp and Wood Energy

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Abstract

The sugar palm (Arenga pinnata Merr) presents significant potential as a source of biomass energy and raw material for pulp production. In West Sumatra, particularly within the Tanah Datar and Lima Puluh Kota regencies, the cultivation of this plant spans approximately 376.75 hectares and 285.00 hectares, respectively. Although sap extraction for palm sugar and bioethanol remains the predominant application, the non-productive trunks are largely underexploited. This study aimed to evaluate the physical and chemical properties of these trunks, focusing on fiber dimensions, chemical composition, and calorific value. The results indicated that trunks sourced from Lima Puluh Kota exhibited longer fiber lengths (2.70-2.97 mm), power felting (90.33 µm), and higher Runkel ratios, categorizing them as Class I in terms of fiber quality for pulp production. Conversely, samples from Tanah Datar were classified as Class II. In terms of chemical composition, the cellulose content (ranging from 35.21% to 64.63%) and moderate levels of lignin (between 8.02% and 18.40%), both of which are advantageous for pulping processes. However, the calorific values, which ranged from 2,675 to 3,374 cal/g, were found to be below the standards established for biomass fuels at both national and international levels. These findings imply that the unproductive trunks of sugar palm are more appropriately utilized in the pulp and paper industry rather than for bioenergy production. Such optimal utilization could contribute to the development of a circular economy while also enhancing the value provided to local communities.

Keywords: *Arenga pinnata*, Biomass, Non-Productive Trunks, Pulp, Renewable Energy.

Introduction

Arenga palm (*Arenga pinnata* Merr) represents a critical species characterized by multifaceted potential applications. Beyond sap extraction for palm sugar and bioethanol production, other morphological components, notably non-productive trunks, exhibit substantial promise as biomass feedstock for renewable energy applications. In Indonesia, particularly within West Sumatra's highland regions, notably Tanah Datar and Lima Puluh Kota regencies, extensive cultivation of the Arenga palm has been documented. According to the Directorate General of Estates (Ditjenbun), cultivated Arenga palm areas in these regencies span approximately 409 and 389 hectares, respectively [1].

Historically, utilization efforts have predominantly focused on sap processing for palm sugar and bioethanol synthesis. However, non-productive Arenga trunks remain underutilized, often left decomposing in situ despite their theoretically robust potential as renewable biomass feedstock for bio-pellets and biofuel production. Utilizing non-productive Arenga trunk as biomass aligns with circular economy and sustainability principles, thereby reducing dependence on fossil fuel. Recent studies by Maharani, Febrina, and Kasmaniar et al. elucidated competitive calorific profiles of Arenga trunk biomass relative to alternative biomass sources [2], [3]. Additionally, similar palm species, such as non-productive oil palm trunks, have shown potential as raw material for pulp and paper production [4], [5], [6], suggesting similar applications for Arenga palm trunks.

Characterization studies reveal that non-productive Arenga trunks possess favorable physicochemical attributes conducive to pulp and bioenergy production. Fiber morphological properties, including fiber length, diameter, and cell-wall thickness, in conjunction with chemical composition, specifically cellulose, hemicellulose, lignin, and extractive concentrations, critically determine pulp and bioenergy raw material quality. Investigations into anatomical fiber characteristics, chemical composition, and calorific potential of related palm species substantiate their viability as alternative bioenergy and pulp sources [7], [8], [9] also underscored high energetic efficiencies achievable in converting palm biomass, mainly trunks, into bio-pellets.

Within the broader context of renewable energy advancement, meticulous characterization of Arenga trunk anatomical and chemical properties is paramount for fostering bioenergy and biomaterial industries at the local scale. Optimized utilization strategies for Arenga trunks can effectively mitigate agricultural waste generation and enhance economic outcomes for local agrarian communities. At the global scale, biomass utilization from Arenga trunks aligns strategically with decarbonization objectives and climate change mitigation targets [2], [10]. Furthermore, applying Arenga trunk biomass in energy and pulp sectors embodies sustainable agriculture principles through enhanced resource-use efficiency and reduced environmental footprint.

The current study aims to elucidate fiber dimensional attributes, chemical compositions, and calorific values of non-productive Arenga trunks sourced from Tanah Datar and Lima Puluh Kota regencies, West Sumatra. The findings intend to furnish comprehensive scientific evidence underpinning the feasibility and sustainability of Arenga trunk biomass utilization, thereby contributing significantly to bioenergy sector advancement at both local and national levels.

Materials and methods

Materials

This study utilizes non-productive Arenga palm trunks obtained from different trunk heights: lower (5 m), middle (10 m), and upper (15 m). Chemicals and reagents employed include Safranin 1%, Alcian Blue 1%, Hydrogen peroxide (H2O2), graded alcohol series (30%, 50%, 70%, 96%, and 100%), Entellan, xylol, glycerin, chromium wire, methyl orange, oxygen gas (O2), and sodium carbonate.

Methods

Sample Site

Non-productive sugar palm trunks were collected from two locations in West Sumatra: Batusangkar and Lima Puluh Kota Regency (Figure 1). non-productive Arenga palm trunks are collected after 30 years. The fiber dimensions, including fiber length, fiber diameter, lumen diameter, and fiber wall thickness, were measured using the maceration method. Derived fiber dimension indices such as Runkel Ratio (RR), Felting Power (FP), Muhlstep Ratio (MR), Coefficient of Rigidity (CR), and Flexibility Ratio (FR) were calculated based on these measurements. Palm trunks were processed into fine wood particles for chemical composition and energy content analyses. Calorific value, cellulose content, hemicellulose content, lignin content, ash content, and moisture content were subsequently determined. Map generated utilizing the QGIS software application.

Fiber Dimension Measurement and Wood Quality Classification

Fiber dimension measurements were conducted by cutting sugar palm trunks into matchstick-sized pieces (10.8 cm x 6.5 cm x 2.1 cm). These small pieces were heated in a tube containing hydrogen peroxide and glacial acetic acid in a 1:1 ratio. After fiber separation, the fibers were washed under running water and stained with safranin. Subsequently, the fibers were soaked in glycerin for microscopic observation and measurements were conducted to assess the parameters related to fiber derivatives. Quantitative fiber dimension characteristics were determined by measuring fiber length 25 times, whereas fiber diameter and wall thickness were each measured 15 times [11]. Fiber dimension values and wood quality classes were determined based on data from the Directorate General of Forestry[12].

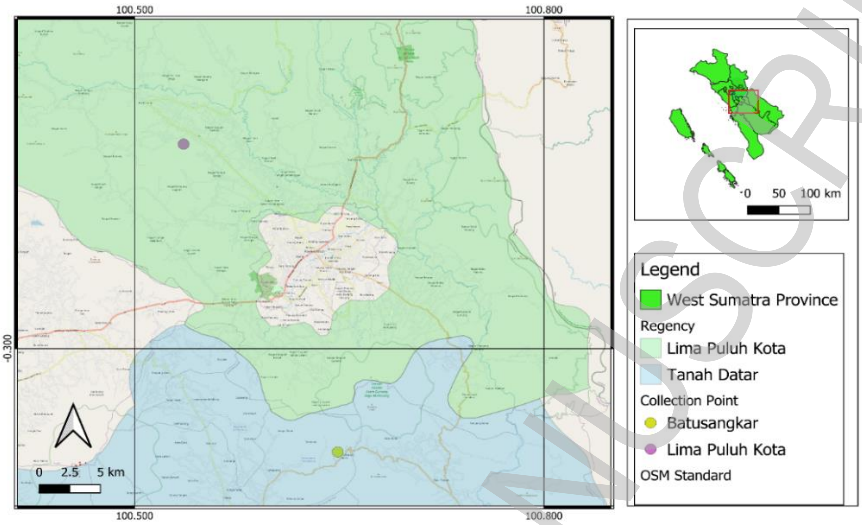

Figure 1. Collection Sites of Non-Productive Sugar Palm Trunks in West Sumatra.

Calorific Value

Wood calorific value was determined according to the Association of Official Analytical Chemistry (AOAC) 1999 method[13]. Nine wood powder samples (three samples per region) were oven-dried at 70 °C. Test samples weighing between 0.5 – 1 gram were measured for calorific value using an adiabatic oxygen bomb calorimeter. The calorific values of test samples were calculated using the calorific value calculation formula

$$\text{Calorific Value (kcal/g)} = \frac{(T_f - T_i) \times W + C}{m} \quad \ldots\ldots(1)$$

Where: Tf = Final temperature (°C), Ti = Initial temperature (°C), W = Water equivalent of the calorimeter system (kcal/°C), C = Corrections (kcal), mmm = Mass of the sample (g)

Moisture Content Analysis

Moisture content was analyzed using the Association of Official Analytical Chemistry (AOAC) 2005 method [14]. Approximately 1 gram of sample was placed into a pre-weighed container. The sample was oven-dried at 100–105 °C until a constant weight was achieved (8–12 hours). Moisture content percentage was calculated using the moisture content calculation formula.

MC= (w-d)/w x 100; MC= x 100 …………………………………………………………….(2)

where: w: wet weight, d: weight after drying

Ash Content Analysis

Ash content was analyzed according to the Association of Official Analytical Chemistry (AOAC) 2005 method [14]. Approximately 1 gram of sample was placed into a pre-weighed container. The sample was burned in a furnace at 600 °C for 4–5 hours (until completely white). The sample was then transferred to an oven at 105 °C, cooled in a desiccator, and weighed. The ash content percentage was calculated using the ash content calculation formula.

AC= (A/B) x100 ………………………………………………………………………(3)

where A: weight of dry ash, B: initial weight sample

Chemical Composition Analysis

Cellulose, hemicellulose, lignin, and extractive substances of non-productive sugar palm trunks were analyzed following the Technical Association of the Pulp and Paper Industry (TAPPI), 1989 method [12]. The palm trunks were planed using a wood planer machine and dried in a cabinet dryer at 70 °C until reaching a constant weight. Subsequently, the material was sieved using a 60-mesh sieve, and the powder passing through the sieve was analyzed for chemical components

Data Analysis

All data were analyzed using both descriptive and quantitative approaches. The descriptive analysis was employed to observe general patterns in fiber dimension values, derived fiber indices, wood quality classification, calorific value, moisture content, ash content, and chemical composition. Meanwhile, the quantitative analysis was applied particularly to the numerical data from chemical composition measurements, enabling a more detailed assessment of the variation and potential correlations among the parameters studied in non-productive sugar palm trunks from two regions in West Sumatra.

Results and Discussion

Fiber Dimension

Wood fibers are essential anatomical components primarily determine mechanical strength and structural integrity of wood [15]. The specific dimensions of these fibers significantly influence wood properties, playing a crucial role in determining their suitability for various industrial applications, particularly in pulp and paper production. Fiber dimensions serve as key distinguishing characteristics that impact the processing quality of hardwoods and softwoods [16].

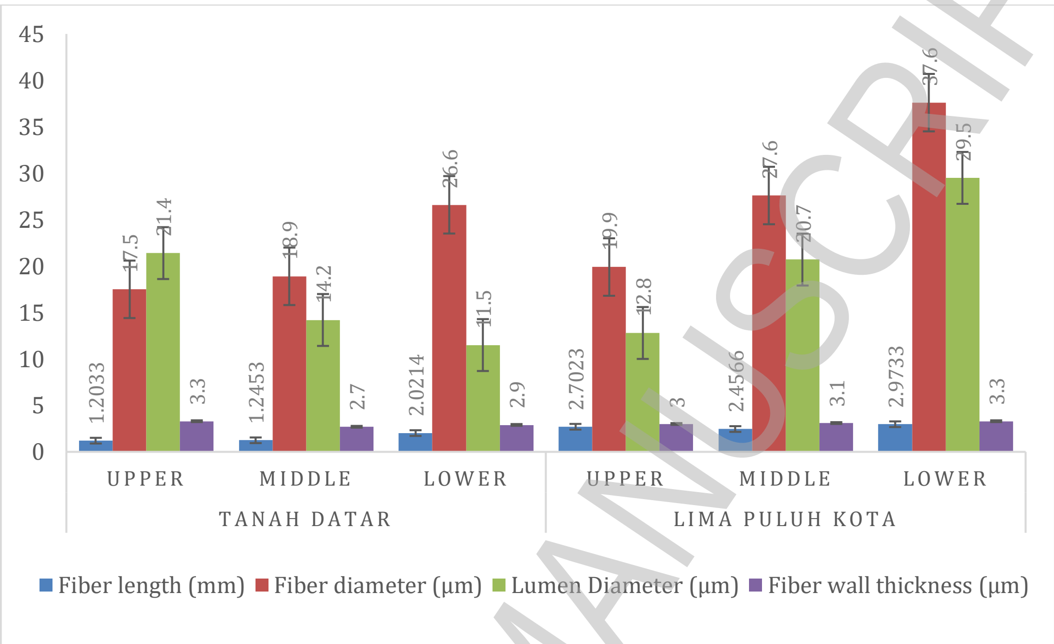

Figure 2. Fiber Dimensions of Non-Productive Sugar Palm (*Arenga pinnata*) Trunks

Fiber length measurements of *Arenga pinnata* trunks from Lima Puluh Kota Regency (1.20-2.02 mm) were significantly greater than those from Tanah Datar Regency (2.70-2.97mm). Variations in fiber morphology, including length and diameter, are strongly influenced by geographical and environmental factors, particularly altitude and slope gradient. Elevation and topographic incline have been shown to substantially affect the anatomical dimensions of wood fibers [17]. Fiber lengths are classified into three categories: short fibers (<0.90 mm), intermediate fibers (0.90–1.90 mm), and elongated fibers (>1.90 mm) [11]. The average fiber lengths recorded for non-productive sugar palm trunks from Lima Puluh Kota clearly align with the elongated fiber classification (>2.4 mm). Conversely, trunks sourced from Tanah Datar demonstrated positional variability, with fibers from upper and middle segments classified as intermediate and those from basal segments classified as elongated.

Fiber length significantly impacts the mechanical attributes of pulp and paper products, influencing tensile strength, tear resistance, and folding endurance. Extended fibers foster superior inter-fiber bonding, enhancing the resultant paper's structural integrity and mechanical robustness. Sugar palm fiber lengths have been reported to range from 1.6 to 2.7 mm [18].

Meanwhile, at the Batusangkar and Limapuluh Kota research locations, the length of the fibers found was respectively 1.2-2.02 mm and 2.70-2.97 mm, classifying them as medium-length classification based on International Association of Wood Anatomists [19]. Fibers within this dimensional spectrum typically yield paper products of moderate mechanical performance, which is optimal for applications such as tissue paper, lightweight cardboard, and general printing paper. Compared to the fibers from *Pinus radiata*, which are prevalent in commercial pulp production, they range from approximately 2.5 to 4 mm, thus conferring superior mechanical properties.

Furthermore, radial and longitudinal positions discernibly influence fiber length variation within sugar palm trunks. Peripheral fibers typically exhibit greater lengths compared to those situated centrally. Longitudinal variation also follows distribution patterns: peripheral fibers display maximum lengths at trunk apices, intermediate lengths at basal positions, and medial minimum lengths. Conversely, central trunk fibers exhibit maximum lengths basally, intermediate lengths apically, and minimum lengths medially. Fiber length values for Lima Puluh Kota (2.11 mm) closely resemble those of sago palm fibers [20].

Additionally, fiber diameter exhibited notable regional and positional variability within sugar palm trunks, influenced by physiological and molecular changes in vascular cambium and secondary xylem cell walls during growth [21], [22]. The basal trunk segments consistently demonstrated greater average fiber diameters relative to medial and apical segments across both Tanah Datar and Lima Puluh Kota regions. Fiber diameter and cell wall thickness have been shown to correlate with exogenous environmental conditions and growth ring formation [23], Notably, the basal segments of non-productive sugar palm trunks exhibit fiber diameters ranging from 26 µm to 37 µm, comparable to the typical hardwood fiber diameters of approximately 25 µm reported by Atchison [24].

Sugar palm fiber diameters have been documented to range from 28 µm to 52 µm, with a progressive decrease toward the apical regions and generally smaller diameters in peripheral areas compared to central trunk locations [18]. Fiber wall thickness exhibited pronounced variability (5 µm–24 µm), dependent on the positional context within the trunk, with the thickest cell walls characteristically observed at peripheral basal positions and the thinnest walls at central apical locations. In the pulp industry, fiber wall thickness plays a critical role in determining pulp strength and quality. Thicker-walled fibers are generally associated with higher mechanical strength, making them suitable for packaging and structural paper products, while thinner-walled fibers provide better flexibility and bonding ability, which are preferred for fine or printing papers [25], [26]. Therefore, the variability in fiber wall thickness observed in sugar palm trunks indicates their potential for diverse pulp applications, depending on the specific fiber source within the trunk.

Fiber Quality Classification

Fiber dimensions and their derived parameters determine the fiber quality classification of wood trunks for pulp and paper production. The derived fiber dimension values for each non-productive sugar palm trunk are presented in Table 1.

Table 1. Derived Fiber Dimensions and Fiber Quality Classification of Non-Productive Sugar Palm (*Arenga pinnata*) Trunks

Criteria	Tanah datar						Lima Puluh Kota					
	Upper (µm)	Value	Middle (µm)	Value	Lower (µm)	Value	Upper (µm)	Value	Middle (µm)	Value	Lower (µm)	Value
FL	1203.3±66.5	50	1245±77.7	50	2021.3±62.9	75	2702.3±51.9	100	2456.6±83.8	100	2973.3±75.0	100
RR	0.32±0.10	75	0.43±0.20	75	0.52±0.08	50	0.58±0.10	50	0.31±0.07	75	0.26±0.09	75
FP	45.5±5.43	50	65.09±11.99	50	116.61±33.07	100	144.50±50.89	100	90.33±18.91	100	80.51±19.633	75
MR	34.9±5.74	75	44.77±12.979	75	57.77±8.055	75	16.09±4.321	100	43.33±9.30	75	40.66±16.56	75
FR	0.80±0.04	75	0.73±0.10	75	0.64±0.07	75	0.73±0.59	75	0.75±0.062	75	0.76±0.113	75
CR	0.13±0.04	75	0.15±0.05	75	0.17±0.01	50	0.16±0.03	50	0.12±0.04	75	0.1±0.05	75
TV		400		400		425		475		500		475
FQC		II		II		II		I		I		I

Notes: FL (Fibre Length); RR (Runcle Ratio); FP (Felting Power); MR (Multiseph Ratio); FR (Flexibility Ratio); CR (Coeff. Of Rigidity); TV (Total Value); FQC (Fiber Quality Class)

The derived fiber dimensions significantly influence fiber quality classifications, determining their applicability in pulp and paper industries. A wooden log can be considered a candidate for durable furniture if its fiber quality class meets within at least Class II [27] As shown in Table 1, the non-productive sugar palm trunks from both Tanah Datar and Lima Puluh Kota meet this requirement. While all samples from Tanah Datar fall into Class II, samples from Lima Puluh Kota demonstrate even better quality, consistently achieving Class I classification. This indicates that the fiber quality in Lima Puluh Kota not only fulfills but exceeds the minimum standard for furniture material. Additionally, other research has also identified sugar palm wood as suitable for constructing watercraft due to its physical properties [28].

Runkel Ratio (RR) measurements for the upper, middle, and basal trunk sections exhibited values ranging from 0.32–0.52 in Tanah Datar and 0.26–0.58 in Lima Puluh Kota. These findings indicate strong pulp production potential. Previous research similarly reported favorable RR values predominantly in the central upper (0.56) and central middle (1.05) trunk sections [18]. Optimal pulp production typically requires lower RR values (<1.00), thinner fiber walls, and larger lumen diameters, facilitating enhanced fiber flexibility and inter-fiber bonding, resulting in pulp sheets with superior tensile and tear strengths [29]. Variations between current and earlier studies may be attributed to disparities in tree maturity, height, and environmental conditions.

Fiber Proportion (FP), indicative of fiber volume within lignocellulosic matrices, demonstrated variability: 45.5 µm–116.61 µm in Tanah Datar compared to 80.51 µm–144.50 µm in Lima Puluh Kota. Elevated FP values observed in Lima Puluh Kota, particularly in basal segments, suggest more tremendous potential for high-grade pulp production due to enhanced fiber abundance. Support this assertion, correlating increased fiber proportions with improved mechanical integrity and pulp sheet durability [30].

Muhsteph Ratio (MR), representing fiber mechanical resistance, ranged from 34.9%–57.77% in Tanah Datar and 16.09%–43.33% in Lima Puluh Kota. Lower MR values are positively associated with improved pulp and paper quality [31]. Compared to *Acacia* spp. (45%–55% MR), reported that the lower MR values observed herein suggest superior strength properties [32]. Moreover, significantly higher MR values (81.24%) in sago fiber papers are characterized by coarse textures and lower compressive strengths, limiting their application in conventional writing paper but suitable for specialized products such as artistic or gift papers [20]. Thus, sugar palm trunks' notably lower MR values affirm their suitability for pulp and paper applications.

Flexibility Ratio (FR) assessments yielded values of 0.64–0.80 in Tanah Datar and 0.73–0.76 in Lima Puluh Kota. Elevated FR values reflect fibers with thinner cell walls capable of substantial deformation, enhancing inter-fiber adhesion and pulp sheet mechanical properties. Increased FR values improve tensile strength and fiber cohesion [29]. Coefficient of Rigidity (CR), the ratio of cell wall thickness to fiber diameter, Table 1 revealed the values of 0.13–0.17 in Tanah Datar and 0.10–0.16 in Lima Puluh Kota. CR values below 0.75 signify increased fiber flexibility and potentially improved pulp yields and densities. Lower CR values enhance inter-fiber contact surfaces, reinforcing fiber bonding and reducing structural rigidity, thereby improving overall pulp characteristics [33].

Differences in fiber characteristics between Tanah Datar and Lima Puluh Kota highlight Tanah Datar's superior fiber strength, whereas Lima Puluh Kota excels in fiber volume and fineness. These distinctions are presumably influenced by environmental variables such as climatic conditions, soil attributes, and tree age, collectively shaping fiber development and subsequent quality.

Wood Energy Characteristics

Calorific values observed in non-productive sugar palm trunks from Tanah Datar and Lima Puluh Kota varied considerably (Table 2). However, the measured calorific values, ash content, and moisture levels of both non-productive palm trunks indicate limited suitability for pellet production. According to Indonesian National Standard (SNI) 8021:2014, the minimum calorific content requirement for pellet materials is 4,000 cal/g. Additionally, European Standard EN-14961-2 specifies an acceptable calorific value range for pellets between 3,941 and 4,538 cal/g [34]. The observed values for both regions fall outside these prescribed thresholds, precluding their potential use in pellet production

Table 2. Wood Energy Characteristics of Non-Productive Sugar Palm (*Arenga pinnata*) Trunks

Parameters	Tanah Datar			Lima Puluh Kota			SNI 8021	EN-14961-2
	Upper	*Middle*	*Lower*	*Upper*	*Middle*	*Lower*		
Caloric content (cal/gr)±SD	2724.14±19.43	2675.32±10.93	2949.55±17.33	3374.16±37.27	2349.28±42.25	3339.03±63.48	Min 4000	3941≤Q≤4538
Moisture content (%)±SD	60.47±0.18	49.57±0.29	52.40±0.23	13.54±0.13	25.43±0.25	31.49±0.05	Max 12	Max 10
Ash Content (%)±SD	6.51±0.24	7.26±0.17	5.59±0.27	2.40±0.35	1.79±0.20	1.52±0.43	Max 1.5	Max 3

Similar research examining other non-productive Arecaceae family members has revealed substantial differences in their biomass potential as solid fuel sources. For instance, studies on coconut trunks (*Cocos nucifera*), also within the Arecaceae family, demonstrated notably higher calorific values than sugar palm trunks. Calorific values for coconut trunks range above the threshold for effective biomass energy use. Aged coconut trunks exhibit elevated calorific values, particularly after thorough drying [35]. By having a moisture content below 15%, coconut trunks easily meet the standards for solid fuel utilization.

Similarly, research on oil palm trunks (*Elaeis guineensis*) has demonstrated significant biomass energy potential, with reported calorific values reaching 17.41 MJ/kg, comparable to certain grades of coal. Their findings underscored how moisture content, typically maintained below 20%, substantially enhances combustion efficiency, aligning closely with industry standards for solid fuel production [36]. These favorable properties underscore the substantial suitability of oil palm biomass as an alternative fuel source comparable to conventional fossil fuels.

In contrast, the calorific values of non-productive sugar palm trunks from Tanah Datar and Lima Puluh Kota (2349.28–3374.16 cal/g) are significantly lower than those of coconut and sago trunks. Elevated moisture levels result in diminished calorific value and increased residue post-combustion, reducing suitability for pellet production and combustion efficiency. Consequently, sugar palm biomass demonstrates reduced compatibility as raw material for pellet production compared to coconut and oil palm biomass, primarily due to higher moisture content and resultant lower energy yield.

Chemical Composition

Non-productive sugar palm trunks from Tanah Datar and Lima Puluh Kota regions exhibit distinct potentials as raw materials for pulp production and biomass or energy pellet applications (Table 3). Variations in chemical composition, focusing on cellulose, hemicellulose, and lignin content, significantly influence their suitability for pulp production and bioenergy generation. High cellulose and lower lignin contents enhance pulp yield and quality, facilitating efficient delignification during pulping processes. Conversely, lignin-rich materials generally produce lower pulp quality due to increased energy consumption and more complex chemical processing requirements.

Table 3. Chemical Composition of Non-Productive Sugar Palm *(Arenga pinnata)* Trunks

Chemical Composition (%)	Tanah Datar			Lima Puluh Kota			(Haigreen &Bowyer, 1996) (Fengel &Wegener, 1989)	
	Upper	Middle	Lower	Upper	Middle	Lower		
Cellulose	40.45 ±4.85	39.86±2.08	35.21 ±2.00	64.63±4.60	62.38±3.84	59.16±3.00	45-50	45-50
Hemicellulose	10.79 ±0.78	10.92±0.30	11.52 ±0.80	6.48±0.19	8.69±0.45	10.55±1.09	15-35	30-32
Lignin	13.63 ±1.78	8.02±0.10	11.96 ±1.08	18.40±0.80	13.63±0.90	14.97±1.59	18-25	25-35
Extractive	7.09±1.07	8.08±1.00	5.09±1.00	8.40±0.20	8.60±1.26	9.00±1.03	0.2 – 0.5	0.2 – 0.5

The cellulose content in non-productive sugar palm trunks from Tanah Datar ranged between 35.21% and 40.45%, whereas trunks from Lima Puluh Kota exhibited significantly higher cellulose content, ranging from 59.16% to 64.63% (Table 3). This difference may be attributed to variations in tree age across these regions, as increasing age correlates with higher cellulose levels [37]. Cellulose is a key component in pulp production, and the high cellulose content in sugar palm trunks from Lima Puluh Kota indicates better potential for high-quality pulp production, comparable to hardwood and softwood species, which typically contain 45–50% cellulose [38], [39]. Eucalyptus is one of the industrial plants used as pulp and has a cellulose content of 39.96% [40]. Chemically, cellulose serves as the primary structural component, providing mechanical strength to fibers [41].

Hemicellulose content in non-productive sugar palm trunks was generally lower than in conventional wood. In Tanah Datar, hemicellulose ranged from 10.79% to 11.52%, while in Lima Puluh Kota, it varied from 6.48% to 10.55%. These values are lower than those typically found in hardwood (15–35%) and softwood (30–32%). Meanwhile, the industrial plant Eucalyptus has a hemicellulose content of 26.41% [40]. Lower hemicellulose content can be beneficial in pulping as it degrades more easily, but it may also affect pulp viscosity. On the other hand, lignin content, which was higher in trunks from Lima Puluh Kota (13.63%–18.40%) compared to those from Tanah Datar (8.02%–13.63%), poses challenges in delignification, as lignin must be removed to improve pulp quality. Hardwood contains approximately 18–25% lignin, while softwood has 25–35% [38], [39]. For biomass applications, lower hemicellulose content contributes to faster combustion but may result in reduced stability. However, lower hemicellulose levels can also lead to lower emissions during combustion, making it more environmentally friendly.

In the sugar palm's upper, middle, and lower trunk sections, lignin content was 8.02%–13.65% in Tanah Datar and 13.63%–18.40% in Lima Puluh Kota. These values are lower than those reported, which found lignin levels to be 46% [42], [43]. Meanwhile, *Acacia mangium*, one of the industrial plants often used as raw material for pulp, has a lignin content of 19.4% [44]. High lignin content in sugar palm trunks presents challenges in pulp production, as lignin acts as an adhesive between fibers but must be removed to prevent darkened paper coloration and reduced paper strength. Delignification of sugar palm trunks requires more intensive bleaching than other commonly used pulpwood species [45]. This is due to the higher chemical demand needed to remove lignin and extractives from sugar palm wood. Additionally, high-lignin pellets are excellent alternative fuels for power generation and heating [46]. High lignin content in biomass improves combustion efficiency, generates more heat, and stabilizes biomass during combustion, making it more suitable for pellet production [47].

Genetic and environmental variability may influence differences in lignin content between sugar palm trunks from Tanah Datar and Lima Puluh Kota. Quantitative trait loci (QTL) related to lignin content in sorghum using Genome-Wide Association Study (GWAS), demonstrating the importance of genetic variation in lignin biosynthesis [48]. Similarly, studies on sugarcane accessions revealed variations in lignin content due to differential expression of lignin biosynthesis genes, indicating that genetic factors are region-specific [49]. Environmental factors already reported such as soil type, climate, and biotic interactions significantly influence lignin production [50].

Extractive content in sugar palm trunks' upper, middle, and lower sections ranged from 5.09%–8.08% in Tanah Datar and 8.40%–9.00% in Lima Puluh Kota. In eucalyptus which is often used as raw material for pulp, the extractive content is 8.26%[40]. Extractives play a diverse role in biomass, particularly in palm trunks, influencing energy values and combustion efficiency. While palm trunks contain lower extractive levels, their presence enhances biomass heating value, as extractives generally exhibit a higher Higher Heating Value (HHV) than polysaccharides and lignin [51]. However, increased extractive content can also lead to adverse effects, such as higher emissions and slag formation during combustion [51], [52]. High extractive content in sugar palm trunks can hinder pulping efficiency and increase production costs.

Additionally, extractives reduce paper manufacturing efficiency by weakening fiber bonding. Further processing is required to eliminate extractives before sugar palm trunks can be used for high-quality pulp production. Despite these technical challenges, non-productive sugar palm trunks can be processed into pulp with relatively good results compared to other tropical raw materials.

Conclusions

This study examined the physical and chemical characteristics of unproductive sugar palm trunks from Tanah Datar and Lima Puluh Kota to assess their potential for pulp and biomass applications.The results showed that the fiber dimensions from both sites meet the standards for pulp production, with Lima Puluh Kota samples classified as higher quality (Class I) than those from Tanah Datar (Class II). Physically, the trunk has suitable fiber length, diameter, and wall thickness, while chemically, it contains moderate levels of cellulose and lignin, supporting its potential for pulp processing. However, the calorific values (3,746–4,075 cal/g) fall below national and international standards for biomass fuel.Thus, unproductive sugar palm trunks are more appropriate for pulp and paper production rather than as biomass energy sources.

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Conflict Of Interest

The authors have declared that no competing interests exist.

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