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Jurnal Biota Vol. 12 No. 1 (2026) https://doi.org/10.19109/biota.v12i1.27559

Research Article

The Potential Utilization of Non-Productive Sugar Palm (*Arenga pinnata* Merr.) Trunks for Pulp and Bioenergy Applications

Silmi Yusri Rahmadani[12*], Alponsin[1], Dimas Surya Pratama[1], Tesri Maideliza[1]
[1]Departement of Biology, Faculty Mathematics and Natural Science Universitas Andalas, Padang, West Sumatera, Indonesia
[2]Departement of Biomedical and Environmental Biology, School of Life Science, Kaohsiung Medical University, Kaohsiung, Taiwan

*Email: silmiyusrirahmadani@sci.unand.ac.id

Received: 10/03/2025	Revised: 02/07/2025	Accepted: 02/07/2025

ABSTRACT
The sugar palm (Arenga pinnata Merr.) has considerable potential as a biomass resource and as a raw material for pulp production. In West Sumatra, particularly in the Tanah Datar and Lima Puluh Kota regencies, cultivation areas cover approximately 376.75 ha and 285.00 ha, respectively. Although sap extraction for palm sugar and bioethanol remains the primary use, non-productive trunks are largely underutilized. This study evaluated the physical and chemical properties of these trunks, focusing on fiber dimensions, chemical composition, and calorific value. Trunks from Lima Puluh Kota exhibited longer fibers (2.70–2.97 mm), higher felting power (90.33), and favorable Runkel ratios, resulting in a Class I fiber quality rating for pulp production. In contrast, samples from Tanah Datar were classified as Class II. The trunks also showed cellulose contents ranging from 35.21% to 64.63% and moderate lignin levels (8.02–18.40%), both of which are advantageous for pulping. However, the calorific values (2,675–3,374 cal/g) were below national and international standards for biomass fuels. Overall, these findings suggest that non-productive sugar palm trunks are better suited for pulp and paper applications than for bioenergy production. Optimizing their use could support circular economy development while increasing value for local communities.

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

Introduction

The Arenga palm (*Arenga pinnata* Merr.) is a valuable species with diverse potential applications. In addition to its widespread use for sap extraction in palm sugar and bioethanol production, other morphological components particularly non-productive trunks show considerable promise as biomass feedstock for renewable energy. In Indonesia, especially in the highland regions of West Sumatera, including the Tanah Datar and Lima Puluh Kota regencies, extensive cultivation of the Arenga palm has been reported. According to the Directorate General of Estates (Ditjenbun), the cultivated areas in these regencies cover approximately 409 ha and 389 ha, respectively [1].

Historically, utilization of the Arenga palm has focused primarily on sap processing for palm sugar and bioethanol production. In contrast, non-productive *Arenga* trunks remain largely underutilized and are often left to decompose in situ, despite their substantial potential as renewable biomass feedstock for bio-pellet and biofuel production. The use of non-productive *Arenga* trunks as biomass aligns with circular economy and sustainability principles by reducing waste and decreasing reliance on fossil fuels. Recent studies by Maharani & Febrina [2]; Kasmaniar *et al.* [3], have reported that *Arenga* trunk biomass exhibits competitive calorific values when compared with other biomass sources. Additionally, similar palm species, such as non-productive oil palm trunks, have demonstrated strong potential as raw materials for pulp and paper production [4–6], suggesting that *Arenga* palm trunks may be suitable for comparable applications.

Characterization studies indicate that non-productive *Arenga* trunks possess favorable physicochemical properties for pulp and bioenergy applications. Fiber morphological characteristics including fiber length, diameter, and cell-wall thickness together with chemical composition, particularly cellulose, hemicellulose, lignin, and extractive contents, play a critical role in determining the suitability of raw materials for pulp and bioenergy production. Previous investigations on related palm species have demonstrated that their anatomical fiber characteristics, chemical composition, and calorific potential support their viability as alternative sources for both pulp and bioenergy [7–9]. These studies also highlight the high energetic efficiency achievable through the conversion of palm biomass, particularly trunks, into bio-pellets.

Within the broader context of renewable energy development, detailed characterization of the anatomical and chemical properties of *Arenga* trunks is essential for supporting the growth of local bioenergy and biomaterial industries. Optimized utilization strategies for *Arenga* trunks can reduce agricultural waste while improving economic outcomes for local farming communities. At the global level, the use of *Arenga* trunk biomass aligns with decarbonization goals and climate change mitigation strategies [2], [10]. Furthermore, the utilization of *Arenga* trunk biomass in the energy and pulp sectors reflects sustainable agricultural practices by improving resource-use efficiency and reducing environmental impacts.

This study aims to elucidate the fiber dimensional characteristics, chemical composition, and calorific values of non-productive *Arenga* trunks collected from the Tanah Datar and Lima Puluh Kota regencies in West Sumatra. The findings are expected to provide comprehensive scientific evidence supporting the feasibility and sustainability of *Arenga* trunk biomass utilization, thereby contributing to the advancement of the bioenergy and biomaterial sectors at both local and national levels.

Materials and Methods

This study utilized non-productive *Arenga* palm trunks collected from three trunk heights: lower (5 m), middle (10 m), and upper (15 m). The chemicals and reagents used included 1% Safranin, 1% Alcian Blue, hydrogen peroxide (H_2O_2), a graded alcohol series (30%, 50%, 70%, 96%, and 100%), Entellan, xylol, glycerin, chromium wire, methyl orange, oxygen gas (O_2), and sodium carbonate.

Sample Site

Non-productive sugar palm trunks were collected from two locations in West Sumatra: Batusangkar (Tanah Datar Regency) and Lima Puluh Kota Regency (Figure 1). The non-productive *Arenga* palm trunks were harvested from trees approximately 30 years old. Fiber dimensions, including fiber length, fiber diameter, lumen diameter, and fiber wall thickness, were measured using the maceration method. Based on these measurements, derived fiber indices Runkel Ratio (RR), Felting Power (FP), Muhlsteph Ratio (MR), Coefficient of Rigidity (CR), and Flexibility Ratio (FR) were calculated. The palm trunks were also processed into fine wood particles for chemical composition and energy content analyses. Subsequently, calorific value, cellulose, hemicellulose, lignin, ash content, and moisture content were determined. Sampling locations were mapped using the QGIS software application.

Fiber Dimension Measurement and Wood Quality Classification

Fiber dimension measurements were performed by cutting sugar palm trunks into matchstick-sized pieces (10.8 cm × 6.5 cm × 2.1 cm). These pieces were heated in a tube containing a 1:1 mixture of hydrogen peroxide and glacial acetic acid. After fiber separation, the fibers were washed under running water and stained with safranin. The stained fibers were then immersed in glycerin for microscopic observation, and measurements were conducted to determine fiber derivative parameters. Quantitative fiber characteristics were obtained by measuring fiber length 25 times, while fiber diameter and wall thickness were each measured 15 times [11]. Fiber dimension values and wood quality classifications were determined based on criteria established by the Directorate General of Forestry [12].

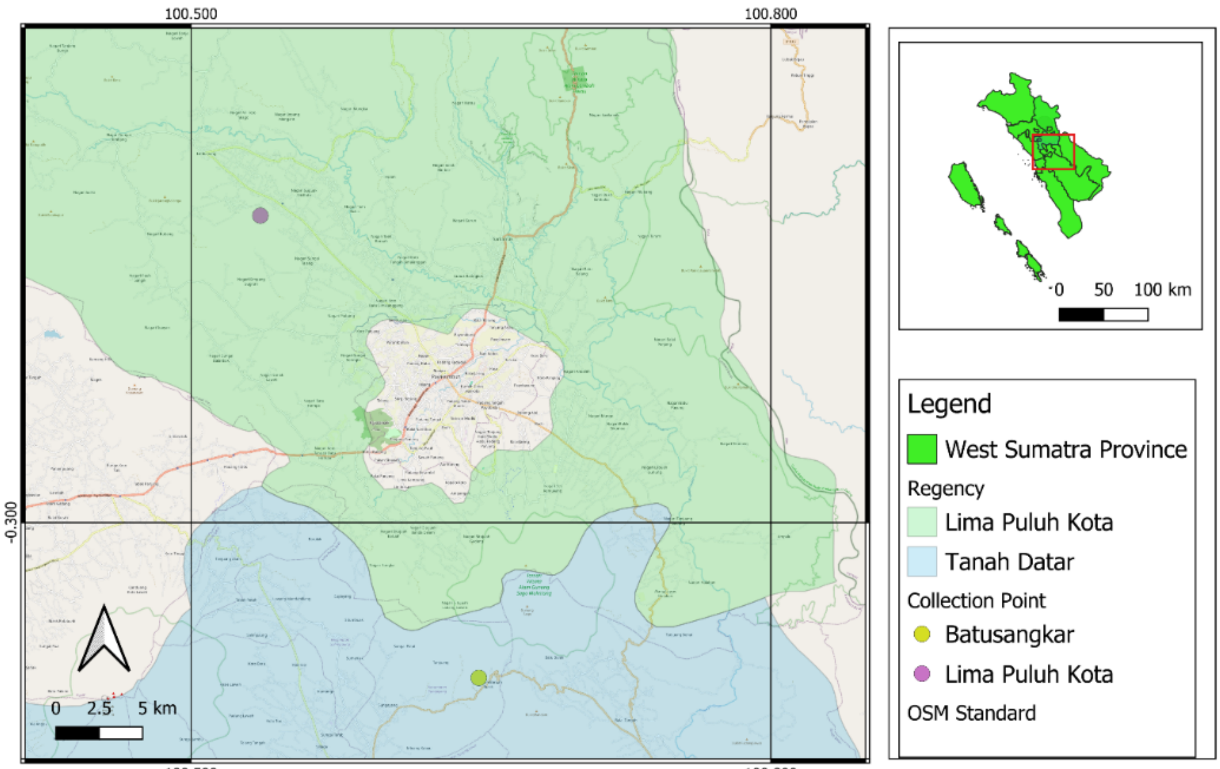

Figure 1. Collection Sites of Non-Productive Sugar Palm Trunks in West Sumatra.

Calorific Value

Wood calorific value was determined in accordance with 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 0.5–1.0 g were analyzed for calorific value using an adiabatic oxygen bomb calorimeter. The calorific values were calculated using the standard calorific value equation.

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

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 determined following the Association of Official Analytical Chemistry (AOAC) 2005 method [14]. Approximately 1 g of sample was placed in a pre-weighed container and oven-dried at 100–105 °C until a constant weight was reached (8–12 h). The moisture content percentage was then calculated using the standard formula for moisture content.

$MC = (w - d)/w \times 100; MC = \times\ 100$ .....*(2)*

Where: w= Wet weight, d= Weight after drying.

Ash Content Analysis

Ash content was determined according to the Association of Official Analytical Chemistry (AOAC) 2005 method [14]. Approximately 1 g of sample was placed in a pre-weighed container and incinerated in a furnace at 600 °C for 4–5 h until complete ashing was achieved. The residue was then transferred to an oven at 105 °C, cooled in a desiccator, and weighed. Ash content was calculated as a percentage using the standard ash content formula.

$AC = (A/B) \times 100$ ………………………….....*(3)*

Where: A= Weight of dry ash, B= Initial weight of the sample

Chemical Composition Analysis

The cellulose, hemicellulose, lignin, and extractive contents of non-productive sugar palm trunks were analyzed following the Technical Association of the Pulp and Paper Industry (TAPPI) 1989 methods [12]. The palm trunks were planed using a wood planer and dried in a cabinet dryer at 70 °C until a constant weight was achieved. The dried material was then ground and sieved through a 60-mesh screen, and the fraction passing through the sieve was used for chemical composition analysis.

Data Analysis

All data were analyzed using both descriptive and quantitative approaches. Descriptive analysis was used to identify general patterns in fiber dimensions, derived fiber indices, wood quality classification, calorific value, moisture content, ash content, and chemical composition. Quantitative analysis was applied specifically to numerical chemical composition data to allow a more detailed evaluation of variation and potential relationships among the measured parameters in non-productive sugar palm trunks from the two regions in West Sumatra.

Results and Discussion

Fiber Dimension

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

Fiber length measurements of *Arenga pinnata* trunks from Tanah Datar Regency (2.70–2.97 mm) were significantly greater than those from Lima Puluh Kota Regency (1.20–2.02 mm). Variations in fiber morphology, including fiber length and diameter, are strongly influenced by geographical and environmental factors, particularly altitude and slope gradient. Elevation and topographic inclination have been reported to substantially affect the anatomical dimensions of wood fibers [17]. Based on established classifications, fiber lengths are categorized into three groups: 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 Tanah Datar Regency clearly fall within the elongated fiber category (>1.90 mm). In contrast, trunks from Lima Puluh Kota Regency exhibited positional variability, with fibers from the upper and middle trunk segments classified as intermediate, while fibers from the basal segments were categorized as elongated.

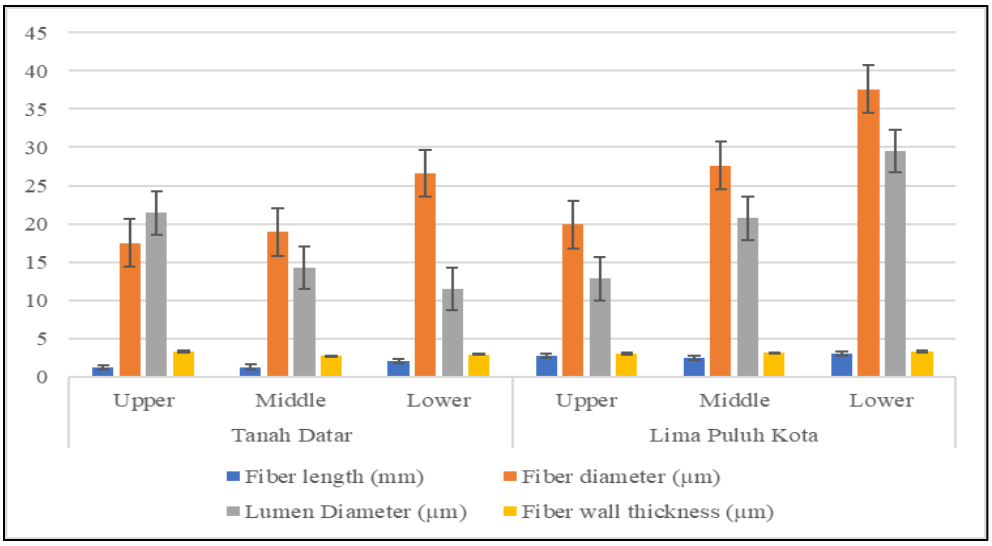

Figure 2. Fiber dimensions of non-productive sugar palm (*Arenga pinnata*) trunks.

Fiber length plays a crucial role in determining the mechanical properties of pulp and paper products, as it directly influences tensile strength, tear resistance, and folding endurance. Longer fibers promote stronger inter-fiber bonding, thereby enhancing the structural integrity and mechanical durability of the resulting paper. Previous studies have reported that sugar palm fiber lengths range from 1.6 to 2.7 mm [18]. In the present study, fibers obtained from the Batusangkar and Limapuluh Kota research locations exhibited length ranges of 1.2–2.02 mm and 2.70–2.97 mm, respectively. According to the classification system of the International Association of Wood Anatomists (IAWA), these fibers fall within the medium-length fiber category [19]. Fibers within this dimensional range typically produce paper with moderate mechanical performance, making them suitable for applications such as tissue paper, lightweight cardboard, and general printing paper. However, when compared to fibers from *Pinus radiata*, which are widely used in commercial pulp production and generally range from approximately 2.5 to 4.0 mm, sugar palm fibers exhibit comparatively shorter lengths, resulting in relatively lower mechanical strength characteristics.

Furthermore, radial and longitudinal positions discernibly influence fiber length variation within Furthermore, radial and longitudinal positions significantly influence fiber length variation within sugar palm trunks. Fibers located in the peripheral region generally exhibit greater lengths than those situated in the central region. Longitudinal variation follows a distinct distribution pattern: in the peripheral zone, fiber length is greatest at the apical portion of the trunk, intermediate at the basal portion, and shortest at the middle section. Conversely, in the central zone, fibers exhibit maximum lengths at the basal portion, intermediate lengths at the apical portion, and minimum lengths at the middle section. The average fiber length recorded for sugar palm trunks from Lima Puluh Kota (2.11 mm) closely resembles that reported for sago palm fibers**,** suggesting comparable anatomical characteristics and potential similarities in their pulp and paper performance [20].

Additionally, fiber diameter exhibited pronounced regional and positional variability within sugar palm trunks, largely driven by physiological and molecular processes occurring in the vascular cambium and during secondary xylem cell wall development [21], [22]. Across both Tanah Datar and Lima Puluh Kota regions, basal trunk segments consistently displayed greater average fiber diameters than those observed in the medial and apical segments. Previous studies have demonstrated that fiber diameter and cell wall thickness are closely associated with exogenous environmental conditions and growth ring formation [23]. Notably, the basal segments of non-productive sugar palm trunks exhibited fiber diameters ranging from 26 to 37 µm, which are comparable to the typical hardwood fiber diameters of approximately 25 µm reported by Atchison [24].

Sugar palm fiber diameters have been reported to range from 28 to 52 µm, exhibiting a progressive decrease toward the apical regions and generally smaller diameters in peripheral areas compared with central trunk locations [18]. Fiber wall thickness also showed pronounced variability (5–24 µm), strongly dependent on positional context within the trunk. The thickest cell walls were typically observed in peripheral basal regions, whereas the thinnest walls occurred in central apical positions. In the pulp and paper industry, fiber wall thickness is a critical determinant of pulp strength and overall product quality. Fibers with thicker cell walls are commonly associated with higher mechanical strength and are therefore well suited for packaging and structural paper products. In contrast, thinner-walled fibers exhibit greater flexibility and improved inter-fiber bonding capacity, making them more desirable for fine and printing papers [25], [26]. Consequently, the observed variability in fiber wall thickness within sugar palm trunks highlights their potential for diversified pulp applications, contingent upon the specific radial and longitudinal fiber sources.

Fiber Quality Classification

Fiber dimensions and their derived parameters serve as key indicators for assessing the suitability and quality of wood fibers in pulp and paper applications. The derived fiber dimension indices for non-productive sugar palm trunks are presented in Table 1.

The derived fiber dimension indices significantly influence fiber quality classification, thereby determining their suitability for applications in the pulp and paper industry. A wooden log may be considered suitable for durable furniture manufacturing if its fiber quality classification meets at least Class II criteria [27]. As presented in Table 1, non-productive sugar palm trunks from both Tanah Datar and Lima Puluh Kota satisfy this requirement. Notably, while all samples from Tanah Datar were classified as Class II, samples from Lima Puluh Kota consistently achieved a Class I classification, indicating superior fiber quality. This finding suggests that sugar palm trunks from Lima Puluh Kota not only meet but also exceed the minimum quality standards required for furniture materials. Furthermore, previous studies have also reported that sugar palm wood is suitable for watercraft construction, owing to its favorable physical and mechanical properties [28].

Runkel Ratio (RR) values measured in the upper, middle, and basal trunk sections ranged from 0.32 to 0.52 for samples from Tanah Datar and 0.26 to 0.58 for those from Lima Puluh Kota, indicating strong potential for pulp production. Similar findings have been reported in previous studies, which documented favorable RR values, particularly in the central upper (0.56) and central middle (1.05) trunk sections [18]. Optimal pulp production is generally associated with lower RR values (<1.00), thinner fiber walls, and larger lumen diameters. These characteristics enhance fiber flexibility and inter-fiber bonding capacity, resulting in pulp sheets with improved tensile strength and tear resistance [29]. The observed differences between the present study and earlier reports may be attributed to variations in tree maturity, trunk height, and local environmental conditions.

Fiber Proportion (FP), which reflects the relative abundance of fibers within the lignocellulosic matrix, exhibited notable variability between regions. FP values ranged from 45.50 to 116.61 µm in Tanah Datar, whereas higher values of 80.51 to 144.50 µm were recorded in Lima Puluh Kota. The elevated FP values observed in Lima Puluh Kota, particularly in the basal trunk segments, indicate a greater potential for high-quality pulp production due to increased fiber abundance. This interpretation is supported by previous studies demonstrating that higher fiber proportions are positively correlated with improved mechanical integrity and enhanced durability of pulp sheets [30].

Muhsteph Ratio (MR), which reflects the mechanical resistance of fibers, ranged from 34.90% to 57.77% in samples from Tanah Datar and from 16.09% to 43.33% in those from Lima Puluh Kota. Lower MR values are generally associated with improved pulp and paper quality, as they indicate greater fiber flexibility and enhanced inter-fiber bonding potential [31]. When compared with *Acacia* spp., which typically exhibit MR values in the range of 45–55%, the relatively lower MR values observed in the present study suggest superior strength-related properties of sugar palm fibers [32]. In contrast, sago fiber papers have been reported to possess significantly higher MR values (up to 81.24%), resulting in coarse surface textures and reduced compressive strength. Such characteristics limit their suitability for conventional writing papers but make them appropriate for specialized applications, including artistic and gift papers [20]. Overall, the notably lower MR values recorded for sugar palm trunks further confirm their suitability as a promising raw material for pulp and paper applications.

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	50	12.45	50	2021.3	75	2702.3	100	2456.6	100	2973.3	100
RR	0.32	75	0.43	75	0.52	50	0.58	50	0.31	75	0.26	75
FP	45.5	50	65.09	50	116.61	100	144.50	100	90.33	100	80.51	75
MR	34.9	75	44.77	75	57.77	75	16.09	100	43.33	75	40.66	75
FR	0.80	75	0.73	75	0.64	75	0.73	75	0.75	75	0.76	75
CR	0.13	75	0.15	75	0.17	50	0.16	50	0.12	75	0.1	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).

Flexibility Ratio (FR) values ranged from 0.64 to 0.80 in samples from Tanah Datar and from 0.73 to 0.76 in those from Lima Puluh Kota. Higher FR values indicate fibers with thinner cell walls and greater capacity for deformation, which enhances inter-fiber adhesion and improves the mechanical properties of pulp sheets. Increased FR values have been shown to positively influence tensile strength and fiber cohesion [29]. The Coefficient of Rigidity (CR), defined as the ratio of cell wall thickness to fiber diameter, exhibited values of 0.13 to 0.17 in Tanah Datar and 0.10 to 0.16 in Lima Puluh Kota, as presented in Table 1. CR values below 0.75 are indicative of higher fiber flexibility and are generally associated with improved pulp yield and sheet density. Lower CR values increase the effective inter-fiber contact area, thereby enhancing fiber bonding and reducing structural rigidity, which ultimately improves overall pulp quality [33].

Differences in fiber characteristics between Tanah Datar and Lima Puluh Kota indicate that fibers from Tanah Datar exhibit comparatively greater strength-related properties, whereas those from Lima Puluh Kota demonstrate superior fiber abundance and fineness. These distinctions are likely driven by environmental factors such as climatic conditions, soil characteristics, and tree age, which collectively influence fiber development and ultimately determine fiber quality.

Wood Energy Characteristics

Calorific values measured in non-productive sugar palm trunks from Tanah Datar and Lima Puluh Kota exhibited considerable variation (Table 2). Nevertheless, the combined results for calorific value, ash content, and moisture content indicate that both materials have limited suitability for pellet production. According to the Indonesian National Standard SNI 8021:2014, the minimum required calorific value for pellet feedstock is 4,000 cal/g. Similarly, the European standard EN 14961-2 specifies an acceptable calorific value range of 3,941–4,538 cal/g for pellet materials [34]. The calorific values obtained from sugar palm trunks in both regions fall outside these specified thresholds, thereby precluding their potential use as raw materials for pellet production.

Comparable studies on other non-productive members of the Arecaceae family have revealed substantial differences in their biomass potential as solid fuel sources. For example, investigations on coconut trunks (*Cocos nucifera*), which also belong to the Arecaceae family, have reported significantly higher calorific values than those observed for sugar palm trunks. The calorific values of coconut trunks generally exceed the minimum thresholds required for effective biomass energy utilization. In particular, aged coconut trunks have been shown to exhibit elevated calorific values, especially following thorough drying processes [35]. When moisture content is reduced to below 15%, coconut trunks readily meet the standards for use as solid fuel feedstock.

Similarly, studies on oil palm trunks (*Elaeis guineensis*) have demonstrated considerable biomass energy potential, with reported calorific values reaching 17.41 MJ/kg, which are comparable to those of certain coal grades. These findings highlight the critical role of moisture content, showing that maintaining levels below 20% significantly enhances combustion efficiency and aligns well with industry standards for solid fuel production [36]. Collectively, these favorable properties underscore the strong suitability of oil palm biomass as an alternative energy source with performance characteristics comparable to conventional fossil fuels.

In contrast, the calorific values of non-productive sugar palm trunks from Tanah Datar and Lima Puluh Kota (ranging from 2349.28 to 3374.16 cal/g) are substantially lower than those reported for coconut and sago trunks. Elevated moisture content contributes to reduced calorific value and increased residual ash following combustion, thereby diminishing both combustion efficiency and suitability for pellet production. Consequently, sugar palm biomass exhibits lower compatibility as a raw material for pellet production compared with coconut and oil palm biomass, primarily due to its higher moisture content and the resulting lower energy yield.

Chemical Composition

Non-productive sugar palm trunks from the 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 particularly in cellulose, hemicellulose, and lignin contents play a critical role in determining their suitability for both pulp manufacturing and bioenergy utilization. Higher cellulose content combined with lower lignin levels enhances pulp yield and quality by facilitating more efficient delignification during the pulping process. In contrast, lignin-rich materials tend to produce lower-quality pulp due to increased energy demands and more complex chemical processing requirements.

The cellulose content of non-productive sugar palm trunks from Tanah Datar ranged from 35.21% to 40.45%, whereas trunks from Lima Puluh Kota exhibited significantly higher cellulose contents, ranging from 59.16% to 64.63% (Table 3). This disparity may be attributed to differences in tree age between the two regions, as increasing age has been reported to correlate with higher cellulose accumulation [37]. Cellulose is a critical constituent in pulp production, and the elevated cellulose content observed in sugar palm trunks from Lima Puluh Kota indicates a strong potential for producing high-quality pulp. These values are comparable to, or even exceed, those typically reported for hardwood and softwood species, which generally contain 45–50% cellulose [38], [39]. For instance, *Eucalyptus*, a widely used industrial pulp species, has been reported to contain approximately 39.96% cellulose [40]. From a chemical perspective, cellulose functions as the primary structural polymer in plant cell walls, conferring mechanical strength and integrity to fibers [41].

The hemicellulose content of non-productive sugar palm trunks was generally lower than that typically reported for conventional wood species. In Tanah Datar, hemicellulose content ranged from 10.79% to 11.52%, whereas in Lima Puluh Kota it varied from 6.48% to 10.55%. These values are substantially lower than those commonly found in hardwoods (15–35%) and softwoods (30–32%). By comparison, the industrial pulp species *Eucalyptus* has been reported to contain approximately 26.41% hemicellulose [40]. Lower hemicellulose content can be advantageous during pulping, as hemicellulose degrades more readily than cellulose, thereby facilitating fiber separation. However, reduced hemicellulose levels may also influence pulp viscosity and fiber bonding properties. In contrast, lignin content an important factor affecting delignification efficiency was higher in trunks from Lima Puluh Kota (13.63–18.40%) than in those from Tanah Datar (8.02–13.63%). Since lignin must be removed to enhance pulp quality, elevated lignin levels generally require more intensive chemical processing. For reference, hardwoods typically contain 18–25% lignin, while softwoods contain 25–35% [38], [39]. From a bioenergy perspective, lower hemicellulose content may promote faster combustion rates but can reduce thermal stability. Nevertheless, reduced hemicellulose levels are also associated with lower emission potential during combustion, which may offer environmental advantages in biomass utilization.

Table 2. Wood energy characteristics of non-productive sugar palm (*Arenga pinnata*) trunks

Parameters	Tanah Datar (±SD)			Lima Puluh Kota (±SD)			SNI 8021	EN-14961-2
	Upper	*Middle*	*Lower*	*Upper*	*Middle*	*Lower*		
Caloric content (cal/gr)	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 (%)	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 (%)	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

Across the upper, middle, and basal sections of sugar palm trunks, lignin content ranged from 8.02% to 13.65% in Tanah Datar and from 13.63% to 18.40% in Lima Puluh Kota. These values are considerably lower than those reported in previous studies, which documented lignin contents of up to 46% in sugar palm wood [42], [43]. By comparison, *Acacia mangium*, a widely used industrial pulpwood species, has been reported to contain approximately 19.4% lignin [44]. Elevated lignin content in sugar palm trunks poses challenges for pulp production, as lignin acts as a binding agent between fibers but must be removed to prevent dark paper coloration and reduced mechanical strength. Consequently, delignification of sugar palm wood often requires more intensive bleaching processes than those applied to commonly used pulpwood species [45]. This increased processing demand is attributed to the higher chemical requirements needed to remove lignin and associated extractives [46]. Conversely, from a bioenergy perspective, high-lignin biomass is advantageous for pellet production. Lignin-rich pellets have been reported to exhibit improved combustion efficiency, higher heat generation, and enhanced thermal stability during combustion, making them well suited for power generation and heating applications [47].

Genetic and environmental variability may contribute to the observed differences in lignin content between sugar palm trunks from Tanah Datar and Lima Puluh Kota. Previous studies have identified quantitative trait loci (QTLs) associated with lignin content in sorghum through Genome-Wide Association Studies (GWAS), highlighting the critical role of genetic variation in lignin biosynthesis [48]. Similarly, investigations of sugarcane accessions have revealed significant variation in lignin content driven by differential expression of lignin biosynthetic genes, suggesting that genetic regulation of lignin accumulation can be region-specific [49]. In addition to genetic factors, environmental variables such as soil type, climatic conditions, and biotic interactions have been widely reported to significantly influence lignin production in plants [50].

Extractive content in the upper, middle, and basal sections of sugar palm trunks ranged from 5.09% to 8.08% in Tanah Datar and from 8.40% to 9.00% in Lima Puluh Kota. For comparison, *Eucalyptus*, which is widely used as an industrial pulp raw material, has been reported to contain approximately 8.26% extractives [40]. Extractives play diverse roles in biomass materials, particularly in palm trunks, by influencing energy value and combustion efficiency. Although sugar palm trunks generally contain moderate extractive levels, their presence can enhance biomass heating value, as extractives typically exhibit higher Higher Heating Values (HHV) than polysaccharides and lignin [51]. However, elevated extractive content may also produce undesirable effects, including increased emissions and slag formation during combustion [51], [52]. From a pulping perspective, high extractive content in sugar palm trunks can reduce pulping efficiency and increase production costs due to additional chemical consumption and processing requirements.

Additionally, extractives can reduce paper manufacturing efficiency by impairing inter-fiber bonding. Consequently, additional processing steps are required to remove extractives before sugar palm trunks can be utilized for high-quality pulp production. Despite these technical challenges, non-productive sugar palm trunks can still be processed into pulp with relatively good performance when compared to other tropical lignocellulosic raw materials.

Table 3. Chemical composition of non-productive sugar palm (*Arenga pinnata*) trunks

Chemical Composition	Tanah Datar (%)			Lima Puluh Kota (%)			Ref (*)	
	Upper	Middle	Lower	Upper	Middle	Lower		
Cellulose	40.45	39.86	35.21	64.63	62.38	59.16	45-50	45-50
Hemicellulose	10.79	10.92	11.52	6.48	8.69	10.55	15-35	30-32
Lignin	13.63	8.02	11.96	18.40	13.63	14.97	18-25	25-35
Extractive	7.09	8.08	5.09	8.40	8.60	9.00	0.2-0.5	0.2-0.5

*Notes: * [53], [54].*

Conclusion

This study investigated the physical and chemical characteristics of non-productive sugar palm trunks from Tanah Datar and Lima Puluh Kota to evaluate their potential for pulp and biomass applications. The results demonstrated that fiber dimensions from both locations meet the requirements for pulp production, with samples from Lima Puluh Kota classified as higher quality (Class I) compared to those from Tanah Datar (Class II). From a physical perspective, the trunks exhibit suitable fiber length, diameter, and cell wall thickness. Chemically, they contain moderate levels of cellulose and lignin, which support their feasibility for pulp processing. However, the measured calorific values (3.746–4.075 cal/g) fall below both national and international standards for biomass fuel utilization. Therefore, non-productive sugar palm trunks are more suitably utilized as raw materials for pulp and paper production rather than as biomass energy sources.

Acknowledgments

This study is supported by the Ministry of Higher Education, Science, and Technology Republic Indonesia through the Non-Tax Revenue Fund (PNBP) of Universitas Andalas, in accordance with research contract number T/14/UN.16.17/PT.01.03/IS-RDP/2021.

Conflict of interest

Authors declare no conflict of interest regarding the study.

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