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The Effect of Chemical Composition and Boiling Time in Kraft Method on Paper Making Based on Palm Oil Trunk (*Elaeis guineensis* Jacq.)

Muhammad Syukri[1*], Rina Maharany[2], M. Thoriq Al Fath[5], Ika Ucha Pradifta Rangkuti[3], Dina Arfianti Saragih[4], Dini Aprilia[3], Vikram Alexander[5], and Sarah Hafitz Syaurah[1]

[1]*Department of Chemical Engineering, Faculty of Science and Technology, Institut Teknologi Sawit Indonesia, Medan, Indonesia*
[2]*Department of Plantation Cultivation, Faculty of Vocation, Institut Teknologi Sawit Indonesia, Medan, Indonesia*
[3]*Department of Technology of Processing Plantation Products, Faculty of Vocation, Institut Teknologi Sawit Indonesia, Medan, Indonesia*
[4]*Department of Agribusiness, Faculty of Science and Technology, Institut Teknologi Sawit Indonesia, Medan, Indonesia*
[5]*Department of Chemical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Jl. Almamater Kampus USU, Medan, Indonesia*

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*** Corresponding author:**
E-mail: msrk@itsi.ac.id

ABSTRACT

The rapid expansion of palm oil plantations in Indonesia generates significant waste, including an estimated 77.692 tons/ha of palm oil trunks. It is essential to recycling these trunks into valuable raw materials. Given their high cellulose content, palm oil trunks are promising for paper production. This study investigates the production of paper from palm oil trunks (*Elaeis guineensis* Jacq.) using the kraft process with variations in chemical composition and boiling time. Three chemical compositions are tested, involving sodium hydroxide (NaOH), sodium sulfate (Na_2SO_4), and sodium carbonate (Na_2CO_3), along with boiling times of 90, 120, and 150 min. Paper quality are analyzed through water absorption, tensile strength, grammage, and visual appearance. The optimal kraft method for water absorption and tensile strength involves a 120-minute boiling time and a chemical composition of 20% NaOH, 9% Na_2S, and 4% Na_2CO_3, resulting in a water absorption of 59.33 mm, tensile strength of 11.26 kN/m, and a grammage of 65 g/m². Additionally, the clean, hole-free surface of the best-performing paper further validates the method's effectiveness. This study demonstrates that high-quality paper can be produce from palm oil trunks using optimal kraft process parameters, supporting sustainable waste utilization.

HIGHLIGHTS

- Palm oil trunks were recycled into paper using the kraft process.
- The study varied chemicals and boiling times to optimize paper quality.
- The best results had 20% NaOH, 9% Na_2S, and 4% Na_2CO_3, boiled for 120 mins.
- Optimal paper showed 59.33 mm water absorption and 11.26 kN/m tensile strength.
- Findings support sustainable waste utilization by converting trunks to paper.

1. INTRODUCTION

The area of palm oil plantations continues to increase every year. The total area of palm oil plantations in Indonesia in 2022 is 14.99 million ha, an increase of 2.49% compared to the previous year, which was only 14.62% (Putra et al., 2024). Along with the increasing development of palm oil plantations, waste production will also increase, one of which is palm oil trunks. In 1 ha of palm oil plantations will produce palm oil trunk waste of 77.692 tons/ha (Veronika et al., 2019). If these palm oil trunks are left to rot on plantation land, during the rotting process,

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they will release carbon into the atmosphere, thereby increasing the greenhouse effect (Ayundra et al., 2022). So far, palm oil trunks have been used as a substitute for wood, such as sandwich laminated lumber (SLL) or plywood (Kaima et al., 2023) and fiber cement (Zakaria and Soh, 2023). Apart from that, palm oil trunks can also be used as compost (Lau et al., 2024), fuel in the form of biopellets (Wistara et al., 2017), bioethanol (Siti et al., 2024), and brown sugar (Gozan et al., 2024).

Palm oil trunks have a high cellulose content, namely at the base of 51.58%, the middle of 50.86%, and the tip of 47.37%, palm oil trunk hemicellulose of 46.50%, and palm oil trunk lignin of 22.20% (Joseph et al., 2024). The high cellulose content in palm oil trunks can be used as raw materials in making paper. Some of the raw materials that have been used to make paper include *Acacia crassicarpa* (Sahan et al., 2024), a combination of sugarcane waste and rice husks (Abdelatif et al., 2024; Yennam et al., 2024), banana pseudo stem, banana leaf, and banana peduncle (Ferdous et al., 2021). Chemical papermaking can be done by three methods, namely the soda method, the sulfite method, and the kraft method (Michael et al., 2024). The soda method is done by cooking wood with a sodium hydroxide solution (Low et al., 2024). The sulfite method uses softwood as the raw material and an acidic cooking solution, namely a bisulfite solution of calcium (Ca) or magnesium (Mg) (Vachlepi, 2019).

The kraft method is a paper-making process with active chemicals consisting of sodium hydroxide (NaOH), sodium sulfate (Na_2SO_4), and sodium carbonate (Na_2CO_3) (Nova, 2011). In the kraft process, sodium sulfate (Na_2SO_4) is used to maximize the delignification process or removal of lignin from palm oil trunks. The lignin content in palm oil trunks will affect the boiling process (delignification). The delignification process aims to perfect the breaking of the lignin chain to produce a higher yield (Liu et al., 2024). The chemical composition of the kraft method in paper making is essential to study to enhance pulp production efficiency and ensure quality paper products.

Several researchers who have made paper using natural materials, such as Pulungan (2017), compared the composition of recycled paper made from organic and inorganic waste. The results obtained were 65% paper waste, 5% plastic waste, and 30% mustard greens with a grammage value of 110 g/m^2, a tensile strength of 3.37 kN/m, water absorption of 56.40 g/m^2, and a tensile strength value of >1,600 mN (Pulungan, 2017). Fenny and Farma (2016) utilized banana peels with newspaper and corn stalks with newspaper against recycled paper's tensile index and tear index. The results obtained using corn stalks and newspaper obtained a tensile index value of 7.31 Nm/g at a grammage of 50.90 g/m^2 (Fenny and Farma, 2016). Based on the results of previous studies, the results of parameter acquisition can be improved to achieve maximum results in accordance with the Indonesian National Standard (SNI). Previous studies focused on the composition of raw materials. This study uses the kraft method with the influence of chemical composition and boiling time, a novelty that fills in information that has been done by previous studies. This study uses palm oil trunks as raw materials in paper making.

This study aims to determine the effect of variations in the chemical composition and boiling time of the kraft method on paper making based on palm oil trunks. This research has the potential to encourage industry to develop efficient technology to process palm oil trunks into paper and switch to more sustainable and environmentally friendly raw materials, such as palm oil trunks. This research can also provide added value to palm oil trunks.

2. METHODOLOGY

2.1 Research materials and equipment

This research was conducted at the Chemistry and Physics Laboratory of the Institut Teknologi Sawit Indonesia, Medan, Indonesia, and the Forest Products Technology Laboratory, Universitas Sumatera Utara, Medan, Indonesia. The time of this research was carried out from February-March, 2023. The materials needed are palm oil trunks taken from the Institut Teknologi Sawit Indonesia garden area, Medan, Indonesia. Chemical used were purchased in local shop in Medan, Indonesia, such as aquadest, sodium hydroxide (NaOH, Merck, purity of 99%), sodium sulfate (Na_2SO_4, Merck, purity of 99%), sodium carbonate (Na_2CO_3, Merck, purity of 99%), hydrogen peroxide (H_2O_2, Merck, 10%) solution, and tapioca flour.

The tools used include A5 molds (14.8×21.0 cm), Memmert ovens, 30 mesh sieves, 5-liter capacity pans, machetes, Rinai brand stoves, thermo hotplates, 500 mL pyrex glass beakers, 30 cm rulers, turbo brand blenders, buckets with a capacity of 10 liters and kern analytical scales with an accuracy of 0.1 mg.

2.2 Research design

This research was conducted using a Factorial Completely Randomized Design (CRD), consisting of 2 factors:

2.2.1 Factor 1: Kraft method consists of 3 levels, namely:

- L1 = NaOH 10%+Na_2SO_4 5%+Na_2CO_3 2%
- L2 = NaOH 15%+Na_2SO_4 7%+Na_2CO_3 3%
- L3 = NaOH 20%+Na_2SO_4 9%+Na_2CO_3 4%

2.2.2 Factor 2: Boiling time consists of 3 levels, namely:

- T1 = 90 min
- T2 = 120 min
- T3 = 150 min

The number of treatment combinations is 3×3 totaling 9 treatments and there are 3 replications. If the data obtained is significantly different, it is continued with Duncan's Multiple Range Test at the 5% level.

2.3 Research procedure

The procedure described by (Hailemariam and Woldeyes, 2024) was followed with slight modification. The complete research scheme depicted in Figure 1. The palm oil trunks were chopped to a size of ±1 cm to reduce the size of the palm oil trunks, washed to remove dirt that stuck to them, and then dried in the sun until the water content reached 10%. The dried palm oil trunks were blended until smooth and then sieved using a 30 mesh sieve, resulting in 150 g of palm oil trunk powder.

The first boiling was carried out, the finely ground palm oil trunk powder was put into a pan, and then NaOH, Na_2SO_4, and Na_2CO_3 solutions were added sequentially according to the composition contained in the research design. The temperature was maintained at room temperature during the chemical addition step. Boiling at 100°C was carried out to soften the pulp and remove the lignin content contained in the pulp. After the boiling process was complete, the pulp was slowly filtered and rinsed with water at a temperature of 100°C, as much as 1 L; then, the pulp was squeezed and rinsed again with clean water until the resulting juice was clear.

The second boiling was carried out using a 7% H_2O_2 bleach solution for 1 hour at 90°C using a hotplate. After that, it was washed using clean water until the smell of the bleach solution was gone and then drained.

The pulp that has gone through the boiling process is mashed again using a blender until it becomes porridge, and 15 g of tapioca flour is added as an adhesive dissolved in hot water.

Before printing, the pulp is put into a bucket filled with ±10 liters of water. The pulp is filtered using a screen printing screen with a print size according to A5 paper (14.8×21.0 cm). After the printing process is complete, the paper is dried using an oven at 80°C for 45 min. After drying, the paper is removed from the mold using a knife.

2.4 Water adsorption analysis

The water adsorption test is carried out using the clamp method. A 1.5×20.0 cm paper is inserted, and the paper is hung perpendicular to the water surface, with one end dipped into the water to a depth of ±1 cm. After 10 min, a reading of the height of the increase in water absorbed on the surface of the paper is carried out using a ruler.

2.5 Grammage analysis

Paper grammage is a term used to determine the thickness of the same type of paper. The calculation is shown in equation 1.

$$G = \frac{A}{a} \quad (1)$$

Description: G=Paper sheet grammage (g/m^2); A=Tested sheet mass (g); a=Tested sheet area (m^2).

2.6 Tensile resistance analysis

Paper tensile resistance is measured using a Tensile Tester followed SNI 14-4737-1998 (National Standardization Agency (BSN), 1998). The tensile index can express the tensile strength and the tensile strength ratio to its grammage.

2.7 Appearance analysis

Analysis of the appearance of paper when it is clean and without holes. The appearance test can be done visually by carefully observing the entire surface of the paper. The paper appearance test involved ten respondents as representative respondents who filled out a questionnaire regarding the appearance of clean and without holes.

Figure 1. The complete research schemes applied in this study

3. RESULTS AND DISCUSSION

3.1 Results of water adsorption analysis

The results of observations and analysis of paper water adsorption test parameters can be seen in Figure 2. The best combination of treatment between boiling time and kraft method for the water adsorption test in Figure 2 is shown in the T2L3 treatment (boiling time 120 min and kraft method (NaOH 20%, Na_2S 9%, Na_2CO_3 4%) with a water adsorption value of 59.33 mm. This shows that the length of boiling time and the kraft method significantly affect the water adsorption value. The longer the boiling, the more the concentration of the solution must also be increased at least once from the boiling time because the dominant factor in the water adsorption test is the concentration of the solution. This is in line with the opinion of Ramadhani (2019), which states that the higher the concentration of the solution in the pulping process, the lower the lignin content produced will tend to be (Ramadhani, 2019).

The combination of boiling time and kraft method treatment with the lowest water adsorption test was in the T3L1 treatment (boiling time 150 min and NaOH concentration 10%, Na_2S 5%, Na_2CO_3 2%) with a water adsorption value of 19.00 mm. This shows that the longer the boiling, the lower the water adsorption if sufficient solution concentration is not given because boiling time that is too long will cause the fibers to become smoother and will affect the roughness of the paper surface. This is in line with the opinion of Syamsu et al. (2012), which states that smooth paper surfaces tend to have fewer pores compared to rough paper surfaces, so their water adsorption capacity also tends to be low (Syamsu et al., 2012). Statistical analysis using ANOVA on water adsorption was presented in Table 1. Based on the results of the analysis, the p value was obtained, which indicated that the data was normally distributed and therefore insignificant. The results of the statistical analysis showed that the treatments were not significantly different according to the Duncan test at the 5% test level.

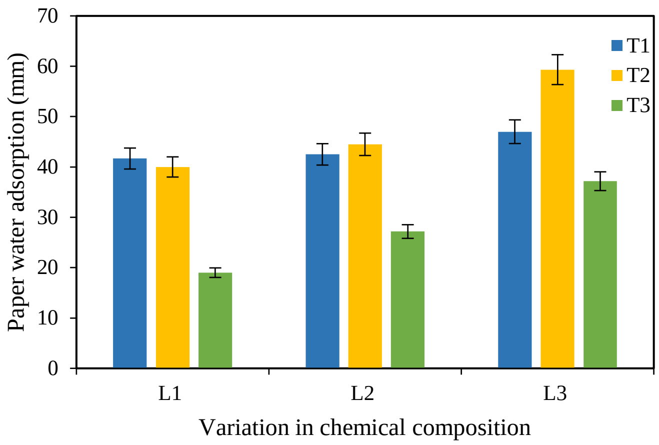

Figure 2. Effect of chemical composition and boiling time in kraft method on paper water adsorption

Table 1. Analysis of Variance (ANOVA) for the water adsorption analysis

Source	Degrees of freedom	Sum of squares	Mean squares	F-calculated	F-table	
					$F_{5\%}$	$F_{1\%}$
Variation	8	3196.41	399.55	26.47	2.51	3.71
T	2	2036.24	1018.12	67.46	3.55	6.01
L	2	959.13	479.56	31.77	3.55	6.01
T×L	4	201.04	50.26	3.33	2.93	4.58

3.2 Results of paper grammage analysis

The results of the observations and analysis of paper grammage test parameters were presented in Figure 3. Based on these results, the L1 and T1 treatment variations produced the highest paper grammage values of 76.11 g/cm^2 and 89.44 g/cm^2, respectively. Statistical analysis using ANOVA on grammage analysis was presented in Table 2. Based on the results of the analysis, the p value was obtained, which indicated that the data was normally distributed and therefore insignificant. Statistical analysis using Duncan's test at a 5% significance level showed that the treatments were not significantly different. Although some decreases in paper grammage were observed, it remained within an acceptable range and did not significantly impact the overall results. The lack of interaction between the two treatment factors such as boiling time and solution concentration, indicates that these factors did not support each other in enhancing paper grammage. Kraft pulping primarily targets lignin removal rather than drastic fiber structural changes (Silva et al., 2012). This suggests that boiling time and chemical variations in kraft methods may not sufficiently alter fiber morphology to affect grammage. This suggests that the observed variations were influenced by external factors such as equipment changes during the experimental process. One of the main external factors contributing to this was the change of tools during the paper printing process, which led to significant differences in paper thickness (Qiao et al., 2023). Additionally, the use of manual printing introduced surface unevenness, further contributing to variations in paper grammage (Itamiya and Sugita, 2015). Hence, grammage is primarily determined during the forming stage.

3.3 Results of paper tensile strength analysis

The results of observations and analysis of paper tensile strength test parameters can be seen in Figure 4. The best combination of treatment and kraft method for the tensile strength test based on Figure 4 is in the T2L3 treatment (120 min with 20% NaOH, 9% Na_2SO_4, 4% Na_2CO_3) with a tensile strength value of 11.26 kN/m. The boiling time and kraft method affect the tensile strength test value. The higher the solution concentration, the better the tensile strength test will be with sufficient boiling time (Kaima et al., 2023). The higher the solution concentration, the tensile strength will tend to increase. This is because the high concentration of the solution causes the cellulose to expand, the fiber cross-section becomes rounder, and the fiber crystallinity increases, which makes the tensile strength between fibers higher (Lu et al., 2023).

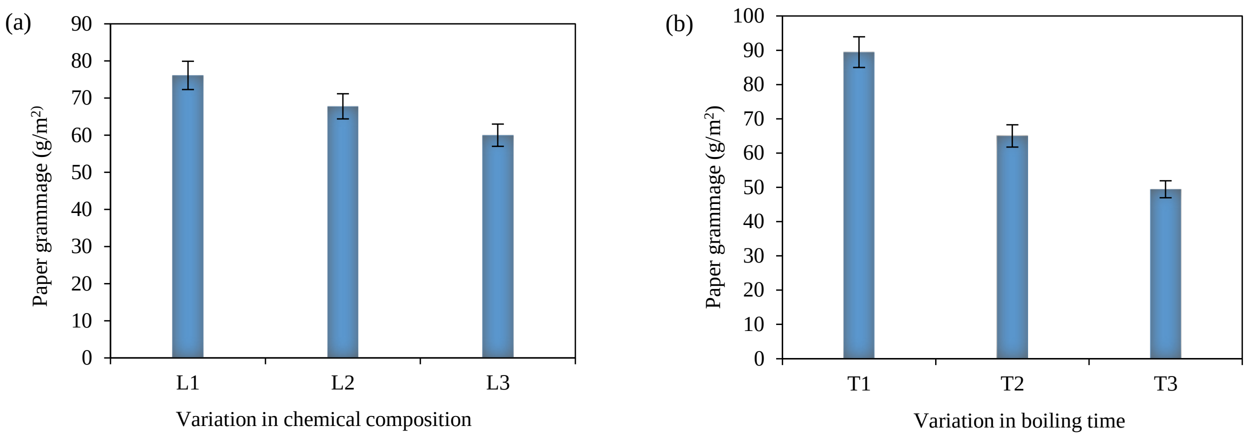

Figure 3. Average results of treatment on grammage parameters in variations of a) chemicals in the kraft method and b) boiling time.

Table 2. Analysis of Variance (ANOVA) for the paper grammage analysis

Source	Degrees of freedom	Sum of squares	Mean squares	F-calculated	F-table	
					$F_{5\%}$	$F_{1\%}$
Variation	8	8562.96	1070.37	20.28	2.51	3.71
T	2	7318.52	3659.26	69.33	3.55	6.01
L	2	1168.52	584.26	11.07	3.55	6.01
TxL	4	75.93	18.98	0.36	2.93	4.58

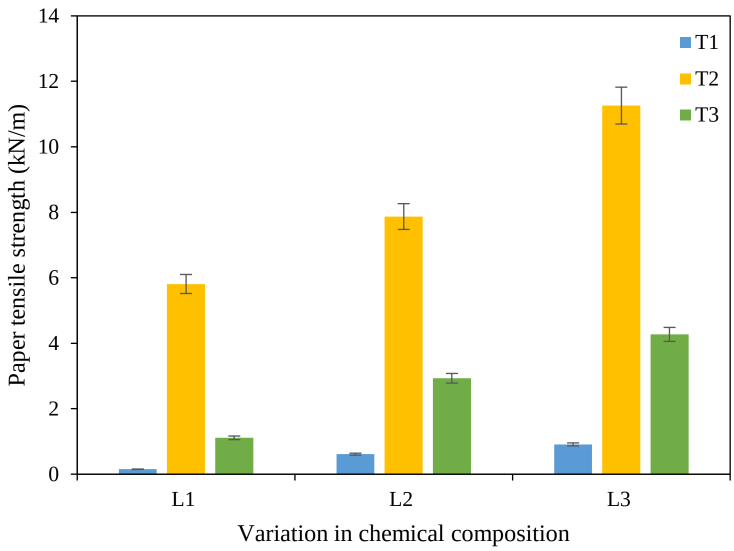

Figure 4. Effect of chemical composition and boiling time on paper tensile strength test parameters

The lowest combination of boiling time and kraft method treatment for tensile strength test was in T1L1 treatment (90 min with 10% NaOH, 5% Na_2SO_4, 2% Na_2CO_3) with a tensile strength value of 0.15 kN/m. This shows that boiling time is too fast, insufficient concentration causes lignin not to degrade properly, and cellulose is not perfectly soft, so there is no bond between fibers. Longer boiling times increase lignin removal by allowing more time for chemical or thermal breakdown of lignin bonds. However, low chemical concentrations require prolonged thermal exposure to compensate, which accelerates fiber degradation (Senthilkumar et al., 2025). Low chemical concentrations (e.g., in mild kraft pulping) necessitate longer boiling times, exacerbating thermal degradation (Sharma et al., 2019). This is in line with the opinion of Ek et al. (2009), which states that tensile strength is influenced by fiber strength, fiber length, the number of bonds between fibers, and the surface structure of the paper (Ek et al., 2009).Statistical analysis using ANOVA on tensile strength was presented in Table 3. Based on the results of the analysis, the p value was obtained, which indicated that the data was normally distributed and therefore insignificant. The results of the statistical analysis showed that the treatments were not significantly different according to the Duncan test at the 5% test level.

Table 3. Analysis of Variance (ANOVA) for the tensile strength analysis

Source	Degrees of freedom	Sum of squares	Mean squares	F-calculated	F-table	
					$F_{5\%}$	$F_{1\%}$
Variation	8	348.37	43.55	140.10	2.51	3.71
T	2	287.01	143.50	461.69	3.55	6.01
L	2	43.91	21.96	70.64	3.55	6.01
T×L	4	17.44	4.36	14.03	2.93	4.58

3.4 Results of visual appearance of paper production

The results of paper produced from palm oil trunks using the kraft method can be seen in Figure 5. Paper made from palm oil trunks shows a variety of appearances. Paper close to SNI is found in the T2L3 treatment combination (120 min with a concentration of 20% NaOH, 9% Na_2SO_4, and 4% Na_2CO_3), which is clean and has no holes. The treatment with the highest concentration has a good appearance; this happens because when boiling palm oil trunks, there is lignin that can be degraded perfectly, so the higher the concentration of the solution used, the more lignin will be degraded with sufficient time. This is supported by Faris et al. (2017) about the observation that kraft lignin contains substantial guaiacyl units, which are more effectively degraded at higher concentrations (Faris et al., 2017). Study from Coura et al. (2023) about the FTIR analysis typically reveals specific peaks associated with functional groups present in lignin. For instance, peaks around 1,600 cm^{-1} indicate aromatic skeletal vibrations, while peaks near 1,500 cm^{-1} correspond to C=C stretching. A reduction in the intensity of these peaks after treatment suggests effective lignin degradation (Coura et al., 2023). The FTIR spectra may also show new peaks corresponding to functional groups formed as a result of lignin degradation. For example, the formation of ether bonds or other linkages can be detected, indicating that not only is lignin being degraded but also that new compounds are being synthesized from its breakdown products (Ghahri and Park, 2023). The combination of treatment between boiling time and the kraft method in the appearance test that does not comply with SNI is found in the T1L1 treatment (90 min with a concentration of 10% NaOH, 5% Na_2SO_4, 2% Na_2CO_3). Due to the low concentration of the solution, so it is not degraded properly. Boiling time also affects the appearance of the paper. Boiling time short enough will produce fibers that are not soft, and lignin is not thoroughly degraded.

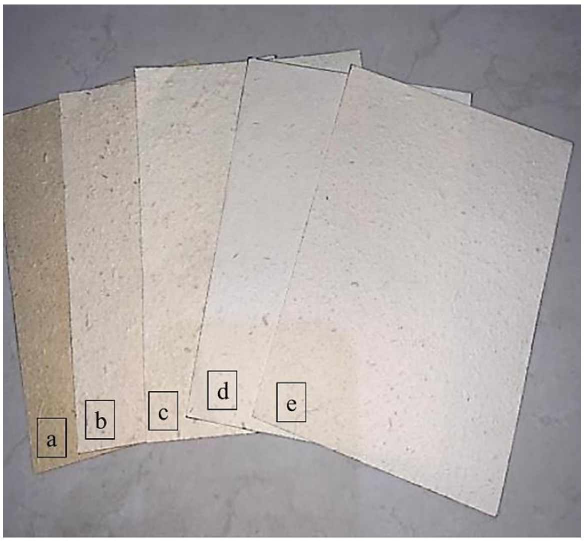

Figure 5. Appearance of the paper produced in this study (a) T1L1, (b) T1L2, (c) T2L2, (d) T3L2, and (e) T2L3

3.5 Comparative analysis

A summary of the results of this study compared with other studies and Indonesian national standards is shown in Table 4.

Table 4 summarized of the results of this study compared with other studies such as empty palm oil bunches, organic waste, banana peel and Indonesian national standards. However, there are other sources such as Moringa pods (Castelló et al., 2024) and Taro (*Colocasia esculenta* cv *fouê*) corm (Amon et al., 2014) are also noteworthy. The findings of this research demonstrate that palm oil trunk has significant potential as a raw material for paper production. The grammage of paper produced in this study is 67.78 g/m², which is well within the SNI and ISO standard range. This value is lighter than paper derived from empty palm oil bunches (78.10 g/m²) (Tarigan, 2017) and organic waste (110.00 g/m²) (Pulungan, 2017), but closely comparable to banana peel-based paper (50.90 g/m²) (Fenny and Farma, 2016). The lightweight property of palm oil trunk paper makes it particularly suitable for applications requiring low grammage materials.

Table 4. Summary of the results of this study compared with other studies and Indonesian national standards

Raw material	Parameter analysis of paper			References
	Grammage (g/m^2)	Tensile strength (kN/m)	Water adsorption (mm)	
Empty palm oil bunches	78.10	4.30	-	Tarigan (2017)
Organic waste	110.00	3.35	56.40	Pulungan (2017)
Banana peel	50.90	7.31	-	Fenny and Farma (2016)
Palm oil trunk	67.78	11.26	59.33	This research
SNI	50-100	Min. 2.0	-	BSN (2008)
ISO	80-100	-	-	ISO (2019)
	-	10-20	-	ISO (2008)
	-	-	25-45	ISO (2014)

In terms of tensile strength, this research records a value of 11.26 kN/m, significantly exceeding the SNI minimum and ISO standard. This tensile strength is superior to papers made from empty palm oil bunches (4.3 kN/m) (Tarigan, 2017), organic waste (3.35 kN/m) (Pulungan, 2017), and banana peel (7.31 kN/m) (Fenny and Farma, 2016). The exceptionally high tensile strength highlights the structural advantages of palm oil trunk fibers, making it a strong candidate for high-strength applications, such as industrial packaging.

The water adsorption value of palm oil trunk paper is 59.33 mm, which is exceeds the ISO range but comparable to the water adsorption of organic waste-based paper (56.4 mm) (Pulungan, 2017). Although water adsorption data for papers made from empty palm oil bunches and banana peels were not available, the results suggest that palm oil trunk paper offers moderate water resistance. This property could be further enhanced through surface modifications or chemical treatments, enabling its use in environments with higher moisture exposure. This research highlights the balanced properties of palm oil trunk paper, combining lightweight characteristics with exceptional tensile strength and moderate water resistance. Compared to other raw materials, palm oil trunk demonstrates a unique potential for producing durable and sustainable paper products. Its performance exceeds many commonly cited lignocellulosic alternatives, highlighting the value of further investment in its processing optimization and supply chain development. Given the massive availability of palm-producing countries like Indonesia, its integration into the circular bio economy could support both environmental and economic sustainability targets.

4. CONCLUSION

This study demonstrates that both boiling time and the kraft method significantly influence key physical properties of paper produced from oil palm stem fibers in reducing greenhouse gas emissions from decomposing palm oil trunk. The optimal treatment, T2L3 (boiling for 120 min with 20% NaOH, 9% Na_2SO_4, and 4% Na_2CO_3), yielded water adsorption of 59.33 mm, paper grammage of 67.78 g/cm^2, and tensile strength of 11.26 kN/m, with physical characteristics that meet the requirements set by SNI 2008 standards. The results highlight the potential of utilizing agricultural residues like oil palm stems in sustainable paper production, offering a viable alternative to conventional wood-based sources. This approach not only adds value to biomass waste but also supports circular economy principles. To further assess its feasibility and impact, future research should use automated methods to standardize thickness, focus on pilot-scale implementation, cost-benefit analysis, and particularly on conducting life-cycle assessments to quantify the environmental advantages of the process compared to traditional paper manufacturing.

AUTHOR CONTRIBUTIONS

Conceptualization, Muhammad Syukri, Rina Maharany, M. Thoriq Al Fath, Ika Ucha Pradifta Rangkuti, and Dina Arfianti Saragih; Validation, Muhammad Syukri, Rina Maharany, M. Thoriq Al Fath, Ika Ucha Pradifta Rangkuti, Dini Aprilia, and Dina Arfianti Saragih; Formal Analysis, Dini Aprilia, Sarah Hafitz Syaurah, and Vikram Alexander; Investigation, Dini Aprilia, Sarah Hafitz Syaurah, and Vikram Alexander; Data Curation, Dini Aprilia, Sarah Hafitz Syaurah, and Vikram Alexander; Supervision, Muhammad Syukri, Rina Maharany, M. Thoriq Al Fath, Ika Ucha Pradifta Rangkuti, and Dina Arfianti Saragih.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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