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Article

Influence of Hydrogen Peroxide on the Bleaching Process of Pulp Derived from Oil Palm Fronds and Empty Fruit Bunches

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A B S T R A C T

Oil palm fronds and empty fruit bunches (EFB) are the main by-products of oil palm plantations. Typically, these residues are used for organic fertilizer, mat production, or as a growing medium for plants and fungi. However, oil palm fronds and EFB have high cellulose content, making them promising raw materials for pulp and paper production. This study aimed to investigate the pulp and papermaking process using oil palm fronds and EFB as raw materials. A soda pulping process was applied, followed by bleaching using various concentrations of hydrogen peroxide, namely 8%, 10%, 12%, 14%, and 16%. The results showed that optimal pulp and paper quality was achieved using 16% hydrogen peroxide, which produced pulp with a brighter and whiter appearance. The resulting paper showed a thickness of 0.62 mm, a grammage of 56.58 g/m², and a density of 35.07 kg/m³.

1. Introduction

The development of the pulp and paper industry is fundamentally driven by the increasing global demand for paper. Currently, global paper consumption has reached approximately 349 million tons per year, while domestic demand in Indonesia reaches 8.9 million tons per year. As population growth increases, paper demand is also expected to increase. Consequently, paper production in Indonesia must be increased to meet this growing demand. Currently, Indonesia has 111 pulp and paper manufacturing companies, with a national pulp production capacity of 12.13 million tons per year, placing Indonesia as the 8th largest pulp producer in the world. Furthermore, the national paper production capacity reaches 18.26 million tons per year, placing Indonesia as the 6th largest paper producer in the world (Tuto et al., 2022).

The pulp and paper industry in Indonesia still predominantly relies on wood as its primary raw material. However, the availability and supply of wood can no longer keep pace with the increasing demand for this resource. A major issue faced by domestic pulp and paper producers is their heavy dependence on forest-derived wood as a source of cellulose fiber. Approximately 90% of the pulp and paper produced in Indonesia is made using wood-based raw materials (Astuti & Asngad, 2020).

The declining availability of wood-based raw materials has resulted in unmet demand for wood in the pulp and paper industry. This situation has prompted the industry to explore alternative fiber sources to replace wood. Among the potential substitutes, oil palm fronds and empty fruit bunches (EFB) have emerged as promising renewable resources for pulp and paper production. These agricultural residues offer an abundant and sustainable source of cellulose fiber that can help reduce dependency on forest-derived materials (Nanna et al., 2020).

Oil palm fronds possess significant potential for various applications. Traditionally, they are mainly utilized as organic fertilizer or as a growing medium for plants and fungi. However, due to their high lignocellulosic content, oil palm fronds can be used as a raw material for paper production. Their substantial cellulose content makes them a highly promising alternative source of fiber for the pulp and paper industry (Aisyah & Trihernawati, 2023).

In addition to oil palm fronds, empty fruit bunches (EFB) from oil palm also contain key chemical components such as cellulose, hemicellulose, and lignin—similar to those found in wood and other fibrous plants. EFB holds great potential as a non-wood fiber source for pulp and paper production. Moreover, effective utilization of EFB as a raw material not only contributes to sustainable paper manufacturing but also offers added value in managing palm oil industry waste (Rizky Amelia et al., 2021).

In paper production, the bleaching process plays a crucial role. Bleaching is intended to remove residual lignin remaining in the pulp or fibers, thereby achieving a high and stable level of brightness. Chemical agents such as hydrogen peroxide are commonly used in the bleaching process. Hydrogen peroxide is considered an environmentally friendly bleaching agent, as it decomposes into non-toxic byproducts—namely oxygen and water—without leaving behind harmful residues (Apriani, 2021).

Hydrogen peroxide offers other advantages, including the production of bleached pulp with high durability and minimal reduction in fiber strength. This makes it a preferred bleaching agent in sustainable and high-quality pulp and paper manufacturing.

2. Literature Riview

2.1 Oil Palm Fronds

Oil palm fronds are leaf-like structures that grow along the trunk of the oil palm tree. Their availability is continuous throughout the year, as fresh fruit bunches (FFB) are harvested daily. The fronds pruned during harvesting generate a substantial amount of agricultural waste, particularly in Indonesia, with significant quantities found in regions such as North Sumatra, Riau, and South Sumatra. This abundance makes oil palm fronds a readily available and underutilized biomass resource for industrial applications (Maulana et al., 2023).

During the harvesting of fresh fruit bunches (FFB), 1 to 2 oil palm fronds are cut to facilitate pollination and ease subsequent harvesting activities. A mature oil palm tree can produce approximately 40 to 50 fronds per year, with each frond having an average dry weight of about 4.5 kilograms. Oil palm fronds are classified as wet biomass waste due to their high moisture content (wet by – product) Due to their high moisture content—approximately 75%—oil palm fronds are prone to rapid degradation if not processed promptly. They are considered one of the solid wastes generated by the palm oil industry. Each oil palm tree can produce up to 22 fronds, and on average, around 6.3 tons of fronds can be generated per hectare annually (Aisyah et al, 2023).

Oil palm fronds have long been underutilized by local communities and are generally treated as waste, often left in piles around plantations or near the base of trees. However, these fronds have significant potential as an alternative raw material for paper production due to their high content of cellulose (40.96%), hemicellulose (20.69%), lignin (18.9%), silica (0.6%), and moisture (10.10%) (Apriani, 2021).

2.2 Fruit Empty Bunch

The primary products derived from oil palm trees are the fresh fruit bunches (FFB), which are processed to extract oil from the mesocarp (palm oil) and kernel (palm kernel oil). After the oil extraction process, a significant amount of waste is generated in the form of empty fruit bunches (EFB). EFB is the main solid waste produced by the palm oil processing industry. From each ton of processed fresh fruit bunches, approximately 0.21 tons (21%) of crude palm oil (CPO) and 0.05 tons (5%) of palm kernel oil (PKO) are obtained. The remaining portion—about 20% to 23%—is EFB waste, representing a substantial by-product of the palm oil supply chain

(Aisyah & Trihernawati, 2023).

He availability of empty fruit bunches (EFB) in the field is considerable, especially with the increasing number and capacity of palm oil mills to process fresh fruit bunches (FFB). EFB is typically used as compost fertilizer or as a growing medium for fungi. Physically, EFB consists of various types of fibers and contains approximately 45.95% cellulose, 16.49% hemicellulose, and 22.84% lignin. Given its high cellulose content, EFB has strong potential as an alternative raw material for pulp and paper production (Putri et al., 2022).

2.3 Sodium Hydroxide (NaOH)

Sodium hydroxide (NaOH) is a base oxide-derived compound formed by dissolving sodium oxide in water. When dissolved, sodium hydroxide forms a strong alkaline solution. It appears as white crystalline solids and is highly corrosive to the skin. In industrial contexts, NaOH is commonly referred to as caustic soda. Its dissolution in water is an exothermic reaction, releasing heat.

The chemical properties of NaOH include: a white or nearly white appearance; it is available in pellets, flakes, rods, or other solid forms. It is strongly basic and readily ionizes into sodium and hydroxide ions in solution. It is hard, brittle, and exhibits a crystalline fracture. When exposed to air, it quickly absorbs carbon dioxide and moisture. It is highly soluble in water and ethanol but insoluble in ether. When dissolved in water, it forms a strong base (Linda. Kusumayanti. 2020).

2.4 Hydrogen Peroxide

Hydrogen peroxide, with the chemical formula H_2O_2, is an organic compound known for its strong oxidizing properties. In chemistry, a strong oxidizing agent refers to a substance that readily oxidizes other elements or compounds while itself being reduced. Hydrogen peroxide exhibits several physical characteristics: it is a colorless liquid available in various concentrations, has a slightly acidic odor, and is highly soluble in water. Its molecular structure, represented by H–O–O–H covalent bonds, forms hydrogen bonds with nonpolar characteristics that differ from the hydrogen bonds found in water.

Hydrogen peroxide is widely used in the chemical industry. Its industrial applications are diverse, particularly as a thickening agent and bleaching agent in the pulp, paper, and textile industries. It also functions as a non-polluting oxidizing compound, making it an environmentally friendly alternative in various chemical processes.

Hydrogen peroxide is considered one of the most effective bleaching agents due to its ability to eliminate stains or color at the molecular level. This occurs through an oxidation process in which H_2O_2 releases oxygen atoms. These free oxygen atoms react with the oxygen-containing components of stains or pigments, forming molecular oxygen (O_2) as a byproduct. As a result, the stains or color compounds are broken down and removed along with the released oxygen gas (Andari et al., 2022).

2.5 Soda Process

The soda process is a pulping method that involves cooking raw materials with the addition of sodium hydroxide (NaOH) as a cooking liquor, under high pressure. The typical ratio of cooking liquor to raw materials is 4:1. Although effective, the soda or alkali process presents challenges in recovering chemicals from the spent liquor, making it less commonly used compared to the sulfite process. However, one of the main advantages of the soda process is its flexibility in using a variety of raw materials (Kusumaningrum & Kusumayanti, 2016).

2.6 Pulp

Pulp is a product composed of cellulose fibers derived from wood or non-wood sources, processed by dissolving as much lignin as possible. The primary goal of the pulping process is to obtain the maximum amount of fiber, characterized by high yield, while minimizing lignin content. During the pulping process, lignin is degraded by the cooking liquid into smaller, soluble molecules that then dissolve into the black liquor. This process is known as delignification.

2.7 Paper

The English word "paper" comes from the Dutch term papier. Paper is a man-made material in the form of a thin sheet that can be torn, rolled, folded, glued, or written on, and has properties different from those of its original raw materials - especially substances derived from plants.

Paper is a thin and flat material produced by compressing fibers derived from pulp. The fibers used are typically natural and primarily composed of cellulose and hemicellulose. Paper is manufactured to meet a wide range of human needs across various sectors (Dharosno & Pundu, 2020).

Paper is widely recognized as the primary medium for writing, printing, and painting, with numerous other applications such as tissue paper for dining, hygiene, and sanitation purposes. The invention of paper marked a revolutionary advancement in the history of writing, playing a significant role in the development of global civilization.

Before the discovery of paper, ancient civilizations used various materials for recording information, such as clay tablets that were baked—common in Sumerian culture - as well as stone inscriptions, wood, bamboo, animal skins or bones, silk, and palm leaves. In the Indonesian archipelago, palm leaf manuscripts (lontar) were commonly used in past centuries and assembled in specific formats for documentation and recordkeeping. (Wardhana Wahyu Dharosno, 2020).

3. Research Methodology

The main equipment used in this study includes: a blender, which was used to cut or reduce the size of raw materials; an analytical balance for weighing samples; an autoclave for cooking the raw materials; and an oven and hot plate for heating processes. A reflux apparatus was employed during the analysis of lignin and cellulose content. A screen-printing frame was used for paper sheet formation. Additional laboratory tools included a Mohr pipette, measuring cylinders, volumetric flasks, beakers, Erlenmeyer flasks, funnels, filters, spatulas, glass stirring rods, dropper pipettes, large containers, sponges, fabric sheets, as well as personal protective equipment such as masks and gloves.

The materials used in this study included oil palm fronds and empty fruit bunches (Elaeis guineensis Jack) as the primary raw materials for pulp production; recycled paper as a blending component; 15% sodium hydroxide (NaOH) for the delignification process; sulfuric acid (H_2SO_4) for lignin content analysis; hydrogen peroxide (H_2O_2) as a bleaching agent for the pulp; and starch powder as a binder in the pulp preparation.

The paper-making process in this study was carried out as follows:

3.1 The initial stage of the process involved the preparation of raw materials.

Oil palm fronds were cleaned by removing the leaflets and midribs, while the empty fruit bunches (EFB) were cleaned to remove any adhering impurities. Both materials were then dried and cut into small pieces before being processed using a cuttermill to produce chips of the desired particle size (20–30 mesh). A total of 250 grams of raw material was used, consisting of 125 grams each of palm fronds and EFB. To achieve the target particle size, the materials were sieved using a 20-mesh screen with the assistance of a blender.

3.2 Pulping Process

This process was carried out using an autoclave. The first step involved preparing the cooking liquor, which consisted of 37.5 grams of sodium hydroxide (NaOH), equivalent to 15% of the raw material weight, dissolved in 1000 mL of distilled water. The blended raw materials (250 grams) were placed into a 2000 mL Erlenmeyer flask, then mixed with the prepared cooking liquor. The ratio of liquor to solid was 4:1 (4 mL of NaOH solution per 1 gram of solid), using 1000 mL of NaOH solution for 250 grams of raw material.

The mixture was then heated in the autoclave at 120°C for 2 hours. After cooking, the mixture was washed and filtered to separate the cooking residue, known as black liquor, from the raw pulp. Filtration also helped to remove any remaining impurities from the pulp after cooking.

3.3 Pulp Bleaching Process

The bleaching process was carried out using hydrogen peroxide solutions with concentration variables of 8%, 10%, 12%, 14%, and 16%. These concentrations were prepared by diluting 30% hydrogen peroxide using a 100 ml volumetric flask. The dilution was done by pipetting 26.6 mL for an 8% solution, 33.3 mL for 10%, 40 mL for 12%, 46.6 mL for 14%, and 53.33 mL for 16%, and then adding distilled water up to the mark on the flask for each respective variable.

Before bleaching, the obtained pulp was first refined into a slurry and filtered. For each concentration variable, 20 grams of pulp was weighed. The pulp was then soaked in the corresponding hydrogen peroxide solution for 30 minutes. After soaking, the pulp was rinsed thoroughly with clean water. The final step involved drying the pulp using an oven until dry pulp was obtained.

3.4 Paper-making process

The bleached pulp treated with 8% hydrogen peroxide was mixed with 20 grams of recycled paper waste that had been previously pulped using water and a blender. The recycled paper waste consisted of used writing paper, cardboard, and HVS (wood-free) paper. A starch-based adhesive was prepared by dissolving 2.4 grams of starch (equivalent to 6% of the total mixture weight) in water and heating it until it became clear. The pulp and adhesive were then combined in a container and thoroughly mixed.

A screen mold was prepared in a water bath. The pulp mixture was poured into the mold, then the mold was lifted to form a sheet. The paper was left to dry at room temperature until fully dried. This same procedure was repeated for the remaining hydrogen peroxide concentration variables: 10%, 12%, 14%, and 16%.

3.5 Pulp and Paper Testing

In this study, the produced pulp and paper were subjected to specific tests. The pulp was analyzed for its lignin content, while the paper was tested for its grammage (basis weight) and density.

4. Results and Discussion

Table 1 Lignin Content of Oil Palm Fronds and Empty Fruit Bunches

Raw Material	Mark	Reference
Fronds	18,85%	28,2%
Bunches	17,07%	19,32%

"Based on Table 1, the lignin content of oil palm frond raw material was found to be 18.85%. In the study conducted by Jenifer (2020), the lignin content of the fronds was reported to be 28.2%. Thus, the lignin content of oil palm fronds in this study is lower than the reference value reported in the previous study. In this study, the lignin content of empty fruit bunches was found to be 17.07%.

According to Sarono (2023) the lignin content of oil palm empty fruit bunches was reported to be 19.32%. This indicates that the lignin content analysis of the raw materials in this study was successful, as the obtained values are close to the reference lignin content reported in the previous study.

4.1 Raw Material Preparation

The initial stage of raw material preparation involved cleaning the oil palm fronds by removing the midribs and leaves. Meanwhile, the empty fruit bunches (EFB) were cleaned to remove any attached impurities. The fronds and EFB were then dried and cut into small pieces to facilitate and accelerate the cooking process, as smaller particle sizes increase the surface area, thereby enhancing the reaction rate during cooking. The desired particle size was 20–30 mesh, using 125 grams of fronds and 125 grams of EFB. To achieve this size, the materials were sieved using a 20-mesh screen and further processed with the aid of a blender.

Figure 1 Raw Material Preparation

4.2 Pulp Making Process

The pulping process was carried out using the soda method. The soda method involves cooking the raw material with the addition of NaOH as the cooking liquor. NaOH functions to break the bonds linking lignin, hemicellulose, and cellulose. The cooking process is conducted under high pressure, allowing for faster and more energy-efficient pulping compared to cooking processes that do not utilize high pressure.

The initial step involved preparing the cooking liquor by dissolving 37.5 grams of NaOH (equivalent to 15% of the raw material weight) in 1000 mL of distilled water. The pre-processed raw material was placed into a 2000 mL Erlenmeyer flask, followed by the addition of the cooking liquor. The ratio used was 4:1 (4 mL NaOH solution for every 1 gram of solid), with 1000 mL of NaOH solution and 250 grams of raw material.

The cooking process was carried out in an autoclave, which operates under high pressure and allows for easy control of temperature, time, and pressure, thus minimizing the risk of process failure. The cooking was conducted under optimal conditions: 1 bar pressure, 120°C temperature, and a duration of 2 hours.

If the pressure, temperature, and cooking time exceed the optimal values, excessive reactions may occur between the cooking liquor and lignin, potentially degrading the cellulose—an undesirable outcome. Conversely, if the pressure, temperature, and time are too low, the lignin degradation will be insufficient, resulting in poor-quality pulp and paper.

The cooking process aims to accelerate the separation of cellulose from other components and to soften the resulting fibers (pulp). After cooking, the mixture was washed and filtered to separate the residual cooking liquor (black liquor) from the raw pulp. Filtration was also used to remove impurities from the cooked pulp. Once cleaned, the pulp was dried in an oven. Finally, pulp yield was calculated, and lignin content analysis was conducted.

Figure 2 Pulp making process

Yield is an important parameter in product manufacturing. Yield refers to the ratio of the dry weight of the product obtained to the weight of the raw material (Safrizal et al., 2022). Yield is obtained by dividing the weight of the resulting pulp by the initial weight of the raw material before grinding. The yield obtained from the pulping process was 42.8%. Based on the lignin content analysis of the pulp, the lignin content values are presented in Table 2 as follows:

Table 2 Pulp Lignin Content

Lignin content	Reference
8,12%	9,89% (Rusmanto)

Based on the table above, the lignin content of the resulting pulp is relatively low, at 8.12%. This data also indicates a reduction in lignin content from the initial raw materials, where the lignin content of oil palm fronds was 18.85% and that of empty fruit bunches was 17.07%, down to 8.12% in the pulp. The decrease in lignin content is due to the delignification process that occurs during cooking, as well as multiple washing steps performed to remove any residual cooking liquor. According to Putri (2022), the optimal lignin content in pulp is 9.89%. Therefore, the pulp produced from a mixture of oil palm fronds and empty fruit bunches is close to meeting the criteria for paper-grade pulp.

4.3 Bleaching Process

The pulp bleaching process was carried out using hydrogen peroxide solution. Hydrogen peroxide was chosen because it is a highly effective oxidizing agent capable of quickly removing stains or color from materials. In addition, bleached pulp has higher durability and experiences minimal fiber strength degradation. The hydrogen peroxide concentrations used were 8%, 10%, 12%, 14%, and 16%, in order to determine the most suitable and effective concentration for the bleaching process.

Before bleaching, the obtained pulp was first refined into a slurry and filtered to ensure a more uniform and effective bleaching result. Then, 20 grams of pulp was weighed for each concentration variable. The pulp was soaked in the hydrogen peroxide solution with the specified concentrations for 30 minutes.

Next, the pulp was rinsed using clean water. The subsequent step was drying the raw pulp in an oven until dry pulp was obtained. After drying, the whiteness level of each sample was compared. The results showed that the bleaching process using 16% hydrogen peroxide produced pulp with the highest whiteness compared to those treated with lower concentrations. This is because the higher the concentration of hydrogen peroxide, the greater the degree of pulp whiteness achieved.

Figure 3 Bleaching Process

4.4 Paper making process

The initial step in paper-making involved mixing the pulp that had been bleached using 8% hydrogen peroxide with 20 grams of finely ground paper waste. The paper waste—consisting of used writing paper, cardboard, and HVS paper—was blended with water using a blender. Then, an adhesive was prepared using 6% starch (2.4 grams based on the total mass of the mixture). The starch adhesive was heated until it turned clear. The pulp and adhesive were then mixed in a container.

A monil mold was prepared in a water-filled basin. The pulp mixture was poured into the mold, the mold was lifted, and the sheet was left to dry at room temperature until completely dry. The same procedure was repeated for the pulp samples bleached with hydrogen peroxide concentrations of 10%, 12%, 14%, and 16%.

Figure 4 Paper Making process

4.5 Paper quality testing

4.5.1 Paper Thickness

The purpose of this paper thickness test is to determine the perpendicular distance between the two surfaces of the paper. The method used follows the Indonesian National Standard (SNI) 14-6519-2001, utilizing a micrometer with an accuracy of 0.01 mm. The measurements were taken at each corner and side of the paper sheet. The data from the paper thickness test are presented below:

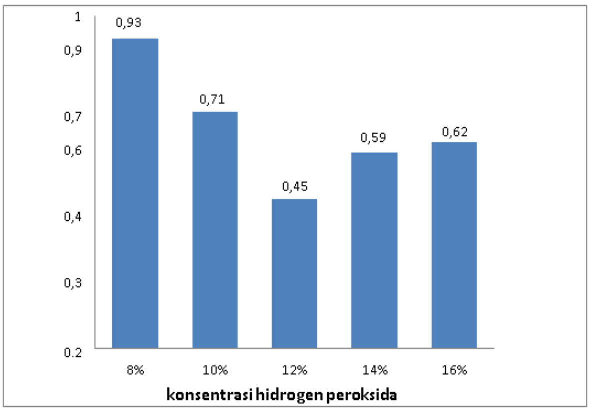

Figure 5 Paper Thickness

Based on the figure above, the thickest paper was produced using 8% bleaching concentration, with a thickness of 0.93 mm, while the thinnest paper was produced using 12% bleaching concentration, with a thickness of 0.45 mm. The data show that the paper thickness varied across different concentrations and sides, likely due to imperfections in the production process and the use of simple equipment, which reduced the accuracy in forming the pulp into paper.

It can also be concluded from the data that the paper thickness exceeded the Indonesian National Standard (SNI 14-6519-2001), which specifies a standard thickness range of 0.110 mm to 0.142 mm. This may be due to the high fiber content obtained during the pulping process, resulting in paper that is thicker than the SNI standard.

4.5.2 Paper Grammage (GSM)

According to SNI 14-0440:2006, grammage is defined as the mass of a sheet of paper or board in grams divided by its area in square meters (m^2), measured under standard conditions. The equipment used to determine the paper grammage includes a 2-decimal analytical balance, a ruler, and a knife or scissors.

The initial step in grammage testing involves cutting a paper sample to a size of 10 cm × 10 cm. Then, measure the area of the sample and weigh its mass. Repeat the procedure from the beginning three times to ensure accuracy.

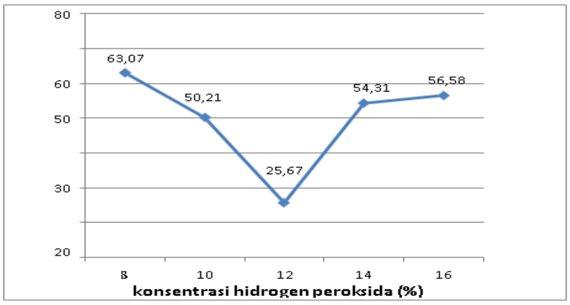

Figure 6 Paper Grammage

Based on the graph above, the highest grammage was recorded in the sample with 8% hydrogen peroxide concentration, at 62.07 g/m², while the lowest was in the 12% concentration sample, at 25.67 g/m². The grammage for the 16% concentration sample was 56.58 g/m². These results indicate that the hydrogen peroxide concentration does not have a significant effect on the paper grammage.

The data also suggest that the paper produced falls under the category of paper rather than cardboard, as the grammage requirement for paper is 14–100 g/m², whereas for cardboard it is 112–1000 g/m² (SNI 14-0440:2006).

4.5.3 Paper Density

According to SNI 0123:2008, density is a quantity that expresses the ratio between the mass of paper and its volume, measured under standard conditions. The equipment used to determine the paper density includes an analytical balance, a knife or scissors, and a micrometer.

The procedure for determining paper density begins by cutting a sample measuring 10 cm × 10 cm. Then, record the area, volume, and thickness of the paper to be weighed. Weigh the sample and record the result. Repeat the test for each sample several times to ensure consistency.

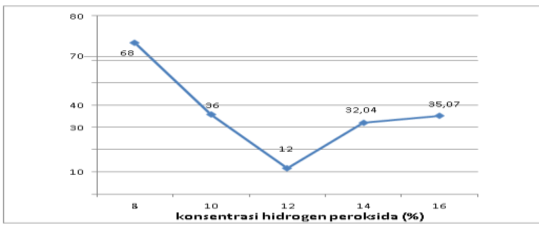

Figure 7 Paper Density

The data indicate that the paper does not meet the minimum standard of SNI 0123:2008, which requires a minimum paper density of 700 kg/m³. This is likely due to poor fiber formation during the pulping process, which affected the thickness of the paper, as fiber quality plays a crucial role in determining both the thickness and density of paper.

5. Conclusion

The process of making pulp and paper from palm fronds and stalks starts from raw material preparation, pulp making, bleaching, paper making and finally paper testing. In the pulp bleaching process, five variations of hydrogen peroxide concentration variables are used, namely 8%, 10%, 12%, 14% and 16%. The best hydrogen peroxide concentration based on research conducted is a hydrogen peroxide concentration of 16%. The quality of the paper produced does not meet the SNI 14-6519: 2001 standard regarding paper thickness and does not meet the SNI 0123: 2008 standard regarding paper density, but has met the SNI 14-0440: 2006 standard regarding paper and cardboard grammage. The best paper produced is paper with a hydrogen peroxide concentration of 16% with a thickness of 0.62 mm with a mass density of 35.67 kg/m3 and a grammage value of 56.58 gr/m2.

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