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Exploiting the Potential of Oil Palm Frond Fibre in Recycled Pulp Blending for Improved Paper Strength and Sustainability

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ABSTRACT

Recycled fibres often exhibit reduced conformability and inter-fibre bonding capability compared to virgin fibres due to hornification. However, the lost potential of recycled pulp can be reclaimed through various methods, including mechanical beating, additive utilization, physical fractionation, and blending. This study focuses on the blending approach, utilizing oil palm frond fibre to enhance the strength of paper made from recycled pulp. Despite the widespread cultivation of oil palm trees in Malaysia, the utilization of oil palm fibre remains limited, often being regarded as waste. Two different chemical pulping methods, namely sodium hydroxide and sodium sulphite, were employed to produce pulp from oil palm frond fibre, with the addition of anthraquinone to enhance pulping yield. Three different weight percentages of fibre loading (25%, 45%, or 65%) were used, with the remaining content supplemented with newspaper pulp. The resulting paper was evaluated for tensile strength, modulus of elasticity, and examined using scanning electron microscopy to observe its morphology. The findings indicate that sulphite-soda anthraquinone treatment yielded superior pulp for paper production, and a 45% weight percentage of fibre loading exhibited the highest tensile strength, yielding the best paper quality. Overall, this study highlights the potential of incorporating oil palm frond fibre into the pulp and papermaking process, contributing to both economic growth and environmental sustainability.

1. Introduction

The rapid growth of the pulp and paper industry worldwide has created a substantial demand for raw materials. These materials can be broadly categorized into wood, non-wood, and recycled paper [1]. With the increasing emphasis on the circular economy, the market for recovered paper, which is made from recycled fibers, presents significant opportunities [2]. However, despite these prospects, only a mere 8% of printing and writing paper in the market is produced using recycled fiber [3]. The

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limited utilization of recycled fiber in papermaking can be attributed to inherent limitations in the fiber itself. The process of recycling used paper back to pulp leads to a reduction in sheet strength due to the formation of irreversible hydrogen bonds, a phenomenon known as hornification. Additionally, the drying process of recycled paper pulp progressively diminishes capillary voids, resulting in less swollen and flexible cell walls. When rewetted, the pulp undergoes coalescence, impeding complete refibrillation and causing the fibril structure to collapse. Hornification also increases non-reversible bonding between microfibrils, hindering their expansion upon rewetting and leading to pore closure, ultimately reducing the paper's ability to absorb energy and increasing its brittleness [4]. To address these challenges, blending recycled fiber with virgin fiber is a common approach in papermaking. However, the goal of utilizing recycled fibers is to reduce reliance on wood fibers, making the use of virgin fibers from wood counterproductive. Consequently, there is growing interest in substituting wood fibers with non-wood fibers [5]. In Malaysia, one abundant source of non-wood fibers is derived from the oil palm plant (Elaeis guineensis), which covers over five million hectares of land. The oil palm biomass, comprising residues from trunks, fronds, shells, and empty fruit bunches, primarily consists of oil palm fronds (OPF) accounting for around 58% of the total biomass produced. The regular disposal practices of OPF, such as natural decomposition for nutrient replacement and mulching purposes or burning on-site, are environmentally unfriendly and fail to align with the principles of the circular economy. Moreover, they overlook the untapped potential value of these waste materials [6,7]. Thus far, less than 10% of the biomass waste has been utilized for niche downstream applications, primarily due to a lack of appropriate technologies [8]. For example, it is apparent from Figure 1 that shows scholarly works related to oil palm fibres. Although this plant originated from Africa, Malaysia has been growing oil palm since 1960s and by 1990s, Malaysia emerged as the world's largest palm oil producer [9]. However, the scholarly works on utilising oil palm waste did not start until later, with the most study was taken between 2010-2018.

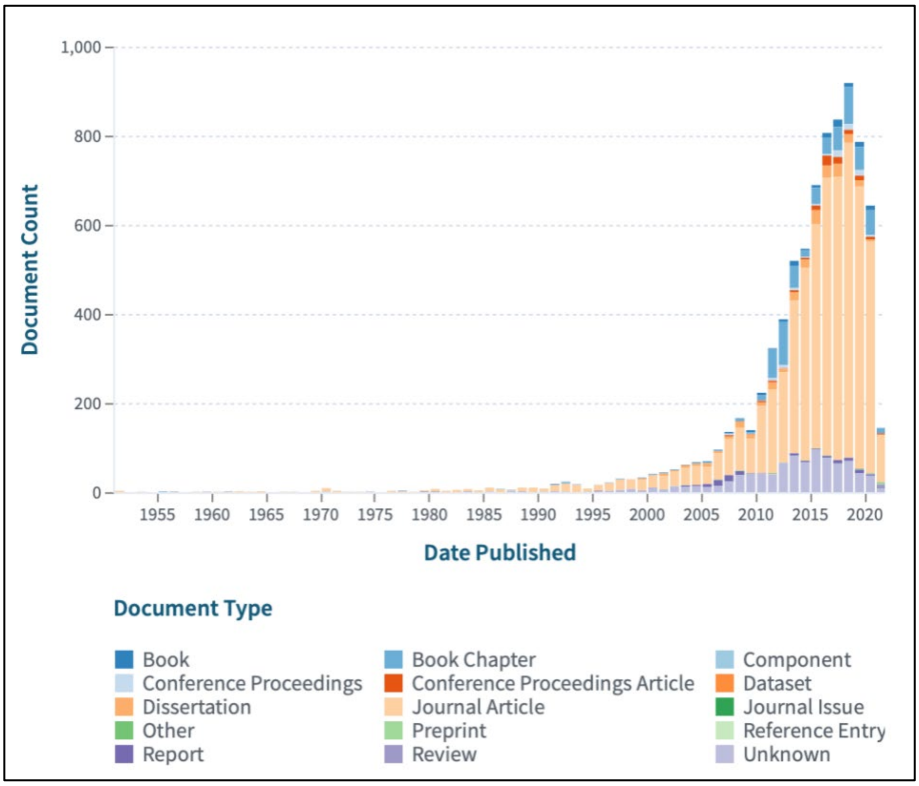

Fig 1. Scholarly works related to oil palm fibres over the years [9]

However, in recent years, there has been a growing focus on utilizing OPF for pulp and paper production [10]. Several studies have explored the fundamental characteristics and quality of OPF for pulp and paper production, with findings revealing the richness of holocellulose (82.2%) and α-cellulose (47.6%) in OPF strands. High cellulose content is advantageous in pulp and paper production, as it contributes to higher pulp yields and is crucial for paper strength [11]. While the lignin content in fibers should be low due to its detrimental effects on paper properties, OPF exhibits a low lignin content of only 15.2%, much lower than that typically found in hardwood, such as Eucalyptus, commonly used in papermaking. Furthermore, the lignin removal process is challenging and expensive [12]. This favorable characteristic of OPF enhances its suitability for paper production.

Paper production is a two-step process in which the fibrous raw material is first converted into pulp, and later the pulp is converted into paper. The pulping process can be done mechanically or chemically [13]. Therefore, appropriate fibre extraction processes, either chemical, mechanical, chemo-mechanical, or enzymatic, are essential to produce the desired cellulose fibre. Pulping process of non-wood fibres is much easier than the wood because: (1) low lignin content in non-wood fibres, (2) it requires lower cooking chemical dosage with less intensive pulping conditions (i.e. temperature, time) and (3) uses less energy for mechanical separation of the fibres [14]. However, they also pose a few challenges mainly related to the high silica content that is resulting in (1) difficulties in recovering liquor because silica dissolves in the cooking liquor, (2) forms deposit in recovering chamber, which limits heat transfer, (3) decrease causticising efficiency, lime reuse and recycling [16]. Reports show that 74.1% of world pulp was produced using chemical pulping, 21.4% used a mechanical process, and the remaining 4.5% used various techniques [17]. The most common chemical pulping method used is Kraft, sulphite, soda and organosolv [1]. The primary aim for chemical pulping is to degrade lignin and hemicellulose into small water-soluble molecules that can be washed away from the cellulose fibres without depolymerising the cellulose fibres. Removal of lignin and hemicellulose renders the fibres flexible and increases contact between cellulose fibres, resulting in a higher-strength paper [18]. Despite these challenges, non-wood fibers offer promising opportunities for sustainable paper production.

The main objective of this paper is to explore the potential of utilizing oil palm frond (OPF) fibers in combination with recycled pulp for paper production. To achieve this, the study initiates with a thorough literature review focusing on the characteristics of OPF fibers derived from oil palm biomass. The primary research question revolves around identifying the most suitable pulping method for OPF fibers. As such, the subsequent sections delve into various pulping methods, aiming to determine the optimal approach for processing OPF fibers. Once the suitable pulping method is established, a laboratory-scale pulping and papermaking process will be executed, incorporating OPF fibers with recycled pulp. The final stage of the study involves evaluating the mechanical properties of the produced paper, including tensile strength and modulus of elasticity. Additionally, scanning electron microscopy will be employed to observe and analyze the paper's morphological properties, providing valuable insights into its structure and characteristics. By investigating the potential of OPF fibers in combination with recycled pulp, this study aims to contribute to sustainable practices within the pulp and paper industry. It seeks to offer valuable insights into the utilization of non-wood fibers as an alternative to reduce reliance on wood fibers, thereby promoting environmental sustainability and enhancing economic viability in the papermaking process. Through the exploration of novel approaches and the assessment of mechanical and morphological properties, this research aspires to advance the understanding and application of non-wood fibers in the pursuit of a more environmentally friendly and efficient paper production.

2. Materials And Methods

2.1 OPF Pulping Selection Method

This study suggested five critical factors should be considered when choosing a pulping process for oil-palm frond for a lab-scale experiment which are as follows:

i. Novelty: Novelty refers to the new element in the research, which could be a new methodology or observation contributing to the body of knowledge. In this paper, the novelty would be in the pulping process itself, whether other researchers have worked on the same material or it is an entirely new process for OPF fibre.
ii. Chemical: The chemical that is used must have a low environmental impact. It also must be safe and low risk. It will be an advantage if the chemical can be recycled, which would make the process cost-effective and favourable for the larger scale.
iii. Techniques and technology: The process to be carried out must consider the limited facilities in the laboratory. In addition, it would be advantageous to consider simple techniques and technology that are possible for scale-up.
iv. Process scale-up: The process must be able to be scale-up so that the output from this research would be helpful for the industrial adaptation.
v. Output: Overall, it is crucial that the process would be able to produce a high pulp yield, long fibre or other characteristics that are advantageous for OPF pulp.

A preference matrix would be helpful to guide the decision-making process on the laboratory scale pulping process to be selected for OPF fibre. The matrix allows a set of options to be evaluated against criteria leading to quantifiable scoring based on a clear structure even though the criteria may be unquantifiable. The ratings for each of the factors are shown in Table 1.

Table 1
Table of ratings for each factor

Rating/ Factors	0	1	2	3	4	5
Novelty*	The method has been tested on OPF	The method has been tested on wood fibre only	The method has been tested on other non-wood fibre only	The method has been tested on other oil palm fibre only	The method has never been tested on OPF	Completely new method
Chemical	Harmful to the environment and risky to use	Harmful to the environment but low risk	Harmful to the environment and not recyclable	Harmful to the environment but recyclable	Low environmental impact but no chemical recovery process developed yet or not suitable to be recycled	Low environmental impact and recyclable
Techniques and technology*	The process is impossible to be carried out in a lab	Complicated process (need adjustments on the workflow) to be carried out in the lab	A complicated process to be carried out in the lab but still can be done	A simple process that can be carried out with significant adjustment in the process	A simple process that can be carried out with minor adjustment processes	Simple process to be carried out in the lab

Process scale-up	The process is impossible for scale-up	The process can be scale-up with significant modification in the process and would affect the output	The process can be scale-up with significant modification in the process but would not affect the output	The process can be scale-up with a minor modification in the process and would affect the output	The process can be scale-up with a minor modification in the process and would not affect the output	The process can be scale-up with no modification in the process
Output	The process does not produce any promising output	The process produces low yield and short fibre	The process produces low yield but good fibre length	The process produces sufficient yield and good fibre length	The process produces high yield and good fibre length	The process produces high yield and long fibre length

*the weightage for techniques and technology are counted are two because this paper focus to find the practical lab-scale process for OPF fibre.

The performance matrix are then mapped in Table 2.

Table 2
The performance matrix of different chemical pulping and its compatibility with OPF fibre

Factors	Novelty (weightage = 1)	Chemical (weightage = 1)	Techniques and technology (weightage = 2)	Process scale-up (weightage = 1)	Output (weightage = 1)	Total
Kraft pulping	4 This process has never been tested on OPF fibre	4 The chemicals are not harmful, but the chemical recovery would reduce the quality of pulp [19]	4 The process is simple and can be done on the lab-scale with minor adjustments to the process	4 The process is well established for wood but not optimum for non-wood, so there will be some modification needed in the process	3 The process produces high pulp yield, but the strength is lower than the Soda method	23/30
NACO process	4 This process has never been tested on OPF fibre	4 The chemicals are not harmful, but no chemical recovery process was found	0 The process is impossible to be carried out on lab-scale	5 The process is well established; therefore, no modification is needed for the scale-up	5 The output is suitable for any application with high-quality fibre	18/30
Soda method	4 This process has never been tested on OPF fibre	5 The absence of sulphur avoid the generation of malodorous cooking gases and simplify the chemical recovery	5 The process is simple and can be done on the lab-scale	5 The process is well established; therefore, no modification is needed for the scale-up	2 The process produces lower yield but good strength	26/30

Neutral sulphite pulping	4 This process has never been tested on OPF fibre	1 The chemicals involved are harmful to the environment	5 The process is simple and can be done on the lab-scale	5 The process is well established; therefore, no modification is needed for the scale-up	4 The process produce higher yield compared to soda method and easier to bleach	24/30
Alkaline sulphite pulping	4 This process has never been tested on OPF fibre	2 The chemicals involved are less harmful to the environment compared to the neutral sulphite pulping	5 The process is simple and can be done on the lab-scale	5 The process is well established; therefore, no modification is needed for the scale-up	2 The process produces low yield but good fibre length [20]	23/30
Methanol-NaOH	4 This process has never been tested on OPF fibre	0 The use of methanol is highly flammable and it is toxic	2 Complicated process to be carried out in the lab but still can be done	5 The process is well established; therefore, no modification is needed for the scale-up	5 The process produces pulp with high yield and strong tensile strength	16/30
Alkaline sulphite anthraquinone methanol process	4 This process has never been tested on OPF fibre	0 The use of methanol is highly flammable and it is toxic	2 Complicated process to be carried out in the lab but still can be done	5 The process is well established; therefore, no modification is needed for the scale-up	5 The process produces pulp with high yield and strong tensile strength [21]	16/30
Alkaline sulphite-anthraquinone ethanol process	4 This process has never been tested on OPF fibre	5 Ethanol can be recovered by the distillation process	2 Complicated process to be carried out in the lab but still can be done	5 The process is well established; therefore, no modification is needed for the scale-up	5 The process produces pulp with high yield and strong tensile strength	23/30
Organic pulping	4 This process has never been tested on OPF fibre	0 Organic acids are highly corrosive and may cause a severe corrosion problem	0 The process is impossible to be carried out on lab-scale	3 The process needs modification for scale-up and is still not well established	3 The process produces sufficient yield and good fibre length	10/30

From Table 2, it can be concluded that the soda method is the most suitable for OPF fibre pulping, followed by neutral sulphite pulping. Therefore, the treatment process is developed using these two methods.

2.2 Sample Preparation

The papermaking process involved the utilization of two primary materials: Oil Palm Frond (OPF) fibers (Figure 2) and newspaper, with the newspaper serving as a bonding agent to promote adhesion among the OPF fibers and create a cohesive paper sheet. Before the pulping process, the OPF fibers underwent size reduction by crushing using a Low-Speed Mini Granulator (Model: AA-150). The crushed fibers were then sieved to select particles with a size of 1.18 mm for further processing. Subsequently, the selected OPF fibers were blended with the newspaper pulp, ensuring a homogeneous mixture. Various weight percentages of OPF fibers (25%, 45%, and 65%) were employed in the blending process, with the remaining content filled by the newspaper pulp. The blended pulp mixture was then subjected to sheet formation, where the fibers were dispersed in water and formed into continuous sheets using appropriate techniques. Excess water was removed through pressing to consolidate the sheets, followed by drying to eliminate remaining moisture, typically accomplished by air drying or thermal drying methods. The resulting paper sheets were subsequently tested for mechanical properties and analyzed morphologically. This comprehensive experimental procedure was conducted in a laboratory environment to evaluate the potential of oil palm frond fibers for enhancing paper strength and quality.

Fig 2. Untreated OPF fibre

2.3 Pulping Process

In this study, two different pulping methods were employed: soda AQ (Figure 3) and sulphite-soda AQ (Figure 4). The addition of AQ (anthraquinone) in these methods aimed to enhance the rate of delignification, resulting in reduced pulping time, lower temperature requirements, decreased chemical usage, and improved pulp yield. The fiber percentage for each method was determined using Eq. (1).

$$\text{Percentage, \% w/v} = \frac{\text{Mass of Solute (g)}}{\text{Volume of Solution (ml)}} \times 100 \quad (1)$$

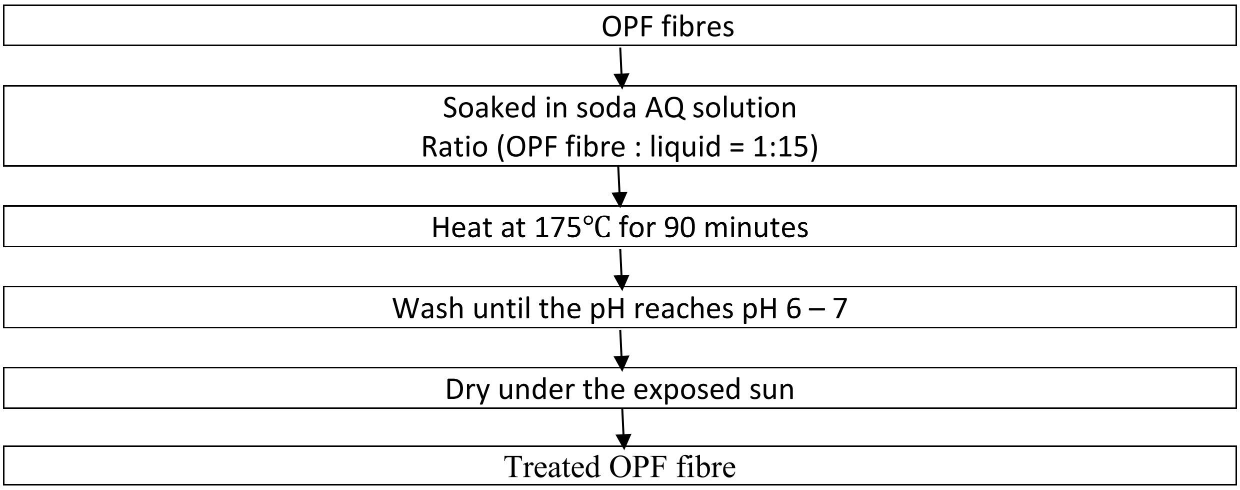

Fig 3. The experimental procedure for OPF fibre pulping with soda AQ solution

The first pulping method (Figure 3) can be described as follows. Initially, the OPF fibers, derived from oil palm fronds, are immersed in a solution containing soda AQ (anthraquinone) in a specific ratio of OPF fiber to liquid, typically 1:15. This soaking step serves to prepare the fibers for subsequent treatments. Subsequently, the fibers are subjected to heat treatment at a temperature of 175℃ for a duration of 90 minutes. This thermal process facilitates chemical reactions and induces desired transformations in the fibers. After the heat treatment, the fibers undergo thorough washing, involving repeated rinsing to remove any residual chemicals or impurities. The washing process continues until the pH of the fibers reaches a range of pH 6 to 7. This step aims to ensure the removal of any unwanted substances that may interfere with subsequent processing stages. Following washing, the fibers are dried under direct sunlight. This natural drying method allows for the evaporation of moisture from the fibers, leading to their desiccation. The exposure to sunlight aids in the removal of remaining water content and promotes further modification of the fibers' physical and chemical properties. Upon completion of the aforementioned steps, the OPF fibers are considered "treated" and become suitable for subsequent utilization in the papermaking process. The treatment process involving soaking, heat treatment, washing, and drying contributes to enhancing the fibers' characteristics and prepares them for further stages of paper production. This treatment procedure signifies a specific approach to optimize the OPF fibers using a soda AQ solution, aimed at modifying their properties to improve their suitability for paper manufacturing.

The second pulping method (Figure 4) can be delineated as follows: Firstly, the fibers are immersed in a sulphite AQ (anthraquinone) solution at a specific ratio of OPF fiber to liquid, typically 1:15. This immersion facilitates impregnation of the fibers with the sulphite AQ solution, initiating subsequent modifications. Subsequently, the fibers undergo a heat treatment at 185℃ for a duration of 60 minutes, enabling chemical reactions and desired alterations in fiber properties. Following the heat treatment, thorough washing of the fibers is performed until attaining a pH range of 6 to 7, thereby ensuring the elimination of residual chemicals and impurities. Thereafter, the fibers are subjected to another soaking process, this time in a soda AQ solution, maintaining the ratio of fiber to liquid at 1:15. The soda AQ soaking step complements the effects of the preceding sulphite AQ treatment, contributing to further fiber modifications. Consequently, the fibers are subjected to a second heat treatment at 175℃ for 90 minutes, intensifying the desired transformations and enhancements in fiber characteristics. Subsequent thorough washing, until achieving the pH range of 6 to 7, ensures the removal of any remaining chemicals and impurities, thus preparing the fibers for subsequent processing stages. Upon completion of washing, the fibers are dried through exposure to direct sunlight, utilizing the natural drying method. This solar drying approach expedites moisture evaporation from the fibers, resulting in desiccation. The drying process further influences the physical and chemical properties of the fibers. Upon the conclusion of the aforementioned steps, the OPF fibers are deemed "treated," signifying their readiness for utilization in subsequent processing stages.

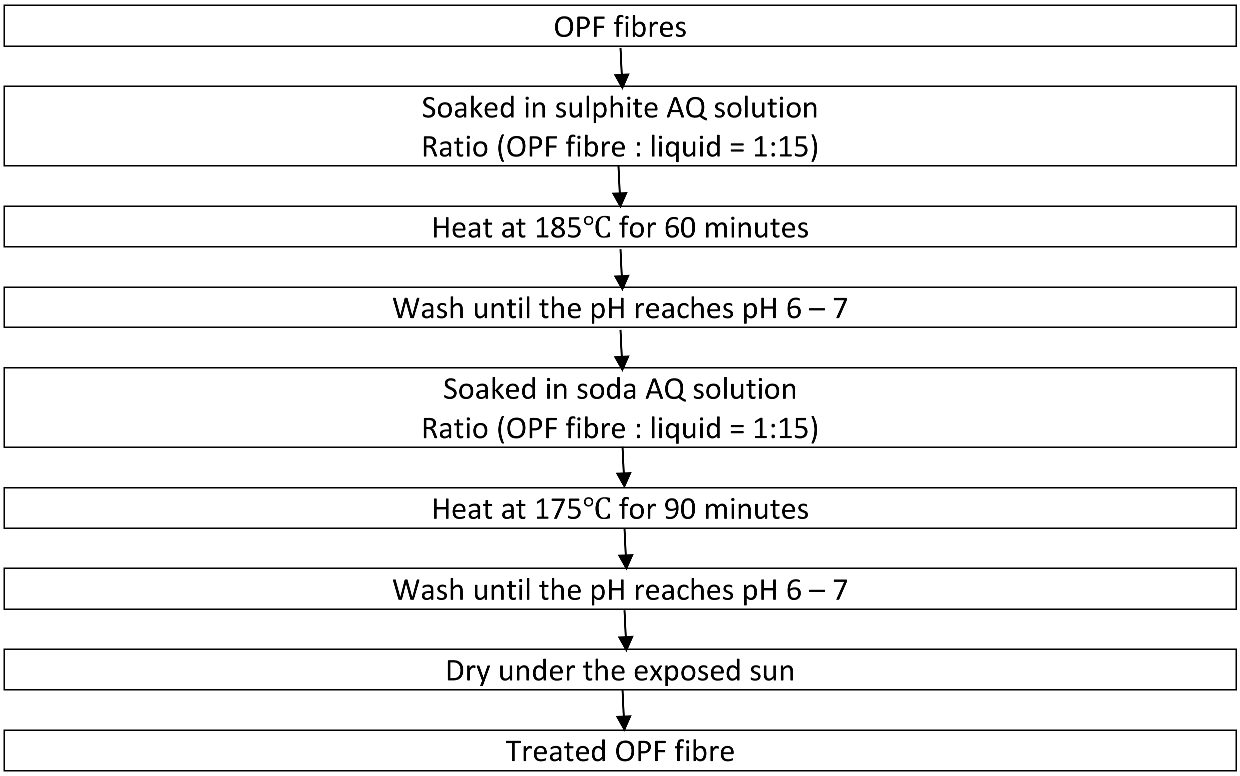

Fig 4. The experimental procedure for OPF fibre pulping with sulphite-soda AQ solution

2.4 Paper Fabrication Process

Following the completion of the pulping process, the OPF fibers were combined with newspapers using a blender to create a homogeneous mixture. Subsequently, hydrogen peroxide was introduced to the mixture as a means of enhancing the brightness of the pulp. Notably, hydrogen peroxide is widely recognized as the predominant oxygen-based bleaching chemical employed in the pulp and paper industry [22]. To conclude the bleaching process and ensure appropriate pH levels, an acetate buffer was incorporated into the mixture of newspapers and OPF fibers. This buffer solution effectively neutralized the acidity or alkalinity resulting from the bleaching treatment. The addition of the acetate buffer helps maintain a suitable pH range for the subsequent processing stages. For further reference, Table 3 provides a concise overview of the distinctive chemical compositions employed in the soda AQ pulping and sulphite-soda AQ pulping methods, highlighting the variations between the two processes in terms of chemical content and their respective contributions to the overall treatment of the OPF fibers.

The papermaking process proceeds with the subsequent step of sheet formation. In this study, handsheet paper was fabricated employing a wire woven frame mould. Initially, a mixture of newspapers and OPF fibers was carefully poured into a basin, and the mould was immersed in the basin. Subsequently, the mould was gently agitated to ensure thorough coverage of the mould surface by the OPF fiber and newspaper mixture. To eliminate excess water, a sponge was pressed against the mould, facilitating the drainage of water. Upon completion of the drainage process, the paper sheet was carefully detached from the mould and transferred to a waterproof board for the subsequent air-drying stage. The sheet was left to dry naturally, allowing for the complete evaporation of any remaining moisture. This meticulous handsheet preparation technique using the wire woven frame mould ensured the formation of uniform paper sheets, facilitating subsequent analysis and evaluation of their properties.

Table 3
The pulping conditions

Parameters	Soda AQ pulping			Sulphite-soda pulping		
Ratio of OPF fibre to newspaper	1:3	9:11	13:7	1:3	9:11	13:7
NaOH (%w/v)	16	16	16	40	40	40
Na_2SO_3 (%w/v)	-	-	-	20	20	20
Hydrogen peroxide (%w/v)	35	35	35	35	35	35
Acetate buffer (%w/v)	-	-	-	25	25	25
AQ (%w/v)	0.3	0.3	0.3	0.3	0.3	0.3

2.5 Methods for Testings
2.5.1 Tensile test

The tensile test, an essential component of the experimental procedure, was conducted using the Hegewald & Peschke Universal Tensile Machine 10kN, following the guidelines outlined in the ASTM standard D638. The purpose of this test was to evaluate the mechanical properties of the paper samples. Rectangular-shaped samples, as depicted in Figure 5, were prepared specifically for the tensile test. During the test, the machine recorded the force exerted on the samples and the corresponding elongation or deformation of the material until failure or rupture occurred. By subjecting the paper samples to the tensile test, it was possible to determine important mechanical properties such as tensile strength, elongation at break, and modulus of elasticity. These properties provide valuable insights into the paper's structural integrity, flexibility, and resistance to external forces, which are crucial considerations for various applications in the paper industry.

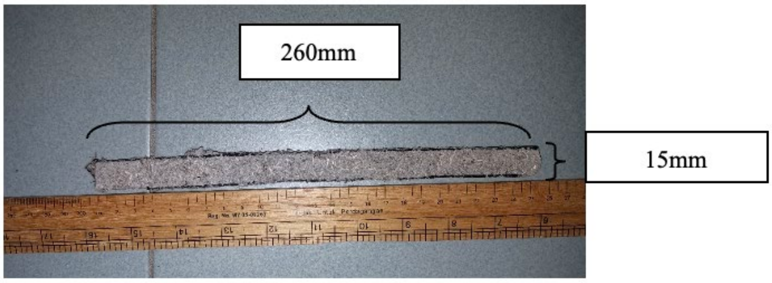

Fig 5. Specimen used for the tensile test

2.6 Morphology

The morphological characterization of the paper samples was conducted utilizing a scanning electron microscope (SEM) model Jeol JSM-6000 Plus. This advanced imaging technique allowed for detailed examination of the surface features and microstructure of the papers. Prior to observation, a thin layer of gold was applied to the paper samples through a process known as sputter coating.

This gold coating served two purposes: it enhanced the electrical conductivity of the samples and provided a conductive surface for optimal imaging during the SEM analysis. During the observation, a beam of electrons with an energy level of 10 kilovolts (10kV) was employed as the illumination source. The SEM offered a range of magnification options, enabling the examination of the samples at different scales of detail. By employing the SEM, the researchers were able to visualize and analyze various morphological aspects of the paper samples, including the surface topography, fiber arrangement, porosity, and any notable structural features.

3. Results And Discussion

3.1 Tensile Test

The tensile strength of paper is influenced by factors such as the loading ability and length of the fibers [23]. In this study, the average results of the tensile test were analyzed for paper samples produced with varying weight percentages of fibers (25%, 45%, and 65%) and subjected to two different types of chemical treatment: soda AQ pulping and sulphite-soda AQ pulping. The findings, as presented in Table 4 and Figure 6, indicate among the samples, the highest tensile strength of 0.725 MPa was observed in the paper made from sulphite-soda AQ pulping with a fiber content of 45%. The second observation drawn from the tensile test is that the paper produced from sulphite-soda AQ chemical treatment has higher tensile strength than paper produced from soda AQ chemical treatment for all three different weight fibre percentages. Khristova *et al.,* [24] supported this, which found higher tensile strength in unbleached bagasse treated with alkaline-sulphite AQ than in soda AQ pulped fibre. The incorporation of fibers into a matrix has been widely recognized to significantly improve the tensile properties of materials due to the high strength and stiffness values of fibers [25]. However, in the present study, a contrasting trend was observed in the tensile strength of paper produced from soda AQ pulping as the fiber content increased. Conversely, for sulphite-soda AQ pulping, the tensile strength initially increased with an increase in fiber content from 30% to 45%, but subsequently dropped at 60% fiber content. This finding is consistent with the study conducted by Hargitai *et al.,* [26], who reported that the Young's modulus of composite materials increased with increasing fiber content until reaching a maximum value at 50% hemp fiber loading. Similar results were also observed by Khoathane *et al.,* [27] in bleached hemp fiber, where the tensile strength of the fiber-reinforced 1-pentene/polypropylene copolymer composite increased up to 20% fiber loading, but then decreased to the lowest tensile strength. From this study and previous studies, it can be found that the values of tensile strength increase with increasing fibre loading up to a maximum value before falling back. This can be attributed to many factors such as incompatibility between matrix and fibres, improper manufacturing process and fibre degradation [25].

Table 4
Average tensile strength for different chemical treatments and fibre weight percent

	Tensile Strength (MPa)		
Wt% Fibre	25	45	65
Soda AQ pulping	0.445	0.345	0.185
Sulphite-soda AQ pulping	0.570	0.725	0.460

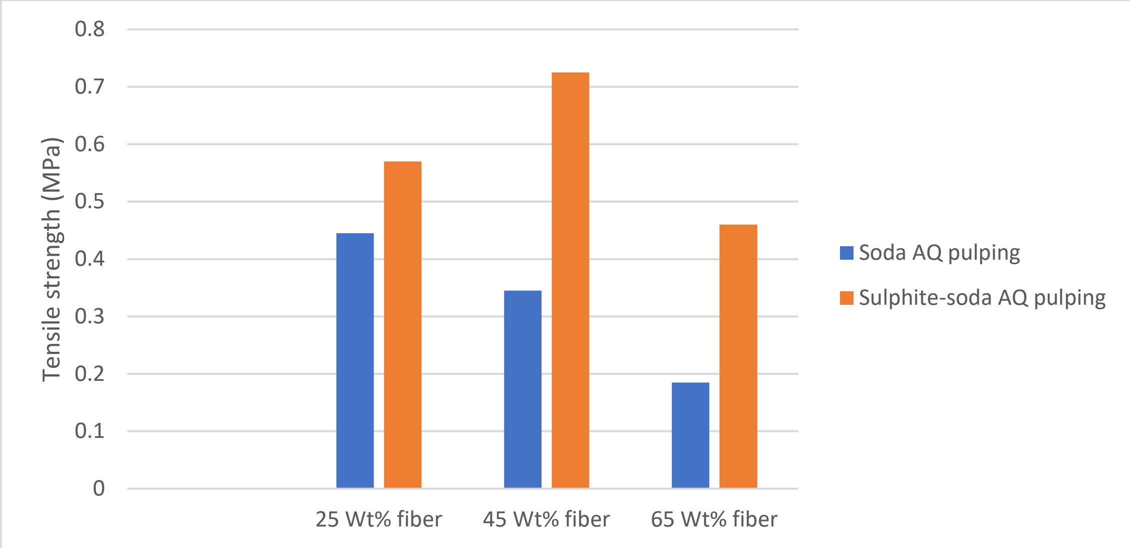

Fig 6. Tensile strength vs different chemical treatment with the percentage by weight of fibre

3.2 Modulus of Elasticity (MOE)

The modulus of elasticity (MOE) is a fundamental property of paper that characterizes its resistance to deformation, stiffness, and structural rigidity [28]. In this study, the average MOE results were examined for paper samples produced using two different chemical treatments: soda AQ treatment and sulphite-soda AQ treatment, with varying weight percentages of fibers (25%, 45%, and 65% by weight). The corresponding results are summarized in Table 5, and a visual representation is provided in Figure 7. From the observation of Figure 7, it is evident that the MOE decreases as the fiber loading increases. This finding suggests that the weight percentage of fibers has an impact on the thickness of the paper, leading to an increase in the presence of holes and voids, which subsequently reduces the MOE. This observation aligns with the findings of a previous study conducted by Ramlee *et al.,* [29], who reported that the weight percentage of fibers influences the thickness of the resulting product. The highest MOE value of 0.085 GPa was observed in the samples produced through sulphite-soda AQ pulping with a fiber loading of 25%. This finding highlights the potential for achieving improved stiffness properties by employing this specific combination. It is worth noting that the use of non-wood fibers in conjunction with recycled paper can further enhance the MOE. This assertion is supported by the research conducted by Fagbemi *et al.,* [28], who exclusively utilized kenaf bark and corn husk fibers to produce paper. Their study demonstrated that the highest MOE value achieved was only 0.042 GPa for paper composed of 75% kenaf bark and 25% corn husk. Thus, the inclusion of recycled fibers becomes crucial for enhancing the MOE of paper. These findings underscore the significance of considering the weight percentage of fibers and the incorporation of recycled fiber sources in optimizing the MOE of paper.

Table 5
MOE for different chemical treatment and fibre weight percent

	MOE (GPa)		
Wt% Fibre	25	45	65
Soda AQ pulping	0.045	0.250	0.015
Sulphite-soda AQ pulping	0.085	0.070	0.040

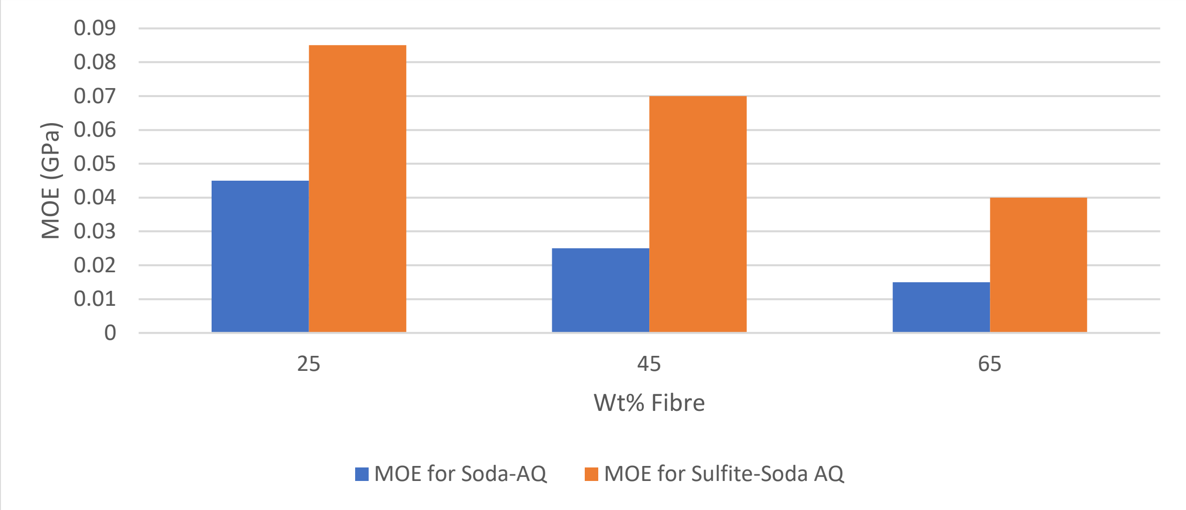

Fig 7. MOE vs different chemical treatment with the percentage by weight of fibre

3.3 Morphology

SEM observation plays a crucial role in examining the bonding between oil palm frond (OPF) fibers and newspaper pulp. It is essential to conduct a detailed investigation of the surface morphology of the produced papers, considering the various treatments applied to the OPF fibers, as these treatments can significantly impact the fiber morphology. The treatments involve the removal of non-cellulosic and macromolecular substances, such as hemicelluloses, lignin, pectin, and wax, from the fibers. The bleaching process employed in the treatment leads to the splitting and flattening of the OPF fibers, as observed in a comprehensive morphological study of the treated fibers [30]. The SEM micrographs (Figure 8 to 13) exhibit distinct variations in the fiber surface based on the specific treatment utilized. Figure 8, 10, and 12 display the samples treated with soda pulping at different fiber percentages in combination with newspapers, while Figure 9, 11, and 13 represent the samples treated with sulphite-soda pulping. The incorporation of soda in the treatment process results in cleaner fibers with reduced surface roughness, as it effectively eliminates impurities such as wax and cuticle. Generally, the soda pulping and bleaching processes disrupt the lignocellulosic complex, solubilize lignin and hemicellulose, and expose a greater porosity and surface area of the underlying cellulose. This phenomenon leads to the alignment and distribution of cellulosic fibers, enhancing their accessibility for the cellulose extraction process [31]. However, it is important to note that the bleaching process can also influence the crystallinity of the pulp, reducing its overall crystallinity and yielding weaker fibers [30]. This provides an explanation for the observed lower tensile strength and MOE in the treated samples as discussed in the previous subsection.

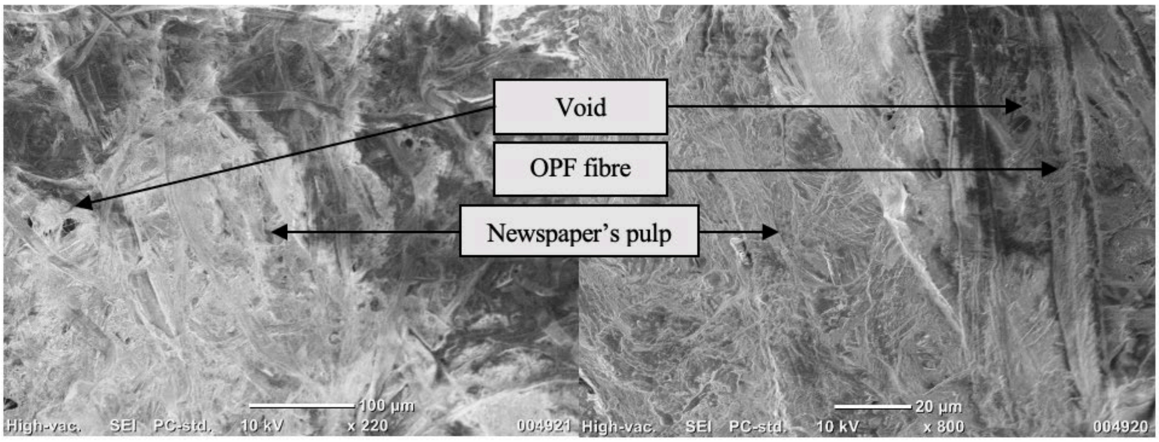

Fig 8. 25% OPF fibre (Soda AQ)

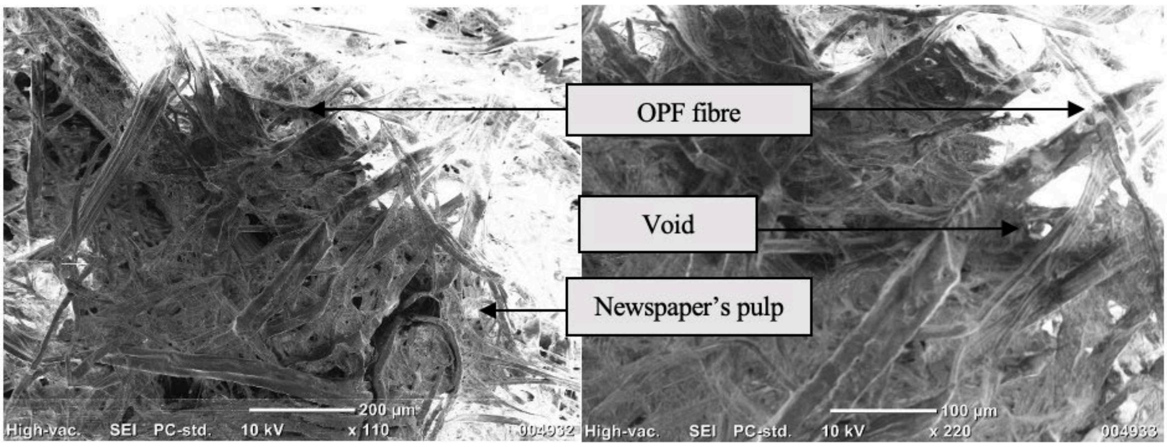

Fig 9. 25 % OPF fibre (sulphite-soda AQ)

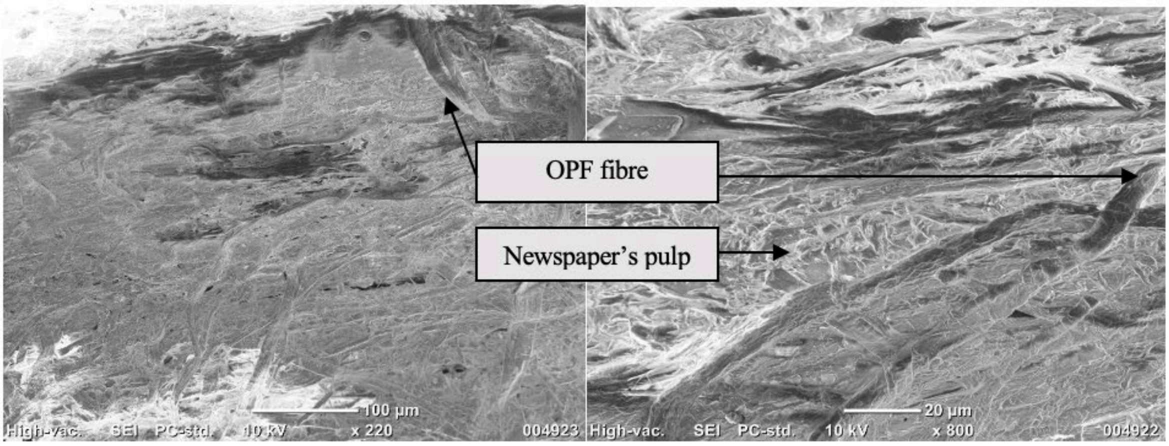

Fig 10. 45% OPF fibre (Soda AQ)

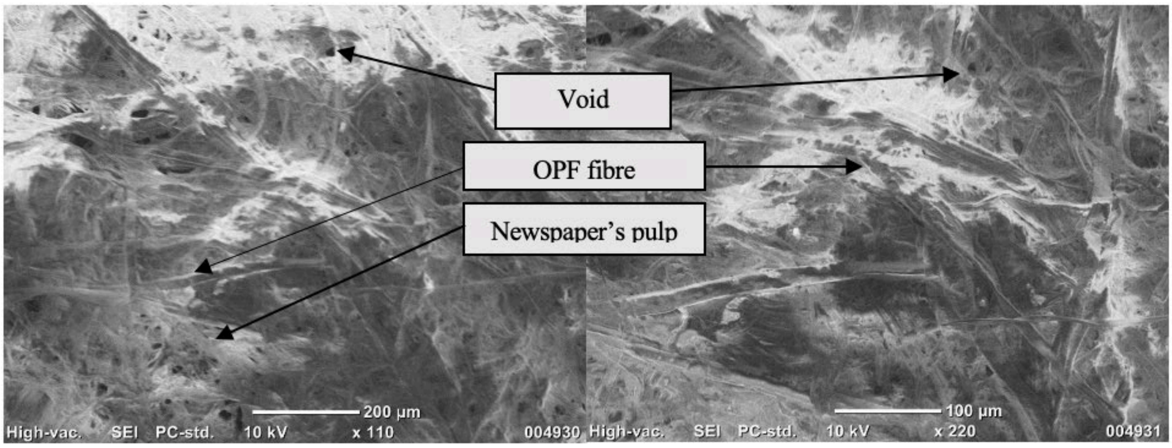

Fig 11. 45% OPF fibre (Sulphite-soda AQ)

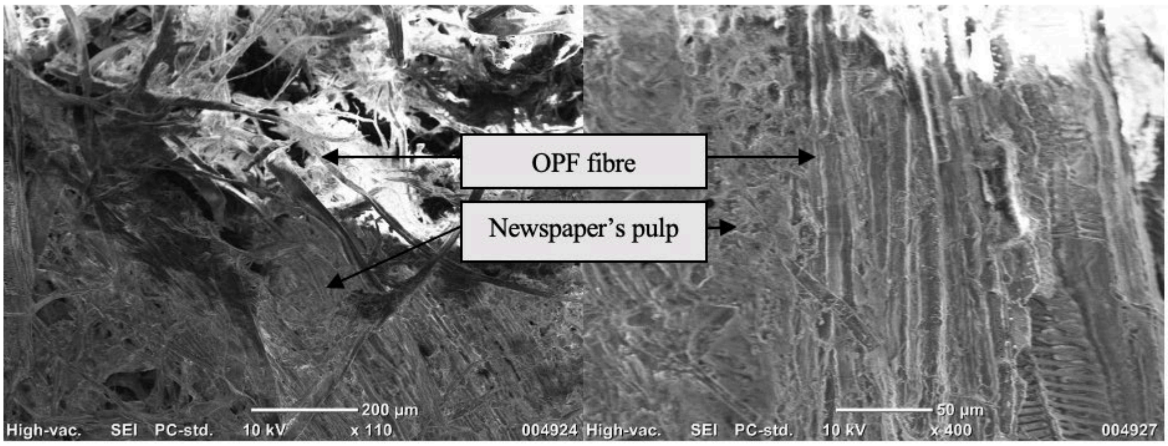

Fig 12. 65% OPF fibre (Soda AQ)

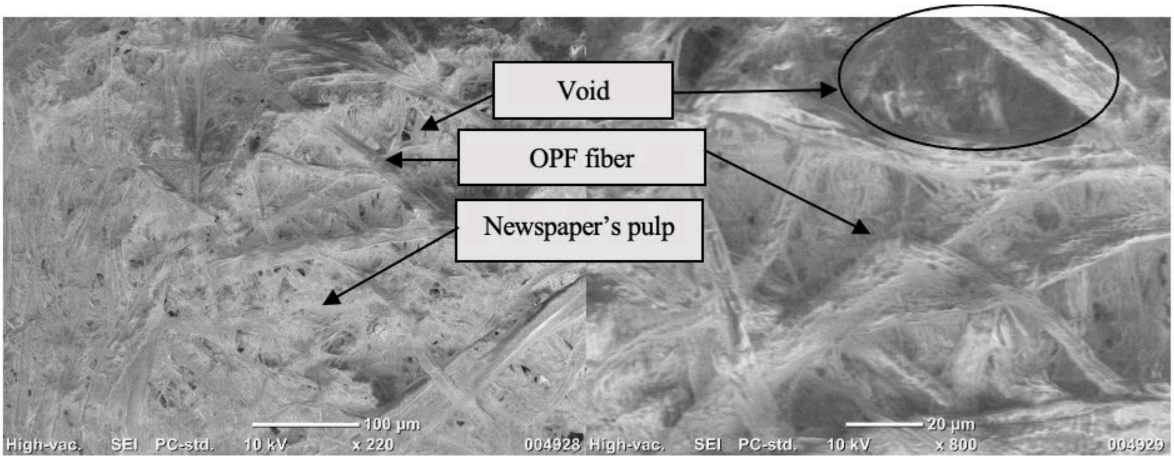

Fig 13. 65% OPF fibre (Sulphite-soda AQ)

This study focuses on the novel approach of utilizing oil palm frond fibers to enhance the strength of paper made from recycled pulp. While the utilization of recycled fibers in papermaking is a known practice, this study explores a specific method—blending with oil palm frond fibers—that has not been extensively studied before. The novelty lies in the potential of this approach to reclaim the lost potential of recycled pulp and contribute to economic growth and environmental sustainability. This study sheds light on the underutilized oil palm biomass as a non-wood fiber source in Malaysia. Oil palm fronds, which constitute a significant portion of the biomass, are often considered waste and disposed of through environmentally unfriendly practices. By investigating the characteristics and suitability of oil palm frond fibers for paper production, the study addresses the challenge of finding alternative non-wood fibers to reduce reliance on wood fibers, supporting the principles of the circular economy. The contribution of this research lies in providing valuable insights into the pulping and papermaking process using oil palm frond fibers. It evaluates two different chemical pulping methods—sodium hydroxide and sodium sulphite—applied to oil palm frond fibers and analyzes their effects on paper quality. By testing different weight percentages of fiber loading, the study identifies the optimal conditions for achieving the highest tensile strength and paper quality. This research contributes to the advancement of sustainable practices in the pulp and paper industry by demonstrating the potential of using non-wood fibers and recycled pulp in combination.

4. Conclusions

This study demonstrates the viability of utilizing oil palm frond (OPF) fibers in combination with recycled pulp for paper production. The findings reveal that the sulphite-soda AQ chemical treatment outperforms the soda AQ chemical treatment in terms of paper quality. Particularly noteworthy is the paper treated with sulphite-soda AQ, containing 45% OPF fiber, which exhibited the highest tensile strength at 0.725 MPa. Similarly, the paper treated with sulphite-soda AQ and comprising 25% OPF fiber demonstrated the highest Modulus of Elasticity (MOE) at 0.085 GPa. The analysis of the specimens' fracture patterns and the scanning electron microscopy (SEM) evaluation revealing the presence of holes and voids highlight the need for improved adhesion between the newspaper and OPF fibers. To enhance the properties of the resulting paper, suggestions include implementing a compressing process to enhance interfacial adhesion between OPF fibers and newspaper, and exploring the incorporation of additives and alternative fibers to further augment performance. The significance of this study lies in its successful demonstration of the practicality of utilizing OPF fibers for paper production using a streamlined and viable laboratory-scale process. This finding has implications for the pulp and paper industry, offering opportunities to reduce reliance on wood fibers and promote more sustainable papermaking practices. By embracing non-wood fibers like OPF, the industry can diversify its raw material sources and adopt environmentally responsible approaches.

The study's implications extend to paper product development, as the combination of recycled pulp and OPF fibers may lead to innovative paper products with enhanced strength and performance characteristics. Such improved papers could find applications in various fields, including packaging materials, industrial papers, or specialty papers requiring heightened durability and mechanical properties. The study also underscores the importance of sustainability and circular economy principles. By repurposing agricultural waste materials like OPF fibers into valuable resources for paper production, the research contributes to reducing environmental impact and conserving natural resources. This aligns with the broader environmental sustainability goals that the pulp and paper industry should strive to achieve. Despite the valuable insights gained from this research, there remains ample room for further scientific inquiry and optimization. Future investigations could explore different blending ratios, alternative chemical treatments, and innovative manufacturing techniques to further enhance the mechanical properties and overall quality of the paper. A comprehensive assessment of the economic feasibility and scalability of integrating OPF fibers into large-scale papermaking operations would provide valuable guidance for industry-wide adoption.

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References
[1] Abd El-Sayed, Essam S., Mohamed El-Sakhawy, and Mohamed Abdel-Monem El-Sakhawy. "Non-wood fibers as raw material for pulp and paper industry." *Nordic Pulp & Paper Research Journal* 35, no. 2 (2020): 215-230. https://doi.org/10.1515/npprj-2019-0064
[2] Takala, Markus. "Paper for recycling in tissue production." (2021).
[3] Martin, Joshua, and Mandy Haggith. "The State of the Global Paper Industry: Shifting Seas: New Challenges and Opportunities for Forests." *People and the Climate, Environmental Paper Network* (2018).
[4] Ang, Shaun, Debjani Ghosh, Victoria Haritos, and Warren Batchelor. "Recycling cellulose nanofibers from wood pulps provides drainage improvements for high strength sheets in papermaking." *Journal of Cleaner Production* 312 (2021): 127731. https://doi.org/10.1016/j.jclepro.2021.127731
[5] Zainuddin, Zarita, Wan Rosli Wan Daud, Pauline Ong, and Amran Shafie. "PULP AND PAPER FROM OIL PALM FRONDS: WAVELET NEURAL NETWORKS MODELING OF SODA-ETHANOL PULPING." *BioResources* 7, no. 4 (2012). https://doi.org/10.15376/biores.7.4.5781-5793
[6] Sheh, Hong Lim, Darah Ibrahim, and Ibrahim Che Omar. "Effect of Physical Parameters on Second Generation Bio-Ethanol Production from Oil Palm Frond by Saccharomyces cerevisiae." *BioResources* 8, no. 1 (2013). https://doi.org/10.15376/biores.8.1.969-980
[7] Nordin, Noor Afeefah, Othman Sulaiman, Rokiah Hashim, and Mohamad Haafiz Mohamad Kassim. "Oil palm frond waste for the production of cellulose nanocrystals." *Journal of Physical Science* 28, no. 2 (2017): 115-126. https://doi.org/10.21315/jps2017.28.2.8
[8] Awalludin, Mohd Fahmi, Othman Sulaiman, Rokiah Hashim, and Wan Noor Aidawati Wan Nadhari. "An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction." *Renewable and Sustainable Energy Reviews* 50 (2015): 1469-1484. https://doi.org/10.1016/j.rser.2015.05.085
[9] Shevade, Varada S., and Tatiana V. Loboda. "Oil palm plantations in Peninsular Malaysia: Determinants and constraints on expansion." *PLoS One* 14, no. 2 (2019): e0210628. https://doi.org/10.1371/journal.pone.0210628
[10] Jarupan, Lerpong, Ratanapat Hunsa-Udom, and Nattinee Bumbudsanpharoke. "Potential use of oil palm fronds for papermaking and application as molded pulp trays for fresh product under simulated cold chain logistics." *Journal of Natural Fibers* 19, no. 7 (2022): 2772-2784. https://doi.org/10.1080/15440478.2021.1889433
[11] Wanrosli, W. D., Z. Zainuddin, K. N. Law, and R. Asro. "Pulp from oil palm fronds by chemical processes." *Industrial crops and products* 25, no. 1 (2007): 89-94. https://doi.org/10.1016/j.indcrop.2006.07.005
[12] Abd El-Sayed, Essam S., Mohamed El-Sakhawy, and Mohamed Abdel-Monem El-Sakhawy. "Non-wood fibers as raw material for pulp and paper industry." *Nordic Pulp & Paper Research Journal* 35, no. 2 (2020): 215-230. https://doi.org/10.1515/npprj-2019-0064
[13] Laftah, Waham Ashaier, and Wan Aizan Wan Abdul Rahman. "Pulping process and the potential of using non-wood pineapple leaves fiber for pulp and paper production: a review." *Journal of Natural Fibers* 13, no. 1 (2016): 85-102. https://doi.org/10.1080/15440478.2014.984060
[14] Liu, Zhong, Huimei Wang, and Lanfeng Hui. "Pulping and papermaking of non-wood fibers." *Pulp and paper processing* 1 (2018): 4-31. https://doi.org/10.5772/intechopen.79017
[15] Pettersen, Roger C. "The chemical composition of wood." *The chemistry of solid wood* 207 (1984): 57-126. https://doi.org/10.1021/ba-1984-0207.ch002
[16] Jahan, M. Sarwar, M. Mostafizur Rahman, and Yonghao Ni. "Alternative initiatives for non-wood chemical pulping and integration with the biorefinery concept: a review." *Biofuels, Bioproducts and Biorefining* 15, no. 1 (2021): 100-118. https://doi.org/10.1002/bbb.2143
[17] Azeez, Mayowa Akeem. "Pulping of non-woody biomass." *Pulp and paper processing* 24, no. 7 (2018): 1213-1232. https://doi.org/10.5772/intechopen.79749
[18] Mboowa, Drake. "A review of the traditional pulping methods and the recent improvements in the pulping processes." *Biomass Conversion and Biorefinery* 14, no. 1 (2024): 1-12. https://doi.org/10.1007/s13399-020-01243-6
[19] Tran, Honghi, and Esa K. Vakkilainnen. "The kraft chemical recovery process." *Tappi Kraft Pulping Short Course* (2008): 1-8.
[20] Latibari, Ahmad Jahan, Mohammad Ali Hossein, and Reza Hossienpour. "Application of alkaline sulfite pulping on corn stalks." *BioResources* 6, no. 1 (2011): 48-58. https://doi.org/10.15376/biores.6.1.48-58

[21] Moradbak, Amin, Paridah Md Tahir, Ainun Zuriyati Mohamed, and Rasmina Halis. "Alkaline sulfite anthraquinone and methanol pulping of bamboo (Gigantochloa scortechinii)." *BioResources* 11, no. 1 (2016). https://doi.org/10.15376/biores.11.1.235-248

[22] Syamani, Firda Aulya, and A. Suryani. "Changes in oil palm frond fiber morphology, cellulose crystallinity and chemical functional groups during cellulose extraction phases." *Chemistry and Materials Research* 7, no. 3 (2015): 105-114.

[23] Niskanen, Kaarlo. "Kraft fibers in paper–Effect of beating." In *Cellulosic Pulps, Fibres and Materials*, pp. 249-260. Woodhead Publishing, 2000. https://doi.org/10.1533/9781845698546.249

[24] Khristova, P., O. Kordsachia, R. Patt, and S. Dafaalla. "Alkaline pulping of some eucalypts from Sudan." *Bioresource Technology* 97, no. 4 (2006): 535-544. https://doi.org/10.1016/j.biortech.2005.04.006

[25] Ku, Harry, Hao Wang, N. Pattarachaiyakoop, and Mohan Trada. "A review on the tensile properties of natural fiber reinforced polymer composites." *Composites Part B: Engineering* 42, no. 4 (2011): 856-873. https://doi.org/10.1016/j.compositesb.2011.01.010

[26] Hargitai, Hajnalka, Ilona Rácz, and Rajesh D. Anandjiwala. "Development of hemp fiber reinforced polypropylene composites." *Journal of Thermoplastic Composite Materials* 21, no. 2 (2008): 165-174. https://doi.org/10.1177/0892705707083949

[27] Khoathane, M. C., O. C. Vorster, and E. R. Sadiku. "Hemp fiber-reinforced 1-pentene/polypropylene copolymer: the effect of fiber loading on the mechanical and thermal characteristics of the composites." *Journal of reinforced plastics and composites* 27, no. 14 (2008): 1533-1544. https://doi.org/10.1177/0731684407086325

[28] Fagbemi, O. D., Taiwo K. Fagbemigun, O. Otitoju, E. Mgbachiuzor, and C. C. Igwe. "Strength properties of paper from pulp blend of kenaf bark and corn husk: A preliminary study." *British Journal of Applied Science & Technology* 4, no. 28 (2014): 4124-4129. https://doi.org/10.9734/BJAST/2014/10745

[29] Ramlee, Nor Azlina, Mohammad Jawaid, Edi Syams Zainudin, and Shaikh Abdul Karim Yamani. "Tensile, physical and morphological properties of oil palm empty fruit bunch/sugarcane bagasse fibre reinforced phenolic hybrid composites." *Journal of Materials Research and Technology* 8, no. 4 (2019): 3466-3474. https://doi.org/10.1016/j.jmrt.2019.06.016

[30] Syamani, Firda Aulya, and A. Suryani. "Changes in oil palm frond fiber morphology, cellulose crystallinity and chemical functional groups during cellulose extraction phases." *Chemistry and Materials Research* 7, no. 3 (2015): 105-114.

[31] Kumneadklang, Sureeporn, O. Sompong, and Siriporn Larpkiattaworn. "Characterization of cellulose fiber isolated from oil palm frond biomass." *Materials Today: Proceedings* 17 (2019): 1995-2001. https://doi.org/10.1016/j.matpr.2019.06.247