Pulp Production from Pineapple Leaf Waste for Sustainable Paper Manufacturing

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The agricultural sector generates considerable amounts of waste annually, particularly during harvest periods. This study explored the potential of pineapple (*Ananas comosus* Merr.) leaves, a cellulose-rich byproduct of the pineapple industry, as a sustainable raw material for paper production. Mechanical strength, renewability, and cost-effectiveness make pineapple leaves a promising alternative for eco-friendly papermaking. The research focused on analyzing the chemical composition of the leaves, optimizing the pulping process, and evaluating the physical properties of the resulting paper. Utilizing TAPPI test methods, the chemical analysis revealed high concentrations of holo-cellulose (82.6%), alpha-cellulose (69.7%), and hemicellulose (12.9%), along with relatively low levels of solvent extractives (14.7%) and ash content (4.9%). The physical attributes of the produced paper include a tensile index of 50.1 Nm/g, a tear index of 6.33 mNm²/g, and a burst index of 3.31 kPa·m²/g. Additionally, the brightness of the unbleached paper was measured at 28.8 % ISO, which was increased to 69.7 % ISO after the bleaching process. Pineapple leaves possess more alpha cellulose than most other wood and non wood sources and paper made from these leaves has shown better physical properties. These findings underscore the potential of pineapple leaves as a viable alternative pulp source for the paper industry, contributing to the advancement of sustainable and environmentally friendly manufacturing practices.

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INTRODUCTION

Paper plays a vital role in the advancement of societal, economic, and environmental development in any nation. Traditionally, paper production has relied heavily on renewable natural fibers, primarily derived from wood, non-wood sources, and recycled fiber materials (Bajpai 2018). However, with the rapid growth in global population and economic expansion, the demand for various forest products, including paper, has increased significantly. This growing demand has led to heightened competition for raw materials within the pulp and paper industry (Sutradhar *et al.* 2018). To address these challenges, the use of non-wood and recycled fibers has emerged as a promising alternative to conventional wood-based fibers (Nayak and Bhushan 2019). This will help to reduce cutting down of woody sources and help to minimize the the unused plant based waste materials.

The utilization of non-wood fibers and recycled materials for pulp and paper production offers numerous advantages, including easier pulping processes, the potential to produce high-quality bleached pulp than many existing pulp sources with proper modifications, and a more sustainable source for paper manufacturing (Atchison 1976; Laftah and Wan Abdul Rahman 2016). Globally, pineapple yield has seen a substantial rise, which opens a new door to harness the potential of pineapple leaf (PAL) fiber as an alternative raw material for papermaking. In Bangladesh, despite the abundance of available raw materials, the productive capacity of PAL fiber remains largely underutilized (Hoque 2016).

About 29.64 million metric tonnes of pineapple have been producd annually worldwide in 2023, and global production has increased fourfold since 1960s. With a cultivation rate of 21 metric tons per hectare (DAE 2011), pineapples have become the third-largest horticultural product and a rapidly expanding sub-sector within Bangladesh (Hoque 2016). Commercial pineapple production is concentrated in regions, such as Rangamati and Modhupur, along with smaller-scale homestead cultivations aimed at local consumption. Major pineapple-growing areas include Modhupur, Sylhet, and the Chittagong Hill Tracts (Hoque 2016; Jalil *et al.* 2021).

Despite these figures, the full potential of PAL fiber remains untapped. Pineapple leaves, which are rich in high-quality natural fibers, are often discarded as agricultural waste. The PAL fiber is distinguished by its fine texture, creamy white appearance, silk-like sheen, and excellent dye retention properties. The fiber can be obtained from fresh pineapple leaves. The dimensions of PAL bast fibers depend on pineapple species, growth condition, extraction methods, and chemical treatments. However, these fibers are typically 60 to 75 cm in length and 0.18 to 0.27 cm thick (Gebino and Muhammed 2018). The PAL fiber has shown promise in various applications, such as reinforcement for plastics, sound insulation, and thermal insulation (Kengkhetkit and Amornsakchai 2012).

Pineapple leaves contain key chemical components, including cellulose, hemicellulose, lignin, and extractives such as gums and resins (Abdul Khalil *et al.* 2006). Compared to other natural fibers, PAL fiber is notable for its low lignin content, which facilitates easier chemical processing during fiber extraction (Mantanis *et al.* 2010). Pineapple leaf fiber has a lignin content of 10.5%, which is significantly lower than banana stem (18.6%), oil palm (20.5%), and coconut fibers (32.8%) (Cherian *et al.* 2010). This low lignin content suggests that PAL fiber may undergo bleaching more efficiently and exhibit superior fiber strength compared to other natural fibers. Additionally, PAL fiber is characterized by high cellulose content (70 to 82%), in comparison to lignin (5 to 12%), and minimal ash content (~1.1%) (Daud *et al.* 2015; Gaba *et al.* 2021; Jalil *et al.* 2021; Laftah and Wan Abdul Rahman 2016). The typical yield of pineapple fiber ranges from 1.6% to 2.5% of the leaf mass (Laftah and Wan Abdul Rahman 2016), but when pineapple plants are specifically cultivated for fiber production rather than fruit, the fiber yield is higher, and its quality is improved. Fresh pineapple leaves, often treated as byproducts of fruit production, offer additional revenue streams for farmers. Countries such as the Philippines have historically utilized PAL fiber for textiles, ropes, and twines. More recently, there has been growing interest in PAL fiber for commercial textile applications, but a significant portion of the fiber is still underutilized and either composted or burned by farmers (Al-Zyoud *et al.* 2009).

The investigation of non-wood fibers, including pineapple leaves, as viable raw materials for pulp and paper production presents an alternative resource that can alleviate pressure on traditional wood-based fiber sources (El-Sayed *et al.* 2020). Studies have demonstrated the suitability of pineapple leaves for paper production, highlighting their satisfactory tensile strength and tearing resistance (Aremu *et al.* 2015; Daud *et al.* 2015; Sibaly and Jeetah 2017). Furthermore, chemical pulping processes applied to pineapple leaves have shown the potential to produce high-quality paper while simultaneously reducing deforestation pressures. For Bangladesh, the utilization of pineapple leaf pulp could offer a sustainable pathway for paper production, conserving forest resources while creating economic opportunities for local farmers.

This study aimed to explore the feasibility of using pineapple leaves as an alternative raw material for pulp and paper production. Specifically, the objectives were to evaluate the suitability of pineapple leaves for pulp-making, to analyze the chemical composition of pineapple leaves to understand their potential for pulping, develop methods to enhance the mechanical strength and quality of paper produced from pineapple leaf pulp and to optimize processing techniques to improve properties such as brightness, smoothness, and durability. Through investigating the potential of agricultural residues like pineapple leaves. The goal is to develop sustainable raw material sources for the pulp and paper industry.

EXPERIMENTAL

Raw Materials Processing

In December 2022, pineapple leaves were collected from the Chattogram Hill Tracts, specifically from Nainnerchor in Rangamati and Manikchori in Khagrachori. This hilly area of Bangladesh remains mostly cool and dry, with temperatures ranging from 10 to 25 °C during winter. This climatic condition provides suitable environment for pineapple production. The collected leaves were transported to the Pulp and Paper Division of the Bangladesh Forest Research Institute (BFRI) in Chattogram for further processing. Upon arrival, the leaves were manually segmented into 76.2 mm (3-inch) pieces. These segmented pieces were subjected to a sun-drying process for 30 days at temperatures ranging from 15 °C to 30 °C in stainless steel trays and to ensure thorough moisture removal, the pieces were further subjected to oven drying at temperature 120±5 °C for 24 hours.

Following the drying process, the desiccated leaf chips underwent chemical analysis and kraft pulping for pulp production. Before the chemical treatment and pulping procedures, the dry matter content (DMC) of the air-dried leaf chips was determined. For chemical composition analysis, a portion of the dried chips was ground and sieved through a filter. The fraction retained on the sieve was collected and used for determining the chemical composition, including cellulose, hemicellulose, lignin, and other extractive contents. The kraft pulping process was then initiated, with the dried and prepared pineapple leaf chips undergoing chemical digestion to separate the fibers. This procedure was carefully optimized to produce high-quality pulp while retaining the key physical and mechanical properties necessary for papermaking.

Chemical Analysis

The pineapple leaf chips were first ground using a Wiley Mill, followed by sieving through a 40-mesh screen, with retention on a 60-mesh screen. This process allowed for the isolation of a suitable fraction for chemical composition analysis. Solubility in cold and hot water, 1% caustic solution, acid-soluble lignin, Klason lignin, ash content, and extractives were determined using the following TAPPI methods such as T207 cm-08 (2022), T212 om-12 (2022), um-250 (1991), T222 om-22 (2022), T211 om-22 (2022) and T204 cm-17 (2017), respectively. All procedures adhered to the specified TAPPI test protocols to ensure accuracy and consistency in the results. Following the removal of extractives, the extractive-free material was treated with a sodium chlorite ($NaClO_2$) solution to differentiate holo-cellulose (TAPPI T249 cm-21 2021) and alpha-cellulose (TAPPI T203 cm-22 2008) were done using T249 cm-21 (2021) and T203 cm-22 (2008) methods.

The following chemicals were used for the analyses: sodium hydroxide (CAS no. 1310-73-2, Qualikems Chem Pvt Ltd), sodium sulfide (CAS no. 1313-82-2, Qualikems Chem Pvt Ltd), sodium thiosulfate (CAS no. 7772-98-7, VWR Chemicals BDH), potassium permanganate (CAS no. 7772-64-7, VWR Chemicals BDH), glacial acetic acid (CAS no. 64-19-7, VWR Chemicals BDH), sodium chlorate (CAS no. 7775-09-9, VWR Chemicals BDH), potassium iodide (CAS no. 7681-11-0, VWR Chemicals BDH), hydrochloric acid (CAS no. 7647-01-0, VWR Chemicals BDH), sulfuric acid (CAS no. 7664-93-9, VWR Chemicals BDH), acetone (CAS no. 7647-14-5, VWR Chemicals BDH), toluene (CAS no. 108-88-3, VWR Chemicals BDH), absolute ethanol (CAS no. 64-17-5, VWR Chemicals BDH), potassium dichromate (CAS no. 7778-50-9, VWR Chemicals BDH), sodium carbonate (CAS no. 497-19-8, VWR Chemicals BDH), oxalic acid (CAS no. 6153-56-6, VWR Chemicals BDH), formaldehyde (CAS no. 50-00-0, VWR Chemicals BDH), barium chloride (CAS no. 10361-37-2, VWR Chemicals BDH), and starch solution (CAS no. 9005-25-8, VWR Chemicals BDH).

Kraft Pulping

Two kilograms of oven-dried (OD) pineapple leaf chips were processed in a 5-L stainless steel valley digester under steam heating. The kraft pulping process was conducted at a temperature of 170 °C for 150 minutes, following a preheating period of 90 minutes to reach the desired cooking temperature. Sodium sulfide (Na_2S) and sodium hydroxide (NaOH), both of analytical grade, were employed as the pulping chemicals. The liquor-to-wood ratio was maintained at 4:1 (L/kg) throughout the cooking process. To achieve varying degrees of delignification, two levels of active alkali were applied, with all kraft cooks using a consistent sulfide content of 25%. Upon completion of the cooking process, the fibers were washed overnight in a screen box using running water to remove any residual cooking liquor. The pulp was then gently agitated using a slow-speed electric mixer in a bucket to further cleanse the fibers.

The resulting pulp slurry was screened using a Johnson vibratory screen to eliminate uncooked material (screening rejects). The wet pulp was subsequently processed through a screw press to remove excess water, and samples were collected for dry matter content analysis. The pulp yield was determined following the T208 WD-98 (2008) standard. Screening rejects were collected, dried, and weighed to calculate the total pulp yield. The Kappa number, a key indicator of lignin content, was determined following the T236 om-22 (2011) standard.

$D_0E_pD_1$ Bleaching

The pineapple leaf pulp underwent a multi-stage bleaching process utilizing the D_0EpD_1 bleaching sequence, which included the following stages: D_0 (2% chlorine dioxide), Ep (peroxide-reinforced alkaline extraction), and D_1 (1% chlorine dioxide). Chlorine dioxide (ClO_2), the essential bleaching agent, was synthesized in the laboratory by reacting sodium chlorite ($NaClO_2$) with hydrochloric acid (HCl).

In the initial delignification stage (D_0), the pulp was treated with 2% ClO_2 at 70 °C for 60 minutes, maintaining a pulp consistency of 10%. The pH of the system was adjusted to 2.5 using dilute sulfuric acid (H_2SO_4). After the D_0 stage, the pulp was subjected to peroxide-reinforced alkaline extraction (Ep), utilizing a mixture of 2% sodium hydroxide (NaOH) and 0.5% hydrogen peroxide (H_2O_2) based on the oven-dry weight of 150 g pulp. This extraction was conducted at 70 °C for 60 minutes to enhance the removal of residual lignin and improve brightness. In the final brightening stage (D_1), 1% chlorine dioxide (ClO_2) was applied along with a small addition of NaOH to regulate the final pH to 4.5. The bleaching efficiency and brightness of the pulp were determined according to the T236 om-22 (2011) standard, ensuring the accurate assessment of the bleached pulp's optical properties.

Handsheet Making and Physical Properties Testing

Handsheets were produced using a laboratory hand sheet former. The pineapple leaf (PAL) pulp was subjected to refining in a PFI mill to achieve targeted Canadian Standard Freeness (CSF) values of 450 mL and 250 mL, following the SCAN-C 21:65 (2006) standard. Following the refining process, the pulp was conditioned at a controlled environment of 23 °C and 50% relative humidity to ensure uniformity before further testing. The physical strength characteristics of the resulting hand sheets, including tensile, tear, and burst indices, were evaluated following the SCAN-C 28:69 (2006) standard. These evaluations aimed to assess the mechanical performance of the PAL pulp with standard industrial requirements for paper production.

Statistical Analysis

Statistical analyses were conducted using R Software (Version 4.2.3) to ensure the robustness of the experimental results. Correlation analysis was performed to examine the relationships between the physical strength indices of the produced hand sheets, allowing for a deeper understanding of the interdependencies among the measured properties. Additionally, graphical representations of the data, particularly boxplots, were employed to visualize the distribution and variability of the physical strength characteristics, providing a clear depiction of the results for comparative analysis.

RESULTS AND DISCUSSION

Chemical Composition of PAL

Figure 1 and 2 presents the chemical composition and solubility of pineapple leaf pulp (PAL) as determined by the TAPPI Test standard. The percentages of chemical constituents and solubility of pineapple leaves are relative to the oven-dried weight of the pineapple leaves sample.The analysis reveals a moderate solubility of PAL in cold water, measured at 19.34% ± 3.23%, which increased considerably in hot water to 26.90% ± 1.85%. The solubility under alkaline conditions, specifically in 1% caustic soda, reaches 40.73% ± 1.40%. These results indicate that PAL exhibits a higher solubility profile compared to banana leaf, as highlighted by Ferdous *et al.* (2023). The elevated solubility in caustic soda suggests a reduction in the degree of polymerization, which correlates with an increased decomposition of cellulose within the PAL fiber, as noted by Misbahuddin *et al.* (2019).

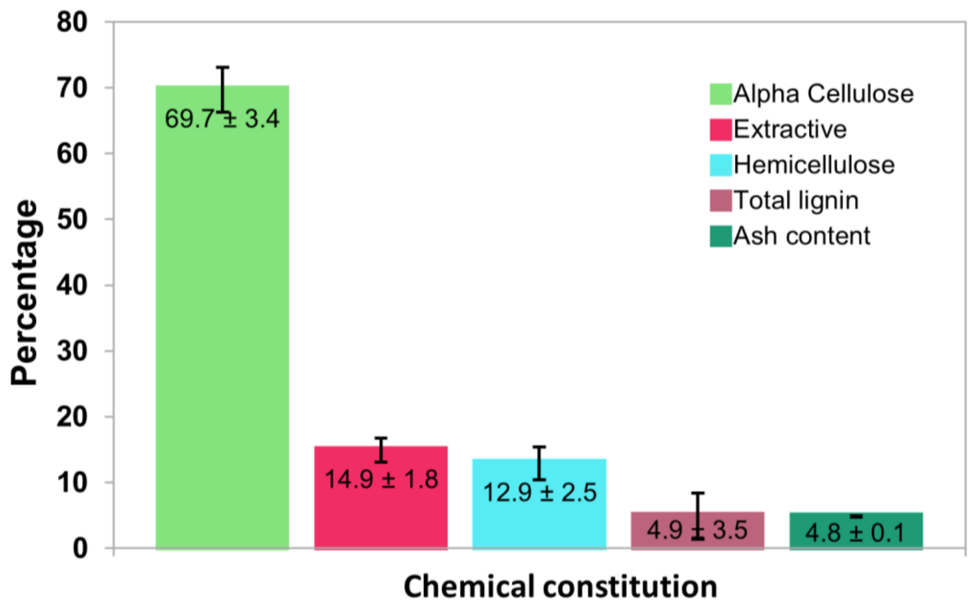

Fig. 1. Chemical constituents of PAL

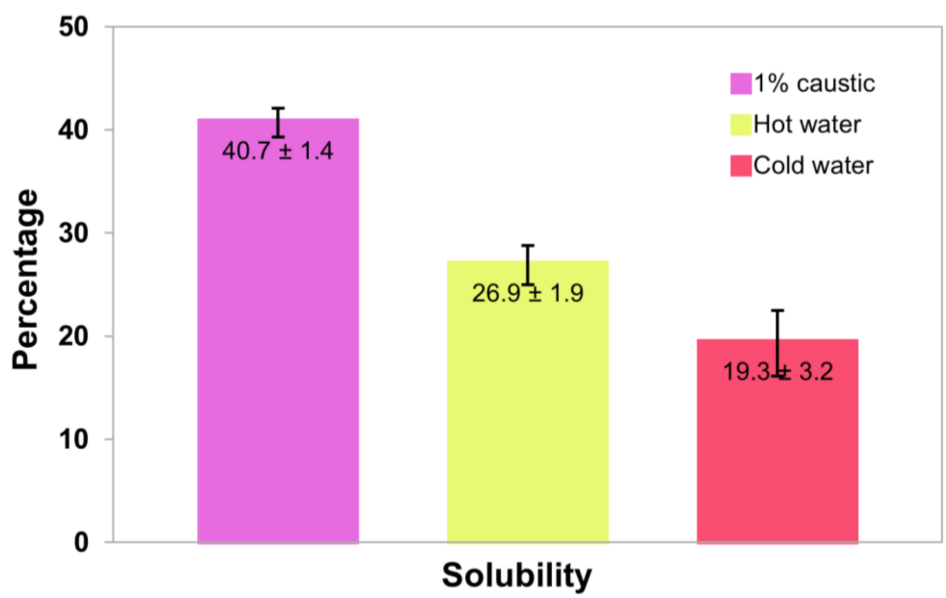

Fig. 2. Solubility of PAL

The ash content of the PAL was found to be relatively low, at 4.85% ± 0.1%, indicating a minimal presence of inorganic, non-combustible materials. Extractives accounted for 14.90% ± 1.75% of the composition, while holo-cellulose was predominant, comprising 82.60% ± 4.12% of the fiber, which includes both cellulose and hemicellulose components. Further analysis revealed that hemicellulose constituted 12.92% ± 2.49%, while alpha-cellulose represented 69.68% ± 3.42% of the overall composition. This high alpha-cellulose content suggests that PAL fiber is primarily composed of cellulose, which is advantageous for its application in papermaking.

Notably, the alpha-cellulose content of 69.7% considerably exceeds that found in typical hardwoods (31 to 64% alpha-cellulose) and softwoods (30 to 60% alpha-cellulose) (Wan Nadirah *et al.* 2012). Similarities between the findings of this study and those of Wan Nadirah *et al.* (2012) regarding holo-cellulose, alpha-cellulose, lignin, extractives, and ash content further validate the composition of PAL fiber. Furthermore, PAL fiber demonstrates higher holo-cellulose and alpha-cellulose contents compared to banana leaf (Ferdous *et al.* 2023), characteristics known to positively influence pulp yield and the properties of paper produced.

Table 1. Comparison of Chemical Properties between Pineapple Leaf and Other Commercially Important Woods, Agricultural Residues

Species	Holocel-lulose	α-cellulose	Hemicel-lulose	Lignin	1% NaOH solubility	Extrac-tives	Ash content	Ref
Ananas comosus Merr. (Pineapple leaf)	82.60	69.68	12.92	4.87	40.73	14.90	4.8	This study
Melocanna baccifera (bamboo)	74.1	47	27.1	25.8	19.5	-	1.9	(Chaurasia *et al.* 2016)
Saccharum officinerum (sugarcane bagasse)	71.03	42.34	28.60	-	32.29	-	2.10	(Agnihotri *et al.* 2010)
Eucalyptus camaldulensis	70.5	42.8	-	26.8	17.2	-	0.9	(Palmer *et al.* 1989)
Dendrocalamus giganteus (Sembilang)	65.96	46.88	-	23.85	28.19	4.51	3.70	(Sugesty *et al.* 2015)
Beech wood	-	45.8	31.8	21.9	-	-	0.4	(Demirbas 1998)
Spruce wood	-	50.8	21.2	27.5	-	-	0.5	(Demirbas 1998)
Rice straw	60.70	41.20	-	21.90	57.7	-	9.20	(Rodríguez *et al.* 2008)
Triticum sp. (wheatstraw)	70.7	41.3	-	21.67	-	-	-	(Sun & Tomkinson 2005)
Pine needles	-	41.04	-	35.10	-	-	3.2	(Asadullah *et al.* 2006)

The lignin content of PAL fiber was measured at 4.87% ± 3.46%, which is low compared to other plant fibers. Although lignin serves to provide structural rigidity within plant cell walls, its low concentration in pineapple leaves is beneficial for pulping processes, reducing the energy and chemical inputs required for lignin removal (Wan

Nadirah *et al.* 2012). The lower lignin content of pineapple leaves compared to many hardwoods and softwoods supports its favorable pulping characteristics. Additionally, the ash content of 4.8% in PAL surpasses that of typical hardwoods and softwoods, indicating a higher concentration of inorganic matter, including silica (Jahan *et al.* 2021, Daud *et al* 2013).

From Table 1, it is evident that pineapple leaf has more alpha cellulose than any other hard wood, soft wood or non wood sources that are primarily used in pulp and paper making. Furthermore, lignin content, considered highly undesirable for paper making, had found to be substantially lower than other pulping sources. But the ash content in pineapple is much greater than other sources, second only to rice straw.

Pulping of PAL

Figure 3 presents a comparative analysis of the effects of active alkaline concentrations on the pulping of pineapple leaves, emphasizing key parameters such as chemical consumption, Kappa number, and pulp yield. The pulping process employed varying active alkali charges ranging from 18% to 24%. Throughout the experimental range, the chemical consumption consistently remained within 17 to 19% across all samples.

As anticipated, increasing the alkali charge from 18% to 24% resulted in a significant reduction in pulp yield, which decreased from 32.9% to 29.5%. This decline can be attributed to the enhanced delignification occurring at higher alkali levels, which facilitates the breakdown of lignin. Correspondingly, the Kappa number—a measure of lignin content—decreased with increasing alkali charge, transitioning from 22.0 at 18% alkali to 15.5 at 24% alkali. This trend indicates the effectiveness of higher alkali doses in promoting lignin removal, thereby enhancing the overall pulping process.

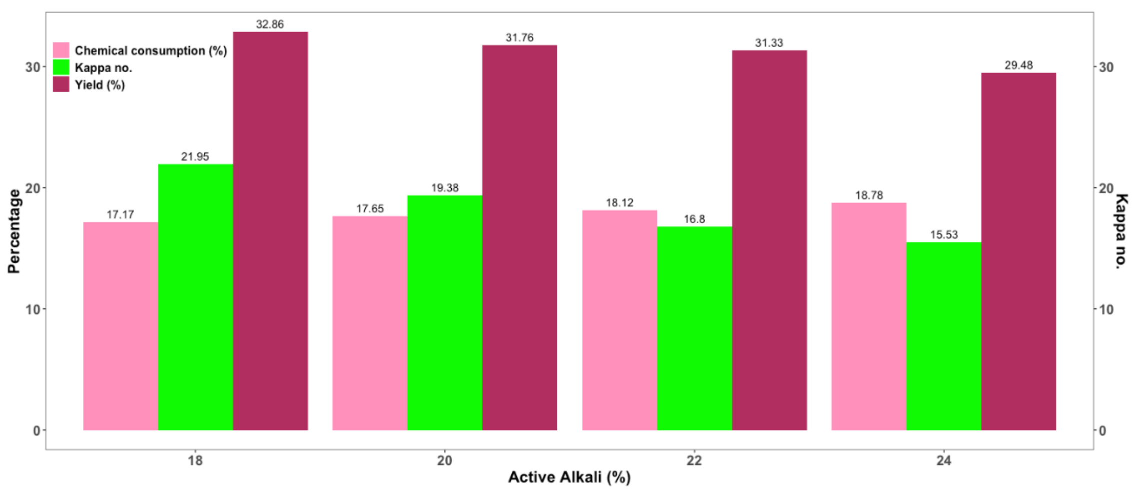

Fig. 3. The active alkali of PAL kraft pulping

In a related investigation, Tran (2006) reported a pulp yield of 31% at a Kappa number of 20, and a yield of 33% at a Kappa number of 22. Those results closely align with the findings of the current study. The Kappa number for pineapple leaf pulp in this research ranged from 15.5 to 22.0, indicating a lower lignin content compared to bagasse pulp, which was documented to have a Kappa number of 25.2 (Akhtaruzzaman *et al.* 1991).

This suggests that the pulp derived from pineapple leaves may require less intensive bleaching, thereby reducing chemical input and associated costs.

Furthermore, the Kappa number of pineapple leaf pulp was comparable to the value of 19.5 reported for whole-length jute pulp (Shafi *et al.* 1993). This similarity suggests promising potential for utilizing pineapple leaf pulp in papermaking applications, with the possibility of decreasing reliance on bleaching chemicals and ultimately lowering production costs.

Although having high alpha-cellulose content in comparison most other woody sources, the low pulp yield in this specific operation may to attributed to some key factors such as NaOH concentration, temperature, and time. NaOH is used to hydrolize lignin, this reaction occurs at relatively low temperature than the hydrolysis of cellulosic chains (Wanrosli *et al.* 2004). High alkali concentration with high temperature followed by an extended period of time may have accelerated the hydrolysis of cellulosic chains in this case. Optimum alkali ceoncentration and temperature profile is important to achieve maximum pulp yield. Higher temperature with more shorter period of time could have resulted in more pulp yield at a specific alkali concentration (Tran 2006). Another study has pointed out the optimum temperature range of 105 to 115° C when yield had reached a peak value (Wutisatwongkul *et al.* 2016)

Brightness of PAL Fiber

Figure 4 illustrates the influence of active alkaline levels on the brightness of both bleached and unbleached pineapple leaf (PAL) fiber, with brightness serving as a critical parameter for assessing paper quality. The brightness has been evaluated according to ISO 2470-1:2009 standard. The average bleaching yield was found to be 87.5%. The unbleached pulp exhibited a noticeable increase in brightness, rising from 23.5% ISO to 28.7% ISO as the active alkali charge was elevated from 18% to 24%. This trend corresponds with the higher degree of delignification observed at increased alkali levels, as evidenced by the decreasing Kappa numbers.

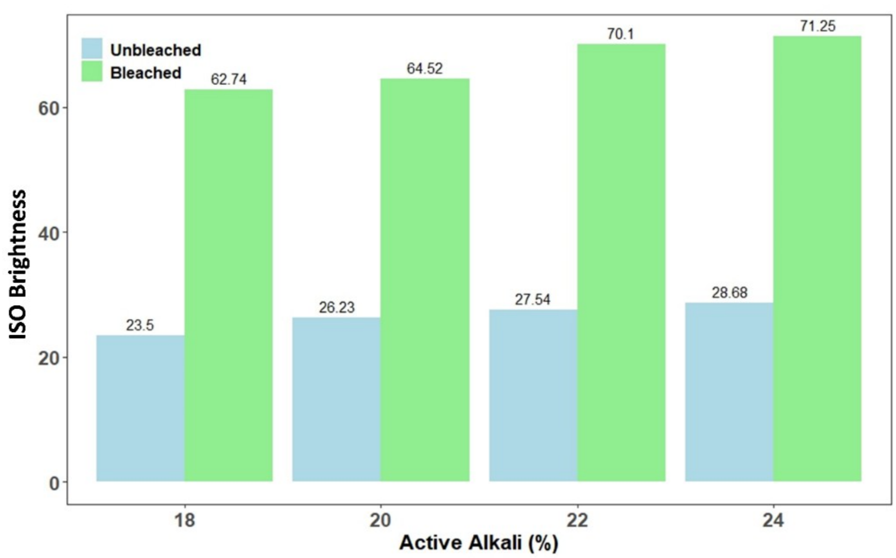

Fig. 4. Active alkaline levels on the bleached and unbleached states of PAL fiber

Following the bleaching process, the brightness of the pulps further improved, increasing from 62.7% ISO at 18% alkali to 71.2% ISO at 24% alkali. This enhancement underscores that pulping at higher alkali charges facilitates greater brightness development during bleaching, attributed to the reduced residual lignin content. The brightness gain during the bleaching process was particularly pronounced for pulps treated with higher alkali levels, with a brightness increase of 39.2% ISO for the 18% alkali pulp, compared to 42.6% ISO for the 24% alkali pulp.

In summary, the results indicate that pulping at elevated active alkali levels leads to pulps characterized by lower residual lignin and enhanced bleachability, culminating in substantial improvements in brightness. However, this benefit necessitates a careful consideration of the trade-offs involved, particularly the reduction in pulp yield associated with higher alkali levels. A comprehensive cost-benefit analysis is essential to optimize the pulping process for maximum efficiency and economic viability.

Furthermore, the pineapple leaf paper produced in this study exhibited an ISO brightness of 69.8%, which is comparatively lower than the brightness values reported for papers derived from Muli bamboo (77.2% ISO) (Jahan *et al.* 2013), mixed hardwoods (approximately 77% ISO) (Siddhartha *et al.* 2010), and Gamar (78% ISO) (Jahan *et al.* 2017). This lower brightness level is indicative of the higher lignin and extractive content inherent in pineapple leaves, which limits their light absorbance capacity.

Physical Properties of PAL Fiber

Figure 5 illustrates the influence of active alkali levels on the strength characteristics of handsheets produced from bleached pineapple leaf (PAL) pulp for both CSFs. The pulp was treated with varying alkali charges ranging from 18% to 24% before sheet formation. The tear index exhibited an increasing trend, ranging from 6.15 to 7.22 mN·m²/g as the alkali charge was elevated. Notably, both the burst index and tensile index demonstrated considerable enhancements with increasing alkali concentrations. Specifically, the burst index improved from 1.77 kPa·m²/g at 18% alkali to 3.31 kPa·m²/g at 24% alkali, while the tensile index rose from 27.1 to 50.1 Nm/g across the same range.

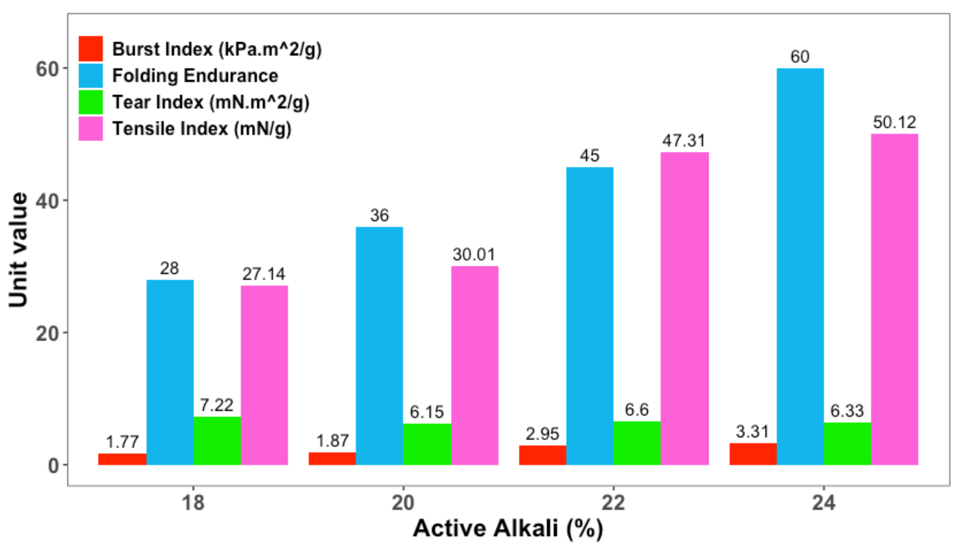

Fig. 5. Active alkali charge on paper strength characteristics

Pulp sheets treated with 24% alkali exhibited the highest recorded values for burst strength, tensile strength, and folding endurance, measuring 3.31 kPa·m²/g, 50.12 Nm/g, and 60 folds, respectively (Fagbemigun *et al* 2016). These findings suggest that an active alkali charge of 24% optimally enhances the critical strength properties of paper derived from pineapple leaf pulp.

The mechanical properties of pineapple leaf fiber can be attributed to its elevated alpha-cellulose content, as noted by Sibaly and Jeetah (2017). Tran's investigation (2006) reported a tensile index of 39 Nm/g for pineapple crown leaf pulp using a 20% alkali charge, which closely aligns with the current study's result of 30 Nm/g under similar conditions. This reinforces the notion that a 20% active alkali concentration is effective for obtaining pineapple leaf pulp with adequate strength. Furthermore, the tensile strength considerably improved to 50.1 Nm/g with a 24% alkali charge, indicating the optimality of this concentration for maximizing tensile strength.

The tear index for pineapple leaf paper was measured at 6.82 mN·m²/g, which is consistent with values reported in previous studies. Although the burst index recorded in this study was lower compared to some earlier findings, it remains commendable for applications in writing papers. The observed increase in folding endurance, rising from 28 to 60 folds with escalating alkali dosage, is correlated with enhanced delignification, resulting in improved paper strength. This enhancement in folding endurance is primarily driven by the reduction in residual lignin content due to the higher alkali dosage, which fosters increased flexibility and bonding between fibers, thereby augmenting overall paper strength.

Table 2. Physical Property Comparison of Pulp of Different Wood, Non-Wood and Pineapple Leaf Pulp

Wood type	Tensile index (N·m/g)	Burst index (kPa·m^2/g)	Tear index (mN·m^2/g)	Reference
Pineapple leaf	50.12	3.31	6.33	Present study
Acacia mangium	47.42	1.90	5.04	(W. D. Wan Rosli *et al.* 2009)
Eucalyptus globulus	68.3	4.1	7.0	(Anjos *et al.* 2015)
Brich	105.8	7.2	3.2	(Przybysz *et al.* 2018)
Pinus taeda	54.14	6.78	-	(Dang *et al.* 2006)
Black spruce	97.77	8.78	9.76	(Wistara & Young 1999)
Pine	103.9	6.9	6.1	(Przybysz *et al.* 2018)
Rice straw	36.33	1.48	3.49	(Kaur *et al.* 2017)
Sugarcane bagasse	85.41	4.9	5.98	(Ferdous et al. 2021)
Jute fiber	85.7	6.8	20.8	(Ferdous *et al.* 2021)

CONCLUSIONS

1. The considerable cellulosic content in pineapple leaf fiber, marked by high levels of holo-cellulose (82.6%) and alpha-cellulose (69.7%), positions it as a highly viable raw material for papermaking applications. Increasing the alkali charge during kraft pulping, specifically from 18% to 24%, substantially enhanced de-lignification, reduced kappa numbers, improved pulp brightness, and improved tensile index, burst index, and folding endurance.

2. Optimal de-lignification and corresponding enhancements in paper strength were achieved at an active alkali charge of 24%. However, this optimization necessitated a careful assessment of the trade-offs associated with decreased pulp yield observed at higher alkali levels.
3. The tensile index, burst index, and folding endurance of paper produced from pineapple leaf pulp either matched or exceeded those of various non-wood fibers, such as banana fibers, underscoring the potential of pineapple leaf fiber as an alternative resource for sustainable paper production.
4. Paper strength properties revealed a negative correlation between the tear index and properties, such as tensile index, burst index, and folding endurance, while strong positive correlations among the latter properties were noted.
5. An alkali charge in the range of 20% to 22% is recommended to achieve the desired attributes in papermaking, balancing chemical composition, physical properties, and brightness considerations.
6. The alpha-cellulose content is found to be higher than other wood and non-wood species such as *Melocanna baccifera*, *Eucalyptus camaldulensis*, beech wood, rice straw, spruce wood, and pine needles. The paper made from pineapple leaves showed better physical properties than *Acacia mangium* and rice straw The findings of this study advocate for the utilization of pineapple leaf fiber as a sustainable and effective alternative for the papermaking industry.

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