

Sustainable Valorization of Banana Pseudo-Stem Waste through Optimized NaOH Pulping: A Chemical Engineering Approach.

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Abstract

The increasing environmental burden of synthetic packaging materials has driven the search for renewable alternatives derived from agricultural residues. In this study, banana pseudo-stem fibre, an abundant lignocellulosic waste from banana cultivation, was utilized to produce biodegradable wrapping paper through alkaline pulping using sodium hydroxide (NaOH). The process involved fibre preparation, pulping, washing, refining, and sheet formation by screen moulding. Key process parameters, including alkali concentration, cooking temperature, and fibre-to-liquor ratio, were optimized to obtain uniform pulp yield suitable for paper formation. The physical and mechanical properties of the prepared sheets, such as grammage, thickness, and tensile strength, were evaluated using standardized methods at an accredited textile testing laboratory. The banana fibre-based wrapping paper exhibited satisfactory strength and surface quality comparable to commercial recycled wrapping papers. The alkaline pulping route demonstrated acceptable fibre bonding and moderate chemical consumption, indicating technical feasibility for small-scale decentralized production. Preliminary sustainability analysis suggests that utilizing banana pseudo-stem waste for paper making could significantly reduce raw-material dependency on wood fibres and divert agricultural residues from disposal. The results confirm that banana fibre represents a viable and eco-friendly raw material for producing biodegradable wrapping paper, supporting the transition toward sustainable packaging solutions.

Keywords

Banana fibre · Wrapping paper · NaOH pulping · Mechanical properties · Biodegradable packaging · Sustainable materials

1. Introduction

The extensive global reliance on synthetic packaging materials, particularly plastics, has resulted in profound environmental consequences due to their long-term persistence and non-biodegradable nature. Recent estimates indicate that over 300 million tons of plastic waste are produced annually, with a substantial portion originating from single-use packaging applications ^[1]. This escalating environmental burden underscores the urgency for developing biodegradable and sustainable alternatives derived from renewable biomass sources ^[2].

Among the available lignocellulosic feedstocks, banana pseudo-stem waste emerges as a highly promising raw material for paper production. Banana cultivation generates large volumes of agricultural residues—primarily pseudo-stems—which are typically discarded after fruit harvesting ^[3,4]. Previous compositional analyses have shown that banana fibres possess high cellulose content (approximately 60–65%) and moderate levels of lignin and hemicellulose, conferring suitable characteristics for pulping and papermaking processes ^[5,6].

Several studies have demonstrated the feasibility of converting banana pseudo-stem fibres into handmade or laboratory-scale paper using mechanical and chemical pulping methods ^[7–10]. For instance, Ramdhonee and Jeetah ^[1] successfully produced wrapping paper from banana fibres via alkaline pulping, achieving tensile and printability properties comparable

to recycled papers. Further investigations have confirmed the effectiveness of sodium hydroxide (NaOH)-based alkaline pulping in enhancing fibre separation and delignification efficiency [5,7].

However, despite these advancements, prior research has predominantly emphasized pulp quality, fibre morphology, and basic sheet formation, with limited systematic evaluation of the mechanical performance of banana fibre-based wrapping papers or their direct comparison with commercial products [8,9,11]. Additionally, standardized testing of physical parameters—such as grammage, thickness, and tensile strength—under controlled laboratory conditions remains insufficiently addressed, yet is essential for establishing industrial relevance and reproducibility [12–14].

In this context, the present investigation focuses on the development of biodegradable wrapping paper from banana pseudo-stem fibres through NaOH pulping. The study emphasizes optimization of process feasibility and mechanical performance evaluation, contributing to the advancement of sustainable materials engineering. This work demonstrates the valorization potential of an abundant agro-waste resource and provides a practical foundation for decentralized, small-scale, and low-cost production of environmentally responsible packaging materials.

2. Materials and Methods

2.1. Raw Material Collection and Preparation

Banana (*Musa paradisiaca*) pseudo-stems were collected from local banana farms immediately after fruit harvesting. The outer layers were peeled to expose the fibrous portion, which was thoroughly washed to remove sap and debris. The cleaned fibres were dried for 3–4 days until the moisture content dropped below 10 %. The dried material was then cut into approximately 5 cm pieces to ensure uniform pulping and consistent alkali penetration.

Fig. 1: Collection and drying of banana pseudo-stem fibres



(i) Peeling off banana fibre



(ii) drying in oven



(iii) dried fibres

2.2. Chemical Pulping Process

Chemical pulping was performed using the soda pulping (NaOH) method, a process widely reported for banana fibre delignification ^[5, 7]. A 10 % w/v sodium hydroxide solution was prepared and used with a liquor-to-fibre ratio of 10:1 (v/w). The fibres were cooked at 90–95 °C for 2 hours under continuous heating and occasional stirring. After cooking, the pulped mass was washed repeatedly with distilled water until the filtrate reached neutral pH, ensuring removal of residual alkali and dissolved lignin.

Fig. 2: NaOH pulping of banana fibres



(i) At the beginning of cooking



(ii) After cooked

2.3. Fibre Refining and Sheet Formation

The washed pulp was mechanically refined using a domestic blender in short pulses to improve fibre fibrillation and bonding potential. The refined pulp was diluted with water to form a uniform slurry of moderate consistency. Paper sheets were produced by **manual screen moulding** using a wooden frame fitted with a fine stainless-steel mesh. The wet sheets were drained, pressed gently to remove surface water, and then **air-dried at ambient temperature (28–32 °C)** for 24 hour.

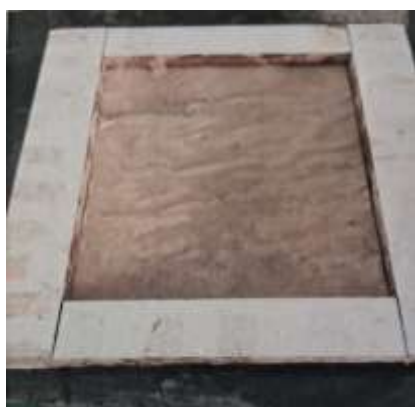


Fig 3: Screen moulding process



Fig. 4: Air-drying of formed paper sheet

2.4. Characterization of Prepared Paper

2.4.1. Physical Properties

The grammage (basis weight) and bursting strength of the paper were determined using standard TAPPI procedures (T 410, T 403).

2.4.2. Mechanical Properties

Mechanical strength tests were conducted at the South India Textile Research Association (SITRA), Coimbatore, using a Zwick/Roell Universal Testing Machine in accordance with TAPPI T 494. Test strips were prepared with dimensions of 15 mm × 150 mm, conditioned at 23 ± 2 °C and 50 ± 5 % RH, and tested at a crosshead speed of 10 mm min⁻¹.

2.4.3. Surface and Morphological Observation

The prepared paper sheets exhibited moderate surface roughness with visible fibre orientation and occasional bonding gaps caused by manual sheet formation. Visual comparison with a commercial recycled wrapping paper showed comparable opacity and stiffness but slightly higher surface texture due to the natural fibre morphology.

2.5. Data Analysis

All reported results represent the average of three replicate tests. Descriptive statistical analysis (mean and standard deviation) was used to assess repeatability using SPSS ver.21. The obtained values were compared with literature data for banana-fibre and other agro-residue-based papers ^[1, 5, 7, 10, 13] to evaluate relative mechanical performance and potential for packaging applications.

3. Results and Discussion

3.1. Physical Characteristics

The prepared wrapping paper exhibited a grammage of 120.88 g m⁻², placing it within the medium-weight category suitable for packaging applications. The bursting strength of 2.92 kg cm⁻² indicates that the paper can withstand moderate pressure without rupture. This is comparable to other non-wood wrapping papers derived from agricultural residues ^[1, 5, 7]. The slightly higher density and stiffness of the banana-fibre paper compared to recycled commercial wrapping paper (Fig. 6) are attributed to the fibre's intrinsic thickness and residual lignin content, which enhance rigidity but reduce flexibility. These findings align with observations by Deshmukh *et al.* ^[7] and Ramdhonee & Jeetah ^[1], who reported similar mechanical behaviour in soda-pulped banana fibre sheets.

Fig. 6: Surface comparison between banana-fibre paper (A) and commercial wrapping paper (B)



Banana-fibre paper (A)

Commercial wrapping paper (B)

3.2. Mechanical Properties

The tensile testing results (Table 1) demonstrate a maximum load of 109 N (lengthwise) and 56.1 N (width wise) with corresponding elongations of 5.8 % and 8.3 %, respectively. The higher strength in the machine direction is typical of hand-formed sheets where fibre alignment occurs during drainage ^[8].

Table 1. The results of tensile strength and elongation measurements.

Direction	Maximum Load $F_{\max}$ (N)	Elongation (%)	Bursting Strength (kg cm^{-2})	Grammage (gm^{-2})
Lengthwise	109.0 N	5.8 %	2.92	120.88
Widthwise	56.1 N	8.3 %	2.92	120.88

These results are consistent with earlier studies reporting tensile strengths of 90–120 N for banana fibre paper produced via alkaline pulping ^[1, 5, 10]. The moderate elongation values suggest that the fibre network possesses balanced bonding and flexibility—adequate for wrapping applications but inferior to high-grade kraft papers, which typically exceed 6–8 % elongation ^[9, 13]. The mechanical strength improvement can be attributed to NaOH pulping, which effectively removes hemicellulose and weak lignin layers, exposing more hydroxyl groups for hydrogen bonding between cellulose fibrils ^[5]. However, incomplete delignification due to the relatively low cooking temperature (90–95 °C) may have limited inter-fibre bonding, slightly reducing tensile performance relative to optimized soda-anthraquinone pulping reported by Merais *et al.* ^[4].

3.3. Structural and Surface Observation

Visual examination (Fig. 6) revealed a relatively uniform fibre dispersion and moderate surface roughness. The slight irregularities and visible fibre ends arise from manual sheet formation without calendaring. Similar morphological features were described by Samath *et al.* ^[11] and in other agro-fibre handmade papers, where surface porosity contributes to natural texture and improved print adhesion.

Despite the unpolished finish, the sheet demonstrated adequate flexibility, opacity, and folding endurance, comparable to low-grade recycled wrapping paper. The presence of minor dark fibre fragments is a byproduct of limited bleaching—an acceptable trade-off in environmentally friendly, unbleached wrapping materials.

3.4. Comparative Assessment

The results from Table 2 compares the present study's results with published data on banana-fibre-based paper prepared by different pulping processes. The mechanical properties obtained here fall within the reported range for NaOH and soda-anthraquinone pulps, confirming the technical viability of the process.

Table 2. Comparison of mechanical properties with previous studies.

Source	Pulping Method	Tensile Strength (N)	Bursting Strength (kg cm^{-2})	GSM (g m^{-2})
Ramdhonee & Jeetah (2017)	NaOH	95–110	2.8	115–125
Deshmukh et al. (2019)	Soda	100–120	3.0	120
Merais et al. (2022)	Soda–AQ	120–140	3.1	110–130
Present Study	NaOH	109	2.92	120.88

The close agreement with published data validates both the chemical treatment and mechanical integrity of the produced paper. It also confirms that banana pseudo-stem waste can serve as a reliable fibre source for decentralized small-scale wrapping paper manufacturing, requiring minimal chemical input and energy.

3.5. Overall Evaluation

The combination of tensile, bursting, and GSM values demonstrates that banana-fibre wrapping paper can meet basic functional requirements for eco-friendly packaging, particularly where biodegradability and strength-to-weight ratio are prioritized over surface finish. The process remains simple, reproducible, and scalable with minimal infrastructure, aligning with the sustainability goals emphasized in current pulp and paper research [2, 10, 14].

4. Conclusion

This study showed that banana pseudo-stem fibre can be used to make eco-friendly wrapping paper through a simple soda pulping (NaOH) process. The handmade sheets had good strength and quality suitable for light packaging, with results comparable to other agro-waste papers. The method uses minimal chemicals and moderate temperature, making it a sustainable small-scale option. However, the paper's strength and surface finish are lower than commercial kraft paper due to partial lignin and manual preparation. Further improvements can be made by optimizing pulping conditions, adding natural binders, and testing printability and biodegradability. Overall, banana pseudo-stem waste can be effectively turned into an environmentally friendly paper product.

5. Author Contribution

The authors confirm that the work reported in this manuscript was carried out by the listed contributors. All authors made substantial contributions to the conception, design, experimentation, analysis, and manuscript preparation. All authors have read and approved the final version of the manuscript for publication.

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7. Conflict of Interest

The author(s) declare that there are no conflicts of interest regarding the publication of this paper.

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