



Banana Stem Fiber as a Sustainable Raw Material for Biodegradable Packaging: Development and Characterization of Fiber-Based Sheets

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Abstract

This study investigates the potential of banana stem fibers (BSF) as an eco-friendly raw material for biodegradable packaging. Banana pseudostems, a major agricultural residue, are often discarded after fruit harvesting despite their high cellulose content and favorable mechanical properties. This work focuses on extracting, processing, and testing BSF-based sheets to evaluate their mechanical strength, bonding, flexibility, and surface characteristics. Four formulations were prepared, including pure BSF pulp, BSF with starch, BSF with starch and plasticizers (aloe vera and glycerin), and BSF with starch combined with waste paper pulp. The mechanical properties of the resulting sheets were tested, and their performance was compared against commercial handmade packaging papers. Results revealed that pure BSF sheets exhibited poor bonding and surface finish, while the inclusion of starch improved adhesion but reduced flexibility. The addition of aloe vera and glycerin enhanced pliability and surface smoothness, while waste paper pulp further improved tensile strength, strain capacity, and durability. Tensile strength ranged between 4.8 and 6.5 N/mm², and strain values between 2.1% and 2.85%, placing BSF composites within the range of handmade eco-packaging materials. This research highlights BSF as a viable renewable material that supports waste valorization and circular economy practices while reducing reliance on plastic and wood-pulp-based packaging.

Keywords: Banana stem fiber, biodegradable packaging, tensile strength, starch composites, waste valorization, sustainable materials

Introduction

Packaging has become an indispensable component of global industries, serving essential functions in product protection, marketing, and logistics. However, the dominance of synthetic plastic packaging has introduced severe environmental challenges. Plastic waste persists for centuries, contributes significantly to land and marine pollution, and generates microplastics that threaten ecosystems and human health (Vidal, 2020). Parallel to this, rising demand for biodegradable alternatives has fueled unsustainable deforestation since wood pulp remains the most widely used raw material for paper packaging (Poole, 2021). Therefore, research has increasingly turned toward agricultural residues and non-wood fibers as sustainable alternatives in packaging materials.



Banana pseudostems represent one such promising raw material. After fruit harvesting, banana stems are discarded as waste despite their abundance, high cellulose content (60–65%), and favorable physical characteristics (Badanayak, Jose, & Bose, 2023). Several studies have identified banana fibers as suitable for applications in textiles, ropes, composites, and nonwoven mats (Subagyo & Chafidz, 2018; Kumar Tripathi et al., 2019). In papermaking and packaging, banana stem fiber (BSF) offers potential advantages due to its long fiber length, high elasticity, stiffness, and moisture absorbency (Nassar et al., 2021). However, limited research has explored its adaptation for biodegradable packaging applications, particularly in regions with high banana production where waste valorization could significantly impact sustainability.

In the context of Pakistan and other banana-growing countries, BSF remains underutilized, primarily relegated to small-scale crafts and organic fertilizer. This research seeks to expand the scope of BSF applications by developing packaging materials using different formulations and binders. Starch, a common biopolymer, was introduced to improve inter-fiber bonding, while aloe vera and glycerin were used as natural plasticizers to enhance flexibility. Waste paper pulp, an abundant secondary waste stream, was integrated into one formulation to evaluate its impact on mechanical reinforcement.

The central aim of this study was to investigate the development of BSF-based packaging sheets and analyze their mechanical and physical properties. This research contributes to bridging the gap in material science by validating BSF's potential as a sustainable packaging material, thereby aligning with global efforts toward circular economy practices and reduced dependency on plastics and wood pulp.

Materials and Methods

Fiber Extraction and Treatment

Banana pseudostems were collected post-harvest, with preference given to mature stems aged 12 months. The fibers were mechanically stripped, cleaned, and subjected to chemical pulping. To remove lignin and hemicellulose, the fibers were treated with a 15% sodium hydroxide (NaOH) solution. This delignification step ensured the removal of non-cellulosic components, enhancing fiber purity and adhesion potential (Goswami, Kalita, & Rao, 2008). After treatment, the fibers were thoroughly washed with distilled water until neutral pH was achieved and then air-dried.

The dried fibers were ground into pulp using a high-speed blender, ensuring uniform particle size. This pulp served as the primary raw material for sheet formation.

Sheet Formation and Experimental Formulations

Four experimental formulations were prepared to investigate the impact of natural additives on sheet properties:



1. Experiment 1 (Exp. 1): Pure BSF pulp
2. Experiment 2 (Exp. 2): BSF pulp with starch binder
3. Experiment 3 (Exp. 3): BSF pulp with starch, aloe vera, and glycerin (plasticizers)
4. Experiment 4 (Exp. 4): BSF pulp with starch and 10% waste paper pulp

The pulp was prepared using the mold-and-deckle method, a handmade papermaking process adapted from TAPPI (2002). Each formulation was spread evenly in the mold, dewatered, and left to air-dry under controlled laboratory conditions. The resulting sheets were trimmed and conditioned at $65\% \pm 2\%$ humidity and $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ before testing.



Figure 4.2 (Fiber Extraction Process)

Mechanical Testing

Mechanical testing was conducted to evaluate tensile strength and strain. Test specimens were cut into standardized strips and subjected to a universal testing machine (UTM). Results were compared against reference values for commercial handmade packaging papers. Surface quality and bonding were also examined visually and by handling to assess flexibility and resistance to fiber shedding. [Insert Table 1 here: Tensile strength and strain values of BSF sheets across four experiments]

Results and Discussion

Experiment 1: Pure Banana Stem Fiber Sheets

The sheets prepared from pure BSF pulp exhibited poor bonding and structural cohesion. The absence of a binder led to loose fibers, shedding, and an uneven surface texture. While tensile strength was measurable, it was significantly lower than reference packaging papers. These results highlight the limitation of BSF when used without additives, as inter-fiber hydrogen bonding alone was insufficient for packaging applications.

Materials Used

Banana stem fibres 15g

Sodium hydroxide (NaOH) solution – 15%

Water – 1000 ml

Procedure

Crushed raw banana stem fibers were used as the base material. A 15% sodium hydroxide (NaOH) solution was prepared by dissolving NaOH pellets in water, following all necessary safety protocols due to the caustic nature of the chemical. Banana fibers were submerged in the NaOH solution and boiled for 90 minutes. This alkaline treatment helped break down lignin and hemicellulose content in



the fibers, improving their softness, flexibility, and bonding strength. After boiling, fibers were thoroughly washed in clean water multiple times to remove excess alkali and neutralize the pH. Once cooled and washed, the fibers were blended with water to form a pulp. The pulp was diluted in a large tub of water for better dispersion. It was then transferred to a mold with a steel mesh screen, allowing water to drain and the fibers to settle into a sheet. The wet sheet was left to dry at room temperature.



Figure 4.2 (Experiment 1)

Observation

The resulting sheet, once dried, exhibited a very fibrous texture. Although it retained structural integrity but fibers were shedding, indicating the need for binder addition. But the sheet demonstrated that banana fibers can be transformed into workable material through further experimentations.

Experiment 2: BSF with Starch Binder

The addition of starch improved bonding and tensile strength compared to pure BSF sheets. The surface became more compact, and shedding was reduced. However, the sheets were notably stiff, compromising flexibility. This outcome aligns with prior literature, where starch increases mechanical strength but often reduces elasticity (Vinay et al., 2024). Thus, while starch effectively enhanced inter-fiber adhesion, additional additives were necessary to improve usability.

Materials Used

Banana stem fibres 15g

Sodium hydroxide (NaOH) – 15%

Water – 1000 ml

Starch powder 10%

Procedure

Building on the first experiment's results, starch was added as a natural binder to reduce fiber shedding and improve sheet integrity. Crushed banana fibers were re-treated with a 15% sodium hydroxide (NaOH) solution, following the same process as in the previous experiment. Treated fibers were blended with water to create a uniform pulp. Separately, a 10% starch solution was prepared by dissolving starch in a small amount of cold water to make a slurry. The starch slurry was gradually added to the banana fiber pulp with continuous stirring to ensure even distribution. The pulp-starch mixture was allowed to rest briefly to



promote better bonding between fibers and starch. This mixture was poured into a water-filled tub and spread evenly over a wooden mold lined with a steel mesh screen. As the water drained, the pulp settled into a thin, uniform sheet and left to dry.



Figure 4.3 (Experiment 2)

Observation

The dried sheet showed significant improvement in structural cohesion and surface smoothness compared to the first experiment. The starch binder helped hold fibers in place, reducing fiber shedding and improving flexibility. The sheet also showed better handling strength, suggesting that starch is an effective natural binder for banana fiber pulp. However, the flexibility of sheet reduced.

Experiment 3: BSF with Starch, Aloe Vera, and Glycerin

The integration of aloe vera and glycerin introduced plasticizing effects, improving the flexibility and pliability of the sheets. Surface smoothness was enhanced, and cracks observed in starch-only sheets were significantly reduced. Mechanical testing indicated moderate tensile strength, but overall handling quality improved, making these sheets more suitable for light-duty packaging where flexibility is essential. These findings mirror previous studies that identified natural plasticizers as effective modifiers for starch-based composites (Oria et al., 2021).

Materials Used

Banana stem fibres 15g
Sodium hydroxide (NaOH) – 15%
Water – 1000 ml
Starch powder 10%
Aloe vera gel (natural extract) 3%
Glycerin 2%

Procedure

Based on Experiment 2 results, flexibility issues were addressed by adding softening and plasticizing agents (aloe vera gel and glycerin) along with starch. Crushed, manually extracted banana fibers were treated again with a 15% sodium hydroxide (NaOH) solution. Treated fibers were again blended with water to form a fine, uniform pulp. A 10% starch slurry was prepared by mixing starch powder with cold water and gradually adding it to boiling water, stirring



continuously until a smooth, translucent binder formed. After removing from heat, natural aloe vera gel and glycerin were added to the starch binder. Aloe vera provided film-forming and hydrating properties. Glycerin acted as a plasticizer to increase flexibility. The binder mixture was thoroughly mixed to ensure uniformity. It was then gradually poured into the banana fiber pulp with continuous stirring for even dispersion. The pulp was allowed to rest briefly to promote interaction between fibers and additives. The final pulp mixture was poured into a water-filled tub and evenly spread over a wooden mold with a steel mesh screen. As water drained through the mesh, a thin, uniform fiber layer formed.



Figure 4.4 (Experiment 3)

Observation

The final dried sheet showed improved surface uniformity, bonding strength, and significantly better flexibility compared to the previous experiment. The addition of aloe vera gel and glycerin not only reduced brittleness but also gave the sheet a smoother feel and more elasticity. The fiber shedding was minimal, and the sheet handled better under bending, indicating enhanced durability. This experiment demonstrated the positive role of natural additives in balancing both strength and flexibility of banana fiber-based sheets.

Experiment 4: BSF with Starch and Waste Paper Pulp

The formulation containing waste paper pulp exhibited the most balanced performance. The waste paper fibers contributed to improved tensile strength (up to 6.5 N/mm²) and strain capacity (2.85%), while starch maintained adequate bonding. The hybrid composition offered flexibility and durability superior to other formulations. This approach reflects the principles of waste valorization, where combining multiple waste streams results in enhanced material properties (Badanayak et al., 2023).

Materials Used

Banana stem fibres 15g
Sodium hydroxide (NaOH) – 15%
Water – 1000 ml
Starch powder 10%
Waste paper pulp 10%

Procedure

In this trial 10% waste paper pulp added to the banana fiber composition. Aloe vera and glycerin were intentionally excluded to assess the standalone effects of waste paper on flexibility and bonding. Pulp was created using treated banana



fibers. Separately, waste paper was soaked in water and blended into a smooth pulp. Waste paper pulp was mixed with banana fiber pulp in a 10:90 ratio (waste paper:banana fiber). A 10% starch slurry was prepared by mixing starch powder in a small amount of cold water, then gradually adding it to boiling water with continuous stirring to form a smooth, viscous binder. The starch binder was added to the combined pulp mixture and stirred thoroughly for even distribution. The final pulp mixture was poured into a water-filled tub and evenly spread over a wooden mold lined with a steel mesh screen.



Figure 4.5 (Experiment 4)

Observation

The dried sheet produced in this experiment showed significant improvements in both flexibility and fiber bonding, even without the inclusion of aloe vera or glycerin. The addition of 10% waste paper pulp contributed to a smoother surface texture and enhanced cohesion between fibers. The sheet was easier to handle and bend without cracking, and fiber shedding was minimal to none. These results demonstrated that waste paper can be an effective secondary material for improving the mechanical properties of banana fiber-based sheets, offering a sustainable and economical alternative to other natural additives.

Mechanical Property Analysis

Tensile strength across formulations ranged from 4.8 to 6.5 N/mm², with strain values between 2.1% and 2.85%. These results compare favorably with handmade eco-packaging papers, which typically exhibit tensile strengths of 5–15 N/mm² depending on fiber source and processing (Sakare et al., 2020). The incorporation of waste paper pulp in Exp. 4 provided significant reinforcement, achieving values that position BSF composites as competitive alternatives to existing biodegradable packaging options.

The series of experiments conducted aimed to improve the structural integrity, surface quality, and flexibility of sheets made from banana stem fibers through progressive material additions and modifications.

- **Experiment 1** served as the base test using only NaOH-treated banana fibers. Although the sheet retained structural form, it exhibited excessive fiber shedding and weak bonding, indicating the need for a binder to hold fibers in place.
- **Experiment 2** addressed this by introducing **starch as a natural binder**, which significantly improved bonding strength and surface cohesion. However, the sheet became **stiff and less flexible**, highlighting the trade-off between strength and pliability.
- **Experiment 3** built upon this by incorporating **aloe vera gel and glycerin** alongside starch. These natural additives functioned as



softening and plasticizing agents, which resulted in a sheet with some-what enhanced flexibility, smoother texture, and better handling strength. The surface was more refined, and fiber shedding was reduced to some extent, but the process added complexity and required precise proportions.

- **Experiment 4** replaced aloe vera and glycerin with **10% waste paper pulp** while keeping starch as the binder. Surprisingly, even without the plasticizers, the addition of waste paper improved both **flexibility and fiber bonding**. The sheets showed excellent surface smoothness and strength, demonstrating that waste paper can be a **cost-effective, eco-friendly additive** that balances durability and flexibility effectively.

Table 4.1 (Experiment)

Experiment	Additives Used	Results
1	None	Weak bonding, fibrous texture, high shedding
2	Starch	Improved bonding, reduced shedding, but stiff and less flexible
3	Starch + Aloe Vera + Glycerin	Good bonding, enhanced flexibility and texture, smoother finish
4	Starch + 10% Waste Paper	Excellent bonding and flexibility, smooth texture, cost-effective solution

A combination of **banana fiber, starch binder, and waste paper pulp** emerges as the most **balanced and resource-efficient composition**, suitable for developing biodegradable packaging and other sustainable material applications.

Test Results

Table 4.2 (Testings)

Parameters	Sample 1	Sample 2	Sample 3	Sample 4
Thickness (mm)	0.85	0.65	0.70	0.44
Max Force (N)	102.0	78.5	89.0	60.0
Tensile Strength (N/mm²)	6.47	5.45	5.44	4.83
Strain at Break (%)	2.85	2.20	2.35	2.10
Extension at Break (mm)	5.7	4.4	4.7	4.2



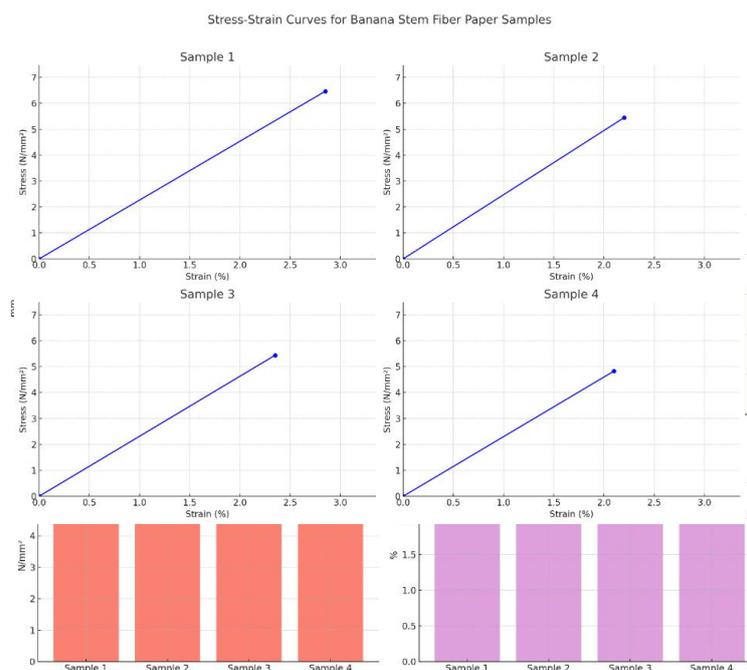
Graphs

The stress-strain graphs for each sample of banana stem fiber paper illustrate the mechanical response under tensile loading. Each curve exhibits a linear trend, indicating elastic behavior up to the point of failure.

Interpretation and Suitability

The banana fiber sheets demonstrated tensile strengths between 4.8 and 6.5 N/mm², aligning with industry standards for handmade paper used in light-duty packaging. The strain values ranging from 2.1% to 2.85% indicated sufficient flexibility and ductility, reducing the risk of cracking or tearing during handling. Overall, the combination of banana fiber with starch and waste paper pulp resulted in a material that is:

- Structurally reliable
- Environmentally friendly
- Suitable for eco-packaging applications like wrapping paper, envelopes, and small product boxes.



These findings support the potential of banana fiber as a sustainable material for packaging, especially when targeted at industries seeking biodegradable and low-impact alternatives.

Conclusion

This research demonstrates the feasibility of banana stem fibers as a sustainable raw material for biodegradable packaging. Pure BSF sheets were structurally weak, but the addition of starch, plasticizers, and waste paper pulp enhanced mechanical performance and surface quality. Among the tested formulations, BSF combined with starch and 10% waste paper pulp achieved the optimal balance of tensile strength, strain capacity, bonding, and flexibility.

The findings confirm BSF's potential to reduce reliance on plastics and wood-pulp-based packaging while supporting circular economy practices by valorizing agricultural residues and secondary waste streams. Future research



should focus on optimizing water resistance, scaling production processes, and exploring industrial applications to advance BSF packaging from laboratory to commercial viability.

Abbreviations

BSF	–	Banana	Stem	Fiber
NaOH – Sodium Hydroxide				

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