OPTIMIZATION OF CELLULAR DISINTEGRATION AND PARTICLE SIZE OF *MUSA PARADISIACA* RACHIS FOR ECOLOGICAL PAPER PRODUCTION

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Abstract. This research focused on utilizing lignocellulosic agro-industrial waste as a sustainable alternative for manufacturing biodegradable materials with a reduced environmental impact. In this context, the potential of Musa paradisiaca rachis as a raw material for producing eco-friendly paper under conditions typical of the tropical Amazon was evaluated. The experimental procedure included washing, drying, particle size reduction, alkaline treatment, and pulping. Subsequently, sheets of eco-friendly paper were produced, and properties such as basis weight, tensile strength, moisture absorption, and fiber yield were assessed. The results showed statistically significant differences between the applied treatments ($p < 0.05$), demonstrating that adequate particle size reduction promotes fiber compaction and improves the paper's mechanical properties. The most efficient experimental condition yielded an average basis weight of 84 g/m², a tensile strength of 0.146 kg/15 mm, a moisture absorption of 69.8%, and a pulp yield of approximately 79.5%. Furthermore, the statistical analysis showed a coefficient of determination of $R^2 = 0.78$, indicating a significant relationship between the level of cell disintegration and the mechanical behavior of the eco-friendly paper.

1. Introduction

The increasing generation of agro-industrial waste has driven the search for sustainable alternatives that allow for the valorization of these materials and reduce the environmental impacts associated with their final disposal. Lignocellulosic waste represents an important source of renewable raw materials due to its high content of cellulose, hemicellulose, and lignin, structural components with potential for the production of biodegradable materials and paper products [1–3].

Among these residues, the rachis of Musa paradisiaca stands out, a byproduct generated during the harvesting and marketing of bananas, which is generally discarded or used for low value-added purposes. Several studies have demonstrated that residues derived from banana cultivation possess favorable physicochemical characteristics for obtaining cellulosic fibers, due to their high content of structural polysaccharides and their ability to form materials with mechanical properties suitable for industrial applications.[2,4].

Particle size reduction and cell disintegration are fundamental operations in the processing of lignocellulosic materials, as they promote fiber release, increase surface area, and improve the efficiency of subsequent chemical treatments. These structural modifications facilitate the partial removal of lignin and hemicellulose, promoting greater cellulose availability for the formation of interfibrillar bonds during papermaking [1,4]. Consequently, significant improvements can be achieved in properties such as basis weight, mechanical strength, moisture absorption, and pulp yield.

Furthermore, recent research has indicated that the valorization of banana waste for the production of sustainable materials constitutes a viable alternative within the principles of the circular economy, contributing to the reduction of agricultural waste and the development of production processes with less environmental impact. [3,5,6].

Therefore, the present study evaluated the influence of cell disintegration and particle size of the rachis of Musa paradisiaca on the physical and mechanical properties of ecological paper, with the aim of identifying the most favorable conditions for its use as an alternative raw material in the production of sustainable materials

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2. Materials and methods

2.1. Preparation of raw materials

The rachis of Musa paradisiaca used in the research was collected from plantations located in the Amazon region of Peru. Initially, the material underwent a manual selection process to remove impurities, soil debris, and deteriorated plant material. Subsequently, it was washed with running water to remove particles adhering to the surface and ensure the uniformity of the raw material used in the process.

Once cleaned, the rachis was cut into smaller fragments and dried until it reached suitable conditions for mechanical processing. The dried material was then shredded and classified to obtain different particle sizes, which were used to evaluate the influence of size reduction on the properties of the eco-friendly paper.

Subsequently, the resulting particles underwent an alkaline treatment designed to promote cell disintegration and the partial removal of non-cellulosic compounds, primarily lignin and hemicellulose. This stage favored the release of cellulosic fibers and improved the conditions for pulp production. After treatment, the material was washed to remove chemical residues and then defibrated to obtain a homogeneous suspension of cellulosic fibers

The pulp obtained was used to produce sheets of eco-friendly paper through forming, pressing, and drying processes under controlled laboratory conditions. The samples produced were conditioned prior to physical and mechanical evaluation to ensure uniformity in the tests performed.

2.2. Evaluation of paper properties

The sheets of eco-friendly paper obtained were conditioned prior to testing and subsequently characterized by determining physical and mechanical properties considered relevant for evaluating the quality of the finished material. The response variables analyzed were basis weight (g/m²), tensile strength (kg/15 mm), moisture absorption (%), and pulp yield (%).

Basis weight was determined from the ratio between the mass of the samples and the corresponding area of the sheets produced. Tensile strength was used as an indicator of the paper's mechanical behavior under tensile stress, allowing for the evaluation of the degree of bonding and compaction achieved by the cellulose fibers during sheet formation. Moisture absorption was used to determine the hygroscopic capacity of the material, while pulp yield was calculated as the percentage ratio between the mass of pulp obtained and the initial mass of raw material processed.

The experimental data obtained were subjected to statistical analysis in order to evaluate the effect of cell disintegration and particle size on the properties of ecological paper.
An analysis of variance (ANOVA) was applied to identify significant differences between the evaluated treatments, considering a significance level of 5% ($p < 0.05$). A regression analysis was also performed to determine the relationship between the degree of cell disintegration and the mechanical behavior of the material, by estimating the coefficient of determination (R^2).

3. Results and discussion

The results showed that the level of cell disintegration and particle size reduction significantly influenced the physical and mechanical properties of the eco-friendly paper made from the rachis of Musa paradisiaca. Analysis of variance revealed statistically significant differences between the treatments evaluated ($p < 0.05$), indicating that the modifications applied during the conditioning of the raw material had a direct effect on the quality of the final product.

It was observed that decreasing particle size favored the release of cellulosic fibers and promoted a more homogeneous distribution of the fibrous matrix during sheet formation. This behavior contributed to greater structural compaction of the paper, increasing the interaction capacity between fibers and improving the mechanical properties of the resulting material. The most efficient experimental condition yielded an average basis weight of 84 g/m², a tensile strength of 0.146 kg/15 mm, a moisture absorption of 69.8%, and a pulp yield of approximately 79.5%, values that reflect a suitable balance between biomass utilization and the physical-mechanical performance of the eco-friendly paper.

Furthermore, the regression analysis showed a positive relationship between the degree of cell disintegration and the mechanical resistance of the product, obtaining a coefficient of determination of $R^2 = 0.78$. This result indicates that 78% of the variability observed in the mechanical behavior of the paper can be attributed to the structural modifications generated by the reduction in size and the release of fibers during the processing of the raw material.

The results obtained suggest that optimizing size reduction and cell disintegration processes is a determining factor in obtaining eco-friendly paper from lignocellulosic waste. Improved fiber compaction and interfibrillar bond formation yielded materials with properties suitable for sustainable applications, demonstrating the potential of Musa paradisiaca rachis as an alternative source of cellulosic fibers for eco-friendly paper production in the tropical Amazon.

Table 1. Physical and mechanical properties of ecological paper made from the rachis of Musa paradisiaca under the optimal experimental condition.

Parameter	Unit	Worth
Weight	g/m²	84
Tensile strength	kg/15 mm	0.146
Moisture absorption	%	69.8
Pulp yield	%	79.5

Table 2 presents the behavior of the physical and mechanical properties of the eco-friendly paper made from the rachis of Musa paradisiaca under different levels of cell disintegration. An increasing trend is observed in basis weight, tensile strength, and pulp yield as the degree of cell disintegration increases, with the best results achieved in treatment T4 (very high). In contrast, moisture absorption showed a progressive decrease, suggesting greater compaction and cohesion of the cellulosic fibers. These results demonstrate that greater fiber release favors the formation of a more homogeneous and resistant structure, improving the quality characteristics of the resulting eco-friendly paper.

Tabla 2. Physical and mechanical properties of ecological paper obtained from the rachis of Musa paradisiaca under different levels of cell disintegration.

Treatment	**Level of cell disintegration**	**Weight (g/m²)**	**Tensile strength (kg/15 mm)**	**Moisture absorption (%)**	**Pulp yield (%)**
T1	Low	74.2 ± 1.8	0.091 ± 0.005	75.4 ± 1.6	70.8 ± 1.7
T2	Half	78.6 ± 1.5	0.114 ± 0.004	73.1 ± 1.4	74.3 ± 1.5
T3	High	81.9 ± 1.3	0.132 ± 0.003	71.5 ± 1.2	77.2 ± 1.3
T4	Very high	**84.0 ± 1.1**	**0.146 ± 0.003**	**69.8 ± 1.1**	**79.5 ± 1.2**

The values correspond to means ± standard deviation of the evaluated variables.

The results presented demonstrate a positive relationship between the level of cell disintegration and the tensile strength of the eco-friendly paper, with a progressive increase in this property observed as the release of cellulosic fibers increases. Furthermore, the regression analysis showed a coefficient of determination of $R^2 = 0.78$, confirming a significant association between the two variables.

4. Mathematical relationships and process evaluation

The properties evaluated during the production of ecological paper were determined using mathematical relationships used to quantify the process performance and the physical behavior of the material obtained.

$$RP = \frac{M_p}{M_i} \times 100$$

Donde:
RP = rendimiento de pulpa (%)
Mp = masa de pulpa obtenida (g)
Mi = masa inicial de raquis procesado (g)

$$AH = \frac{M_h - M_s}{M_s} \times 100$$

Donde:
AH = moisture absorption(%)
Mh = wet mass of the sample(g)
Ms = dry mass of the sample(g)

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}$$

Donde:
R² = determination coefficient
yi = observed values
wi = values estimated by the model
3 = mean of the observed values

Equation (1) was used to determine the pulp yield obtained from the rachis of Musa paradisiaca, while Equation (2) allowed for the evaluation of the moisture absorption capacity of the produced eco-friendly paper. Equation (3) was used to analyze the relationship between the level of cell disintegration and the mechanical strength of the material, yielding a coefficient of determination of $R^2 = 0.78$.

Conclusions

Optimizing cell disintegration and reducing the particle size of the Musa paradisiaca rachis significantly influenced the physical and mechanical properties of the ecological paper produced, showing statistically significant differences between the treatments evaluated ($p < 0.05$).

The experimental condition with the highest level of cell disintegration showed the best results, reaching a weight of 84 g/m², a tensile strength of 0.146 kg/15 mm, a moisture absorption of 69.8% and a pulp yield of 79.5%, which demonstrates that adequate fiber release favors structural compaction and improves the quality of the material obtained.

Furthermore, the regression analysis showed a coefficient of determination of $R^2 = 0.78$, indicating that the mechanical behavior of the paper is closely related to the degree of cell disintegration achieved during the processing of the raw material.

The results obtained confirm that the rachis of Musa paradisiaca constitutes a viable and sustainable alternative as a source of lignocellulosic fibers for the production of ecological paper, contributing to the use of agro-industrial waste and the generation of materials with less environmental impact.

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References

[1] Badanayak, P., Mohanty, S., Nayak, S.K. (2023) Banana pseudostem fiber: A critical review on fiber extraction, characterization and surface modification. *Journal of Natural Fibers*, 20(1), 2168821.
[2] Arriola-Villaseñor, E., Hernández-Fernández, M., Méndez-Montealvo, G., Velázquez, G. (2024) Enhanced Cellulose Extraction from Banana Pseudostem Waste. *Polymers*, 16, 2786.
[3] Waithaka, A., Wanjiku, E., Mwangi, J. (2025) Cellulose-Based Biopolymers from Banana Pseudostem Biomass: A Review. *Polymers*, 3(4), 37.
[4] Xu, S., Xiong, C., Tan, W., Zhang, Y. (2015) Microstructural, thermal, and tensile characterization of banana pseudo-stem fibers obtained with mechanical, chemical, and enzyme extraction. *BioResources*, 10(2), 3724–3735.
[5] There, U., Badhiye, S., Thakare, G., Choudhary, V. (2024) Comparative Analysis of the Extraction and Characterization of Cellulosic Fibers and Lignin from Banana Pseudo-Stem and Cotton Stalk for Value Addition. *International Journal of Innovative Scientific Research*, 2(4), 54–66.
[6] Abdullah, N., Sulaiman, F., Taib, R.M. (2014) Characterization of banana plantation wastes as a potential renewable energy source. *International Journal of Biological, Veterinary, Agricultural and Food Engineering*, 8(4), 325–330.