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Obtaining cellulose fiber from *Oryza sativa* (rice husk)

Obtención de fibra de celulosa a partir de *Oryza sativa* (panca de arroz)

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Abstract

Rice straw is a lignocellulosic agricultural residue derived as a byproduct of oryza sativa cultivation, whose industrial utilization remains limited. In this study, this biomass was evaluated as a raw material for cellulose fiber production through a detailed physicochemical characterization and the application of chemical treatments aimed at lignin removal. These processes included alkaline pretreatments optimized by varying operational parameters such as concentration, reaction time, and temperature. Experimental result indicated a composition of 35.44% cellulose, 18% lignin, and 28.24% hemicellulose, confirming the suitability of the material for cellulose extraction and its potential for industrial application. From the extracted fibers, Kraft-type paper was produced, exhibiting thickness values between 0.53 and 0.96 mm, a slightly alkaline pH with an average value of 8.63, and mechanical properties dependent on processing conditions. Paper sample 1 showed grater ductility, reaching a maximum displacement of 0.775± 0.289 mm. Finally, a preliminary economic analysis estimated a unit cost of USD 1.57 per Kraft paper sheet produced (per unit of finished product), including amortization, indicating favorable margins under viable commercialization scenarios. Overall, the results, demonstrate the technical and economic feasibility of the proposed process.

Keywords: agricultural residues, cellulose, lignocellulosic, Oryza sativa, rice straw, vegetable fiber.

Resumen

La panca de arroz es un residuo agrícola lignocelulósico, subproducto del cultivo de Oryza sativa, cuya utilización industrial sigue siendo limitado. En la presente investigación, esta biomasa fue evaluada como materia prima para la obtención de fibra de celulosa, mediante una caracterización fisicoquímica detallada y la implementación de tratamientos químicos destinados a la exclusión de lignina. Entre estos procesos se incluyeron pretratamientos alcalinos, optimizados mediante la variación de parámetros operativos como concentración, tiempo de reacción y temperatura. Los resultados experimentales mostraron una composición de 35.44% de celulosa, 18% de lignina y 28.24% de hemicelulosa, lo que confirma la aptitud del material para la extracción de celulosa y su potencial aplicación industrial. A partir de la fibra obtenida se elaboró papel tipo Kraft, con espesores entre 0.53 y 0.96 mm, un pH ligeramente alcalino con un valor medio de 8.63 y propiedades mecánicas dependientes de las condiciones de procesamiento. El papel 1 presentó mayor ductilidad, alcanzando un desplazamiento máximo de 0.775±0.289 mm. Finalmente, el análisis económico preliminar estimo un costo unitario de USD 1.57 estimado por hoja de papel Kraft producida (por unidad de producto elaborado), incluyendo la amortización, lo que evidencia márgenes favorables bajo escenarios de comercialización viables. En conjunto, los resultados demuestran viabilidad.

Palabras clave: celulosa, fibra vegetal, oryza sativa, panca de arroz, residuos agrícolas.

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1 Introduction

Rice is a fundamental cereal for global food consumption and trade. Although cereal stocks and global trade declined in the 2024/2025 season, rice remained stable and even grew, surpassing the previous year's levels. For 2025/2026, record production is forecast, maintaining its essential role in food security, especially in regions where it constitutes the basis of the diet (FAO, 2025; SERGIY *et al*., 2025).

In Ecuador, the province of Manabí, with more than 709 thousand hectares devoted to agricultural and livestock activities, depends largely on this sector (Vivas Saltos, 2021) INEC, 2020). However, practices such as burning agricultural residues and the intensive use of machinery, chemicals, and fertilizers generate polluting emissions and contribute to climate change (Vivas Saltos, 2021). In this context, the adoption of sustainable technologies and good agricultural practices is key to reducing impacts, in line with UN SDG No. 12.

In this context, natural-fiber composites stand out due to their eco-friendly and biodegradable nature. Cellulose, abundant in plant cell walls, offers valuable mechanical properties, although its purity is limited by its association with hemicellulose and lignin(Rachtanapun *et al*., 2012). Cellulosic agricultural residues have emerged as a sustainable alternative for obtaining value-added materials (Maleki & Singh, 2016). Among these residues is rice straw, which corresponds to the set of stems, leaves, and sheaths that remain after harvesting the rice grain (*Oryza sativa*). This agricultural byproduct is generated in large volumes and, in many cases, is underutilized or disposed of through open-field burning, which causes negative environmental impacts. Recently, studies have highlighted the potential of wild grasses and lignocellulosic residues as a sustainable source of cellulose nanofibers and value-added materials (Herrera-Basurto *et al*., 2024; Gómora-Hernández *et al*., 2025). Due to its high content of cellulose, hemicellulose, and lignin, rice straw has high potential for use as a raw material in sustainable industrial processes. Its fibers have properties similar to those of hardwood fibers, such as their short length, hemicelluloses composed mainly of pentoses (primarily the sugars xylose and arabinose), and lignin. Rice straw fibers have diameters of 5 to 14 cm and lengths of 0.65 to 3.48 mm.(Zhang & Zheng, 2012).

Rice straw has a typical composition of approximately 45% cellulose, 18% lignin, 6% protein, 0.44% fat, and 28% hemicellulose (*La Paja Del Arroz*, s. f.), making it a promising material.

In this context, this research focused on obtaining cellulose fiber from *Oryza sativa* (rice straw), taking advantage of its composition. The study was conducted at the laboratory scale, assessing the feasibility of producing Kraft-type paper and the physicochemical characterization of the raw material.

2 Materials and methods

2.1 Preparation of rice straw

A minimum 5 kg sample of INIAP FL-01 rice straw was collected in the Tierra Amarilla sector, specifically at "Los Zambranos" farm, a rice-producing farm located in the rural area of the canton of Rocafuerte, Manabí Province, Ecuador. The precise coordinates of the sampling site are 0°56'02"S, 80°27'33"W (2024).

Subsequently, it was subjected to an initial cleaning process, which consisted of washing with distilled water at a temperature of 60 °C for 78 min, with the aim of removing impurities. Afterwards, the straw was cut to obtain stalks with a minimum length of 10 cm and a maximum length of 20 cm. Next, the sample was dried at room temperature and stored in a previously sterilized glass container in order to prevent contamination.(Pérez *et al*., 2022).

For conditioning, the dried rice straw was pulverized using a pulverizer mill (High-Speed Multifunction Comminutor 100A). Subsequently, the material was manually sieved using a 600-micron stainless-steel mesh to ensure particle-size homogeneity. Characterization comprised the analysis of moisture, ash, fats, protein, crude fiber, total carbohydrates, cellulose, hemicellulose, and lignin. The procedures were performed in three independent replicates to ensure the reproducibility and consistency of the results.

2.2 Characterization of rice straw

2.2.1 Total ash content

The percentage of total ash was determined using the gravimetric method, which is based on sample calcination, according to the standard (NMX-F-607-NORMEX-2023). The analysis was performed using a muffle furnace (THERMOLYNE-FB410M-Thermo Scientific^{TM}).

2.2.2 Moisture content

The moisture percentage was determined using the thermobalance drying method, according to the standard (*NMX-F-428*-1982). The analysis was performed using a thermobalance (BOECO Germany Moisture Analyzer BMA 150) (Kirk *et al*., 1996).

Table 1. Processing parameters for the seven samples.

Sample	Rice Straw (g)	NaOH(p/v)	vol. NaOH	T (°C)	RPM	T(min)
1	2,04	3	40,8	85 ± 2	600	90-100
2	2,59	3	51,8	85 ± 2	600	90-100
3	3,04	3,75	60,8	85 ± 2	600	90-100
4	4,43	3,75	88,6	85 ± 2	600	90-100
5	4,94	4	98,8	85 ± 2	600	90-100
6	5,28	4	105,6	85 ± 2	600	90-100
7	6,09	4	121,8	85 ± 2	600	90-100

2.2.3 Fat content

The fat percentage was determined using the Soxhlet method, according to the standard (*NMX-F-615-NORMEX*-2018), as indicated by Nielsen (2003).

2.2.4 Total protein content

The protein percentage was determined according to the standard (*NOM-051-SCFI/SSA1*-, 2010), using the Biuret method (Nollet, 2004).

2.2.5 Lignin content

The lignin percentage was determined using the official method (*AOAC 973.18*-, 1977). The analysis employed the acid detergent method, using a drying oven (ELOS HEAT oven with natural circulation) and a muffle furnace (THERMOLYNE-FB410M–Thermo Scientific^{TM})(Lee & Prosky, 1995).

2.2.6 Total carbohydrate content

The percentage of total carbohydrates was determined using the official method(*AOAC 973.18*-, 1977). The analysis used the phenol–sulfuric acid method (DuBois *et al*., 1956).

2.2.7 Crude fiber content

The crude fiber percentage was determined using the standard gravimetric method (Shon *et al*., 2007) described in the standard (*AOAC 962.09-1971*, 2010).

2.2.8 Cellulose and hemicellulose content

The percentage of cellulose and hemicellulose was determined according to the standard (*Tappi-T 203*, 2022) based on alkaline extraction.

2.3 Protocol for obtaining cellulose fiber

2.3.1 Experimental design and processing conditions

Based on the optimal conditions reported by (Calani Quispe, 2013) for cellulose extraction (solvent-to-feed ratio 20 mL/g, NaOH concentration 3–4%, temperature 85 °C, stirring 600 rpm), an experimental plan was designed to evaluate the effect of different conditions on the properties of the Kraft paper obtained.

The selection of NaOH concentration levels (3.0-4.0% w/v), temperature (85±2°C), and reaction time (90 to 100 min) was based on previous studies on cellulose extraction from agricultural residues (Boonterm et al., 2016; Sharma *et al*., 2023). These parameters represent a balance between delignification efficiency and the minimization of cellulose degradation, as reported by Calani Quispe (2013). The solvent-to-feed ratio of 20 ml/g was kept constant to ensure adequate mass transfer and system homogeneity.

Seven samples were prepared by varying the initial mass of rice straw (2.04–6.09 g) and the sodium hydroxide concentration (3.0–4.0% w/v). All samples were processed while keeping the solvent-to-feed ratio constant at 20 mL/g. The specific conditions are presented in Table 1.

2.3.2 Alkaline treatment

Stock NaOH solutions at 3.0%, 3.75%, and 4.0% (w/v) were prepared by dissolving 4.0–4.5 g, 4.7–5.0 g, and 6.0–7.0 g of NaOH, respectively, in 100 mL of distilled water. For each sample, the corresponding mass of sieved straw was mixed with the specified volume of alkaline solution in a glass reactor equipped with mechanical stirring, a thermometer, and a condenser. The mixtures were heated to 85 ± 2 °C with stirring at 600 rpm for 90–100 minutes.

The selection of experimental variables (NaOH concentration, reaction time, and temperature) was based on previous studies on fiber delignification and standardized alkaline pulping protocols. In the literature, concentrations between 3-5% NaOH and temperatures around 85-90 °C are reported to allow partial removal of lignin and hemicellulose without excessively degrading cellulose (Singh & Choudhury, 2014; Biermann, 1996). Therefore, concentrations of 3.0%, 3.75%, and 4.0% were chosen as a representative range, while maintaining the temperature constant at 85 °C and the reaction time between 90-100 minutes to ensure reproducibility and comparability among samples.

2.3.3 *Filtration and washing*

After the alkaline treatment was completed, the samples were filtered through linen cloth (pore size ~1 mm) to separate the pulp from the black liquor. The resulting pulp was thoroughly washed with 500–600 mL of hot distilled water (60 °C) in three stages until neutral pH was reached.

The washing was carried out in three successive stages. At the end od each stage, the pH of the rinse water was measured using a pH meter Thermo Scientific – OAKTON-PH-700-METER).

The recorded pH values were:

Stage 1: 11.2±0.5 pH

Stage 2: 9.1±0.3 pH

Stage 3: 7.1±0.2 pH→neutral

Additionally, the conductivity of the final wash water was measured, yielding a value of 150±20 $\mu s/cm$, which indicates the effective removal of alkaline residues.

2.3.4 *Sizing and sheet formation*

A sizing dispersion was prepared by adding 10 mL of PVA adhesive (Colbón) for each 5 g of initial straw, dissolved in 100 mL of distilled water. This solution was mixed with the wet pulp until complete homogenization. The final mixture was poured onto a 14.8 × 21.0 cm sieve, allowed to drain by gravity, and pressed for 15–20 minutes using four 8" spring clamps (3" opening, nylon body, TPR handle, PRE-8 17702, TRUPER brand) to remove excess water.

2.3.5 *Drying and conditioning*

The paper sheets were dried in an oven at 40 ± 2 °C for 24 hours. Subsequently, glycerin was applied as a plasticizer (~0.5 mL/100 cm^2) by spraying onto both sides. The samples were conditioned at 20–25 °C and 50–60% relative humidity for 48 hours before performing the mechanical tests.

All samples were processed following this standardized procedure, varying. only the parameters specified in Table 1.

2.4 *Determination of properties of the Kraft paper obtained from cellulose fiber*

2.4.1 *Thickness*

The thickness determination for the formed sheet followed the procedure according to the standard (*ISO-534-2011*), The procedure used the equipment (Mitutoyo outside micrometer 0–25 mm, 103-137).

2.4.2 *Tensile strength*

The mechanical properties of Kraft paper made from Oryza sativa cellulose fiber were evaluated by means of uniaxial tensile testing at a constant rate of elongation (Constant Rate of Elongation, CRE), as described in ISO 1924-3. This standard esrablishes the method for constant-rate elongation testing. The samples were cut to dimensions of 49mm × 70 mm (width × initial length) and tested at a constant jaw separation speed. Each test was performed in at least 4 replicates per paper, and the results are presented as mean ± standard deviation.

2.4.3 *pH*

The pH determination of the formed sheet followed the procedure according to the standard (*ISO-6588-1-2020*), the procedure used a pH meter (Thermo Scientific™ OAKTON PH 700 METER).

2.4.4 *Moisture percentage*

The moisture percentage was determined using the thermobalance drying method, according to the standard (*NMX-F-428-1982*) The analysis was performed using a thermobalance (BOECO Germany Moisture Analyzer BMA 150).

3 Results and discussion

3.1 *Characterization of rice straw*

Table 2 presents the values obtained from the physicochemical characterization of *Oryza sativa*. The results correspond to three measurements, since the tests were performed in triplicate to achieve greater accuracy.

Figure 1 shows the mean values (■), standard deviation (♦), and standard error (•) for each of the analyzed components: ash, moisture, fat, proteins, lignin, cellulose, hemicellulose, crude fiber, and total carbohydrates.

Table 2. Results of the physicochemical characterization of rice straw *(Oryza sativa).*

Parameter	Composition (%)		
Ash	14.06	14.0	14.12
Moisture	13.75	14.5	13.0
Fat	0.40	0.48	0.44
Proteins	6.75	6.50	7.0
Lignin	18	18.50	17.5
Cellulose	35	35.44	35.88
Hemicellulose	28	28.48	28.24
Crude fiber	12.12	11.0	11.56
Total Carbohydrates	66.75	66	67.5

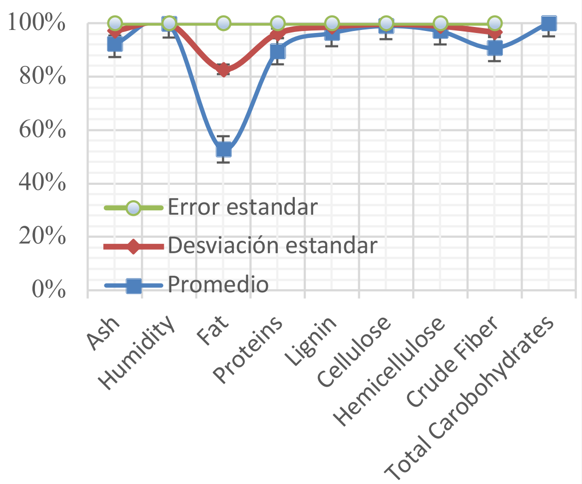

Fig. 1. Variation in the proximate composition of rice straw.

Table 3. Comparison of the results of the physicochemical characterization of rice straw with values reported in the literature.

Parameter	Composition	Rice straw
Ash	14.06 ± 0.04	18.5 ± 0.06
Moisture	13.75 ± 0.43	11.8 ± 0.04
Fat	0.44 ± 0.02	3.15 ± 0.01
Proteins	6.75 ± 0.14	7.6 ± 0.19
Lignin	18 ± 0.28	18.5 ± 0.01
Cellulose	35.44 ± 0.25	35.9 ± 0.10
Hemicellulose	28.24 ± 0.13	28.5 ± 0.18
Crude fiber	11.56 ± 0.32	16.9 ± 0.01
Total Carbohydrates	66.75 ± 0.43	66 ± 0.20

The data in the "Composition" column correspond to the results obtained in this study. The "Rice straw" column is based on the cited literature (S. Ogbuefi *et al*., 2020).

3.2 *Tests performed on the Kraft paper*

3.2.1 *Thickness*

Table 4 presents the values obtained from the thickness evaluation of the cellulose-fiber Kraft paper produced from rice straw (*Oryza sativa*). The results correspond to micrometer measurements taken at multiple points on each sample, in order to achieve greater accuracy and representativeness of the mechanical characteristics of the paper produced.

The thickness values of the paper obtained ranged between 0.32 mm and 1.03 mm. The sample with the greatest uniformity was paper 4, while paper 3 showed greater variability. These variations in sheet formation are consistent with those reported by Tejada-Tovar *et al*. (2025) in the characterization of bio-composites from plant fibers, since thickness uniformity critically depends on the drainage and manual pressing process.

Table 4. Thickness results of the cellulose-fiber Kraft paper samples produced from *Oryza sativa*.

Sample thicknesses (mm)						
1	2	3	4	5	6	7
0,312	0,42	0,506	0,54	0,855	1,025	1,03
0,331	0,45	0,505	0,545	0,847	1,02	1,01
0,315	0,43	0,526	0,53	0,833	1,03	1,045
0,337	0,435	0,512	0,53	0,832	1,031	1,002
0,32	0,45	0,513	0,525	0,843	1,025	1,032
0,34	0,452	0,516	0,53	0,95	0,965	1,035
0,311	0,41	0,517	0,545	0,848	1,045	1,05
0,325	0,4	0,512	0,51	0,952	1,01	1,08

Table 5. Average thickness values obtained from micrometer tests, accompanied by their respective grammages (g/cm^2) and density (g/cm^3).

Paper	Thickness	Grammage	Basis weight
1	0,32±0,01	29,60	0,091
2	0,43±0,02	37,64	0,087
3	0,51±0.006	44,08	0,086
4	0,53±0.01	64,03	0,120
5	0,87±0.051	71,43	0,082
6	1,02±0.024	76,58	0,075
7	1,03±0.024	88,16	0,085

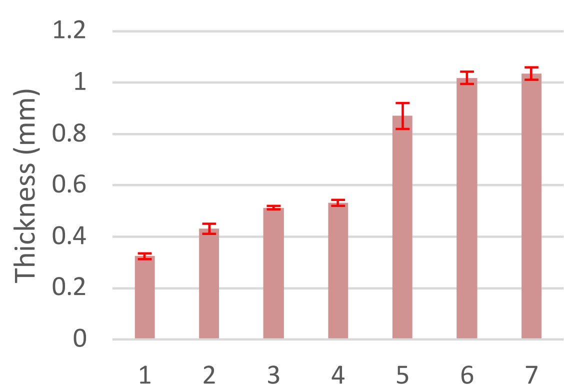

Fig. 2. Comparison of the mean thickness values obtained for the Kraft paper samples.

Figure 2 graphically presents the thickness values obtained for the seven cellulose-fiber paper samples produced from rice straw.

The sample with the greatest uniformity was Paper 3 (standard deviation = 0.0066 mm), whereas Paper 5 showed the highest variability (standard deviation = 0.0505 mm).

The grammage of the sample ranged between 29.6 and 88.2 g/cm^2, depending on the initial fiber load, as indicated in table 5. However, an unusually low apparent density was observed (0.075-0.120 g/cm^3) compared to commercial Kraft paper, which typically ranges between 0.7-0.9 g/cm^3. This low density, accompanied by high thickness values (0.32-1.4 mm), indicates high porosity and a loosely compacted fibrous structure. This suggests that the gravity drainage process and manual pressing with spring were not sufficient to remove interstitial water and collapse the fibers, resulting in a sheet with a specific volume of 8.3–13.3 cm^3/g. These results are consistent with the limitations reported in handmade papermaking without a hydraulic press (ISO 534), where the lack of uniform pressure produces sheets with low mechanical strength and high variability in thickness, as evidenced by the standard deviations in the table 5.

3.2.2 Mechanical behavior of the Kraft paper

Table 6 presents the results of the tensile test performed on the seven Kraft paper samples produced from rice straw (*Oryza sativa*) cellulose fiber, the test was carried out using the ISO 1924-3 standard.

Tabla 6. Mechanical parameters of the tensile tests of cellulose-fiber Kraft paper obtained from rice straw (*Oryza sativa*).

Paper	Δ	Time
1	1,275±0,222	10,290±0,581
2	1,06±0,042	16,073±0,5123
3	1,525±0,096	16,925±0,7838
4	0,7845±0,060	14,760±0,2024
5	0,9325±0,036	10,623±0,1513
6	1,61±0,136	10,575±0,0943
7	2,5±0,356	23,495±0,1714

Independent measurements, while the error the average displacement (Δ) values in mm and rupture time (s) are presented for seven specimens tested under uniaxial tension at a constant rate of elongation, according to ISO 1924. Each value is accompanied by its standard deviation, indicating the experimental variability among replicates. Specimen 7 stands out as the most resistant in terms of ductility, with the greatest displacement and rupture time, which indicates better fiber compaction and bonding. Specimen 4 show lower displacement, reflecting a more rigid and brittle structure. In reference to the above, limited mechanical strength is evident, but with some deformation capacity in certain specimens, particularly specimen 7. These results were similar to the mechanical behavior of bio-composites reinforced with natural fibers recently documented by Iniestra-Galindo *et al.* (2024), who observed that the incorporation of plant fibers significantly modifies the ductility and tensile strength of the base material.

Figure 3 shows the maximum displacement recorded up to the point of rupture for each of the seven Kraft paper samples. The bars represent the mean value of four independent measurements, while the error bars (in red) indicate the standard deviation, reflecting variability among replicates.

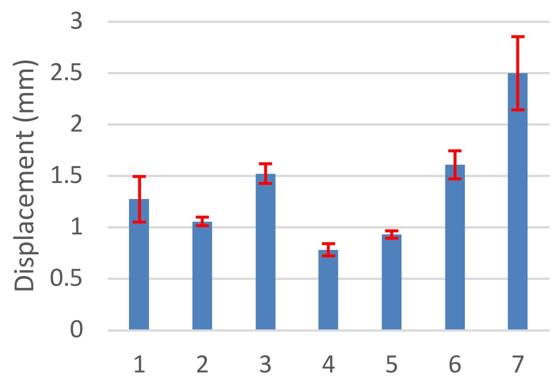

Fig. 3. Maximum displacement to rupture of the cellulose-fiber Kraft paper samples. Bars represent the mean (n = 4), and error bars indicate ±SD.

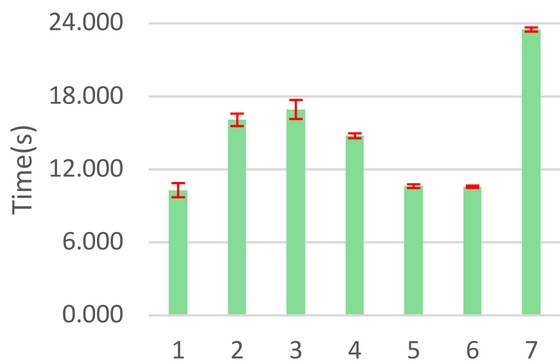

Fig. 4. Time to rupture of the cellulose-fiber Kraft paper samples under tension. Bars represent the mean (n = 4), and error bars indicate ±SD.

A greater displacement indicates greater ductility of the material. Specimens 6 and 7 show the greatest displacements, suggesting better fiber bonding and greater energy absorption capacity before rupture. Specimens 5 and 4 exhibit the lowest values, thus reflecting a more rigid or less compact structure, possibly due to differences in fiber distribution.

Figure 4 presents the time elapsed from the onset of tensile loading to the complete fracture of the specimens. The bars show the mean of four tests per sample, with the error bars (in red) representing the standard deviation. A longer time to rupture suggests a greater capacity of the material to withstand sustained stresses.

Specimen 7 exhibits the longest rupture time (≈ 23.5), indicating that it withstood the load for a longer period before failure. Specimen 6 shows the shortest rupture time (≈ 10.6 *s*), thus reflecting lower strength and faster breakage. The remaining samples fall within 10-17 s, with moderate variations in their standard deviations. In reference to the above, these findings confirm that kraft paper made from Oryza sativa fibers presents rupture times lower than industrial papers but comparable to handmade papers.

Table 7 shows the results obtained for the tensile strength of Kraft paper specimens produced from *Oryza sativa* fibers, compared with references from industrial papers.

Paper	N	MPa	Comparison
1	348	0,101	Similar to weak recycled papers
2	300	0,087	Lower strength, brittle behavior
3	318	0,093	Stable, moderate elongation
4	250	0,0729	Very low strength, rapid rupture
5	280	0,0816	Very low strength, long duration before rupture
6	350	0,1020	Moderate strength, faster rupture
7	420	0,1224	Better performance, high elongation
Industrial Kraft	500-1200	30-80	High strength, packaging
Rice straw paper	400-700	20-45	Better performance with optimized pulping

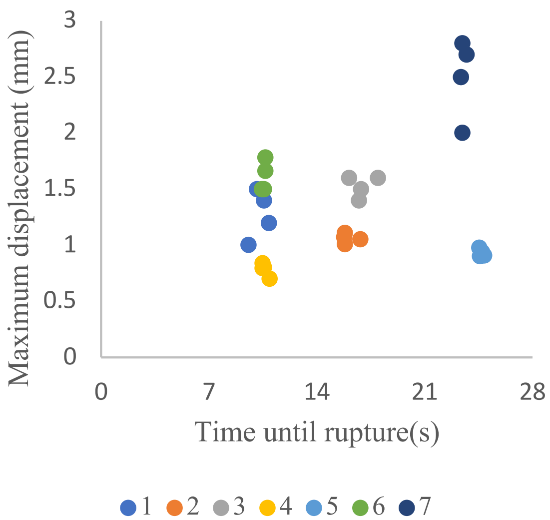

Fig. 5. Relationship between time and displacement to rupture for the seven Kraft paper samples. Each point represents an individual measurement (n = 4 per sample).

Table 7. The data obtained from the seven paper samples were compared with bibliographic data from industrial Kraft and rice paper (Smook, 2002). It shows that specimens 1 to 4 reached tensile strengths between 0.07-0.10 MPa, which is very low compared to industrial Kraft paper but consistent with handmade papers from short fibers. Specimen 3 was the most stable, therefore exhibiting longer rupture time and elongation compared to the others, while specimen 4 was the most brittle. Specimen 5 has low strength (0.102 MPa) but fails more quickly, thus showing more brittle behavior; specimen 6 has intermediate strength (0.102 MPa) but also fails faster; and specimen 7 shows better performance (0.122 MPa), with greater elongation and rupture time. Compared with the literature, papers based on Oryza sativa reach 20–45 MPa, while industrial Kraft can reach up to 800 MPa. This indicates that the values obtained are lower but viable and consistent with non-industrialized processes such as the one carried out in this research.

Figure 5 shows the relationship between time to rupture and maximum displacement for all individual measurements performed. Each point represents an independent test, with different colors indicating the seven samples evaluated. This scatter plot makes it possible to identify mechanical behavior patterns and the inherent variability of each sample.

3.2.3 Physicochemical properties of the Kraft paper

Table 8 presents the results of moisture determination by thermobalance and pH for the seven Kraft paper samples produced. The parameters %M (mass loss during drying), %D (dry mass fraction), %R (moisture-to-dry-mass ratio), and residual mass (g) characterize the moisture content, while pH indicates the residual alkalinity of the paper after the chemical treatments applied.

Table 9 presents the minimum (Min), maximum (Max), and mean values of moisture content. Table 10 presents the minimum (Min), maximum (Max), mean, and pH range values obtained from the Kraft paper samples.

Table 8. Moisture content and pH of the cellulose-fiber Kraft paper samples obtained from rice straw *(Oryza sativa)*.

Weight (g)	% M	% D	% R	G	pH
2,04	10,952	89,048	12,299	0,187	8,8
2,59	10,638	83,362	11,905	0,378	8,21
3,04	9,43	90,57	10,412	0,461	8,74
4,43	8,994	91,006	9,883	0,769	8,65
4,94	8,767	91,233	9,609	0,614	8,65
5,28	9,283	90,717	10,233	0,645	8,89
6,09	3,269	96,731	3,379	0,651	8,56

Table 9. Mean, Min, and Max moisture content values for %M, %D, and %R.%R.

Parameter	Min	Max	Average
%M	3,27	10,95	8,76
%D	83,36	96,73	90,38
%R	3,38	12,3	9,67

Table 10. Min, Max, mean, and pH range.

Parameter	Value	Sample
Min	8,21	2
Max	8,89	6
Average	8,63	
Range	0,68	Units

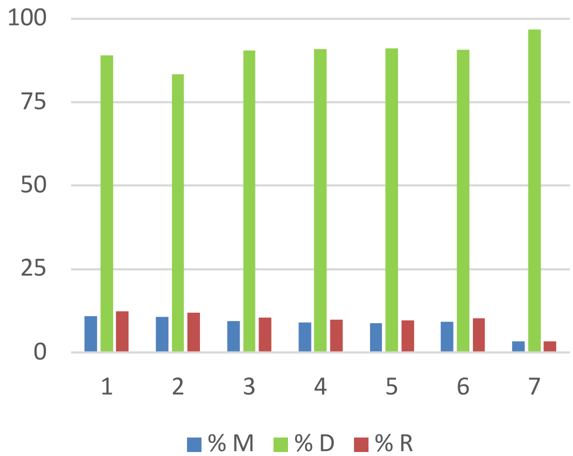

Fig. 6. Moisture content parameters of the Kraft paper samples determined by thermobalance: %M, mass loss; %D, dry mass; %R, moisture/dry-mass ratio (n=7).

Fig. 7. pH values of the cellulose-fiber Kraft paper samples. The line shows the overall trend across samples (n = 7).

Figure 6 shows the moisture content parameters (%M, %D, %R) determined by thermobalance for the seven Kraft paper samples. %M represents mass loss during drying, %D indicates the remaining dry-matter fraction, and %R expresses the ratio between evaporated moisture and dry mass. These parameters make it possible to evaluate residual moisture content after the manufacturing process and the drying conditions applied.

Figure 7 presents the pH values determined for each Kraft paper sample. pH is an important indicator of the residual alkalinity of the paper after NaOH treatments and subsequent washing steps. A slightly alkaline pH (8–9) is desirable in paper to improve its stability and resistance to long-term acid degradation, acting as an alkaline reserve that protects against the natural acidification of cellulosic material.

3.3 *Economic analysis of the laboratory-scale kraft paper production process*

In the context of an experimental laboratory-scale project, it is essential to distinguish between variable costs (raw materials) and the initial investment in equipment and non-consumable inputs (fixed costs). This approach allows for a rigorous economic evaluation, avoiding the overestimation of operating expenses (Guitiérrez & Martínez, 2021).

3.3.1 *Raw material costs*

The materials consumed per experimental batch—50 g of rice straw, distilled water, Colbón, glycerin, and NaOH—have a total cost of USD 5.24, which yields 15 units of Kraft paper. The unit raw-material cost is calculated as:

$$Unit\ cost\ (RM) = \frac{USD\ 5.24}{15\ units} = USD\ 0.35\ per\ unit$$

This value represents the only recurring component of production cost in each experimental cycle.

3.3.2 *Investment in production inputs*

The equipment used (frame, beakers, digital magnetic stirrer, analytical balance, oven, blender, among others) constitutes a one-time investment with a total cost of USD 879.64. Since these inputs are non-consumable and have a long service life, they should not be recorded as a monthly expense, but rather as fixed capital that must be amortized over the total estimated production during their useful life (OCDE, 2019)

For analysis purposes, an annual production of 720 units is assumed (equivalent to one weekly batch of 15 units over 48 weeks). Under this assumption, the amortized cost per unit is:

$$Amortized\ cost\ (PI) = \frac{USD\ 879.64}{720\ units} \approx USD\ 1.22\ per\ unit$$

3.3.3 *Total unit cost and economic viability*

The total unit cost of the process, considering raw materials and input amortization, is:, es:

$$Total\ unitary\ cost = USD\ 0.35 + USD\ 1.22 = USD\ 1.57$$

Table 11. Summary of the economic analysis of the laboratory-scale experimental process.

	Total cost (USD)	Unitary cost (USD)
Raw materials (MP).	5,24/batch	0,35
Production inputs (PI).	879,64	1,22
Total unit cost		1,57

PI amortized over 720 units produced in one year.

Considering a hypothetical commercialization scenario with a selling price of USD 2.00 per unit, the gross margin would be USD 0.43 per unit (21.5%). Although modest, this margin suggests medium-term economic viability, especially if production is increased or initial costs are reduced through shared equipment use (see Table 11).

In an academic or laboratory setting, many pieces of equipment can be shared across projects, which significantly reduces the cost attributable to this process. In addition, the durability of the inputs allows their amortization to extend beyond one year, further lowering the unit cost. Beyond profitability, the process has high research value by promoting the valorization of agricultural residues into sustainable materials (*Crop Prospects and Food Situation #3, September 2022*).

Conclusions

Rice straw (*Oryza sativa*) proved to be a viable and sustainable source for obtaining cellulose fiber, with a favorable composition (35.44% cellulose, 18% lignin, and 28.24% hemicellulose) and physicochemical properties suitable for industrial applications. Through alkaline pretreatment and bleaching, Kraft-type paper was produced with acceptable mechanical and thickness characteristics, as well as a slightly alkaline pH (mean 8.63), indicative of long-term stability. Overall, the results position rice straw as an eco-friendly, low-cost alternative with potential for integration into the cellulosic and paper industry.

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