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Design and analysis of a prototype of a sustainable packaging film using coconut fiber extraction

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Abstract*– This article presents the design and evaluation of a prototype of packaging sheets made from coconut fiber, a biodegradable alternative to the massive use of plastics such as polyethylene (PE) and polypropylene (PP), which have a high environmental impact due to their low degradability. Coconut fiber stands out for its strength, durability, and rapid decomposition. This study compares its environmental impact, mechanical properties, and economic viability against conventional plastics. Regarding carbon footprint, coconut fiber generates between 0.5 and 1.0 kg of CO2, significantly less than PE (2.0- 3.0 kg) and PP (1.8- 2.8 kg). Their biodegradation occurs between 90 and 180 days, while plastics exceed 182,500 days. Although the tensile strength of coconut fiber shows a value of 2.1653 MPa, it is lower compared to 54.4765 MPa of PE and 6.5384 MPa of PP; it also presents good elasticity, high resistance to water, high water resistance, and high corrosion resistance (~ 80 %) and low density (0.7- 0.8 g/cm³). Regarding cost, coconut fiber is a more environmentally friendly option, although it faces economic challenges depending on the market. The contribution of this research is to present a viable alternative to traditional packaging materials, offering adequate mechanical properties and resistance, as well as competitive costs, making it a suitable option for use. In summary, it is an ecologically favorable alternative, with the potential for large-scale replacement.

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***Keywords*— Sustainability, biodegradable, circular economy, ecofriendly, packaging.**

I. INTRODUCTION

The global accumulation of plastic waste has become a pressing environmental issue, with over 300 million tons of plastic produced annually, of which approximately 8 million tons end up in the oceans [1]. This persistent pollution poses severe threats to marine life, ecosystems, and human health due to the non-biodegradable nature of conventional plastics causing serious environmental problems, where it takes centuries to degrade [2]. In response, researchers have increasingly focused on developing sustainable alternatives to plastic packaging.

Coconut fiber is presented as a promising alternative for the manufacture of sustainable packaging. This natural material, obtained from coconut shells, is biodegradable and renewable, making it a viable option to reduce the environmental impact compared to conventional plastics [3]. In addition to degrading faster and safer, coconut fiber can offer mechanical properties like plastic ones, without damaging the environment. According to FAO statistics, over 60 million tons of coconuts are produced globally each year, with an estimated 85% of the husk and fiber discarded as waste [4].

Coconut cultivation faces challenges such as pests, low productivity, limited integration into the production chain, and poor practices, which collectively reduce its profitability. However, efforts are being made to reverse these limitations [5]. In Ecuador, coconut fiber is not significantly exploited industrially and is primarily regarded as an agro-industrial waste product. On the other hand, the world's leading producers are concentrated in Asia, where well-established production chains for processing and marketing exist [6].

Packaging plays an essential role in product protection, storage, and presentation. However, the excessive use of plastics has generated the need to develop more sustainable alternatives [7]. In this context, coconut fiber, derived from coconut shells, stands out for its strength, durability, and flexibility, making it a suitable material for packaging manufacture [3]. In addition, its biodegradable nature allows a faster decomposition at the end of its useful life, which reduces plastic waste and favors the transition towards a circular and more environmentally friendly economy [8].

The research conducted by Radhakrishnan et al. studied bio composites made from ramie and kenaf fibers, eggshell and coconut shell powders in epoxy matrix. The results showed that the ramie/epoxy/coconut shell bio composite has the highest tensile strength (42,3 MPa), flexural strength (30,5 MPa) and energy impact (8,9 kJ/m²). The kenaf/epoxy/coconut shell composite achieved the highest tensile modulus (1,97 MPa) and kenaf/epoxy/eggshell the highest elongation at break (~ 3.6 %). According to the analysis performed, the best interfacial adhesion in the composites stands out [9].

The objective of this research is to design and develop packaging films made from coconut fiber in order to evaluate their mechanical properties and biodegradability. The study contemplates a comparison with materials traditionally used in the packaging industry, such as polyethylene and polypropylene. It is intended to analyze the performance of coconut fiber sheets in fundamental aspects such as tensile strength, flexibility and degradation time, with the objective of determining their viability for commercial applications [10]. This research aims to demonstrate an alternative, sustainable approach to packaging material use that meets the necessary property requirements for packaging. The findings aim to advance academic understanding of biocomposite packaging and support the transition to circular economy practices. Unlike previous studies, this work integrates mechanical testing, environmental impact analysis, and economic feasibility in a single framework.

II. METHODOLOGY

This sustainable packaging design proposal seeks to develop an eco-friendly alternative to conventional packaging materials by extracting and transforming coconut fiber into functional and biodegradable sheets. For this purpose, theoretical and applied research with a qualitative and quantitative approach is proposed, aimed at analyzing the processes of obtaining natural fibers, identifying sustainable technologies, and evaluating the properties of coconut fiber, such as its resistance, flexibility, and low environmental impact.

The expected result is the creation of renewable packaging films ready for industrial application, contributing to the knowledge about using natural mate rials in packaging and promoting more responsible practices in the industry.

This approach seeks to reduce the carbon footprint, energy consumption, and waste generated without compromising the functionality of the packaging. In addition, it responds to an increased consumer demand for eco-friendly products and the business need to adapt to global environmental challenges through innovation and sustainability in their processes [11].

This study is an experimental-comparative investigation with a quantitative approach that aims to evaluate the mechanical properties and environmental impact of coconut fiber sheets and compare them with those of the conventional polymers polyethylene (PE) and polypropylene (PP).

In this study, the following were considered:

- **Independent variables**: the type of material evaluated (coconut fiber, PP, and PE);
- **Dependent variables:** tensile strength (MPa), maximum force (N), biodegradation time (days), carbon footprint (kg CO_2), and energy consumption (MJ).
- **Control variables**: specimen geometry according to ASTM D638/D882, loading rate of the SHIMADZU 300 kN universal testing machine (5 mm/min), laboratory temperature (22 ± 2 °C), and relative humidity (50 ± 5%).

The drying process for the coconut fiber was carried out in a POL EKO SLN 53 oven at 60 °C for 24 hours to ensure uniform residual moisture in all samples. For each material, 10 test specimens were prepared (n=10), a statistically justified number to achieve a power of 80% with a significance level of $\alpha = 0.05$, according to established criteria for testing polymeric materials. The commercial materials (PP and PE) were selected because they are the most widely used polymers in industrial packaging.

According to [12], coconut fiber is a sustainable and biodegradable material that reduces waste and carbon emissions. As an agricultural by-product, its use pro-motes the circular economy and reduces waste. Its use also brings economic and social benefits, promoting rural development and generating long term savings due to its durability. It is a versatile material applicable in sectors such as packaging, construction, and textiles [13].

Coconut fiber, or "COIR", is extracted from coconut husks after a milling process that generates fibers of different sizes, mainly used in horticulture [14]. It is resistant to traction, water, and humidity, which makes it durable in demanding environments. In addition, it offers thermal insulation, useful in food packaging [7] [15].

The development of sustainable packaging based on coconut fiber or other biodegradable materials has been possible thanks to technological advances in mate-rial extraction, processing, and transformation. Some of these advances include: mechanical and chemical extraction methods [16], the use of resins and organic compounds to improve the mechanical properties of fibers [17] and pressing-molding techniques.

Coconut fiber is obtained through a controlled process that preserves its physical properties, utilizing a POL EKO SLN 53 oven for regulated drying in terms of temperature and humidity. This process is key to achieving sheets with optimal mechanical and functional properties.

Similarly, the material was obtained through an optimized process of coconut fiber extraction and sheet creation. This process comprises seven steps: defibration, soaking, initial drying, carding, molding, final drying, and inspection. Fig. 1 illustrates a comparative flow chart between the traditional and optimized processes, where a significant reduction in time is observed as a result of optimization.

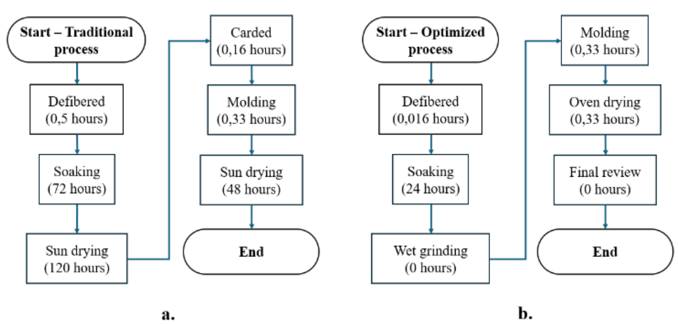

Fig. 1. Comparative flowchart: a. Traditional process, b. Optimized process.

A. *ASTM D638 standard in Tensile Strength Tests [MPa].*

ASTM D638 is a widely used standard to evaluate the mechanical properties of plastics by tensile testing, providing data on ultimate strength, elastic modulus, and elongation at break under controlled conditions that guarantee reproducible results [18] [19]. This test allows for the analysis of the behavior of materials under mechanical stresses, which are fundamental in industrial applications, both in terms of thermal resistance and structural performance [20].

Recent research has studied bio composites such as coconut fiber sheets with plastics, proposing them as a sustainable alternative to conventional plastics. Comparing them with existing standards allows for identifying their advantages and limitations, providing an objective basis for their improvement and commercial implementation, and promoting innovation and sustainability in the industry [21] [22]. For each material, the parameters are shown in Table I.

Obtaining sheets from coconut fiber is a traditional process composed of manual stages, from harvesting to final drying, [21]. In the optimized coir fiber extraction and sheet creation process the coconut fiber can be extracted by mechanical methods, using specialized machinery, or by retting, which consists of submerging the shells in water to facilitate manual or semi-mechanized extraction.

TABLA I
PARAMETERS USED IN TENSILE TESTS.

Properties	Coconut fiber	Polypropylene (PP)	Polyethylene (PE)
Shape	Flat	Flat	Flat
Thickness [mm]	3	0.5	0.25
Width [mm]	13	13	13
Calibrate length [mm]	50	50	50

B. General tensile strength process according to ASTM D638 standard.

The tensile process is a mechanical test used to measure the ability of a material to resist elastic forces before it breaks or permanently deforms. In the case of materials such as coconut fiber, polypropylene, and polyethylene, this test helps to evaluate the durability, strength, and applicability of the material in final products; the steps given for this test are detailed below.

Sample preparation. First, the material samples are cut according to the dimensions and specifications of the test equipment, following the tensile strength standards. For rigid plastics, the ASTM D638 standard is applied, which specifies the geometry of test specimens, while for thin plastic sheets or organic materials such as coconut fiber sheets, the ASTM D882 standard is used, since it is adapted to films and flexible materials. Fig 2 shows the designs in two dimensions for ASTM D638, with measurements based on which the construction of the specimens used for this research was carried out. On the other hand, for test tubes obtained under ASTM D882, only a rectangular section (without a middle section) is used, which must also have a thickness of less than 1 mm.

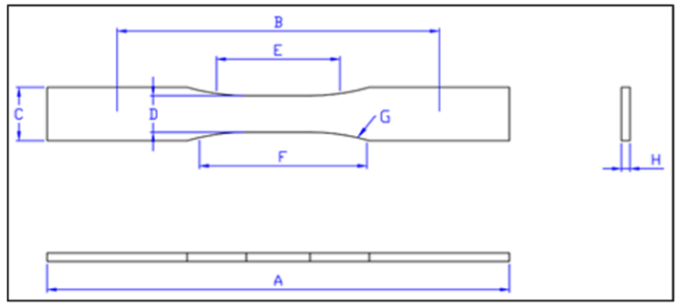

Fig. 2. Specimen dimensions according to ASTM 638.

Table II shows the dimensions according to each type of material. For each material, 10 specimens were made and subjected to tensile tests, the results of which were subsequently analyzed.

Installation of the sample in the traction machine. The specimen is placed in a tensile machine (SHIMADZU universal 300kN), which is equipment designed to apply a constant tensile load on the material. The ends of the sample are clamped in the gripping taps of the pulling machine.

TABLA II
PARAMETERS USED IN TENSILE TESTS.

Measurements [mm]	Coconut fiber	Polypropylene (PP)	Polyethylene (PE)
A (Total length)	165.00	165.00	165.00
B (Distance between clamps)	115.00	115.00	115.00
C (Total width)	19.00	19.00	19.00
D (Width of the narrow zone)	13.00	13.00	13.00
E (Calibrated length)	50.00	50.00	50.00
F (Length of the narrow zone)	57.00	57.00	57.00
G (Splice radius)	76.00	76.00	76.00
H (Total thickness)	3.00	0.50	0.25

Breakage. The test continues until the material breaks or reaches its breaking point. It is crucial as it determines the material's ultimate tensile strength (MPa), which indicates its ability to withstand stress without failure. In some cases, the mate-rial may undergo deformation before breaking, which is also relevant to understanding its behavior under loading.

During and after the test, data on maximum strength, elongation, and mod ulus of elasticity are collected during and after the test. These results allow the calculation of tensile strength in MPa units and are compared to the specifications required for using the material in specific applications.

III. RESULTS

Due to the use of the optimized process for obtaining coconut fiber, the following conditions were improved: duration, efficiency and tools. Likewise, Fig 3 shows the results of the evaluation of the time vs. each stage of the process of obtaining coconut fiber.

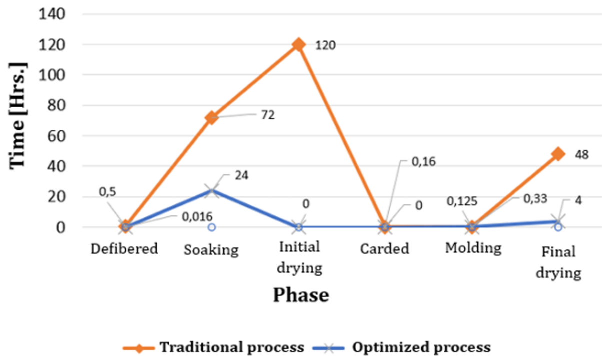

Fig. 3. Comparison of times in the methodologies for obtaining coconut fiber.

The environmental indicators reported in this study were calculated using secondary data from specialized literature and recognized life-cycle inventory databases [23][24].

A Life Cycle Assessment (LCA) certified under ISO 14040/14044 was not performed; instead, a simplified comparative environmental impact assessment approach was adopted, commonly used in exploratory studies of sustainable materials. The functional unit used is 1 sheet of packaging weighing 0.1 kg of material, equivalent to the minimum product unit analyzed in the economic study.

The system boundaries considered follow a cradle-to-gate approach, covering the stages of raw material extraction, processing, and sheet manufacturing, but excluding distribution, use, and final disposal. This scope reflects the availability of data in the literature on natural materials, such as coconut fiber, in the early stages of industrial development.

It is recognized that a full LCA (cradle-to-grave) could alter the environmental conclusions, particularly regarding energy consumption during the use phase and the benefits of biodegradation under actual final disposal conditions. Future research should address this comprehensive assessment.

The analysis of the environmental impact generated by each material was carried out under 4 conditions [23] [24]:

Carbon footprint [kg CO2]$\sum$ (CO2 emissions from the process x amount of material produced) (1)

Biodegradation time (days): Time required to lose 90% of the initial mass. (2)

Waste generation: Initial mass of material – biodegraded or recycled mass (3)

Energy consumption (MJ): $\sum$ (energy used at each stage of the cycle) (4)

Table III below compares the environmental impact generated by the three types of material: coconut fiber, polypropylene, and polyethylene.

TABLA III

COMPARISON OF THE METHODS FOR OBTAINING COCONUT FIBER

Impact factor	Coconut fiber	Polypropylene (PP)	Polyethylene (PE)
Carbon footprint [kg/CO2]	0.5 - 1.0	1.8- 2.8	2.0 - 3.0
Biodegradation time [days]	90 – 180	> 182,500 (500 years)	>182,500 (500 years)
Waste generation [kg]	~0.1	1.3	1.5
Power consumption [MJ]	5 – 10	35 - 50	40 - 60

Coconut fiber has a considerably lower carbon footprint and a much faster biodegradation time, making it an environmentally friendly option compared to PE and PP. Regarding waste generation, coconut fiber is lower, while PE and PP generate more waste per kilogram of material. The energy consumed to produce coir fiber is considerably lower compared to PE and PP.

A. *Tensile strength tests*

Tensile tests were performed on at least 10 specimens per material, establishing specific dimensions to ensure accurate results. Table IV shows the maximum forces obtained for each type of specimen, as well as the average values and standard deviations.

TABLA IV

MAXIMUM FORCES FOR EACH TEST PIECE

Test tube	**Coconut fiber [N]**	**Polypropylene (PP) [N]**	**Polyethylene (PE) [N]**
P1	7.10	40.48	123.79
P2	6.38	30.27	234.22
P3	5.67	49.06	164.18
P4	11.39	45.58	190.31
P5	14.35	49.35	196.03
P6	4.19	42.56	123.48
P7	7.58	32.15	210.94

P8	9.44	44.47	149.38
P9	6.96	46.54	190.96
P10	11.34	44.49	187.22
Average	8.44	42.50	177.05
Standar desviation	3.12	6.54	36.34

In Fig 4, the trend of the force applied in each specimen for each material can be observed. Where coconut fiber, polyethylene and polypropylene, present values in the maximum force of 14.35, 234.22 and 49.35 [N], respectively.

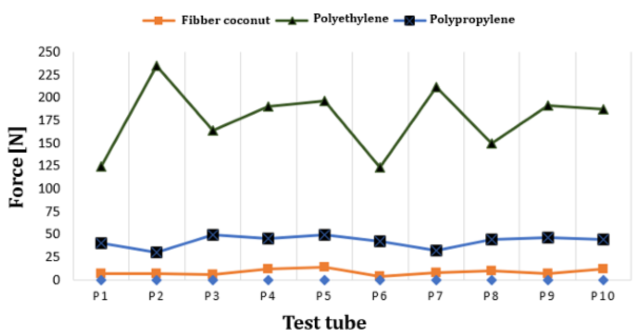

Fig. 4. Results of the force obtained by the tensile test for each material

On the other hand, Table V shows the maximum resistance values generated by each material for 10 tests.

TABLA V
MAXIMUM RESISTANCES GENERATED FOR EACH MATERIAL

Test tube	Coconut fiber [N]	Polypropylene (PP) [N]	Polyethylene (PE) [N]
P1	1.82	6.23	38.09
P2	1.64	4.66	72.07
P3	1.46	7.55	50.52
P4	2.92	7.01	58.56
P5	3.68	7.59	60.32
P6	1.08	6.55	37.99
P7	1.94	4.95	64.90
P8	2.42	6.84	45.96
P9	1.79	7.16	58.76
P10	2.91	6.85	57.61
Average	2.17	6.54	54.48
Standar desviation	0.80	1.01	11.18

To determine the statistical significance of differences in tensile strength among the three materials, a one-way analysis of variance (ANOVA) was performed at $\alpha = 0.05$. The results indicate that there are statistically significant differences between the groups ($F(2,27) = 245.3$; $p < 0.001$), which allows us to reject the null hypothesis of equal means.

Additionally, Tukey's post hoc tests (HSD) were used to identify which pairs of materials exhibit significant differences. The results confirm that the three materials differ significantly from one another ($p < 0.001$ for all compared pairs): coconut fiber vs. PP, coconut fiber vs. PE, and PP vs. PE. These results statistically confirm that, although the average strength of coconut fiber (2.17 MPa) is lower than those of PP (6.54 MPa) and PE (54.48 MPa), the differences are not due to random test variability but rather to the intrinsic mechanical properties of each material. The higher standard deviation observed in PE indicates greater heterogeneity in the commercial samples evaluated.

Similarly, the calculation of the maximum and minimum resistance for each specimen was performed. After the calculations, the trend graph of the maximum resistance for each material and specimen was obtained (see Fig. 5). Tensile strength averages for each material: Coconut fiber: 2.1653 [MPa], Polypropylene: 6.5384 [MPa], Polyethylene: 54.4765 [MPa]. The results shown are related to the values found in [9], where a strength of up to 42.3 MPa was achieved in biocomposites with coconut fiber combined with epoxy resin, suggesting that the use of matrices with this type of mixture is likely to improve the mechanical performance of coconut fiber in packaging materials.

B. Economic viability.

The production costs, sales price and profit margin for both types of packaging, considering labor, basic services, mobility, machinery and non-deductible expenses. The sheet weight of each material is 0.1 kg.

The economic feasibility analysis considers [23]: weight per sheet (0.1 kg), raw material cost (USD 2/kg), production cost (USD 4/kg), and sale price (USD 12/kg).

Raw material cost per sheet (C/sheet): = raw material cost x weight per sheet = \$0.20 *(5)*

Production cost per sheet = production cost x weight per sheet = $0.40 *(6)*

Total production cost per sheet = Raw material cost + production cost = $0.60/kg *(7)*

Selling price per sheet = Selling price x Weight per sheet = $1.20 *(8)*

Profit margin = Selling price per sheet – Total cost per sheet = $0.60 (9)

Performing the same price analysis for non-biodegradable packaging yields a profit margin of $0.28, which is $0.32 less than coconut fiber-based packaging, as shown in Table VI.

TABLA VI
ECONOMIC VIABILITY BETWEEN COCONUT FIBER AND A BIODEGRADABLE MATERIAL

Cost Factor (USD/kg)	Coconut Fiber Based Sheeting	Non-Biodegradable Packaging
Cost of raw materials	2	0.58
Cost of Production	4	0.18
Total cost per sheet	0.60	0.08
Sales price per sheet [USD]	1.20	0.35
Profit Margin [USD]	0.60	0.28

IV. CONCLUSIONS

Although the optimized coconut fiber sheet manufacturing process involves a higher initial cost, it stands out for its speed and efficiency compared to the traditional method. While the latter can take days or weeks to produce a sheet, the optimized process achieves this in less than two days, with more precise control over the properties of the final product. This advantage makes it a promising candidate for potential scale-up, pending detailed technical and economic feasibility studies. From the analysis of both alternatives, the results suggest that an industrialized approach could benefit companies seeking to reduce time, increase capacity, and improve product uniformity; however, further research is required to validate its scalability under real production conditions.

From an environmental perspective, coconut fiber offers notable benefits over polyethylene (PE) and polypropylene (PP), such as a reduction of up to 80 per cent in carbon footprint and a biodegradation thousands of times shorter. Although its average tensile strength (2.1653 MPa) is lower than that of convencional plastics, it can be improved by adjusting the thickness of the sheets, expanding its applications in packaging and logistics. In addition, with a low density (0.7- 0.8 g/cm³) and high-water resistance (~ 80 %), coconut fiber is a versatile material, with potential suitability for packaging in humid environments, subject to further validation under varied conditions. The production of these sheets shows preliminary alignment with by reusing agricultural products, with a profit margin of US$0.60 per sheet, compared to US$0.28 for non-biodegradable ones.

Although the manual process has advantages in terms of low initial cost and flexibility, its slowness and variability in quality may limit its competitiveness in more demanding markets. A potentially viable solution is the progressive incorporation of basic tools and machinery to improve productivity and quality without compromising the initial investment. This strategy could combine the best of both approaches, optimize the manual process while laying the groundwork for an eventual transition toward larger-scale production. However, this transition would require detailed technical, economic, and environmental feasibility studies before it could be considered viable. Therefore, any projection toward full industrial production should be understood as a line of future research by the present study.

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