
Design and Fabrication of a Banana Fiber Extractor: A Sustainable Solution for Agricultural Waste-to-Energy Conversion

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Abstract

The global energy crisis and environmental degradation necessitate the development of innovative waste-to-energy technologies. This study presents the design, fabrication, and analysis of an integrated system centered on a novel banana fiber extractor, conceptualized as the first stage of a sustainable bio-refinery. The primary machine efficiently extracts high-quality banana fibers (diameter: 0.05–0.25 mm) for industrial use. Its core innovation lies in the synergistic valorization of residual biomass for energy production. The extracted fibers are sustainable materials that reduce energy consumption in industries such as textiles. More significantly, the remaining lingo-cellulosic waste (over 70% of the stem mass) is a high-potential feedstock for anaerobic digestion and biofuel production. Our analysis confirmed the suitability of the residual biomass for biogas generation, with a high organic content. This closed-loop model not only addresses the environmental challenge of agricultural waste, which contributes to methane emissions when decomposed improperly, but also transforms it into a renewable energy source. This study demonstrates a viable and scalable pathway for enhancing energy security in rural agricultural communities, promoting a circular economy, and reducing reliance on fossil fuels through distributed biomass-based power generation.

Index Terms: Environmental Sustainability, Bio-refinery, Banana Fiber, Energy, Biodegradable Product

I. INTRODUCTION

Banana cultivation is a major agricultural activity in Pakistan and many tropical countries, generating enormous amounts of lignocellulosic waste post-harvest. Traditional disposal methods, such as open-field burning or decomposition, release significant quantities of methane—a potent greenhouse gas—and represent a missed opportunity for energy recovery. The concurrent crises of energy scarcity and environmental pollution demand innovative solutions that leverage agricultural by-products [1-3].

This paper proposes a paradigm shift: viewing banana waste not as a disposal problem but as a feedstock for a integrated biorefinery. We present the design and fabrication of a banana fiber extraction machine, repositioning it as the initial processing unit in a larger energy-generating system. The high-strength fibers are extracted for use in energy-efficient materials (e.g., reducing vehicle weight for better fuel economy), while the residual biomass, comprising over 70% of the stem, is prepared for conversion into biogas through anaerobic digestion or into solid biofuel pellets.

This integrated approach directly contributes to Sustainable Development Goals (SDGs) related to affordable and clean energy (SDG 7), climate action (SDG 13), and sustainable economic growth (SDG 8). This study details the mechanical design of the extractor and provides a critical analysis of the energy potential inherent in the waste stream it creates, offering a comprehensive model for sustainable power generation from agricultural waste [4, 5].

A) Environmental Impact

Banana waste can be composted, which means it can break down naturally to become a nutrient-rich soil. This reduces the amount of organic waste ending up in landfills and provides a natural fertilizer for plants. Banana waste can also be used in biogas production. Through anaerobic digestion, methane gas can also be extracted from banana stem waste and we shall use it as a renewable energy source [6, 7].

When banana plant waste decomposes in landfills without proper management, it releases methane gas. Methane is a strong greenhouse gas, participating to climate change and global warming.

The production, transportation, and disposal of bananas generate carbon emissions and consume resources like water and energy. Improper waste management magnifies these impacts. If banana waste is improperly disposed of as shown in fig 1, it can contaminate soil and water bodies, result in nutrient imbalances and pollution. This can also harm ecosystems and wildlife [8, 9].

Banana waste can be favorable when managed properly through composting or energy production, its improper disposal can contribute to environmental degradation, including greenhouse gas emissions and pollution. Therefore, it's essential to incorporate effective waste management practices to minimize its negative impacts.



Fig. 1 Improper disposal of Banana Stem in rural areas

Banana waste, like peels and stems, can have both positive and negative environmental impacts. Banana waste can be composted, which means it can break down naturally to become nutrient-rich soil. This decreases the amount of organic waste ending up in landfills and provides a natural fertilizer for plants. Banana waste is able to utilize in biogas generation via digestion processes and extract methane gas to generate the power.

The banana waste burns in landfills deprived of appropriate managing, it causes the pollution. By effective utilization it produces methane gas, contributing to ecological and worldwide warming conditions. The manufacture of methane use in transport, and removal of bananas fiber without any emissions and use of resources like water and energy. Inappropriate wastage controlling impairs these influences. If banana waste is inappropriately discarded produce pollute soil and water [10].

Banana waste can be beneficial when managed properly through composting or energy production, its improper disposal can contribute to environmental degradation, including greenhouse gas emissions and pollution. Therefore, it's essential to implement effective waste management practices to minimize its negative impacts.

B) Growth Rate Of Banana

Asia and the Pacific region's most popular crop is the banana. In Indonesia, Thailand, Vietnam, the Philippines, Bangladesh and the South Pacific island nations, India, and Pakistan, it is one of the most widely grown fruits. Taking in view to the agricultural economies of Australia, Malaysia, Taiwan, Sri Lanka, and Southern China, bananas

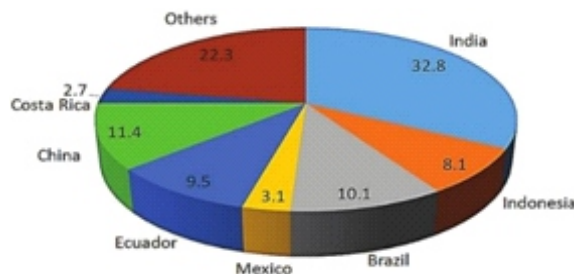


Fig. 2 Percentage data of Banana Cultivation across the world in 2022



Fig. 3 Banana Plant cultivation in Baluchistan Hub

also play significant role. Percentage data of banana production across the world in 2022 is shown in fig 2.

A cultivated banana plant develops from a corm, a structure that looks like a bulb rather than a seed. The plant's "trunk," also known as the "pseudo stem," grows from a corm and it is composed of densely overlapping leaf sheaths that resemble celery stalks. As the plant grows, 4–15 frond-like leaves emerge from the middle of the pseudo stem and unfold at a rate of one per week under ideal circumstances. With their upward and outward expansion, the leaves form broad, lustrous blades that can grow up to 9 feet (2.7 m) long and 2 feet (0.6 m) wide [11-13].

From a major number of leaves, the pseudo stem gives way to the flowering stem, also known as the "inflorescence," which rises through it. It begins as a big, tapering purplish bud. Groups of tubular white blooms grow as the bud opens. There are both flowers (male and female), and the fruit which is essentially a berry develops from the females without the need for pollination. The baby bananas grow into thin green "fingers" as they mature. A ripe fruit cluster forms a "hand," and the stem bends downward toward the ground as a result of the weight of the bananas. Depending on the variety, bananas change from green to yellow or red as they ripen. A single banana plant can grow to a height of more than 100 cm and yield 100–300 individual fruits [14, 15].

Table I: Parameters of design of frame

S.NO	PARAMETER	DIMENSION
FRAME		
a	Height	3 ft
b	Length	2.5 ft
c	Width	2 ft
WHEELS		
a	Diameter	3 inch
b	Quantity	4
SHEETS		
a	Front Sheet Length	2.5 inch
b	Side Sheet Length	2 inch

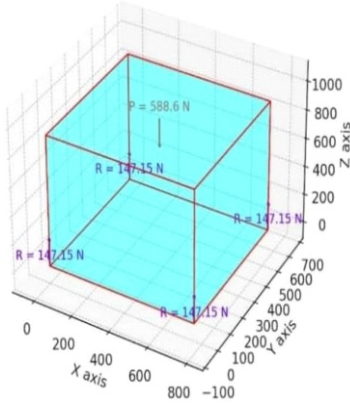


Fig. 4 Free body diagram of frame

Banana cultivation in Baluchistan, specifically in areas like Sakran and Hub, has significantly increased recently. In the 2023-24 season, banana production in Balochistan accounted for 19.9% of the total agricultural output, up from 8.6% in 2018-19. Since for testing the machine we have to collect the stems so we visit Baluchistan Hub area. A small cultivated land is shown in fig 3.

II. DESIGN OF BANANA FIBER EXTRACTOR

A) Design Of Frame

The banana fiber extractor's frame acts as the structural skeleton, giving all other parts of the device support and stability. The rollers, drum, bearings, motor, and other components are all housed in a small, effective configuration within the frame. The frame of the banana fiber extracting machine is designed with modularity in mind, allowing for easy assembly and disassembly for maintenance or transport. It guarantees that the parts are positioned and aligned securely, enabling easy and effective fiber extraction. The frame may also have elements that improve the machine's adaptability and ease of maintenance, like mounting brackets and slots for repositioning different components (Table 1)

Table II: Design parameters of cutting drum

H = 914.4 mm, L = 762 mm, W = 609.6 mm, D = 38.1 mm,
Factory of Safety (FOS) = 2, σ_{yt} = for Mild steel = 250 MPa

Maximum Load on Frame = 60kg

$$\begin{aligned} \text{Force} &= w \times g \\ \text{Force} &= 60 \times 9.81 \\ \text{Force} &= 588.6 \text{ N} \end{aligned}$$

$$\begin{aligned} I &= ???/12 \\ I &= (609.6)(38.1)^3/12 \\ I &= 280\,9562 \text{ mm}^4 \end{aligned}$$

Maximum Bending moment

$$\begin{aligned} M &= F \times \text{perpendicular distance} \\ M &= 588.6 \times 914.4 \\ M &= 538\,216 \text{ Nmm} \end{aligned}$$

Maximum Bending Stress

$$\sigma = M_y/I = 58.4 \text{ N/mm}^2$$

Allowable Shear Stress

$$\sigma_{\text{allow}} = \sigma_{yt}/\text{FOS} = 125 \text{ MPa}$$

Table III: Design parameters of cutting drum

S.NO	PARAMETER	DIMENSION
DISC PLATES (Quantity: 2)		
a	Diameter	8.5 inch
BLADES (Quantity: 8)		
a	Thickness	2 inch
b	Length	17 inch
SHAFT (Quantity: 1)		
a	Diameter	1.15 inch
b	Length	30 inch

B) Calculation Of Frame Design

The calculation (Table 2) and free body diagram of frame is shown below in figure 4.

C) Design Of Cutting Drum

The main part of the banana fiber extractor that is in charge of removing the fibers from the banana stem is the drum. Usually cylindrical, it has serrated edges or sharp blades running the length of its surface. The blades expose and loosen the fibers when the stem of the banana travels through the drum, slicing through the outer layers. For efficient fiber extraction, the drum's design including the placement and edge sharpness of the blades is essential. In order to avoid damage, it must be designed to strike a balance between cutting

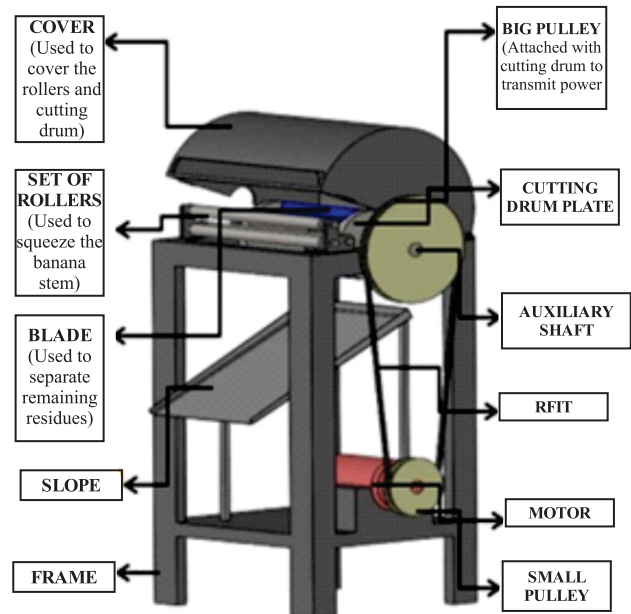


Fig. 5 Solid-works model of Banana Fiber Extractor

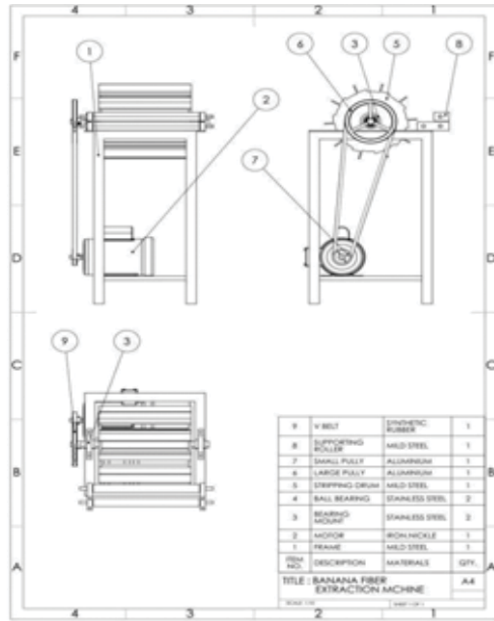


Fig. 6: Isometric views of assembled machine

effectiveness and careful handling of fibers. The motor powers the drum, which rotates at a set pace to process the banana stems thoroughly and consistently. The Disc Plates and shaft is of Mild Steel. The Blades are of Carbon Steel ((Table 3).

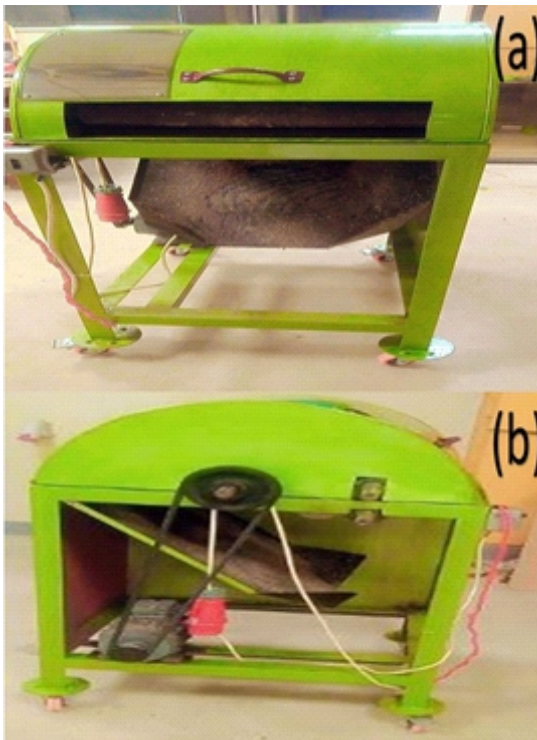


Fig. 7 Final design from (a) front and (b) back sides of banana fiber extractor

Table IV: For banana stem of diameter 80 mm

LAYER	LAYER THICKNESS (mm)	WATER CONTENT PERCENTAGE (%)
Outer Layer	10	70
Inner Layer	7	45
Most Inner(Rough) Layer	4	18

Table V: For banana stem of diameter 100 mm

LAYER	LAYER THICKNESS (mm)	WATER CONTENT PERCENTAGE (%)
Outer Layer	13	74
Inner Layer	9	48
Most Inner(Rough) Layer	5	20

Table VI: For banana stem of diameter 120 mm

LAYER	LAYER THICKNESS (mm)	WATER CONTENT PERCENTAGE (%)
Outer Layer	15	78
Inner Layer	10	50
Most Inner(Rough) Layer	6	23

D) The Labeled Diagram Of Banana Fiber Extractor

The labeled diagram of machine CAD model (Figure 5) is also provided so each and every part is easily recognizable and their function is also mentioned (Figure 6 and 7).

Table VII: For banana stem of height 1 m and thickness 60 mm

LAYER	LAYER DIAMETER (mm)	FIBER DIAMETER (mm)
Outer Layer	30	0.15
Inner Layer	20	0.09
Most Inner(Rough) Layer	10	0.05

Table VIII: For banana stem of height 1.5 m and thickness 80 mm

LAYER	LAYER DIAMETER (mm)	FIBER DIAMETER (mm)
Outer Layer	40	0.20
Inner Layer	25	0.12
Most Inner(Rough) Layer	15	0.07

Table IX: For banana stem of height 2 m and thickness 100 mm

LAYER	LAYER DIAMETER (mm)	FIBER DIAMETER (mm)
Outer Layer	50	0.25
Inner Layer	35	0.18
Most Inner(Rough) Layer	15	0.09

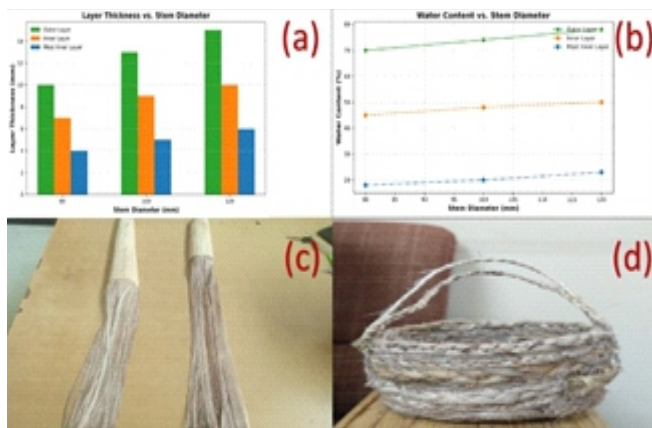


Fig. 8: Summary of banana fiber extraction (a) Relationship between stem diameter (80–120 mm) and layer thickness (outer, inner, most inner); (b) Variation in water content (%) across layers for different stem diameters; (c) Extracted banana fibers demonstrating structural quality; (d) Final woven basket product showcasing practical application of extracted fibers.

III. RESULTS & DISCUSSION

After placing the banana stem into the machine, the process begins with the rotation of the rollers and the action of the drum with blades, which work together to extract the fibers. As the machine operates, the stem is carefully processed, separating the fibrous material from the rest of the plant matter. The result is a collection of banana fibers in a thread-like form, which are fine and strong, making them suitable for various applications. This efficient method of fiber extraction not only maximizes the use of banana waste but also produces a sustainable and eco-friendly material that can be used in textile and composite industries.

A) Analysis of Banana Stem Layers Thickness on Water Content Percentage

The analysis of banana stem layers and their impact on water percentage content is crucial for understanding the moisture retention and mechanical properties of banana fibers. The banana plants made up of various layer and the thickness of banana branches outer and inner contain different material and the fiber processing to design different type of textile and domestic products. Understanding this correlation can help optimize the drying and preparation of banana fibers for sustainable industrial use. By taking banana stems of different diameters and examining the correlation between the stem layer's thickness and the water percentage content, the following results were concluded which are as follows (Table 4-6):

The results indicate a clear trend where the outer layers of the banana stem have higher water content percentages compared to the inner layers. For all stem diameters (80mm, 100mm, and 120mm), the outer layers consistently exhibit the highest water content, ranging from 70% to 78%. As we move inward, the water content decreases, with the innermost layers (referred to as rough layers) having significantly lower water content, as low as 18% to 23%.

This suggests that the water retention capacity of the banana stem is largely concentrated in the outer layers, with a gradual reduction toward the inner sections. The layers made up of different materials

which depends upon the outside moisture and atmosphere. The results consist of diameters of the product on the basis of thickness and water content available in solid material.

B) Analysis Of Banana Stem Layers Diameter On Extracted Fiber Diameter

The banana branches and layers effect the diameter and thickness of fiber removed from the stem. The diameter also effects the structure and potential applications of the designed product. This system is sustainable, globally friendly and long lasting to physically implement. The banana stem, known for its rich fiber content, was meticulously divided into three primary layers for this study: the outer layer, the inner layer, and the most inner layer, deliberately bypassing the intermediate layers. By taking banana stems of different heights and examining the correlation between the stem layers' diameters and the resulting fiber diameter, the following results were concluded which are as follows (Table 7-9):

Based on the results presented for banana stems (Figure 8) of varying heights and thicknesses, a clear relationship is observed between the diameter of the stem layers and the diameter of the extracted fibers. As the diameter of the layers (outer, inner, and most inner) increases, the corresponding fiber diameter also increases. For example, for a stem of 1m height and 60mm thickness, the outer layer diameter is 30mm with a fiber diameter of 0.15mm, while for a stem of 2m height and 100mm thickness, the outer layer diameter is 50mm with a fiber diameter of 0.25mm.

IV. CONCLUSION

This study successfully demonstrates the fabrication of a core component for a sustainable agro-energy system. The banana fiber extractor is not merely a tool for creating commercial products but is the essential first step in a waste-to-energy pipeline. By processing banana stems, the system simultaneously produces a valuable material and prepares biomass for renewable energy production.

This integrated approach (i) Mitigates GHG emissions by preventing open decomposition of waste, (ii) Generates renewable energy (biogas, biofuel) from a sustainable feedstock, (iii) Reduces industrial energy consumption through lightweight bio-composites and (iv) Creates a circular economy in agricultural communities.

Future work will focus on integrating the extractor directly with an anaerobic digester to quantitatively measure the biogas output and overall energy balance of the entire system, providing definitive data on its viability as a decentralized power generation solution.

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