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Original Article

Performance Optimization of a Modular Hyacinth Fiber Decorticator for Sustainable Biomass Utilization

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Abstract

Water hyacinth (*Pontederia crassipes*, formerly *Eichhornia crassipes*) is an ecologically invasive aquatic plant with significant potential as a lignocellulosic fiber source. However, industrial use is limited by its high moisture content, low lignin, irregular fiber structure, and elevated silica and ash, which complicate mechanical extraction. This study evaluates six biomasses: water hyacinth, banana, pineapple, hemp, flax, and sisal and presents the development and testing of a unified semi-automatic, modular fiber decorticator. Adapted from a banana fiber extractor, the machine is engineered to process water hyacinth, banana, and pineapple using features such as adjustable blade pitch, variable roller clearance, corrosion-resistant parts, and anti-clogging systems to handle diverse fiber morphologies and moisture levels.

Mechanical parameters including torque, power, flexural force, and moment of inertia were calculated using beam theory and rotational dynamics, while clustering criteria grouped compatible biomasses by their mechanical and morphological traits. Standardized protocols were used for collection, preparation, and processing, with performance measured by extraction efficiency, fiber yield, and energy consumption. Results show that water hyacinth, banana, and pineapple require similar mechanical input (torque: 5.5-7.5 Nm; power: 0.8-1.2 kW), allowing unified processing without major modifications. In contrast, high-strength fibers like flax and hemp require greater mechanical input (up to 3.2 kW) and machine reinforcement. Operational challenges, such as retrofitting needs and biomass waste management, are discussed. The findings confirm that a modular decorticator designed for banana can efficiently process water hyacinth and pineapple, supporting sustainable, decentralized fiber valorization and advancing circular bioeconomy goals in rural contexts.

Categories: Design and Manufacturing, Energy Efficiency and Conservation, Environmental Engineering and Sustainability

Keywords: invasive aquatic plant, lignocellulosic biomass, mechanical fiber extraction, power optimization, modular decortication system, sustainable rural bioprocessing

Introduction

Pontederia crassipes, or water hyacinth, is a rapidly spreading aquatic plant native to the Amazon basin and is now considered one of the most invasive species in tropical and subtropical waters worldwide [1,2]. Its dense mats disrupt aquatic ecosystems by blocking sunlight, reducing dissolved oxygen, impeding transport, and providing breeding grounds for disease vectors like mosquitoes [3]. Despite these ecological concerns, water hyacinth offers significant

potential as a renewable lignocellulosic biomass due to its high cellulose and hemicellulose content and relatively low lignin, making it suitable for bio-composites, pulp, and fiber products [4,5]. However, industrial utilization remains limited, primarily because scalable fiber extraction technologies tailored to its unique, high-moisture, and delicate structure are lacking.

Fiber extraction from water hyacinth can be achieved through mechanical, chemical, or biological methods. Mechanical extraction is particularly advantageous in rural settings due to its simplicity, low cost, and minimal environmental impact, making it ideal for decentralized processing [6-8]. This typically involves decortication, where machines grate or crush the biomass to separate fibers, sometimes followed by treatments like retting or mild alkali soaking to improve fiber quality [9]. However, machines designed for traditional bast fibers such as jute or flax are not well-suited to water hyacinth's soft, irregular fibers, and high-water content, leading to operational challenges like clogging and reduced extraction efficiency [6,9].

Designing an effective fiber extraction system for water hyacinth requires integrating mechanical design, materials science, and plant anatomy. Key machine parameters such as blade pitch, torque, roller clearance, feed rate, and rotational speed must be optimized for the plant's variable stem structure and delicate fibers, which average 300-500 mm in length and about 50 µm in diameter [10]. Specialized equipment is needed to minimize shredding and prevent clogging.

Existing machines, typically designed for fibers like banana or pineapple, lack the modular adaptability required for water hyacinth and often compromise output quality or durability. Here, "modular" refers to components that can be reconfigured for different materials, while "anti-clogging systems" include features such as self-cleaning rollers or drainage channels to manage fibrous debris during wet biomass processing. For sustainable use, machines must also be compact, energy-efficient, and made from corrosion-resistant materials [11,12].

To address these gaps, this study aims to develop a unified, semi-automatic decortication system capable of extracting fibers from water hyacinth as well as banana, pineapple, sisal, flax, and hemp. The primary objective is to identify optimal mechanical thresholds such as blade pitch and roller clearance that enable efficient extraction across various biomasses with differing moisture and structural properties. The proposed modular prototype will feature corrosion-resistant materials, adjustable components, and integrated anti-clogging systems, specifically designed to handle water hyacinth's high-moisture, low-lignin characteristics. By aligning technical adaptability with the specific requirements of each material, this system aims to transform an invasive species into a valuable rural resource, supporting circular bioeconomy goals and sustainable biomass utilization [9,12,13].

As is evident from this work, which focuses on the valorization of a prevalent aquatic weed, water hyacinth, the optimization of fiber extraction units has been addressed primarily from an energy-efficiency and sustainability perspective. This directly aligns with 8 out of the 17 United Nations Sustainable Development Goals (SDGs). Notably, SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land) are particularly relevant, as the proposed technology promotes ecological restoration, waste-to-resource conversion, renewable material use, and decentralized, low-impact processing.

Materials And Methods

Existing fiber extraction technique

A variety of fiber extraction methods mechanical, chemical, biological, thermal, and hybrid are used for processing lignocellulosic biomass, each with distinct trade-offs in yield, purity, cost, and environmental impact. Most semi-automatic fiber extraction machines are designed for conventional crops like banana, pineapple, sisal, hemp, and flax, utilizing grating or decortication mechanisms suited to their robust outer stems [7]. When these systems are adapted for water hyacinth, essential parameters such as blade geometry and roller clearance are often not optimized for its high moisture, delicate structure, and irregular morphology. As a result, extraction efficiency and fiber quality remain low, underscoring the need for systems specifically engineered for water hyacinth.

Water hyacinth fiber extraction employs various methods discussed in Table *1*, each with distinct benefits and challenges. The most widely used is the semi-automatic mechanical method, which crushes or grates stems using machines. This approach is simple, scalable, and environmentally safe but often leads to wear of biomass due to the plant's high moisture and weak fiber structure [10]. Chemical extraction uses agents like NaOH, H_2O_2, or dilute H_2SO_4 to remove non-cellulosic components and improve fiber quality; however, it produces chemical effluents and necessitates expensive wastewater treatment, limiting its suitability in rural contexts [5,11]. The biological method, which includes traditional retting or enzymatic processing, is eco-friendly and cost-effective but slow, odor-producing, and dependent on environmental factors [4]. Thermal or boiling pre-treatment helps loosen cell walls for easier fiber separation but requires significant energy and water inputs, reducing sustainability in resource-limited areas [14]. Lastly, integrated methods combine mechanical, chemical, and biological processes such as mechanical crushing, alkali soaking, and enzymatic retting to enhance fiber quality and yield, though they are complex and less viable for field-level use [9].

Methods	Length of Fiber (mm)	Advantages	Limitations	References
Mechanical	450-700	Simple, Scalable, No Chemical	Coarse fibers, Clogging issues, Moisture dependent	[6,15]
Chemical	200-350	High fiber quality, Delignification	Environmental Hazards, High Cost	[6,15-17]
Biological (Retting)	250-600	Eco- friendly, Easy to implement	Time Consuming, Odor issue, Weather Sensitive	[15,18,19]
Thermal/Boiling	200-450	Softens fiber, Easy to use	High Energy and Water use	[6,20]
Integrated	300-500	Improved quality, Better to use	Complex Process, requires optimization	[15,16,18,19,21]

TABLE 1: Overview of Water Hyacinth Fibre Extraction Techniques

It is evident that no single method optimally balances yield, cost, scalability, and environmental sustainability. Mechanical methods are preferred for field-level use due to their simplicity and low chemical impact, though fiber quality may suffer without pre-treatment. Chemical and biological methods offer enhanced refinement but are unsuitable for small-scale or rural deployment due to infrastructure demands. Integrated approaches show potential but require customized machinery and operational tuning. These findings support the development of a modular, semi-automatic mechanical decortication system specifically adapted for water hyacinth and similar challenging biomasses.

Machine design principle

Efficient mechanical extraction of water hyacinth fibers requires a robust and adaptable machine design to address the plant's high ash and moisture content and its irregular fiber morphology. Unlike conventional bast fiber crops, these unique properties demand a multidisciplinary approach that integrates mechanical engineering, materials science, and ergonomic considerations to optimize yield and maintain fiber integrity. Currently, no commercial machine is purpose-built for water hyacinth decortication; most available systems are retrofitted from equipment for banana, pineapple, sisal,

jute, or flax, or exist only as academic prototypes [9,11]. To bridge this technological gap, this study proposes a unified mechanical fiber extraction system capable of processing banana, pineapple, water hyacinth, sisal, flax, and hemp, based on their overlapping mechanical and morphological characteristics.

Major parameters include adjustable blade pitch and roller clearance to accommodate different biomasses, variable torque and motor speed for handling both soft and high-lignin crops, integrated drainage and anti-clogging systems for high-moisture materials, and abrasion-resistant blades for silica-rich fibers. The proposed machine architecture consists of a roller-based feeding unit [14], a rotating blade chamber for pith and fiber separation, an integrated scraping mechanism, and a discharge zone for fiber and waste. All moving parts are enclosed for safety, and wet-contact components are modular for easy cleaning and maintenance. This modular, biomaterial-responsive design reflects current trends in decortication technology, emphasizing operational flexibility and energy efficiency [22].

Challenges in the water hyacinth fiber extraction

Water hyacinth, while a promising renewable fiber source, presents significant processing challenges due to its extremely high moisture content (90-95%), which increases transport costs, requires rapid processing to avoid decay, and accelerates machine corrosion [11]. Most usable fiber is concentrated in the petiole and lower stem, with the leaf blades contributing little [14]. Irregular fiber orientation and stem variability further complicate extraction, leading to inconsistent yields and increased mechanical resistance shown in Figure *1*.

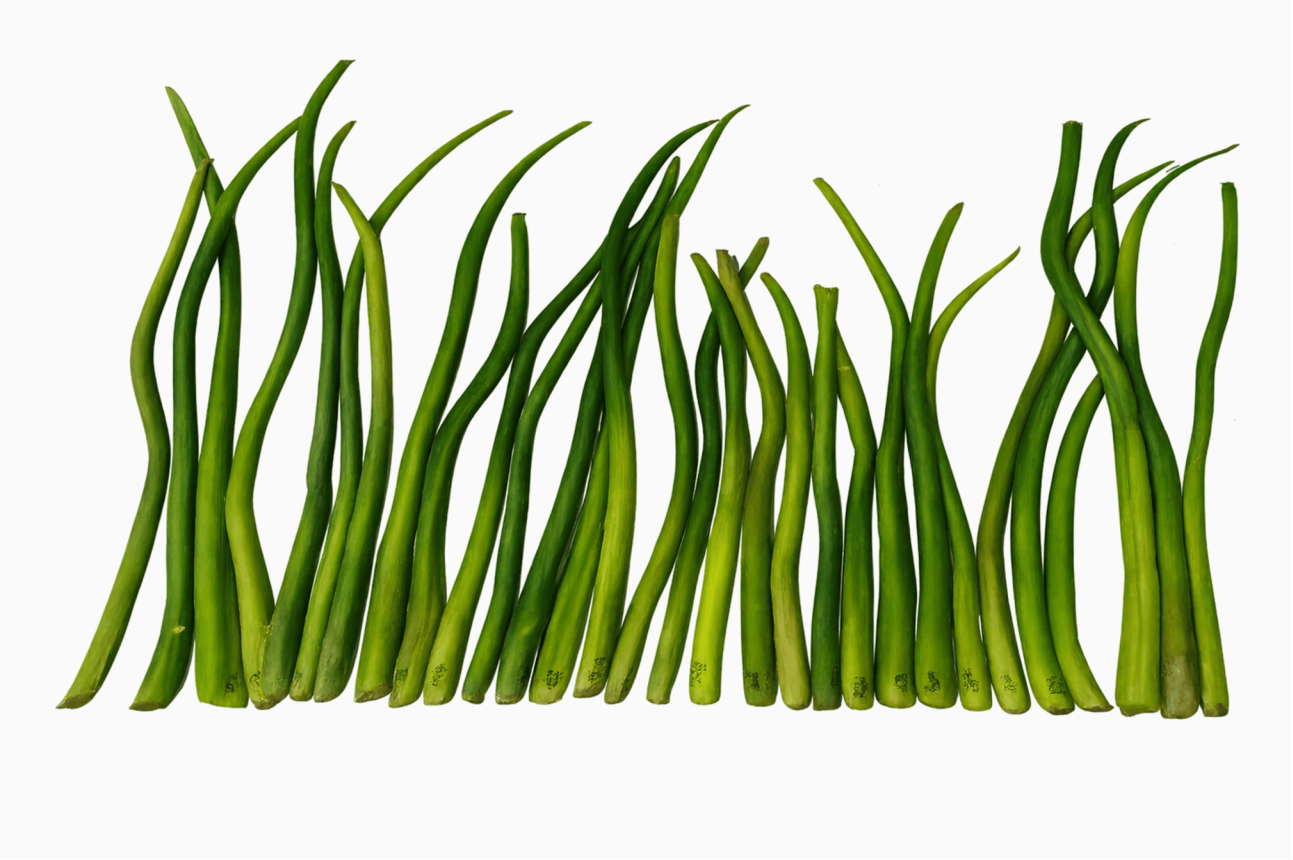


FIGURE 1: Irregular Shape of Water Hyacinth Stem

The plant's delicate fibers often cause clogging and jamming in standard machinery, requiring specialized cutting and crushing systems to prevent excessive shredding and improve efficiency [9,12]. High ash and silica content accelerates blade wear, requiring abrasion-resistant materials in machine construction [22-24]. Additionally, effective fiber use

demands multiple pre- and post-processing steps such as drying, retting, and carding, which are energy-intensive and often impractical for rural settings [5].

Large-scale processing also generates considerable organic waste, which, if unmanaged, can cause environmental issues like leachate, methane emissions, or nutrient runoff [1]. Therefore, any extraction system must address both mechanical efficiency and ecological impacts. The proposed modular decorticator incorporates drainage and anti-clogging features, adjustable components, and corrosion-resistant materials, enabling scalable and sustainable fiber extraction from water hyacinth and similar biomasses.

While various extraction methods exist, none fully address the unique combination of challenges presented by water hyacinth, such as its high internal moisture, low lignin, irregular fiber alignment, and elevated ash and silica content. Mechanical methods are the most scalable and environmentally friendly, but current machine designs are not optimized for water hyacinth's specific morphology. Chemical and biological approaches can improve fiber quality but are often impractical in decentralized settings due to cost, environmental, and logistical barriers. Although integrated approaches offer a balance of benefits, they require machine configurations tailored to water hyacinth's unique processing needs. This gap in engineering design underpins the present study, which proposes a modular, adaptive decortication system capable of efficiently processing water hyacinth alongside other common plant biomasses.

Biomass collection and preparation

Water hyacinth (*Pontederia crassipes*), a fast-growing aquatic macrophyte, was selected as the primary feedstock due to its abundant availability and high lignocellulosic composition. Mature and healthy plants were manually harvested from a freshwater body located in Panchkula, Haryana, India (30°39'45.4"N 76°51'59.2"E) as shown in Figure *2*(a) during early morning hours to minimize wilting and prevent enzymatic degradation. Selection focused on specimens with upright stems and fully developed petioles, as supported by prior studies demonstrating higher fiber yield and tensile performance in these regions [4,5].

Immediately after collection, the plants were thoroughly rinsed with clean water to remove surface impurities and microbial biofilms. Using stainless steel shears, roots and leaves, being fiber-deficient and potentially obstructive to mechanical processing, were trimmed off as shown in Figure *2*(b). Only the central petiole and lower stem sections were retained for further analysis, as these are enriched with cellulose and structured fiber bundles critical for extraction [12] as shown in Figure *2*(c).

The cleaned biomass was then sorted by stem diameter and length to ensure uniformity during machine feeding. Approximately 10 kg of fresh biomass was used per experimental run, as shown in Figure *2*(d), to maintain batch consistency. The sorted samples were air-dried under shaded conditions for 4-6 hours, a duration found sufficient to reduce surface moisture without inducing lignin hardening, which could otherwise hinder fiber release. This initial drying process served as a pre-conditioning step, softening parenchymatous tissues while maintaining fiber integrity to improve decortication efficiency [11].

Other biomass of different natural fibers was collected, and prepared using the same extraction technique according to the structural characteristics of each plant. In the case of banana (*Musa spp.*), the pseudostem was cut near the base, and the bulky stem was trimmed to remove leaves and unwanted tissues, it was cut into manageable sections, and the overlapping sheaths were manually separated so that the fiber-rich layers could be easily processed. For pineapple (*Ananas comosus*), the long leaves were cut close to the base using sickles, gathered into bundles, cleaned to remove soil or debris, and arranged in aligned stacks before feeding them into mechanical extractor. For sisal (*Agave sisalana*), the thick fleshy leaves were individually cut from the plant and stacked in batches, after which the leaf surfaces were cleaned and trimmed so that the fibrous bundles embedded within the leaf tissue could be accessed during processing. For flax (*Linum usitatissimum*), the plants were typically uprooted to preserve the full length of the stem fibers, bundled together, before further mechanical processing. Similarly, hemp (*Cannabis sativa*) stems were cut close to the ground, gathered into bundles, so that the bast fibers can later be separated from the woody core during mechanical decortication. This collection and preparation stage ensures that the biomass is in a suitable physical form for efficient mechanical fiber extraction.

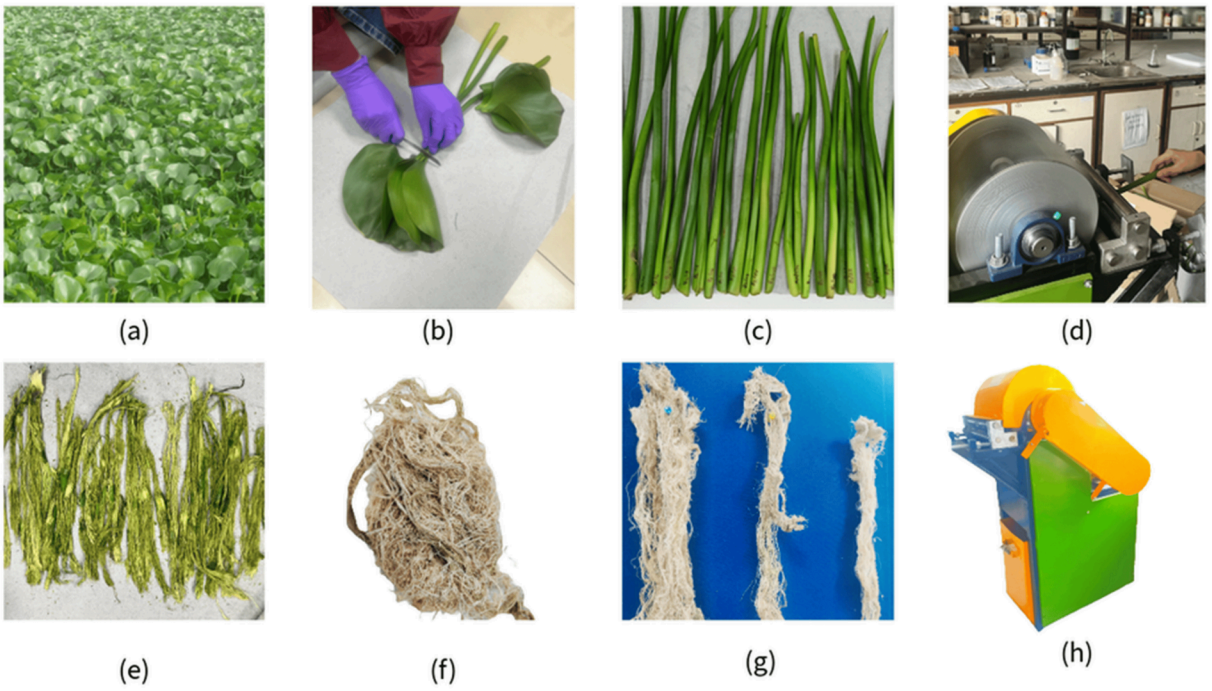


FIGURE 2: (a) Collection of Water Hyacinth; (b) Cutting and Separation of Leaves from Stem; (c) Stems Prepared for Fiber Extraction; (d) Decortication of Water Hyacinth; (e) Extracted Fibers; (f) Dried Fiber in Bunch; (g) Fibers Hanged for Drying; (h) Commercial Fiber Extractor

To assess the initial moisture content of the fiber as shown in Figure *2*(e), representative samples were oven-dried at 105°C for 24 hours following the ASTM D4442-20 standard gravimetric method. Fibers after drying is shown in Figure *2*(f-g). The average moisture content was recorded to evaluate water loss and inform subsequent machine operation parameters.

This systematic preparation protocol ensured uniform and standardized feedstock input across all trials, which was critical for achieving consistency in machine performance evaluation and downstream fiber characterization shown in Figure *3*.

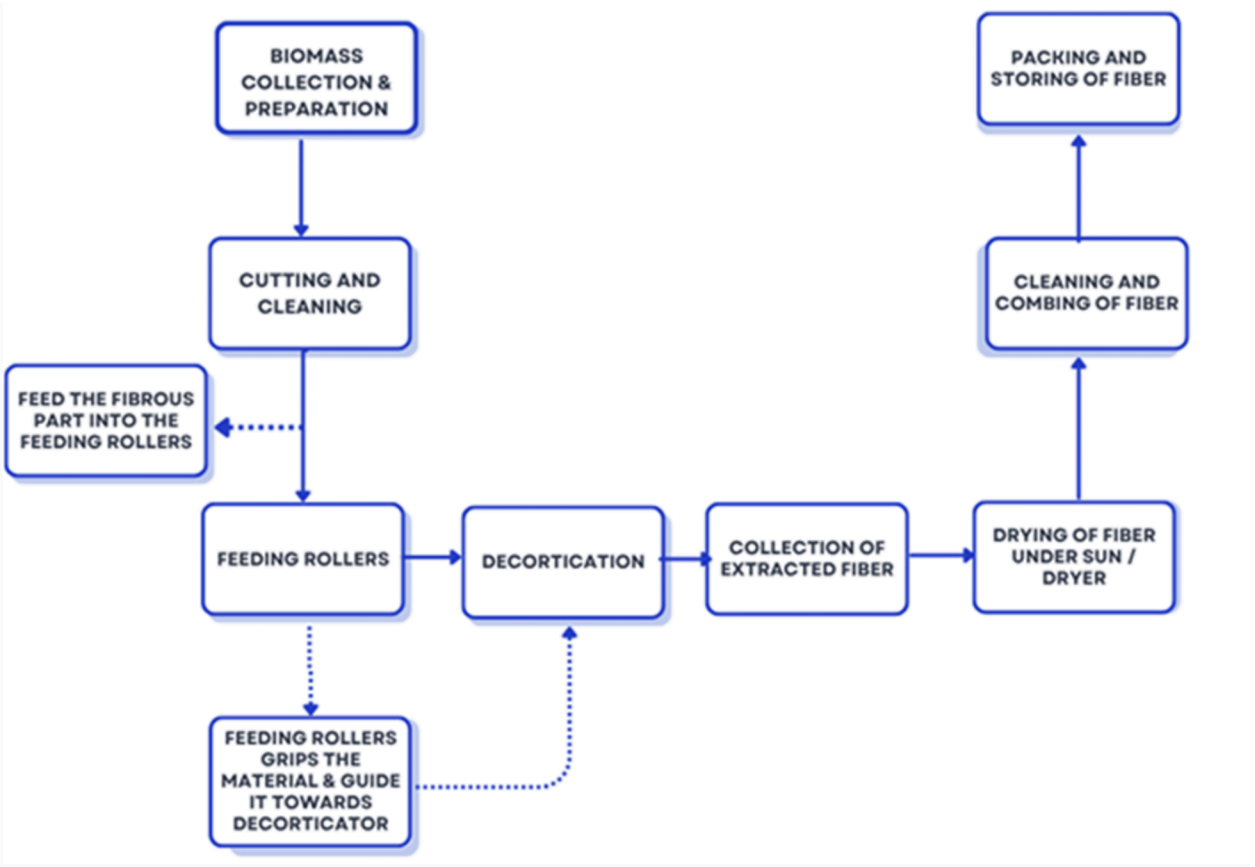


FIGURE 3: Flow Chart of the Generic Fiber Extraction Process Through Mechanical Method

Mechanical characterization of water hyacinth fiber

Mechanical properties of the extracted fibers were evaluated using a Starrett FMS-1000-L2 universal testing machine as shown in Figure *4*. The specimens were subjected to a constant crosshead speed of 5 mm/min with a gauge length of 80 mm. Data acquisition was performed at a high sampling rate using L2 Plus software to capture the precise breaking point and load-displacement characteristics.

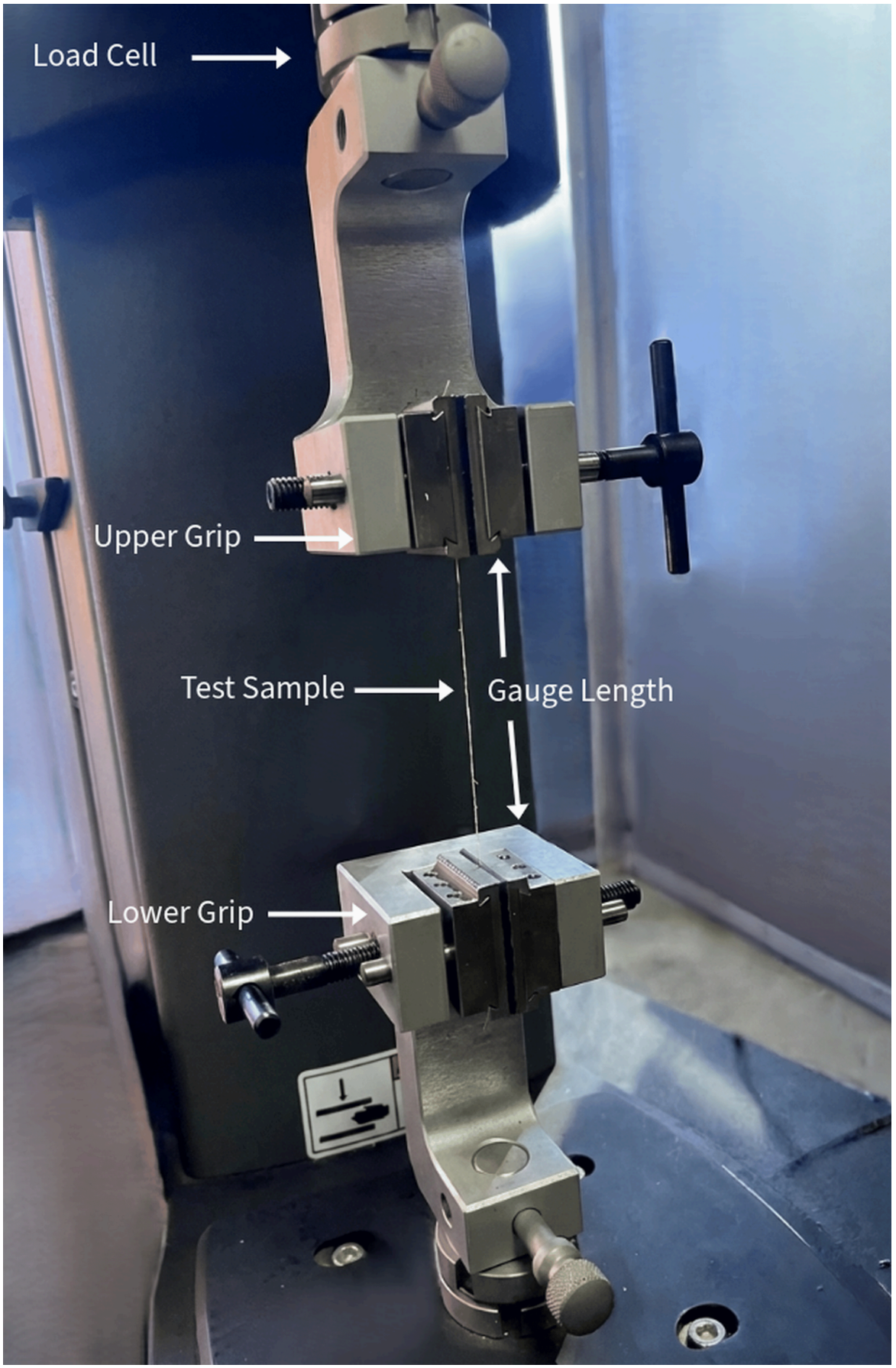

Load Cell
Upper Grip
Test Sample
Gauge Length
Lower Grip

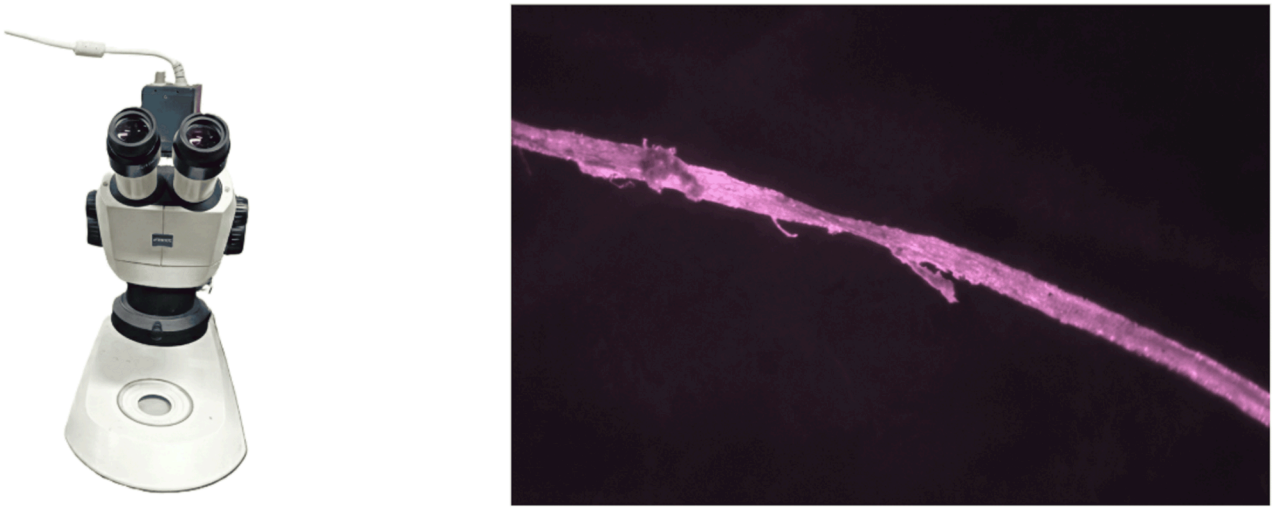
FIGURE 4: Mechanical Analysis of Fiber Using Starrett FMS-1000-L2 UTM

UTM, Universal Testing Machine

Morphological analysis of water hyacinth fiber

The surface morphology of the decorticated water hyacinth fibers was analyzed using a Zeiss Stemi-305 stereo microscope shown in Figure *5*(a). The micrographs shown in Figure *5*(b) revealed a distinct longitudinal cellular structure characteristic of lignocellulosic aquatic biomass. The fiber surface exhibited a relatively rough topography with visible striations, which is indicative of the removal of non-cellulosic constituents like pectin and waxes during the mechanical decortication process.

Unlike terrestrial fibers, the water hyacinth fiber showed a more open, porous arrangement. The optical analysis confirmed that the modular decorticator successfully separated the vascular bundles without causing significant micro-cracks or deep longitudinal shredding, preserving the structural integrity required for mechanical analysis.



(a) (b)

FIGURE 5: (a) ZEISS Stemi 305 Microscope; (b) Micrograph Showing the Surface Topography and Longitudinal Alignment of the Extracted Fiber

Machine description and design parameters

To address the absence of a versatile fiber extraction solution suitable for diverse lignocellulosic biomasses, we repurposed a semi-automatic fiber decortication machine originally developed for banana pseudostem. The machine as shown in Figure *6*(a,b) was selected due to its adaptable mechanical configuration, which we hypothesized could be tuned to accommodate the variable geometry, moisture content, and fiber morphology of materials such as water hyacinth, pineapple, sisal, flax, and hemp. The machine frame as shown in Figure *6*(c), constructed from 40 mm thick mild steel, has a height of 1000 mm and width of 378 mm. Its mass and rigidity serve to minimize vibration during operation. In our performance tests, vibration remained within safe limits without requiring additional dampers.

To ensure cross-biomass adaptability, we integrated adjustable blade pitch and variable roller clearance mechanisms as shown in Figure *6*(d) into the design. These features allowed us to fine-tune the machine for processing soft, moisture-rich stems like water hyacinth as well as more fibrous and tough crops such as sisal or hemp. We did observe that some retrofitting was necessary to avoid excessive fiber entanglement when switching from banana to water hyacinth, specifically in modifying blade sharpness and adjusting feed angle.

As illustrated, the machine comprises a rotor as shown in Figure *6*(e) fitted with eight blades arranged symmetrically along a central shaft. The decortication drum has a total outer diameter of 290 mm, resulting from a 270 mm rotor base with 10 mm blade protrusion on both sides. Each blade measures 258 mm in length and 8 mm in thickness, and weighs approximately 700 g. The total rotating mass, including rotor and blades, amounts to 17.5 kg providing adequate inertial force for continuous cutting and shearing operations. This configuration was found effective during water hyacinth trials, yielding consistent fiber separation without clogging under controlled feed rates.

The rotating shaft is supported by UCP 207 bearings as shown in Figure *7*(a), chosen for their load-handling capacity and ease of maintenance. The shaft itself has a diameter of 35 mm, providing structural stiffness to withstand torsional loads.

Power is delivered by a 2 HP single-phase induction motor as shown in Figure *7*(b) operating at 1440 RPM, selected for its availability in rural settings where three-phase power infrastructure is often lacking. A V-belt transmission system connects the 100 mm diameter driving pulley to an identically sized driven pulley, maintaining a 1:1 speed ratio as shown in Figure *7*(c). The center-to-center pulley distance is fixed at 340 mm, and the V-belt length is 994 mm ensuring proper tension and minimal slippage during operation. Commercial fiber extractor is shown in Figure *7*(d).

All wet-contact components including the decorticating drum and feeding unit were designed to be modular and easily detachable for periodic cleaning. This not only reduces microbial buildup but also ensures hygienic operation during high-moisture biomass processing. We used corrosion resistant alloys for blades and frame components in contact with biomass to extend operational lifespan, particularly for silica- and ash-rich materials like pineapple leaves and water hyacinth.

Table *2* provides a detailed specification of each design parameter. These form the engineering basis for validating the machine's performance across different biomasses. Overall, the adapted design demonstrated reliable operation during trial runs on water hyacinth and offers a scalable framework for multi-biomass fiber decortication in rural or semi-industrial contexts.

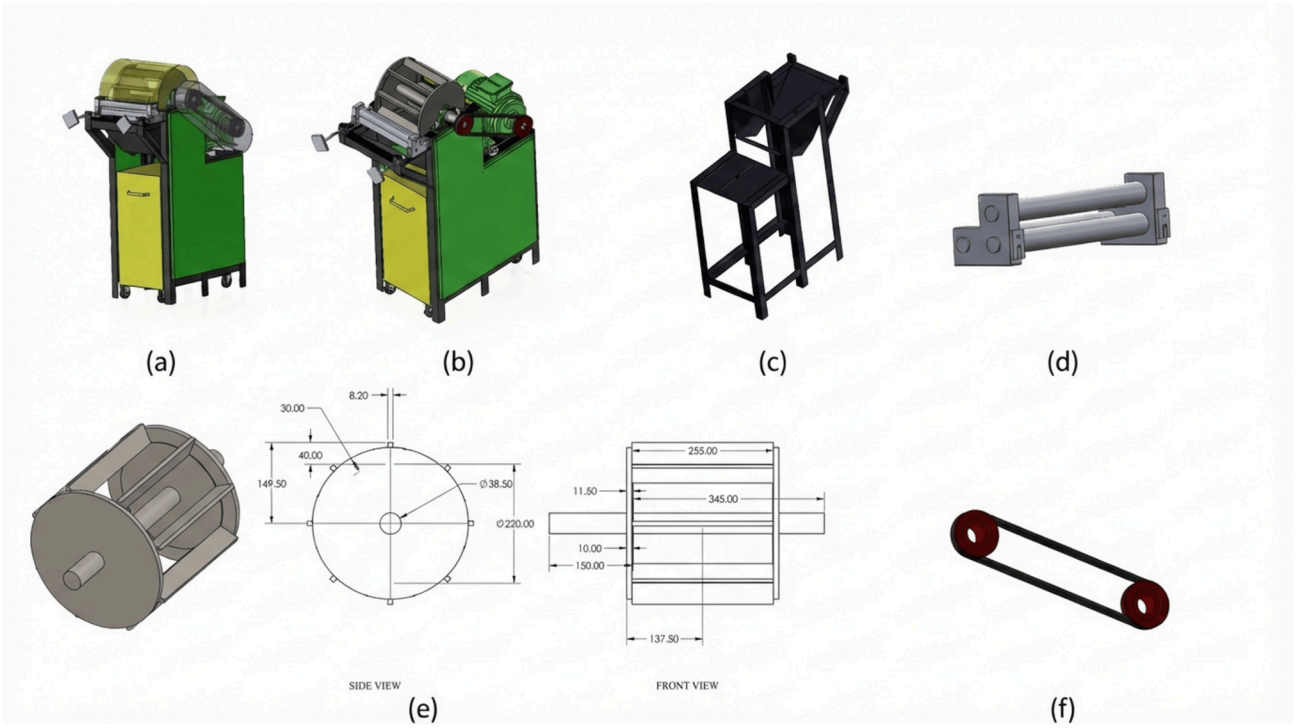


FIGURE 6: (a) CAD Design of the Semi-Automatic Fiber Extraction System; (b) Extractor Assembly Without Protective Casing for Internal Visibility; (c) Structural Frame Supporting the Rotor and Drive Assembly; (d) Feeding Rollers With Bracket for Biomass Intake; (e) Assembled Decorticator Showing the 35 mm Diameter Shaft and 8-Blade Configuration With Technical Drawing; (f) Power Transmission Setup Featuring 100 mm Diameter Driving and Driven Pulleys Connected via V-Belt

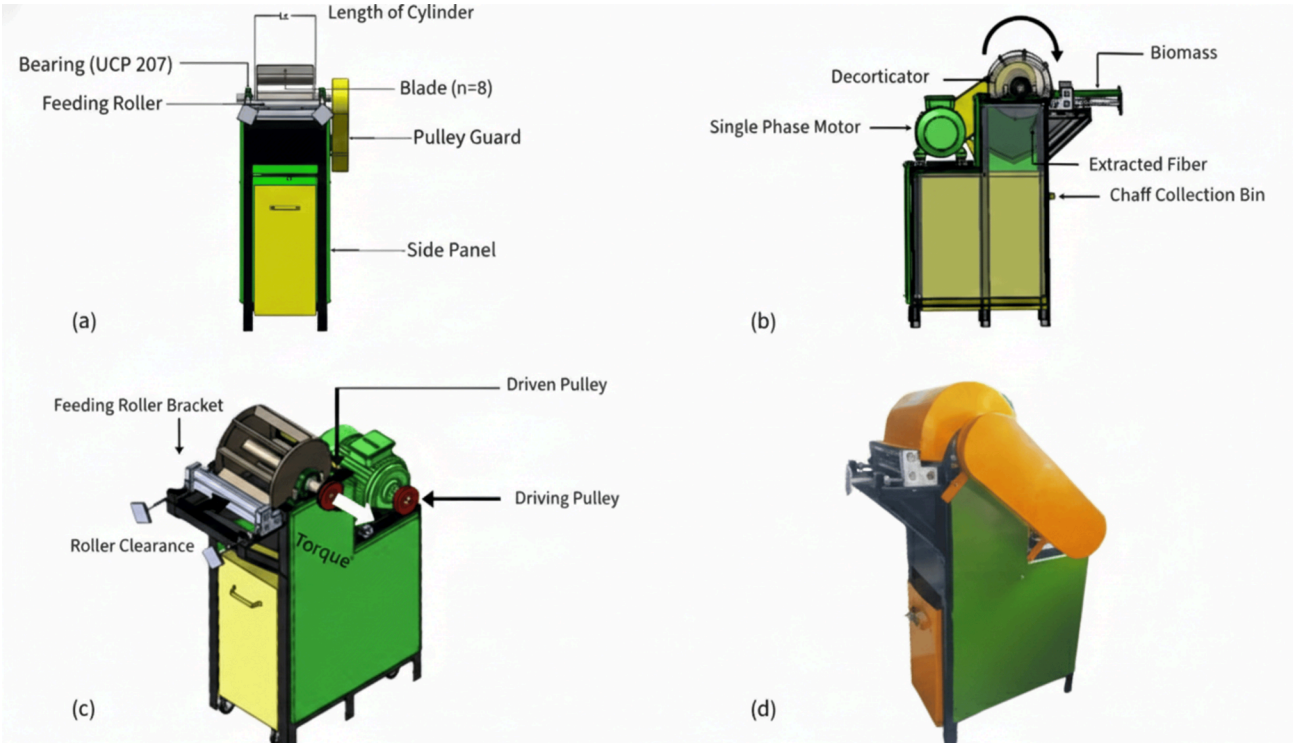


FIGURE 7: (a-c) Detailed Orientation of Major Components and Parameters of Fiber Extractor; (d) Commercial Fiber Extractor

Machine Parameter	Specification
Centre Distance Between Pulleys	340 mm
Decorticating Rotor Radius	135 mm + 10 mm (Blade Extrusion)
	→ Outer Radius = 145 mm
	→ Outer Diameter = 290 mm
Mass of a Single Blade	700 g (per unit)
	→ Total (8 Blades): 5600 g
Number of Blades	08
Blade Thickness	8 mm
Blade Length	258 mm
Decorticating Rotor Length	278 mm
Shaft Diameter	35 mm
Distance Between UCP 207 Bearing and Pulley	15 mm
Overall Mass of Decorticating Rotor (with Blades)	17.500 kg
Driven Pulley Diameter	100 mm
Driving Pulley Diameter	100 mm
Motor Specification	2 H.P/Single Phase/1440 RPM
V-Belt Length	994 mm
Decorticating Rotor Speed	1440 RPM
Bearing Type	UCP 207
Frame Height	1000 mm
Frame Width	378 mm
Frame Thickness	40 mm

TABLE 2: Mechanical Configuration and Component Specifications of the Biomass Decortication Unit

Table 2 details the critical specifications of the semi-automatic fiber extraction machine designed for processing water hyacinth and similar lignocellulosic biomasses. These parameters are essential for ensuring efficient, safe, and reliable operation of the decortication system. The machine parameter table presents a comprehensive summary of the design specifications for a semi-automatic fiber extraction machine specifically engineered for processing water hyacinth and related lignocellulosic biomasses. Each parameter has been carefully selected to optimize operational efficiency, mechanical robustness, and suitability for deployment in decentralized or rural settings. The design addresses the unique challenges associated with high-moisture, silica-rich biomasses such as water hyacinth, ensuring effective fiber extraction while minimizing downtime and wear on machine components.

From rotor geometry and blade configuration to power transmission and frame dimensions, every aspect of the machine has been tailored to promote consistent, high-quality fiber output. The selection of a single-phase motor, appropriate pulley and belt specifications, and robust bearing assembly further enhance the machine's adaptability and reliability. Together, these design choices underpin the machine's capacity to deliver safe, reliable, and efficient fiber extraction, making it well-suited for sustainable biomass processing in resource-limited environments.

Biomass/fiber analysis

A comparative compositional analysis was conducted to assess the compatibility of water hyacinth with other commonly processed lignocellulosic biomasses namely banana, pineapple, sisal, hemp, and flax. The comparison focused on fiber-relevant parameters including cellulose, hemicellulose, lignin, ash, pectin, silica content, tensile strength, fiber diameter, and moisture uptake. These properties directly influence key mechanical performance factors such as blade dulling, torque requirement, clogging risk, and moisture-related corrosion. For example, high ash or silica content, as seen in water hyacinth and pineapple, accelerates tool wear, while elevated pectin levels can lead to fiber clumping, making clean separation more difficult during decortication, as shown in Table 3.

Among the selected biomasses, banana and pineapple exhibit the closest alignment with water hyacinth in terms of hemicellulose content, ash percentage, and general fiber morphology. However, water hyacinth stands out with a lower cellulose range (20-35%) and higher moisture and pectin content, demanding customized mechanical settings such as gentler blade pitch and expanded roller clearance.

Though not perfectly matched, banana and pineapple share layered and irregular fiber structures, respectively types that require adaptable mechanical handling but do not pose the same challenges as strong, unidirectional bast fibers like flax or hemp. These morphological classifications are detailed further in Table 4, which outlines the implications of fiber orientation, strength, and continuity on mechanical processing efficiency.

This clustering supports the rationale for using a modular decortication system with adjustable parameters capable of processing water hyacinth, banana, and pineapple with minimal reconfiguration. The comparative insights gained here are critical for machine validation in later stages and emphasize that although water hyacinth is unique, it can be viably integrated into multi-biomass decortication workflows with targeted design adaptations.

Composition	Water Hyacinth	Banana	Hemp	Pineapple	Sisal	Flax	References
Cellulose (%)	20–35	55–65	65–75	70–82	65–72	70–82	[22]
Lignin (%)	5–13	10–16	3–8	5–12	9–14	2–5	[23]
Hemicellulose (%)	18–32	10–19	18–22	12–18	10–20	15–20	[24]
Pectin Content (%)	4–8	1.5–2.7	0.8–1.5	2–4	1–2	1–2	[25]
Ash Content (%)	10–18	1–3	0.8–1.5	1.1–3.7	0.9–2.5	1–2	[17]
Fiber Structure*	Short, Weak	Layered	Long, Strong	Irregular	Parallel	Fine, Long	[26]
Silica Content (%)	0.5–1.0	0.3–0.7	0.2–0.5	0.5–1.0	2.0–3.0	0.1–0.3	[27]
Tensile Strength (MPa)	50–250	529–914	310–900	170–1627	80–840	300–1500	[22,23]
Fiber Diameter (µm)	80–300	119–130	16–50	20–80	50–200	5–38	[23,24]
Moisture Uptake (%) (Fiber)	94.85–1067	347.1–517.4	6–12	188–201	11–14	6–12	[28-34]

TABLE 3: Comparative Composition of Natural Fibers From Common Non-Conventional Natural Fiber Source

* Fiber Structure row in Table 3 refers to the internal morphology and alignment of fibers within the plant biomass specifically, how fibers are arranged, bonded, and distributed in the stem, stalk, or leaf. These structural traits significantly affect machine design, extraction efficiency, and final fiber quality. Detailed classifications of these structures are provided in Table 4.

Table *3* presents a comparative overview of the chemical composition and physical characteristics of water hyacinth and other lignocellulosic fibers. It highlights the distinctive processing challenges associated with water hyacinth, including its high ash and pectin content, comparatively low cellulose levels, and irregular fiber structure. These factors necessitate customized extraction strategies and underscore the need for adaptable machine design tailored to biomass-specific properties, particularly for sustainable utilization of water hyacinth in fiber production.

Fiber Morphology Type	Structural Description	Mechanical Processing Implications	References
Short, Weak	Fibers are short, loosely bound, and often fragmented.	Easily disintegrates; requires minimal blade force but may clog processing equipment.	[31]
Layered	Fibers arranged in concentric sheaths or layers.	Requires longitudinal separation or controlled shearing; adjustable blade angle and clearance needed.	[35]
Long, Strong	Fibers are continuous, highly tenacious, and well-integrated.	Suitable for decortication; demands higher torque but provides superior fiber yield and quality.	[36]
Irregular	Fibers exhibit non-uniform alignment and density.	Adaptive blade contact necessary; high risk of clogging due to unpredictable curling or entanglement.	[18,37]
Parallel	Fibers are aligned in a consistent, unidirectional manner.	Straightforward processing with properly aligned blades; results in uniform fiber output.	[37]
Fine, Long	Fibers are thin, elongated, and well-oriented.	Requires precise, sharp blades with narrow gaps; low resistance but needs careful handling to avoid damage.	[38]

TABLE 4: Morphological Characteristics of Natural Fibers and Their Implications for Mechanical Extraction Processes

Table *4* serves as a foundational reference for correlating fiber morphology with mechanical extraction strategies. The listed structural types such as short and weak, layered, long and strong, irregular, parallel, and fine and long demonstrate distinct mechanical behaviors during decortication. Each type necessitates specific machine adaptations, including blade geometry, pitch, clearance, and feed rate, to optimize separation efficiency and prevent operational issues like clogging or fiber damage. This classification was directly used in the current study to interpret fiber-machine interactions during processing trials of water hyacinth and other selected biomasses. Understanding these morphological traits is critical to the effective design and deployment of adaptable fiber extraction systems, especially when working with structurally inconsistent feedstocks such as water hyacinth.

Mechanical design calculations for fiber extraction machinery

For better understanding the key parameters common in all fiber extraction process, several research paper were thoroughly reviewed. It was observed that these parameters plays a vital role in fiber extraction. The parameters included the moment of inertia, torque required, efficiency, power for fiber extraction, feed velocity, blade Pitch, cylinder length

[39-42], power required to rotate the decorticator, feed rate, bulk density, and flexural force [40].

In the mechanical design of biomass decorticators, the Moment of Inertia (I) acts as the foundational parameter for estimating the resistance of biomass to bending when subjected to external forces during fiber extraction [39,41]. It is a geometric property that depends entirely on the cross-sectional shape and size of the biomass, mathematically expressed for a rectangular cross-section as [42].

$$I = \frac{B \cdot H^3}{12} (1)$$

Where, B = Breadth of Biomass (across feed section) ; H = Thickness (perpendicular to bending)

Once I is known, it is directly used to compute the Flexural Force (f), which is the bending force required to deform the biomass over a drum or support during mechanical decortication. The flexural force is computed using the relationship [40].

$$f = \frac{EIy}{l^3} (2)$$

Where, E = Modulus of elasticity of the biomass (stiffness); I = Moment of inertia of the biomass cross-section; y = Deflection or deformation assumed in the system; l = Length of the biomass sample or beam span (usually the contact length with the drum) [41].

This equation shows that flexural force increases linearly with material stiffness E, and geometrically with thickness, since Moment of Inertia I depends on thickness as in equation (1). Likewise, increasing the span l significantly reduces f, Since

$$f \propto \frac{1}{l^3} (3)$$

Once f is known, it becomes the basis for determining the torque T required to rotate the decorticator and overcome this resistance. In rotary biomass fiber extraction systems, Torque (T), as shown in Figure *5*(c) is the pivotal mechanical parameter that governs the rotational effort required to overcome the biomass's resistance to deformation. It acts as the link between linear force (applied by blades or rollers) and rotational energy (delivered by the motor and transmitted through the shaft). The basic relationship used to compute torque is [39,40].

$$T = f \cdot r (4)$$

Where, T = Torque required at the decorticator drum; f = Flexural force acting on the biomass; r = Radius of the drum or the point of force application.

Equation (4) highlights that torque is linearly proportional to both the flexural force and the radius of the drum.

Once the required torque is known, it becomes the primary input to calculate the mechanical power P needed by the motor to sustain drum rotation. It is calculated using the fundamental relationship [40].

$$P = \frac{2\pi NT}{60} (5)$$

Where, P = Power in kilowatts (kW); N = Rotational speed in revolutions per minute (RPM); T = Torque in Newton-meters (Nm).

Equation (5) illustrates that power is directly proportional to both torque and speed. This speed corresponds to the motor's near-synchronous operation under a 50 Hz supply, accounting for inherent rotor slip typically observed in squirrel cage induction motors [41,42]. A squirrel cage induction motor was selected due to its high starting torque, robust construction, and compatibility with belt-pulley drive systems. This type of motor is widely preferred for fiber extraction machinery where constant speed, low maintenance, and mechanical durability are essential under biomass loading conditions [40,41,43]. A 4-pole AC induction motor was selected for this application, offering a near-synchronous speed of 1440 RPM under 50 Hz supply conditions. The 4-pole configuration ensures moderate rotational speed and high starting torque, which are ideal for drum-driven fiber extraction mechanisms. This choice eliminates the need for complex gear reductions while maintaining operational stability and fiber extraction efficiency [40,41,43].

Power helps in selection of motor size (kW rating), pulley diameter and belt width. Motor size (kW rating) must be greater than the calculated power, for flexible tolerance. Pulley diameter and belt width must be selected to handle the full torque and RPM. Frame material and structure must be selected for vibration absorption and torque reaction forces caused by this power.

Additionally, knowing the power required allows for the calculation of specific energy consumption (kWh/kg of biomass processed), which is critical for sustainability and economic feasibility.

While the power required to rotate the drum accounts for the machine's rotational motion, the Power for Fiber Extraction P_e specifically reflects the active energy needed to perform the shearing, tearing, and pulling of fibers from the lignocellulosic matrix of the biomass. This is the actual work done on the material and is a more accurate measure of mechanical load when biomass is being decorticated under resistance.

The power for fiber extraction is calculated using the expression [41]

$$P_e = \frac{\pi D_r N f}{60} \quad (6)$$

Where, P_e = Power required for fiber separation (kW); D_r = Diameter of the rotating drum (m); N = Drum rotational speed (RPM); f = Flexural force acting on the biomass (N).

Equation (6) shows that P_e depends linearly on the force applied f and the rotational circumference of the drum (via πD_r). Since f is itself derived from the modulus of elasticity E and moment of inertia I, this power component is biomass-dependent and highly sensitive to both stiffness and cross-sectional geometry.

Thus, P_e captures the actual energy used in the decortication process, not just rotation. Unlike the general power formula in Equation (5), which accounts for the full system load, P_e isolates the energy component directly responsible for separating fibers. It is important as it guides blades design; sharper blades require lower f, reducing P_e. It helps optimize feed rate, high P_e may require slowing the feed to avoid overload. It assists in comparing biomass difficulty, higher P_e implies tougher fiber extraction. It enables energy benchmarking, used in computing specific energy consumption (kWh/kg). In energy-efficient decorticator design, P_e is used to calculate how much of the motor power P is effectively contributing to actual fiber release, and how much is wasted in idle movement or vibration. The power required for fiber extraction is a targeted measure of the energy consumed in the biomechanical breakdown of biomass structure. It is influenced directly by flexural resistance and drum size, and it allows designers to distinguish between useful energy (for extraction) and system losses (friction, inertia). Proper calculation of P_e ensures efficient blade engagement and helps standardize energy use across biomass types [40,41].

Blade Pitch (L_p) refers to the circumferential spacing between successive blades mounted on the rotating drum of a fiber extraction machine. It plays a crucial role in determining the frequency of cutting or impact applied to the biomass as it moves over the drum surface. Uniform and optimized blade pitch ensures effective fiber separation, reduces uncut patches, and maintains mechanical balance. The blade pitch is calculated using the formula [41]:

$$L_p = \frac{\pi D_r}{n} (7)$$

Where, L_p = Blade pitch (mm); D_r = Diameter of the drum (m); n = Number of blades mounted circumferentially.

Equation (7) shows that blade pitch is inversely proportional to the number of blades, increasing the number of blades reduces the distance between them and leads to more frequent contact with the biomass.

Blade Pitch defines the mechanical rhythm of fiber extraction [41]. It controls how often the biomass is engaged during one rotation and therefore directly influences the extraction quality, energy efficiency, and system wear rate. Its correct calibration is essential for balancing throughput with precision, especially when dealing with varied biomass geometries and densities [41].

Cylinder Length (L_c) refers to the axial length of the rotating drum or feedbed required to accommodate and process the incoming biomass effectively as shown in Figure *5*(a). It defines the processing width or the active region where fiber extraction occurs and is vital in determining the machine size, blade distribution, and throughput capacity. It is calculated using the mass flow-based formula [40,41]:

$$L_c = \frac{q}{\mu \cdot \eta \cdot \rho \cdot \alpha} (8)$$

Where, L_c = Required cylinder length (m); q = Biomass feed rate (kg/s); μ = Effective biomass thickness (m); η = Mechanical efficiency of the system (dimensionless); ρ = Bulk density of the biomass (kg/m^3); α = Feed velocity (m/s).

Equation (8) shows that L_c is directly proportional to the biomass input rate and inversely proportional to system capability i.e. the product of thickness, density, feed speed, and machine efficiency.

In the Equation (8), Feed Rate *(q)* refers to the mass of biomass delivered to the decorticator per unit time, typically measured in kilograms per second (kg/s). It is a fundamental input parameter that determines the throughput of the fiber extraction machine and influences the required cylinder length, power input, and motor capacity.

In any mechanical fiber extraction system, Efficiency (η) is a crucial factor that reflects the real-world effectiveness of the machine in converting supplied mechanical energy into useful work i.e., the separation of fibers from biomass. Unlike ideal calculations, real systems are subject to friction, slippage, misalignment, vibrations, and heat loss, all of which reduce efficiency. Efficiency is expressed as a dimensionless ratio between actual output and theoretical input [41].

$$\eta = \frac{\text{Useful Mechanical Output}}{\text{Total Input Power}} (9)$$

In fiber extraction, this "useful output" could be rotational energy reaching the blades, or more specifically, the force used in successfully breaking fibers, while the input is usually motor-driven power. Although η is not directly calculated in early design stages, it becomes a correction factor in key equations where real-world losses must be accounted. A lower efficiency increases the required cylinder length, which cascades into a longer machine footprint and higher power requirements. Several factors affect the efficiency of the machine, which includes blades sharpness and condition majorly worn blades reduces efficiency, Belt/pulley slippage which results in waste torque transfer, Shaft misalignment which results in increase vibration and bearing load.

In Equation (8), Feed Velocity (α) is defined as the rate at which biomass enters or moves through the processing zone of the fiber extraction system. It is typically expressed in meters per second (m/s) and reflects the linear movement of biomass across the length of the drum or feedbed. It is a time-rate control parameter and plays a pivotal role in determining how frequently biomass engages with cutting blades, the load on the system, and ultimately the system's energy and output consistency [41].

In Equation (8), Bulk Density (ρ) is the mass of biomass per unit volume, typically expressed in kilograms per cubic meter (kg/m^3). In contrast, true density refers only to the solid component of the biomass. This distinction is essential, as bulk density governs key machine design variables such as feed rate, required cylinder length, and energy demand in mechanical fiber extraction systems [40,41]. Mathematically, it influences machine design through its role in the cylinder length equation. Cylinder length is inversely proportional to Bulk Density serves as the material foundation upon which biomass throughput, cylinder sizing, and power demand are calculated. By quantifying how much mass is delivered per unit volume, it bridges the gap between biomass characteristics and machine dimensions. Variations in bulk density directly influence system load, energy requirements, and blade interaction frequency, making it an indispensable factor in the design and optimization of fiber extraction systems [40,41].

Results And Discussion

This study assesses the feasibility of using a single semi-automatic decortication system to extract fibers from six lignocellulosic biomasses banana, water hyacinth, pineapple, sisal, flax, and hemp by analyzing whether a common mechanical configuration can accommodate all biomass or only specific biomasses. Key engineering parameters critical to machine design and operation were quantitatively evaluated, including modulus of elasticity (E), flexural force (f), torque (T), mechanical power (P), moment of inertia (I), biomass width (H), and required cylinder length (L_c). The presented ranges reflect values derived through analytical calculations grounded in established mechanical theory, using geometric and material property data gathered from prior literature and adapted to the design specifications of the prototype system. Table *5* consolidates these results, ensuring transparency and reproducibility while accounting for natural variability in biomass morphology. This data-driven approach provides a defensible basis for machine tuning and supports the broader objective of designing an adaptable decorticator capable of multi-biomass processing under real-world constraints.

Parameter comparison

The comparative mechanical analysis revealed significant variation in stiffness, energy requirements, and geometric traits among the six selected biomasses. Modulus of elasticity (E), which determines a material's resistance to deformation under stress, emerged as a critical differentiator. Flax and hemp exhibited the highest stiffness, with E values ranging from 50 to 80 GPa and 30 to 70 GPa, respectively, indicating high resistance to bending. In contrast, water hyacinth showed the lowest modulus (4.5-7.0 GPa), suggesting easier deformation and reduced mechanical resistance during processing. Banana and pineapple presented moderate stiffness values between 18 GPa and 40 GPa, placing them closer to water hyacinth in terms of flexibility.

Flexural force (f), derived from beam bending theory, followed a corresponding trend. High-modulus materials such as flax and hemp required flexural forces exceeding 110 N, while banana and sisal ranged from 85 to 140 N. Water hyacinth and pineapple, being structurally softer, required only 35-60 N of flexural effort, making them less demanding on machine torque and blade engagement.

Using calculated F values and drum radius (r = 0.145 m), torque (T) was determined. Water hyacinth and pineapple required 5.5-7.5 Nm of torque, compared to 16-20 Nm for hemp and flax. This substantial difference reflects both the stiffness and density of the biomass. Power (P), computed using Equation (5), further validated this relationship: lower torque biomasses (e.g., pineapple and water hyacinth) consumed only 0.8-1.2 kW, while higher-resistance materials such as flax and hemp demanded 2.6-3.2 kW.

Moment of inertia (I), calculated from typical biomass cross-sections, was lowest for water hyacinth ($1.20\text{-}1.40 \times 10^{-7}$ m^4) and highest for banana pseudostem ($2.10\text{-}2.40 \times 10^{-7}$ m^4). This parameter directly influenced the bending behavior and was instrumental in predicting torque and power needs.

Cylinder length (L_c), calculated from feed rate, bulk density, efficiency, and feed velocity, ranged from 160 mm for banana to 260 mm for water hyacinth. These differences are primarily driven by moisture content, biomass compaction, and throughput optimization. In case of water hyacinth's loose structure and high moisture, a longer cylinder is necessary to maintain stable feed and consistent cutting performance, whereas denser biomass like banana and hemp can be processed with shorter drum lengths.

Analysis of unified machine feasibility

The comparative evaluation of mechanical parameters indicates that a unified decortication system is not universally applicable across all lignocellulosic biomasses without adjustments. However, a subset namely banana pseudostem, water hyacinth, and pineapple demonstrates considerable compatibility due to shared mechanical characteristics. These include moderate modulus of elasticity (ranging from 4.5 to 32 GPa), relatively low flexural force requirements (35-115 N), and modest torque and power demands (typically under 2.5 kW). These overlapping properties suggest that a single machine design with adaptable features such as variable blade pitch, adjustable roller clearance, and moderate power output can accommodate all three materials without compromising extraction efficiency or machine integrity.

Structurally, these biomasses also exhibit high moisture content and weak or irregular fiber morphology, necessitating specific mechanical configurations. Features like enhanced drainage, anti-clogging mechanisms, and abrasion-resistant components become critical in handling such materials. In the prototype tested, modular blade mounts and a corrosion-resistant frame were particularly effective in supporting consistent fiber release without damage or jamming, validating the machine's baseline suitability for these feedstocks.

Conversely, tougher fibers such as sisal, flax, and hemp presented significantly higher modulus values (up to 80 GPa), increased torque requirements (16-20 Nm), and greater power demands (up to 3.2 kW). These factors place additional stress on the mechanical system and would necessitate specific design reinforcements such as a higher-rated motor, increased structural stiffness, and recalibrated cutting force distribution for efficient decortication. Without such adjustments, fiber quality, energy efficiency, and component lifespan may be compromised when processing these more rigid biomasses.

Therefore, while the current semi-automatic decorticator exhibits strong potential for unified use across banana, pineapple, and water hyacinth, it functions optimally within a specific mechanical envelope. The feasibility of expanding this system to stiffer biomasses lies in developing modular enhancements that allow on-demand adjustment of torque, cutting pressure, and structural robustness. This outcome highlights the importance of parameter-driven machine customization in achieving multi-biomass processing, particularly within low-resource or rural manufacturing environments.

Biomass	Modulus of Elasticity, E (GPa)	Flexural Force, F (N)	Torque, T (Nm)	Power, P (kW)	Moment of Inertia, I ($\times 10^{-7}$ m^4)	Width, H (mm)	Cylinder Length, L (mm)	References
Banana	27–32	85–115	12–16	2.0–2.5	2.10–2.40	28–32	160–170	[44,45]
Sisal	9–22	100–140	14–20	2.3–3.0	1.60–1.70	27	220–240	[46]
Water Hyacinth	4.5–7.0	35–55	5.5–7.5	0.8–1.1	1.20–1.40	25	240–260	[47]
Hemp	30–70	110–140	16–20	2.5–3.2	1.60–1.70	27	195–210	[48-50]
Pineapple	18–40	40–60	5.5–7.5	0.9–1.2	1.40–1.50	26	245–255	[51,52]
Flax	50–80	115–135	16–20	2.6–3.0	1.75–1.85	28	200–210	[53]

TABLE 5: Comparative Mechanical and Geometric Properties of Lignocellulosic Biomass Relevant to Decorticator Design

The analysis of Table *5* reveals critical distinctions in the mechanical performance and decortication requirements of six lignocellulosic biomasses. Notably, flax, hemp, and banana exhibit higher modulus of elasticity and flexural resistance, resulting in greater torque (16-20 Nm) and power demands (2.5-3.2 kW), which necessitate reinforced torque transmission systems and durable frame structures. In contrast, softer feedstocks like water hyacinth and pineapple, characterized by lower stiffness and moment of inertia, require less mechanical effort (5.5-7.5 Nm torque, <1.2 kW power) and are more amenable to adaptive configurations such as adjustable blade pitch, moderate drum lengths (240-260 mm), and lower rotational inertia. These insights directly informed our machine design, where a blade pitch of approximately 114 mm, a 2 HP motor, and a flexible frame layout were selected to accommodate varying biomass rigidity and fiber morphology. The findings underscore the feasibility of a unified fiber extraction system for compatible biomass groups while highlighting the need for tuning in cases of high-strength crops like flax and hemp.

Operational performance analysis of the fiber extraction system

To evaluate the practical viability of the modular semi-automatic fiber extractor under field-like conditions, a performance analysis was conducted. This assessment focused on three key operational aspects such as throughput rate, Extraction Efficiency, Specific Energy Consumption (SEC)-specific energy consumption (performance metric that quantifies the amount of electrical energy required to extract one unit of useful product in this case, 1 kg of fiber) in Table *6*, and observed operating behavior such as noise, vibration, and clogging frequency. These indicators offer a holistic understanding of the machine's performance beyond mechanical design calculations, validating its adaptability to varied lignocellulosic biomasses including water hyacinth, banana pseudostem, and pineapple leaves. SEC is calculated using the equation (10)

$$\mathrm{SEC\ (kWh/kg)} = \frac{P_{\mathrm{input}} \times t}{m_{\mathrm{fiber}}} (10)$$

Biomass	Fresh Biomass Feed Rate (kg/h)	Extracted Fiber Output (kg/h)	Extraction Efficiency (%)	Motor Power (kW)	Processing Time (h)	SEC (kWh/kg fiber)
Water Hyacinth	250	3.5	1.4	1.5	1.0	0.43
Banana Pseudostem	150	3.0	2.0	1.5	1.0	0.50
Pineapple Leaves	200	2.0	1.0	1.5	1.0	0.75

TABLE 6: Throughput, Extraction Efficiency, and Specific Energy Consumption (SEC) of the Modular Fiber Extractor

Banana pseudostem achieved the highest extraction efficiency (2.0%) despite having the lowest feed rate, indicating greater fiber yield per unit of fresh biomass. Water hyacinth, processed at the highest feed rate (250 kg/h), delivered a moderate efficiency of 1.4%, reflecting its low proportion of extractable structural fibers but recording the lowest SEC (0.43 kWh/kg) due to reduced mechanical resistance. Pineapple leaves had the lowest efficiency (1.0%) and the highest SEC (0.75 kWh/kg), suggesting that their tougher structure and higher silica content increased energy demand relative to fiber output. This trade-off shows that while banana offers the best yield, water hyacinth provides an optimal balance between yield and energy efficiency, making it a promising feedstock for low-cost, decentralized fiber valorization in rural settings.

Preparation of biomass fibers for comparative analysis

After extraction, the fibers were allowed to air-dry under normal room conditions so that excess moisture could be removed. Care was taken to select fibers of nearly similar length and diameter to maintain consistency during testing. Before conducting the tensile tests, all samples were kept at room temperature for some time to stabilize their moisture content.

Finally, the fibers were tested using a Universal Testing Machine (UTM) under the same conditions, such as identical gauge length and loading speed. This helped ensure that the differences observed in the results are mainly due to the natural properties of the fibers rather than variations in preparation or testing.

Quantitative assessment of decortication impact on fiber mechanical integrity

The mechanical performance of water hyacinth, pineapple and banana fibers was quantitatively evaluated as shown in Figure *4*. The results, summarized in Table *7*, reflect the structural integrity of the fibers following mechanical extraction. Tensile strength of fibers tested for mechanical characterization is within the range of existing literature discussed in Table *3*.

Metric	Water Hyacinth Fiber (Mean ± SD)	Pineapple Fiber (Mean ± SD)	Banana Fiber (Mean ± SD)
Maximum Load (N)	0.667 ± 0.153	0.912 ± 0.141	0.781 ± 0.128
Elongation at Break (mm)	1.480 ± 0.383	1.635 ± 0.352	2.185 ± 0.417
Time to Failure (s)	17.787 ± 4.637	18.964 ± 4.215	20.376 ± 3.892
Strain at Break (%)	1.850 ± 0.479	2.420 ± 0.438	2.985 ± 0.512
Tensile Strength (MPa)	235.785 ± 54.025	378.452 ± 52.318	428.674 ± 46.205
Young's Modulus (MPa)	9.232 ± 0.917	14.286 ± 0.963	11.742 ± 0.884

TABLE 7: Mechanical Characterization of Water Hyacinth Fibers Extracted via Mechanical Decortication

Morphological characterization of decorticated water hyacinth fibers

The morphological characteristics of the decorticated water hyacinth fibers were examined using a ZEISS Stemi 305 stereo microscope, as shown in Figure *5*(a), with a representative micrograph presented in Figure *5*(b). This stereo microscope provides a continuous magnification range of approximately 8*x*-40*x*, which allows clear observation of the external features of fibrous materials. The instrument is equipped with an integrated LED illumination system and a zoom optical unit, which helps produce well-illuminated and sharp images of the sample surface. Because of its stereo optical configuration, the microscope provides a three-dimensional view of the specimen, making it particularly suitable for examining the surface morphology of natural fibers without requiring complex or destructive sample preparation. Using this system, important structural features such as vascular bundle arrangement, longitudinal striations, fibrillar alignment, and surface irregularities of *Eichhornia crassipes* fibers could be clearly observed. Also, the microscope allows basic dimensional observation, enabling qualitative evaluation of fiber diameter variation, bundle separation, and surface texture, which provide useful insight into the effectiveness of the mechanical decortication process.

The fiber surface displays a distinct longitudinal cellular structure with visible striations, characteristic of lignocellulosic aquatic biomass. The observed rough and porous surface morphology suggests effective removal of surface impurities and non-cellulosic components such as pectin and waxes during the mechanical decortication process. Furthermore, the fibers show minimal micro-cracking or deep longitudinal shredding, indicating that the developed modular decorticator successfully separated the vascular bundles without compromising structural integrity. Such preserved fiber morphology is advantageous for maintaining mechanical strength and facilitating subsequent material processing applications.

Conclusions

This study utilized an existing semi-automatic banana fiber extractor to investigate the mechanical feasibility of extracting fibers from six different lignocellulosic biomasses banana, water hyacinth, pineapple, sisal, flax, and hemp. By analyzing critical design-driven parameters such as modulus of elasticity, flexural force, torque, power, and cylinder length, the study assessed whether overlapping mechanical properties across different biomasses allow for shared processing in a single machine configuration.

The comparative results revealed that banana pseudostem, water hyacinth, and pineapple possess similar mechanical behavior characterized by low to moderate stiffness, torque, and power requirements making them well-suited for processing in a unified decortication system without the need for significant structural modifications. Pineapple is substantially more energy-intensive to process (about 50% higher SEC than banana and 74% higher than water hyacinth), while water hyacinth offers the lowest SEC, making it the most energy efficient of the three on a per kg fiber basis. In contrast, biomasses like flax, hemp, and sisal exhibited higher modulus values and extraction resistance, necessitating reconfiguration or mechanical reinforcement for efficient processing.

The optimized extraction process yielded water hyacinth fibers with a mean tensile strength of 235.79 ± 54.03 MPa and a Young's Modulus of 9.23 ± 0.92 MPa confirming that the mechanical system preserves the structural integrity required for industrial applications.

These findings demonstrate that with appropriate parameter tuning such as adjustable blade pitch, roller clearance, and motor torque, a single decorticator design can be adapted to handle multiple compatible biomasses. This insight supports the development of scalable, cost-effective, and versatile fiber extraction systems for decentralized applications, particularly in resource-limited rural contexts where flexibility across seasonal biomass availability is critical.

Beyond technical performance, the modular semi-automatic fiber extractor demonstrates strong alignment with the SDG framework. It contributes to SDG 6, 7, 8, 9, 11, 12, 13, and 15, addressing ecological, economic, and industrial aspects of sustainability. Its potential to reduce biomass waste, restore clogged waterways, enhance biodiversity, create local jobs, and promote low-carbon production underscores its value as a sustainable technology for inclusive and environmentally responsible development.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

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Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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