UKR Journal of Multidisciplinary Studies (UKRJMS)
Homepage: https://ukrpublisher.com/ukrjms/
Email: submit.ukrpublisher@gmail.com
Volume 1, Issue 10, 2025
ISSN: 3049-432X (Online)

Fibers Extraction Processes of Bambusa Vulgaris (Bamboo) For the Purpose of Ballistic Shield: A Review

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DOI: *https://doi.org/10.5281/zenodo.18031817*

Article History
Original Research Article
Received: 08-12-2025
Accepted: 20-12-2025
Published: 23-12-2025

Citation: Nwosu J. O.; Obiukwu O. O; Ighodaro, O. O.; Anyanwu, E. E., (2025) Fibers Extraction Processes of Bambusa Vulgaris (Bamboo) For the Purpose of Ballistic Shield: A Review, UKR Journal of Multidisciplinary Studies (UKRJMS), 1(10), 33-44.

Abstract

Bambusa vulgaris is a rapidly renewable and highly sustainable plant that has gained significant attention in various industries due to its versatility and eco-friendly nature and offers a rapid replenishment cycle that contrasts starkly with the decades required for many traditional hardwoods to mature. This study investigated the holistic view of Bambusa vulgaris extraction processes as it significant for both academic research and industrial practice. Findings indicate that while the chemical method produces the highest yield, it is accompanied by significant environmental and economic drawbacks, including high energy consumption, waste generation, and elevated operating costs. Conversely, the mechanical method delivers superior fiber quality with moderate yields; however, its energy requirements remain a challenge that impacts overall cost-effectiveness. Notably, the biological extraction process emerged as the most sustainable and economically viable method. Although it yielded slightly lower fiber output, its minimal energy consumption, reduced waste production, and lower operational costs position it as a promising candidate for scalable, eco-friendly bamboo fiber production.

Keywords: *Bambusa vulgaris, Extraction process, Fibers, Biological, Chemical, Mechanical.*

1. INTRODUCTION

Bambusa vulgaris referred to as Bamboo, and by other tribes in Nigeria as Atosi (Igbo), Oparun (Yoruba), Iko (Bini), and kiya (Hausa), is a giant woody plant, which can be used for buildings, furniture, textiles and as a food resource, as it can as well provide a natural ligno-cellulosic fiber, which can be extracted from the bamboo culm, and found in tropical and subtropical areas, especially in the monsoon and wet tropics, (Bystriakova and Kapos, 2006; Panda, 2011). And is often referred to as “green gold,” stands out as one of the most renewable natural resources available today. Owing to its extraordinary growth rate certain species can grow up to 91 centimeters (35 inches) per day (FAO, 2010; Toyin *et al.,* 2014). Bambusa vulgaris offers a rapid replenishment cycle that contrasts starkly with the decades required for many traditional hardwoods to mature. This rapid growth not only ensures a constant supply of biomass but also facilitates significant carbon sequestration, making the cultivation of Bambusa vulgaris an effective tool in mitigating climate change, as well it possesses remarkable adaptability across diverse climatic conditions, thriving in tropical and subtropical regions with minimal inputs. Its resilience to pests and diseases reduces the need for synthetic pesticides, thereby lowering chemical usage and environmental contamination (Sutton, 2016; Liese, 2015).

Fig 1.1: *Pictorial view of a Bambusa ulgaris(bamboo).*

Bambusa vulgaris is a rapidly renewable and highly sustainable plant that has gained significant attention in various industries due to its versatility and eco-friendly nature. It is widely recognized as one of the most sustainable natural resources due to its rapid growth, minimal resource requirements, and ability to regenerate without replanting, above 90% of the whole weight the bamboo is made up of cellulose, hemi-cellulose, and lignin, while the remaining minor parts are soluble polysaccharides, waxes, resins, tannins, proteins and ashes (Li et al., 2007; Nayak and Mishra, 2016). As a member of the grass family (Poaceae), the Bambusa vulgaris exhibits unique properties that make it an attractive alternative to traditional materials. It can grow up to 91 cm per day under ideal conditions, making it one of the fastest-growing plants in the world (Liese, 2015; Chen et al., 2019a), This rapid growth allows for frequent harvesting, reducing pressure on forest resources and contributing to environmental conservation, which further enhances its ability to absorb large amounts of carbon dioxide while releasing significant amounts of oxygen, making it an effective carbon sink (Scurlock et al., 2000). The robust root systems of Bambusa vulgaris also help prevent soil erosion, maintain watershed stability, and hence further enhances its environmental credentials. These characteristics position bamboo as a critical component in sustainable agriculture and reforestation projects, where environmental restoration is as important as resource production, (Chen et al., 2019b).

Fig 1.2: *Bambusa vulgaris root*

The multi-purpose nature of bamboo extends from traditional uses in construction and handicrafts to modern applications in renewable energy and bio-based materials, underscoring its versatility and importance in a sustainable future. One of its key applications is in fiber production, where different extraction methods yield fibers with varying properties. Bambusa vulgaris fiber has emerged as a highly valued material in modern industries due to its exceptional mechanical properties and eco-friendly profile. Bamboo fiber is utilized in textiles, construction, and composite materials, making it an essential resource in sustainable development efforts, (Kumar and Bhowmick, 2017). However, the efficiency and quality of bamboo fiber depend largely on the extraction process used, leading to inconsistencies in fiber properties and limiting its full potential in industrial applications. Most notably, in the textile industry, bamboo fibers are celebrated for their natural softness, breathability, and inherent antimicrobial qualities, which contribute to enhanced comfort and hygiene in apparel and home textiles (Huang, 2017; Kumar et al., 2021). This fiber's natural aesthetic appeal makes it an attractive option for sustainable design in interior décor, furniture, and even packaging. Its ability to be processed into various forms ranging from fine textile yarns to coarse reinforcements in structural composites demonstrates its versatility across industries. In the realm of sustainable materials, bamboo fiber is integral to reducing the carbon footprint of products, thereby supporting green building initiatives and environmentally responsible manufacturing practices. The fibers possess high tensile strength and low density, attributes that are essential for reinforcing polymers and other matrices in composite structures. Such composites are finding applications in automotive components, construction panels, and consumer goods, where the balance of lightweight characteristics and structural integrity is paramount (Tham, 2018). Replacing synthetic reinforcements like glass or carbon fibers with bamboo not only reduces the environmental burden associated with manufacturing these conventional materials but also aligns with circular economy principles by enhancing biodegradability (Huang, 2017). Hence, ongoing research is focused on enhancing processing techniques to optimize fiber extraction and maximize the inherent benefits of bamboo. Consequently, bamboo fiber is not merely a replacement for conventional materials; it is a transformative resource that bridges traditional practices with modern sustainable technologies (Tham, 2018; Kumar et al., 2021). Historically, fiber extraction has relied on chemical processes that effectively break down the lignocellulosic matrix to release the fibers. While these chemical methods can yield high-quality fibers, they often involve the use of aggressive chemicals that pose significant environmental hazards, including water pollution and the generation of hazardous waste (Tham, 2018). Such environmental risks have prompted the search for more sustainable alternatives. Mechanical extraction offers one such alternative by using physical force to separate the fibers from the bamboo matrix. This method reduces chemical dependency, thereby diminishing the potential for environmental contamination. However, mechanical processing can be energy-intensive, and if not optimized, it may also damage the delicate structure of the fibers, compromising their strength and durability (Huang, 2017). Innovations in mechanical processing, such as advanced cutting and decortication techniques are therefore critical to ensure that fiber quality is maintained while energy consumption is minimized. Economic considerations further underscore the need for efficient and eco-friendly extraction processes; hence, optimized methods can lower production costs, reduce waste, and improve the competitiveness of bamboo-derived products in global markets. Bamboo fiber extraction faces a range of technical, environmental, and economic challenges that hinder its optimal industrial utilization. One significant challenge is the prevalent reliance on chemical extraction methods. While these methods efficiently dissolve the lignocellulosic matrix to release high-quality fibers, they involve harsh chemicals that generate hazardous waste and contribute to water and soil contamination if not managed properly. The disposal and recovery of these chemicals not only increase operational costs but also impose additional regulatory burdens, making chemical processes less attractive from a sustainability standpoint (Huang, 2017; Tham, 2018; FAO, 2010). With rising regulatory pressures and growing consumer demand for sustainable products, industries are incentivized to adopt greener technologies. Given the multifaceted challenges in bamboo fiber extraction, a systematic comparison of different extraction techniques is essential to identify and optimize the best practices for industrial application. An increasingly promising approach is biological extraction, which employs naturally occurring enzymes or microorganisms to gently break down non-fibrous components. This method operates under mild conditions, significantly reducing the generation of toxic by-products and aligning with the principles of green chemistry (FAO, 2010). Collectively, these five comparative studies (Tham, 2018; Huang, 2017; Liese, 2015; Sutton, 2016; Chen et al., 2019) have provided valuable insights into the relative merits and limitations of each extraction technique. Despite variations in methodology and evaluation criteria, these studies consistently highlight the need for a balanced approach that optimizes fiber quality, environmental sustainability, and economic feasibility. This body of work lays a solid foundation for further research and underscores the importance of developing standardized protocols for bamboo fiber extraction, as the study intends to investigate a holistic view of bamboo extraction processes.

1.1 Properties of Bambusa Vulgaris Fiber

Botanically, bamboo is characterized by its hollow, segmented culms (stems) and an intricate network of nodes and internodes. These culms, composed primarily of cellulose, hemicellulose, and lignin, provide exceptional tensile strength and resilience. The high cellulose content is particularly significant, as it contributes to the fiber's durability and biodegradability, making bamboo an ideal candidate for sustainable material applications (Liese, 2015). The physical properties of bamboo are further enhanced by its unique growth pattern. Certain species can grow up to 91 centimeters (35 inches) per day, reaching full maturity in as little as three to five years, a stark contrast to traditional timber species that may take decades to mature (FAO, 2010). This rapid growth rate is underpinned by an efficient nutrient uptake system and a robust root network that stabilizes soil and minimizes erosion. Additionally, bamboo's vascular structure, with its well-defined fibrous bundles, is central to the extraction of high-quality fibers. These bundles provide the mechanical strength necessary for various applications ranging from textiles to structural composites. Hence, the botanical architecture of bamboo allows it to be both lightweight and strong. Its hollow structure reduces the overall density while maintaining rigidity, thereby optimizing its strength-to-weight ratio. This unique combination of properties makes bamboo fibers particularly attractive for use in composite materials where both durability and low weight are essential. In essence, the botanical and physical characteristics of bamboo rapid growth, high cellulose content, hollow culms, and excellent tensile strength form the foundational attributes that not only support its widespread use in various industries but also promote its role as a renewable and sustainable resource (Sutton, 2016; FAO, 2010).

1.2 Process of Extracting Bambusa vulgaris Fiber

The process of extracting bamboo fiber involves several steps, including:

- Cutting: The bamboo is cut into smaller pieces, such as strips or chips
- Digesting: The bamboo is digested to remove fat, starch, protein, and saccharide.
- Mechanical processing: The bamboo is mechanically beaten, torn, and split to open the fibers.
- Screening and drying: The bamboo fibers are screened and dried.
- Roller crusher: The bamboo is cut into small pieces using a roller crusher.
- Pin-roller: The small pieces are extracted into coarse fiber using a pin-roller
- Dehydrator: The coarse fibers are boiled at 90 °C for 10 hours to remove fat and then dried in a rotary dryer.
- Steam explosion or heat steaming: These methods are used to extract fiber for bamboo fiber-reinforced composites.
- Retting: This method is used to extract fiber for bamboo fiber-reinforced composites.
- Grinding: This method is used to extract fiber for bamboo fiber-reinforced composites

Bamboo fiber is a natural, biodegradable, and environmentally friendly textile raw material. It can be blended with other materials such as cotton, hemp, tencel, modal, polyester, spandex, and silk.

1.3 Current Applications and Industry Standards

Modern processing techniques have enabled the conversion of raw bamboo into a refined fiber that can be spun into yarn, woven, or knitted to produce fabrics that meet high-performance standards. The versatility of bamboo fiber has led to its integration into a broad spectrum of applications across various industries. In the textile sector, bamboo fibers are prized for their softness, breathability, and natural antimicrobial properties, making them an increasingly popular alternative to cotton and synthetic fibers in apparel and home textiles (Huang, 2017). These advancements have driven the adoption of bamboo in eco-friendly fashion, promoting sustainability in an industry traditionally associated with high environmental impact. In the realm of composites, bamboo fibers are employed as reinforcing agents in polymer matrices to produce lightweight yet robust materials. Industry standards for composite materials now increasingly recognize the need for renewable reinforcements, prompting research into optimizing bamboo fiber extraction and treatment methods to meet rigorous mechanical and durability requirements. Additionally, bamboo fibers are used in sustainable building materials, such as particle boards and fiber-reinforced panels. However, these applications leverage bamboo's inherent strength and environmental benefits, aligning with green building certification programs and sustainable construction practices. The increasing emphasis on reducing carbon footprints has accelerated the integration of bamboo-based materials into mainstream construction, thereby setting new industry benchmarks for performance and environmental responsibility. Standardization in bamboo fiber production is gradually evolving, with emerging guidelines aimed at ensuring quality and consistency across applications. These industry standards address parameters such as fiber length, tensile strength, and moisture content, providing a framework that manufacturers can use to maintain product quality (Liese, 2015). Overall, the current applications of bamboo fiber span textiles, composites, and sustainable construction materials, reflecting a growing recognition of bamboo as a key renewable resource in modern industry.

1.4 Bambusa vulgaris Fiber Extraction Methods

1.4.1 Mechanical Extraction

Mechanical extraction of bamboo fiber relies on physical force to separate the fibers from the lignocellulosic matrix, offering an alternative that avoids the use of hazardous chemicals. The process typically begins with the pre-treatment of bamboo culms, where the outer bark is removed and the culms are decorticated using specialized machinery such as decorticators or roller mills (Tham, 2018). Decortication effectively frees the inner fiber bundles by mechanically cleaving the structural bonds that hold the fibers together. Subsequent processes such as crushing, grinding, and refining further disintegrate the bamboo structure, facilitating the liberation of individual fibers. Mechanical extraction is lauded for its environmental benefits. By eliminating chemical reagents, this method significantly reduces the risk of generating toxic effluents, thereby lowering the need for expensive waste management systems (Huang, 2017). Furthermore, modern mechanical systems can be designed for energy efficiency by optimizing operational parameters such as pressure, speed, and mechanical force application. Efficiency metrics in this method include fiber yield, uniformity, and the preservation of intrinsic fiber properties like tensile strength and fineness. However, achieving an optimal balance is challenging; excessive mechanical force can lead to fiber damage or breakage, thereby reducing the overall quality and mechanical performance of the extracted fibers (Liese, 2015). In contrast to chemical extraction, mechanical methods can suffer from variability in fiber quality due to differences in equipment design and operational conditions. The physical nature of the process often results in fibers with irregular dimensions and potential damage to the cellulose structure. To address these issues, recent research focuses on refining mechanical designs and incorporating automation and real-time monitoring systems that adjust processing parameters dynamically. Moreover, hybrid methods that combine mechanical pre-treatment with mild chemical or biological treatments are emerging as promising alternatives to enhance fiber quality while retaining the environmental advantages of mechanical extraction. Overall, while mechanical extraction provides a more sustainable route for bamboo fiber production, continuous improvements in equipment design and process control are crucial for optimizing fiber yield and maintaining high-quality outputs.

1.4.2 Chemical Extraction

Chemical extraction is a widely adopted method for isolating bamboo fibers, largely because of its effectiveness in dissolving the lignocellulosic matrix that binds the fibers together. In this process, bamboo culms are typically treated with strong chemical agents such as sodium hydroxide (NaOH) to degrade hemicellulose and lignin, the non-cellulosic components that inhibit fiber liberation (Huang, 2017). Additionally, bleaching agents like hydrogen peroxide (H_2O_2) or sodium hypochlorite may be introduced to improve fiber brightness and purity. The reaction mechanism involves the hydrolysis and saponification of ester bonds present in the lignin-hemicellulose network. This chemical attack results in the solubilization of these components, leaving behind a relatively pure cellulose fiber suitable for further processing in textiles or composites (Tham, 2018). One of the significant advantages of chemical extraction is its high efficiency in producing uniform fibers with controlled dimensions and enhanced surface reactivity. This method allows for precise adjustments of parameters such as chemical concentration, temperature, and reaction duration, thereby tailoring the process to meet specific industry requirements. However, these benefits are accompanied by notable drawbacks. The use of harsh chemicals not only poses environmental challenges such as the generation of toxic effluents and hazardous waste but also necessitates elaborate treatment systems to mitigate adverse impacts on water and soil quality (FAO, 2010). Additionally, if the reaction conditions are not rigorously controlled, there is a risk of degrading the cellulose chains, which can compromise the mechanical integrity of the fibers (Liese, 2015). The operational costs associated with chemical reagents and the required safety measures further add to the complexity of scaling up this method for industrial applications. Nonetheless, ongoing research is directed toward optimizing chemical protocols and developing greener alternatives, such as employing less aggressive chemicals or integrating recycling methods for chemical reagents. These innovations aim to preserve the advantages of chemical extraction while reducing its environmental footprint. Overall, chemical extraction remains a critical method for bamboo fiber production when high purity and uniformity are prioritized, despite its environmental and economic challenges.

1.4.3 Biological Extraction

Biological extraction harnesses the power of enzymes or microorganisms to selectively degrade non-cellulosic components of bamboo, offering a highly eco-friendly alternative for fiber separation. In this process, bamboo culms are subjected to a pre-treatment stage where they are exposed to specific enzymes such as cellulases, hemi-cellulases, and ligninases. These biological catalysts target and hydrolyze the glycosidic bonds in hemicellulose and lignin, effectively liberating the cellulose fibers while preserving their structural integrity (FAO, 2010). Alternatively, microbial fermentation methods use specific strains of bacteria or fungi to facilitate similar degradation processes under controlled environmental conditions. The reaction mechanisms in biological extraction are complex yet highly selective. The enzymatic action occurs under mild conditions typically at moderate temperatures and near-neutral pH levels which minimizes the degradation of the cellulose backbone and helps maintain the mechanical properties of the fibers (Tham, 2018). One of the most notable advantages of this method is its minimal environmental impact. Without the need for harsh chemicals, biological extraction produces little to no toxic waste, significantly reducing the ecological footprint and associated disposal costs (Huang, 2017). Moreover, the energy requirements are generally lower compared to mechanical methods since the reactions are driven by biological processes rather than high-intensity mechanical forces. However, biological extraction also presents certain challenges. The process tends to be slower than chemical and mechanical methods, often requiring extended incubation periods to achieve complete degradation of the lignocellulosic matrix. Moreover, maintaining optimal conditions for enzyme activity such as precise control of pH, temperature, and enzyme concentration is critical for achieving consistent fiber quality and yield (Liese, 2015). The variability in the activity of biological agents can result in fluctuations in fiber properties, which complicates scaling up the process for industrial applications.

Recent research efforts are focusing on developing cost-effective enzyme production methods and robust microbial strains that can operate efficiently at larger scales. Additionally, hybrid approaches that integrate biological pre-treatment with mechanical refining are being explored to accelerate processing times while preserving environmental benefits. Overall, biological extraction represents a promising avenue for sustainable bamboo fiber production, aligning well with global initiatives for greener manufacturing practices.

- ***Summary of Past Comparative Studies***

Over the past decade, several studies have undertaken comparative analyses of bamboo fiber extraction techniques, shedding light on the benefits and drawbacks of chemical, mechanical, and biological processes. Liese (2015) contributed to the discourse by examining bamboo as a renewable resource and including a comparative discussion on extraction methods. His work highlighted that while all methods have potential, balancing fiber quality with environmental and economic considerations is crucial for sustainable development. Similarly, Sutton (2016) provided insights into the economic and industrial viability of these methods. He argued that while chemical extraction is often favored for its efficiency at the laboratory scale, its scalability is limited by environmental regulations and higher operational costs. Huang (2017) extended this discussion by focusing on sustainable processing within the textile sector. By comparing chemical and biological extraction methods, Huang emphasized that although chemical methods offer precise control over fiber properties, their environmental impact is considerably higher than that of biological methods. The latter, despite operating under milder conditions and generating fewer toxic by-products, tend to have slower processing times, which may affect industrial scalability. Tham (2018) provided one of the most comprehensive reviews by comparing these three approaches. His study detailed that while chemical extraction yields fibers with high purity and controlled morphology, it also entails significant environmental challenges due to the use of caustic reagents. In contrast, mechanical extraction was noted for its eco-friendly attributes; however, it often resulted in inconsistent fiber quality due to physical damage during processing. In addition to these, Chen et al. (2019) conducted an experimental study that quantitatively compared fiber yield, tensile strength, and energy consumption among the different extraction techniques. Their data underscored the trade-offs between process efficiency and fiber quality. For example, although chemical extraction produced the highest yield, it also led to a reduction in tensile strength compared to fibers extracted via mechanical methods.

2 METHODOLOGY

This study is structured as a comparative experimental investigation aimed at evaluating the performance of bamboo fiber extraction methods; chemical, mechanical, and biological under controlled conditions. The design involves a systematic approach wherein identical bamboo samples, standardized in terms of species, age, and cultivation conditions, are subjected to each extraction process. The experimental setup ensures that only the extraction method varies, while all other variables, such as pre-treatment procedures, sample size, and environmental conditions (e.g., temperature and humidity), remain constant. This controlled approach enables the direct attribution of observed differences in fiber yield, quality, and environmental impact to the extraction process itself. This research design not only facilitates a comparative analysis of the efficiency and sustainability of different extraction methods but also enables the identification of key process parameters that can be optimized for industrial application. By aligning the experimental protocols with standardized industry testing, the study's outcomes are expected to offer actionable insights for both academic research and industrial practice. This holistic approach bridges the gap between laboratory-scale findings and real-world application, ultimately contributing to the development of more sustainable and cost-effective bamboo fiber extraction processes.

2.1 Sourcing of Raw Bambusa vulgaris

The sourcing of raw bamboo is a critical step in ensuring the consistency and reliability of fiber extraction studies. Raw bamboo must be selected based on its availability, quality, and sustainable cultivation practices. In many studies, bamboo from Southeast Asia is favored due to its extensive cultivation and the presence of several high-quality species (FAO, 2010). Researchers typically opt for bamboo grown under controlled agricultural conditions, where parameters such as soil composition, climate, and water availability are optimized. Such conditions not only improve the mechanical properties of the bamboo but also ensure a steady supply of culms that meet the necessary industrial standards. In sourcing bamboo, particular attention is given to the maturity of the plant. Mature culms, usually harvested at 3 to 5 years of age, are preferred because they offer a higher cellulose content and more robust fiber structure compared to younger bamboo, which might have higher moisture content and less developed lignocellulosic structures (Liese, 2015). Furthermore, sourcing from suppliers who adhere to sustainable harvesting practices ensures that the bamboo is collected without depleting natural resources, thereby maintaining ecological balance. Partnerships with certified bamboo farms can provide traceability and quality assurance, which are essential for reproducible research outcomes. Another consideration in sourcing raw bamboo is the minimization of chemical residues and environmental contaminants. Bamboo grown organically or under low pesticide regimes is highly desirable, as contaminants can interfere with both the extraction process and the integrity of the fibers. By carefully selecting raw bamboo that meets these criteria, researchers establish a reliable foundation for subsequent processing and extraction experiments.

2.2 Selection Criteria for Extraction Processes

The selection of extraction processes for this comparative study is guided by a set of clearly defined criteria that ensure the relevance and robustness of the research outcomes. Firstly, the processes are chosen based on their prevalence and potential in current industrial applications. The chemical, mechanical, and biological methods are included because they represent the primary techniques employed in bamboo fiber extraction today (Huang, 2017; Liese, 2015). Each method must have documented usage in academic or industrial settings, demonstrating its feasibility and scalability. Secondly, the criteria emphasize the sustainability and environmental impact of each process. Methods that utilize harsh chemicals or generate significant waste are evaluated against those that operate under milder conditions with lower ecological footprints. This aspect is critical in the current context of increasing environmental regulations and the global shift towards greener manufacturing practices (Tham, 2018). Furthermore, the operational efficiency measured in terms of energy consumption, processing time, and fiber yield forms a crucial selection parameter, ensuring that only processes with practical industrial relevance are considered. Cost effectiveness is also a vital criterion. The processes must offer a balance between operational costs and the quality of the extracted fibers, thereby making them attractive for commercial adoption. In addition, the selected methods are evaluated based on their adaptability to hybridization, which could potentially combine the benefits of different techniques to achieve superior results. This comprehensive set of criteria ensures that the study not only compares established methods but also identifies avenues for innovation and improvement in bamboo fiber extraction. By doing so, the research aims to propose optimized processes that meet both economic and environmental sustainability targets.

2.3 Standardization of Samples (Age, Species, Pre-treatment)

Standardizing bamboo samples is essential for minimizing variability and ensuring that any observed differences in fiber quality or extraction efficiency are attributable solely to the extraction methods used. One of the primary factors for standardization is the age of the bamboo culms. Bamboo's biochemical composition changes significantly with age; mature culms typically possess higher cellulose and lower moisture contents compared to younger ones (Liese, 2015). Therefore, for consistent fiber quality, only culms within a specified age range usually between 3 to 5 years are selected. This age standardization helps in maintaining uniformity in the lignocellulosic matrix, which is critical for reproducible extraction outcomes. Equally important is the selection of a single bamboo species or a clearly defined set of species. Different species exhibit variations in anatomical structure and chemical composition, which can affect the efficiency of fiber extraction (FAO, 2010). By choosing a single species, the study eliminates one significant source of variability, thereby focusing solely on the impact of the extraction method. When multiple species are involved, rigorous classification and documentation become necessary to account for inter-species differences. Pre-treatment standardization further enhances sample uniformity. Pre-treatment processes, such as cleaning, cutting, and controlled drying, are performed uniformly across all samples to remove contaminants and reduce moisture content. In some cases, mild chemical pre-treatments are applied to soften the bamboo matrix, ensuring that the starting material for each extraction method is as similar as possible. This controlled pre-treatment is crucial for isolating the effects of the extraction technique itself from the inherent variability in raw materials. By rigorously standardizing bamboo samples in terms of age, species, and pre-treatment, the study ensures that the experimental comparisons are valid and reproducible. Such meticulous control over sample preparation provides a robust foundation for evaluating and optimizing bamboo fiber extraction methods, ultimately contributing to advancements in sustainable material processing.

2.4 Data Collection Parameters

2.4.1 Yield Measurement: Quantitative Assessment of Fiber Output

Yield measurement is a critical data collection parameter that quantifies the efficiency of bamboo fiber extraction processes. In this study, yield is determined by measuring the mass of fibers produced per unit mass of raw bamboo processed. Initially, raw bamboo samples are weighed before undergoing any extraction process. After extraction, the resulting fiber mass is measured, and the yield is calculated as the ratio of extracted fiber mass to the initial raw material mass. This quantitative assessment provides a direct measure of the extraction efficiency and helps in comparing the performance of chemical, mechanical, and biological methods (Tham, 2018). To ensure accuracy, multiple replicates are processed under identical conditions, and the average yield is computed. Statistical methods, such as analysis of variance (ANOVA), are applied to determine the significance of yield differences among the methods (Huang, 2017). Additionally, yield data are correlated with process parameters like reaction time, temperature, and energy consumption to identify optimal conditions for maximum fiber recovery. This comprehensive yield measurement not only aids in evaluating the feasibility of each extraction method at the laboratory scale but also provides insights into potential scalability for industrial applications. High yield values are indicative of efficient resource utilization and are essential for reducing operational costs, thereby supporting sustainable production practices (FAO, 2010).

2.4.2 Quality Analysis: Mechanical Properties and Microscopic Analysis

Quality analysis of bamboo fibers encompasses the evaluation of mechanical properties such as tensile strength and flexibility, along with microscopic examinations of fiber morphology. Tensile strength tests measure the maximum stress that bamboo fibers can withstand before failure, providing insights into their load-bearing capacity a critical factor for applications in textiles and composites (Liese, 2015). Flexibility assessments evaluate the fibers' ability to bend without breaking, ensuring that they maintain structural integrity under dynamic conditions.

Microscopic analysis, often conducted using scanning electron microscopy (SEM) or optical microscopy, reveals detailed surface characteristics, including fiber diameter, surface roughness, and the extent of fibrillation. This analysis helps identify defects, discontinuities, or irregularities in fiber structure that could compromise mechanical performance (Tham, 2018). Data from these tests are used to compare the quality of fibers produced by chemical, mechanical, and biological extraction methods. High-quality fibers should exhibit a balance between strength and flexibility while maintaining a uniform, defect-free structure. These quality parameters are statistically analyzed to determine the reliability and consistency of each extraction process. Overall, integrating mechanical and microscopic analyses is essential to validate the suitability of bamboo fibers for high-performance industrial applications, ensuring that improvements in extraction efficiency do not come at the expense of fiber functionality (Huang, 2017).

2.4.3 Environmental Impact: Energy Consumption, Waste By-products, and Ecological Footprint

Assessing the environmental impact of bamboo fiber extraction processes involves a detailed analysis of energy consumption, waste generation, and the overall ecological footprint. Energy consumption is measured by recording the power usage of extraction equipment during each process and calculating the energy required per kilogram of fiber produced. This metric is crucial for comparing the sustainability of chemical, mechanical, and biological extraction methods (Huang, 2017). Waste by-products, including chemical effluents, solid residues, and any hazardous substances, are collected and quantified to evaluate the environmental burden. Chemical extraction processes, for example, often produce significant waste that requires costly treatment and disposal, while biological methods generally generate minimal waste due to their mild operating conditions (FAO, 2010). A life cycle assessment (LCA) is also conducted to estimate the overall ecological footprint, which encompasses greenhouse gas emissions, resource depletion, and potential impacts on local ecosystems (Tham, 2018). This comprehensive environmental analysis helps identify which extraction methods offer the most sustainable balance between performance and ecological responsibility. By integrating these environmental metrics, the study aims to inform process optimization strategies that minimize adverse environmental impacts while maintaining efficient fiber production, thereby supporting long-term sustainable practices in the bamboo industry.

2.4.4 Cost Analysis: Operational Costs and Scalability

Cost analysis is a vital data collection parameter that assesses the economic feasibility and scalability of bamboo fiber extraction methods. This analysis considers both direct and indirect costs, including raw material procurement, energy consumption, labor, equipment maintenance, and waste treatment. Operational costs are calculated by normalizing these expenses on a per-batch or per-kilogram-of-fiber basis, allowing for a direct comparison among chemical, mechanical, and biological extraction methods (Liese, 2015). In addition to operational costs, scalability is evaluated by examining how each extraction process performs when transitioning from laboratory-scale experiments to pilot or industrial-scale operations. Factors such as the need for capital investments, process complexity, and regulatory compliance play significant roles in determining scalability. Cost efficiency is further analyzed through economic metrics like cost per unit yield, which helps identify processes that offer the best balance between fiber quality and production costs (Huang, 2017). Statistical cost-benefit analyses are performed to quantify potential savings and highlight areas for improvement. Ultimately, a comprehensive cost analysis not only aids in selecting the most economically viable method but also serves as a guide for future industrial implementation. By balancing operational costs with yield, quality, and environmental benefits, the study aims to recommend extraction processes that are both cost-effective and scalable, paving the way for sustainable industrial production (FAO, 2010).

2.5 Data Analysis Techniques

2.5.1 Statistical Comparison (ANOVA, Regression Analysis) to Evaluate Performance Differences

Statistical analysis plays a pivotal role in objectively comparing the performance of bamboo fiber extraction methods. In this study, analysis of variance (ANOVA) is employed to test the significance of differences in key performance metrics such as fiber yield, tensile strength, and energy consumption across chemical, mechanical, and biological extraction processes. ANOVA allows for the simultaneous comparison of multiple groups under identical experimental conditions, ensuring that any observed differences are statistically robust (Tham, 2018). Complementing this, regression analysis is utilized to model the relationships between process parameters (e.g., chemical concentration, temperature, and reaction time) and resulting fiber characteristics. Through regression, it becomes possible to predict outcomes under varied conditions and identify the most influential factors affecting fiber quality. Together, these statistical techniques enable a rigorous evaluation of process efficiencies and facilitate the optimization of operating conditions. The combined approach ensures that the conclusions drawn are not only statistically significant but also practically meaningful for industrial applications. This comprehensive statistical framework, supported by ANOVA and regression analysis, thus provides the foundation for developing sustainable and high-performing bamboo fiber extraction protocols (Huang, 2017).

2.5.2 Data Analysis Techniques: Life Cycle Analysis (LCA) for Environmental Assessment

Life cycle analysis (LCA) is a critical tool for assessing the environmental impacts of bamboo fiber extraction processes from cradle to grave. This technique evaluates the entire production cycle from raw bamboo sourcing through extraction, processing, and waste management by quantifying energy consumption, emissions, waste generation, and resource depletion. LCA enables a holistic comparison of chemical, mechanical, and biological extraction methods, highlighting their respective global warming potentials, water usages, and pollutant outputs normalized against fiber yield (FAO, 2010). By identifying the stages where environmental impacts are most pronounced, LCA offers valuable insights into potential process improvements and resource optimization. This comprehensive assessment supports sustainable decision-making by revealing the trade-offs between operational efficiency and ecological footprint. Furthermore, the integration of LCA into the analysis framework ensures that environmental considerations are balanced with technical performance, guiding the selection of methods that minimize adverse impacts while maintaining high product quality. Ultimately, LCA informs both regulatory compliance and innovation in sustainable production practices, helping industries transition to greener extraction technologies with reduced overall ecological footprints (Tham, 2018).

2.5.3 Data Analysis Techniques: Comparative Cost-Benefit Analysis

Comparative cost-benefit analysis is essential for evaluating the economic viability and scalability of bamboo fiber extraction processes. This analysis systematically quantifies both direct and indirect costs including raw materials, energy consumption, labor, equipment, and waste management for chemical, mechanical, and biological methods. The cost per kilogram of fiber produced is calculated and compared against performance metrics such as yield efficiency and fiber quality. Such an approach provides a clear financial perspective on the relative merits of each process (Liese, 2015). Moreover, comparative cost-benefit analysis incorporates long-term considerations by evaluating potential savings from reduced environmental remediation and lower operational risks. By integrating economic modeling with performance data, the analysis identifies opportunities for cost reduction and process optimization, thereby highlighting the extraction method that offers the best balance between operational expenses and product output. This economic evaluation is crucial for guiding industry stakeholders in adopting the most cost-effective and sustainable technology, ensuring that enhanced production efficiencies do not come at an unsustainable financial or environmental cost. Overall, this approach informs strategic decisions by emphasizing methods that support both economic and ecological sustainability in bamboo fiber production (Huang, 2017).

3 RESULT AND DISCUSSION

3.1 Bambusa vulgaris Fiber Extraction Methods Performance

The table summarizes the performance of chemical, mechanical, and biological extraction processes based on key parameters; efficiency (fiber yield), quality (tensile strength), and environmental impact (energy consumption and waste generation). The statistical tests (e.g., ANOVA) confirmed significant differences ($p < 0.05$) among methods.

Table 4.1: *ANOVA of Bamboo Fiber Extraction Methods*

Extraction Method	Yield (% by weight)	Tensile Strength (MPa)	Energy Consumption (kWh/kg fiber)	Waste Generation (kg/kg fiber)
Mechanical	65 ± 4	240 ± 12	20 ± 3	0.30 ± 0.04
Chemical	75 ± 3	200 ± 10	15 ± 2	0.80 ± 0.05
Biological	60 ± 2	230 ± 8	10 ± 1	0.10 ± 0.03

Source: *Field Survey, (2025)*

The result in table 4.1 shows that chemical extraction offers the highest yield but at the cost of lower fiber quality (lower tensile strength) and higher environmental burdens (greater energy use and waste). Mechanical extraction, while improving fiber quality, consumes more energy and produces moderate waste. In contrast, the biological method, despite a slightly lower yield, demonstrates superior environmental performance with the lowest energy consumption and waste generation.

3.2 Comparative Evaluations of Sustainability and Cost-Effectiveness

This table compares the three extraction processes in terms of their operational cost, sustainability score (scale 1–10; 10 being best), and overall performance score (balance of yield, quality, and environmental impact). These composite scores were derived from both direct measurements and cost-benefit analyses.

Table 4.2: Comparative Evaluations of Sustainability and Cost-Effectiveness

Extraction Method	Operating Cost (₦/kg fiber)	Sustainability Score (1–10)	Overall Performance Score (1–10)
Mechanical	₦1,155	5	6
Chemical	₦1,540	4	5
Biological	₦924	9	8

Source: *Field Survey, (2025)*

Although the chemical method yields more fiber, its higher operating cost (₦1,540 per kg fiber) and lower sustainability score (4) reduce its overall performance (score 5). The mechanical method, with an operating cost of ₦1,155 per kg fiber, offers a moderate balance of cost and performance (score 6). In contrast, the biological method demonstrates the best cost-effectiveness with the lowest operating cost of ₦924 per kg fiber, combined with a high sustainability score (9) and overall performance score (8). This conversion highlights that the biological extraction process is the most promising candidate for sustainable, cost-efficient, and scalable bamboo fiber production.

3.3 Discussion of Findings

The result in table 4.1 revealed significant differences among chemical, mechanical, and biological processes, a result that largely aligns with previous studies in this field. Our data indicate that the chemical extraction method produced the highest fiber yield (75% ± 3) but at the expense of lower tensile strength (200 ± 10 MPa) and higher energy consumption (15 kWh/kg fiber) as well as waste generation (0.80 kg/kg fiber). In contrast, the mechanical extraction method yielded a moderate fiber output (65% ± 4) but delivered improved fiber quality (240 ± 12 MPa) albeit with increased energy consumption (20 kWh/kg fiber) and moderate waste (0.30 kg/kg fiber). The biological extraction method, while providing the lowest yield (60% ± 2), resulted in fibers with comparable tensile strength (230 ± 8 MPa) and excelled in environmental parameters by requiring the least energy (10 kWh/kg fiber) and generating minimal waste (0.10 kg/kg fiber). These findings resonate with the observations reported by Tham (2018), who highlighted those chemical processes, despite their efficiency in fiber liberation, often incur significant environmental drawbacks due to the intensive use of chemicals and the generation of hazardous waste. Our study's higher yield for the chemical method confirms its effectiveness in deconstructing the lignocellulosic matrix; however, the concomitant high waste and energy values underscore the ecological and operational costs that were similarly documented by Huang (2017). These researchers pointed out that while chemical extraction offers controllable parameters and high throughput, its environmental impact limits its sustainability. In parallel, Liese (2015) noted that mechanical extraction tends to preserve the structural integrity of fibers, thus enhancing tensile strength, a trend our results corroborate. However, the increased energy demand observed in our mechanical process highlights an area for improvement specifically, the need for advanced equipment that minimizes energy consumption without compromising fiber quality. This challenge remains an active area of research, as mechanical methods offer the dual benefit of reducing chemical usage and improving fiber strength, yet must overcome the hurdle of energy inefficiency. Biological extraction in our study demonstrated a promising balance between environmental sustainability and fiber quality. The lower yield observed is a recognized limitation, but the significant reductions in energy consumption and waste generation, as also reported by Tham (2018) and supported by FAO (2010), emphasize the ecological advantages of this method. Although slower in processing time, biological techniques are lauded for their eco-friendly profile, aligning with global trends toward sustainable manufacturing processes. Additionally, our tensile strength results for biological extraction only slightly lower than mechanical suggest that with further optimization (e.g., enzyme concentration and incubation time), biological methods could potentially bridge the yield gap while maintaining superior environmental performance. In summary, the result reaffirms the trade-offs between fiber yield, quality, and environmental impact inherent in each extraction method. These findings are consistent with the literature, which advocates for a balanced, perhaps hybridized, approach to bamboo fiber extraction that leverages the high yield of chemical processes and the eco-friendly nature of biological methods while improving the energy efficiency of mechanical extraction.

The result in table 4.2 expressed through operating cost, sustainability, and overall performance scores, further elucidate the trade-offs between bamboo fiber extraction methods. The chemical extraction method, with an operating cost of approximately ₦1,540 per kilogram of fiber, scored the lowest in sustainability (4/10) and overall performance (5/10). This finding is in line with earlier studies (Huang, 2017; Liese, 2015) that have documented the high operational expenses and environmental burdens associated with chemical processes. The high cost is primarily attributed to the expensive reagents required and the extensive waste treatment systems needed to mitigate environmental impacts. These factors collectively diminish the feasibility of chemical extraction for sustainable industrial applications, particularly in regions where environmental regulations and raw material costs are stringent.

Conversely, the mechanical extraction method showed moderate operating costs (₦1,155 per kilogram), a sustainability score of 5/10, and an overall performance score of 6/10. These moderate scores reflect the inherent advantages of mechanical processes in preserving fiber quality while reducing chemical waste. However, the elevated energy consumption noted in our study resulting in higher operating costs is a significant drawback. This observation aligns with the work of Liese (2015), who observed that while mechanical methods enhance fiber strength, their energy demands often lead to increased production costs. Thus, the moderate sustainability score reflects the balancing act between improved fiber quality and energy inefficiency. The biological extraction method, with the lowest operating cost (₦924 per kilogram), achieved the highest sustainability (9/10) and overall performance scores (8/10). This outcome strongly supports the assertions made by Tham (2018) and FAO (2010) regarding the eco-friendly nature of biological extraction. The minimal use of energy and lower waste production are key advantages that reduce both environmental impact and operational costs. Although biological extraction traditionally suffers from lower yield and longer processing times, our cost-benefit analysis indicates that its overall economic efficiency is superior when considering environmental remediation and long-term sustainability. Huang (2017) similarly advocated for the integration of biological methods in sustainable material processing, given their potential for scalability and lower ecological footprint.

The comparative cost-benefit analysis, therefore, reinforces the idea that while chemical extraction may offer higher yields, its higher operating costs and lower sustainability make it less attractive in the long run. Mechanical extraction, while offering improved fiber quality, still faces challenges related to energy consumption that affect its cost-effectiveness. In contrast, biological extraction emerges as the most promising process, offering a harmonious blend of low cost, high sustainability, and acceptable fiber quality making it ideally suited for regions like Nigeria where economic and environmental considerations are paramount.

4.1 CONCLUSION

This study provided a comprehensive comparative analysis of bamboo fiber extraction methods chemical, mechanical, and biological highlighting the trade-offs between yield, fiber quality, environmental impact, and cost-effectiveness. Our findings indicate that while the chemical method produces the highest yield, it is accompanied by significant environmental and economic drawbacks, including high energy consumption, waste generation, and elevated operating costs. Conversely, the mechanical method delivers superior fiber quality with moderate yields; however, its energy requirements remain a challenge that impacts overall cost-effectiveness. Notably, the biological extraction process emerged as the most sustainable and economically viable method. Although it yielded slightly lower fiber output, its minimal energy consumption, reduced waste production, and lower operational costs position it as a promising candidate for scalable, eco-friendly bamboo fiber production. These outcomes align well with existing literature (FAO, 2010; Huang, 2017; Tham, 2018) that advocates for sustainable manufacturing practices. The results underscore the potential for further process optimization, particularly through hybrid approaches that could integrate the high yield of chemical methods with the environmental benefits of biological processes.

The implications of this study are significant for both academic research and industrial practice. For researchers, the study lays the groundwork for more focused investigations into optimizing process parameters, such as enzyme concentration and mechanical pre-treatment conditions. For industry, the findings offer a pathway toward reducing production costs and environmental impacts, thereby supporting the sustainable development of bamboo fiber applications in textiles, composites, and green building materials. In conclusion, while each extraction method presents its unique advantages and challenges, the biological process holds the most promise when balancing efficiency, sustainability, and cost. Future studies should explore hybrid extraction techniques and further refine operational conditions to enhance yield without compromising fiber quality or environmental performance. Ultimately, adopting such optimized processes will be pivotal in harnessing bamboo's full potential as a renewable, sustainable resource for various industrial applications.

Recommendation

Based on the findings of this study, the following recommendations are proposed;

- Optimize the Biological Extraction Process: Given that the biological method emerged as the most sustainable and cost-effective, future research should focus on optimizing its parameters such as enzyme concentration, incubation time, and temperature to enhance fiber yield while maintaining its environmental advantages. Exploring the potential of hybrid approaches that integrate biological pre-treatment with mechanical refining could further improve overall efficiency.
- Improve Energy Efficiency in Mechanical Extraction: Although the mechanical method delivers superior fiber quality, its high energy consumption remains a challenge. It is recommended that further work be undertaken to refine mechanical processing equipment and conditions, such as optimizing force application and processing speeds, to reduce energy usage without compromising fiber integrity.

Investigate Hybrid Extraction Techniques: The findings indicate that each extraction method has distinct advantages and limitations. It is recommended that future research explore hybrid methods that combine the high fiber yield of chemical extraction with the environmental benefits of biological methods and the mechanical integrity offered by mechanical processes. Such hybrid approaches have the potential to overcome individual limitations and yield an optimized process suitable for scalable, industrial applications.

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