EFFECT OF SODIUM HYDROXIDE SOLUTION ON THE EXTRACTION OF BAMBOO FIBER

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A PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF MATERIALS AND METALLURGICAL ENGINEERING, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN, BENIN CITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR OF ENGINEERING (B. Eng) HONOURS DEGREE IN MATERIALS AND METALLURGICAL ENGINEERING.

APRIL 2024

CERTIFICATION

This is to certify that the project team carried out this research project submitted to the Department of Materials and Metallurgical Engineering, the persons of UGHAKPOTENI FIDEL OGHENEYOMA, YAYA JUBRIL SAIDU and JOHN IMAMA EGBERAODION of the Department of Materials and Metallurgical Engineering University of Benin, Benin City, Edo State Nigeria, under the supervision of Dr. (Mrs.) U.G. Unueroh.

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DR. NOSA ENOMA Date

HEAD OF DEPARTMENT

DEDICATION

This project work is dedicated to Almighty God, our Lord and creator, to our loving parents, our project supervisor, Mrs U.G. Unueroh, and to all our lecturers in the department for making the journey seems easy and for all their immeasurable support and contributions in our lives.

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Our gratitude goes to God Almighty for his infinite mercy and love towards us all through our undergraduate program in the University of Benin.

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We sincerely want to appreciate my distinguished course advisers, Dr. Ufuoma Unueroh, Engr. Noel and Dr. O. Oisakede for their exceptional guidance and support all through our undergraduate program in the University of Benin.

Our unending appreciation goes to our families, who did everything possible to ensure the successful completion of our B. Eng. Program.

ABSTRACT

The growing need for sustainable and environmentally friendly materials across various sectors has generated an increased interest in the extraction of bamboo fibres. The primary objective of this study is to tackle the obstacles linked with bamboo fibre extraction and analyze the effectiveness of sodium hydroxide (NaOH) solution in improving the quality of the extracted fibres. The endeavour was initiated to analyze the historical progression of bamboo fibre extraction techniques, the significance of chemical treatments in fibre processing, and the specific impacts of NaOH treatment on fibre characteristics.

The study encompassed an extensive review of pieces of literature to comprehend the context and importance of bamboo fibre extraction, encompassing both conventional techniques and contemporary advancements. The experimental arrangement for distilled water and NaOH treatment was formulated, encompassing variables such as concentration fluctuations at 5%, 10%, 15% and 20% NaOH. The weight of water used was also calculated to be 1000g, 950g, 900g, 850g, and 800g to form solutions respectively. The Fourier Transform Infrared (FTIR) spectroscopy was applied to investigate the chemical structure of fibres before and after treatment, providing important details on the success of the extraction method. Data collection techniques involved sample preparation, maintenance of controlled environmental conditions, and statistical evaluation of experimental findings.

The outcomes showed that NaOH treatment efficiently dissolved lignin, cellulose, and hemicellulose constituents from the bamboo fibres, resulting in purer and cleaner fibre outputs. FTIR analysis corroborated the partial elimination of non-cellulosic components, with heightened NaOH concentration correlating with increased removal of lignin and hemicellulose. The discoveries from this investigation enhance comprehension of the chemical composition of bamboo fibres and underscore the potential of NaOH treatment in refining extraction processes. Additionally, the implications of the outcomes for industrial utilization, alongside suggestions for future research, are comprehensively deliberated.

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evaluates the bamboo fibre's capability to withstand compressive forces without permanent deformation or failure (Liese, W., & Köhl, M., 2015). Bamboo fibers manifest notable compressive strength, making them appropriate for applications necessitating load-bearing capabilities, such as engineered structural components and support elements (Zakikhani, P., et al., 2016). The elevated compression strength of

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CHAPTER ONE

1.0 INTRODUCTION

1.1 RESEARCH BACKGROUND

From 2000 to 2010, there was a notable rise in the scientific investigation centred around biocomposites that were reinforced with natural fibres, including bamboo fibres. The specific composites used in the research phase were known for their cost-effectiveness, light weight, recyclability, and environmentally friendly qualities, serving as alternatives to the traditional composites made of glass and carbon fibres (Faruk *et al.*, 2012). The essence of bamboo's importance in this research lies in its capacity to provide a sustainable, robust, lightweight, and visually appealing reinforcement for biocomposites. The amalgamation of these characteristics renders bamboo a valuable and adaptable constituent in the progression of materials that are both environmentally friendly and high-performing. The central focus of this study centred on the utilization of bamboo fibres as a reinforcing element within the biocomposite matrix (Faruk *et al.*, 2012).

In Africa, Asia and Latin America, bamboo, which has attracted significant attention over the last two decades as a result of its environmental, economic and aesthetic values, is closely associated with indigenous culture and knowledge and is widely used for housing, forestry, agroforestry, agricultural activities and utensils (FAO, 2007). In Nigeria, bamboo is found in some states, particularly in the southern part of the country, and according to a report by Raw Materials Research and Development Council (2004), the most endowed states in terms of bamboo occurrence are observed to be Ogun, Oyo, Osun, Ondo, Edo, Delta, Rivers, Akwa Ibom, Cross River, Abia, Ebonyi, Enugu, Anambra and Imo States and at least 10% of the natural vegetation in these states is dominated by bamboo, with existing bamboo clumps showing appreciable gregarious growth that is contiguous over large areas. Bamboo is a plant with species totalling up to over 1670 bamboo species in the world, belonging to 125 genera. According to Ffan (2003), some of the species of bamboo that have been identified in Nigeria include

Bambusa vulgaris and Oxytenanthera Abyssinia only; the former attains a height of between 14 - 20 metres at maturity with a girth of about 20cm while the latter reaches between 8 - 12 metres at maturity.

The unique characteristics of bamboo render it a distinctive economic asset for a multitude of purposes, including poverty alleviation. Its rapid growth rate and capacity for annual harvesting without soil depletion make it an environmentally sustainable choice. Additionally, bamboo exhibits adaptability by thriving in marginal land, unsuitable for agriculture or forestry, or as an agroforestry crop. Notably, its hollow culms contribute to its lightweight nature, facilitating easy harvesting and transport without the need for specialized equipment or vehicles (FAO, 2007). The local population, particularly those in the lower strata of society, engage in bamboo processing to create crafts, generating income that supports household expenses, and because of that, its use is often underemphasized.

The economic significance of bamboo as a catalyst for employment, income generation, and poverty alleviation is of utmost importance. Many individuals in rural communities sustain their livelihoods by crafting bamboo-based handicrafts. In rural areas, bamboo is extensively utilized for constructing fences, strategically planted around ponds to act as a watershed and minimize evaporation, crafting wooden gongs, serving as stakes for yam cultivation, enhancing the structural integrity of elevated buildings, supporting the growth of banana and plantain crops, and constructing thatched dwellings (Nwaihu *et al.*, 2015). The use of bamboo doesn't stop there. Bamboo fibre also plays a major role in improving the quality of lives of people other than simply being used as a support for construction works.

The importance of bamboo fibre spreads across various industries. Bamboo fibres are conventionally employed in the realm of textile manufacturing to engender soft and permeable textiles. Moreover, they are employed in the fabrication of paper, furniture, as well as certain environmentally conscious substitutes for conventional plastics. Furthermore, the utilization of bamboo fibers in sundry domestic articles, such as towels and bed linens, is possible, owing to their innate antibacterial characteristics (Kaur *et al.*, 2017).

The bamboo fibre is naturally found in bamboo trees and can be extracted using various methods and processes. Based on the process used the fibres can be further divided into two categories: Bamboo pulp fibre and original bamboo fibres. In original bamboo fibre, the fibres are extracted directly from the natural bamboo using mechanical and chemical methods. Fibres can be extracted mechanically and chemically in various ways (Asiru and Unekwu, 2017). However, the extraction of bamboo fibres presents a set of challenges, like the difficulty in extracting fine and straight fibre, which now requires a thorough investigation of the extraction methods to ensure the effectiveness and quality of the process being used (Kaur *et al.*, 2017). The present techniques tested and used in the extraction process like mechanical retting, steam explosion or even chemical retting techniques, have been found to not only be inefficient but also require a high demand for the resources, thereby impeding the process of maximizing the potential of goods derived from bamboo.

The alkaline treatment stands out. It is a commonly used chemical method for treating and extracting natural fibres, especially in the manufacture of thermoplastics and thermosets. It serves to remove the excessive lignin, wax, and oils that are present on the external surface of the fibre cell. The NaOH treatment facilitates the ionization of the hydroxyl group. The alkaline treatment brings about two separate effects on the fibres: first is the ability to enhance the roughness of the outer surface, thereby promoting mechanical interlocking; secondly, it can increase the amount of cellulose exposure on the fibre surface (Asiru and Unekwu, 2017).

Gaining a thorough understanding of the intricacies related to bamboo fibre extraction is extremely important to fully tap into the possibilities of this sustainable resource in engineering applications.

1.2 PROBLEM STATEMENT

The gross underutilization of bamboo in Nigeria stems from the absence of efficient techniques for extracting fibres that result in a smooth surface devoid of lignin remnants. The current extraction methods available yield bamboo fibres with rough surfaces or lignin residues, thereby restricting their applications and contributing to the widespread underestimation of bamboo's potential in multiple industries. This issue significantly impedes the integration of bamboo fibres into value-added products and hinders the growth of the sustainable bamboo industry in Nigeria.

The lack of suitable fibre extraction methods has resulted in an inadequate perception of bamboo as a versatile and valuable resource. The surfaces of fibres obtained through existing techniques hinder their usability in high-value applications, such as composites, textiles, and construction materials. This limitation obstructs the exploration of bamboo's complete economic and environmental potential, therefore impeding sustainable development initiatives.

A major means of extraction of this bamboo fiber from bamboo is the chemical retting method. This method involves the extraction through the involvement of a basic salt known as sodium hydroxide, NaOH.

However, the involvement of sodium hydroxide in the extraction of bamboo fibre from bamboo stems leaves behind a range of effects on the fibre extracted.

The objective of this study is to address this critical issue by developing and optimizing extraction methods that yield bamboo fibres with smooth surfaces and minimal lignin content. The successful implementation of such techniques is expected to revolutionize the utilization of bamboo in Nigeria, creating opportunities for innovation and economic growth across various sectors ranging from construction to manufacturing.

1.3 AIMS

This work aims to extract bamboo fibres from bamboo stems through several extraction methods without complications to the fibres being extracted.

1.4 OBJECTIVES

The objective of this work is to:

1. Extract bamboo fibre from bamboo stems by soaking the stems in water.

2. Extract bamboo fibre from bamboo stems by soaking the stems in sodium hydroxide solution, NaOH.
3. Compare the effects of the fibres soaked in both different concentrations of sodium hydroxide solution and water using FTIR analysis.
4. Provide insight into better and seamless ways to extract bamboo fibres from bamboo stems.

1.5 SCOPE OF STUDY

This study will centre its attention on the extraction of bamboo fibre from bamboo stems in Nigeria. It will encompass the acquisition of the Bambussa Vulgaris species of bamboo from the University of Benin, Benin City in Nigeria, as well as the utilization of the chemical extraction process, using the alkali, sodium hydroxide solution at various concentrations. Furthermore, this study will encompass determining the effect of the sodium hydroxide solution on the extracted bamboo fibre, contrasting the impact of the resulting fibres, using the FTIR test.

1.6 SIGNIFICANCE OF STUDY

Solving the issue of coarse or lignin-contaminated fibre acquired from inefficient extraction procedures has become a pressing matter due to the numerous applications of bamboo fibre. Consequently, it is imperative to research more efficient methods of extracting fine and straight fibre from the stems at an optimal cost of production to fully utilize its potential. Hence, this research aims to optimize the process parameters that impact the yield of bamboo fibre.

The proposed study surpasses the scope of addressing a particular technical problem; it holds profound implications for the country's economic development, environmental sustainability, and community well-being in Nigeria, establishing the nation as a frontrunner in the sustainable utilization of bamboo resources.

The outcomes of this study manifest in the following ways:

1. Contribute to the advancement of sustainable and environmentally friendly materials, diminishing reliance on synthetic fibres.
2. Facilitate the utilization of bamboo as a valuable resource, thereby fostering substantial economic growth and job creation within the bamboo industry exclusively.
3. Foster a culture of innovation within the manufacturing sector by generating pioneering and high-value products, spanning from composite materials to textiles.
4. Contribute to the preservation of cultural heritage by endorsing the sustainable utilization of traditional resources, nurturing a sense of pride and connection to local customs.
5. Offer valuable insights and knowledge that can be extrapolated to other nations with comparable bamboo availability.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Bamboo fiber, renowned for its environmentally friendly nature and diverse range of applications, stands as a sustainable alternative with substantial economic and environmental advantages. Derived from the cellulose fibers of the bamboo plant, bamboo fiber offers many distinctive properties and potential uses. This section presents a comprehensive exploration of bamboo fiber, encompassing its methods of extraction, characteristics, applications, and socioeconomic implications, with a specific emphasis on Nigeria.

The procedure of extracting bamboo fiber involves a sequence of steps intended to segregate the cellulose fibers from the bamboo plant. The process of extracting bamboo fibers from the raw material stands as a critical stage in harnessing its industrial potential. Initially, bamboo culms are gathered and exposed to mechanical or chemical treatments to eliminate non-fibrous components such as lignin and hemicellulose. These procedures are pivotal in enhancing the quality and utility of bamboo fibers (Zakikhani P. *et al.,* 2014).

One of the primary benefits of bamboo fiber lies in its sustainability and environmental friendliness. Bamboo is a rapidly growing and highly renewable resource, capable of attaining maturity within a short timeframe and regenerating swiftly after harvesting. Furthermore, bamboo cultivation necessitates minimal water, pesticides, and fertilizers in comparison to conventional crops, rendering it a sustainable choice for fiber production (Popat, T.V., & Patil, A.Y., 2017).

Bamboo fiber possesses several desirable attributes that make it appealing for a wide array of applications. It is renowned for its exceptional strength and durability, especially when compared to traditional textile fibers such as cotton and polyester. This inherent strength ensures the longevity and resilience of bamboo-based products, rendering them suitable for diverse uses (N. Kaur, *et al.,* 2017).

Moreover, bamboo fiber exhibits inherent antibacterial and hypoallergenic properties, making it ideal for sensitive skin and applications that require resistance to odours. These properties enhance the comfort and hygiene of bamboo-based textiles, particularly in the realm of clothing and bedding (Kaur N., *et al.,* 2017).

Furthermore, bamboo fiber demonstrates excellent moisture-wicking capabilities, owing to its porous structure. This enables bamboo fabrics to swiftly absorb and evaporate moisture, keeping the wearer cool and dry in humid conditions. Consequently, bamboo-based textiles are highly favoured for activewear, sportswear, and outdoor apparel (Kaur N., *et al.,* 2017).

In addition to textiles, bamboo fiber finds extensive applications in composite materials. Bamboo fibre-reinforced composites provide exceptional mechanical properties, including elevated strength, rigidity, and resistance to impact. Bamboo composites possess these properties, making them suitable for a wide range of applications, including automotive components, construction materials, and consumer goods (Kaur N., *et al.,* 2017).

Exploiting the economic and environmental advantages of bamboo fiber holds significant potential, particularly in Nigeria. Bamboo cultivation and fiber extraction can engender employment opportunities and stimulate economic growth, particularly in rural areas where bamboo resources are abundant. Furthermore, the promotion of bamboo fiber production can contribute to environmental conservation efforts and alleviate deforestation, thus fostering sustainable development in Nigeria (Abbas, A. M., & Amanabo, U. H.*,* 2017).

In Nigeria, where bamboo resources are plentiful, there is increasing recognition of the potential economic and environmental benefits of bamboo fiber production. The government and various stakeholders are progressively investing in bamboo cultivation and processing infrastructure to harness these benefits. By promoting bamboo fiber production, Nigeria can diversify its economy, generate employment, and reduce reliance on traditional industries while simultaneously contributing to environmental sustainability and biodiversity conservation (Abbas, A. M., & Amanabo, U. H., 2017).

The harnessing of the economic and environmental advantages of bamboo fiber possesses considerable potential, specifically within Nigeria. The cultivation and extraction of bamboo fiber can generate employment opportunities and stimulate economic progress, particularly in rural regions abundant with bamboo resources. Moreover, the promotion of bamboo fiber production can contribute to endeavours aimed at conserving the environment and ameliorating deforestation, thereby fostering sustainable development within Nigeria (Abbas, A. M., & Amanabo, U. H., 2017).

On the whole, bamboo fiber serves as a sustainable and adaptable substitute for conventional textiles and composites, proffering an array of distinct qualities and applications. Its economic and environmental advantages render it an invaluable resource, particularly in areas such as Nigeria, where its cultivation and utilization can propel socioeconomic advancement and environmental sustainability.

2.1.1 The Historical Development Of Bamboo Fiber

The historical development of bamboo fiber is a subject that has been studied extensively, spanning numerous centuries. Throughout history, civilizations have recognized the unique properties of bamboo and have utilized them for the production of textiles. The extraction and weaving of bamboo fiber were deeply ingrained in cultural practices and local craftsmanship, resulting in a diverse range of textile traditions across Asia and other regions.

Among the earliest civilizations to appreciate the value of bamboo as a textile material were the ancient Chinese. Dating back thousands of years, Chinese artisans developed intricate techniques for extracting bamboo fibers and weaving them into textiles of exceptional beauty and quality. These fabrics, renowned for their softness, breathability, and antibacterial properties, were highly sought-after commodities both domestically and internationally (Abbas, A. M., & Amanabo, U. H., 2017).

In Japan, the art of bamboo fiber extraction and textile production reached unparalleled levels of sophistication and refinement. Japanese artisans mastered the complex process of transforming bamboo into fine fabrics, such as "bashofu" and "kibiso," which were revered for their elegance, durability, and natural sheen. These traditional textiles became emblematic of Japanese culture and were integral to ceremonial attire, household items, and artistic expressions (Zakikhani P. *et al.,* 2014).

Over time, advancements in technology and changing consumer preferences led to the evolution of bamboo fiber extraction and textile production techniques. Modern methods, including mechanical and chemical processes, have revolutionized the industry, facilitating the mass production of high-quality bamboo-based textiles on a commercial scale (Popat, T.V., & Patil, A.Y., 2017).

In recent decades, the global demand for sustainable textiles has sparked a renewed interest in bamboo fiber as an eco-friendly alternative to conventional materials. Countries like China and India have emerged as leading producers of bamboo fiber, leveraging their abundant bamboo resources and manufacturing capabilities to meet the growing worldwide demand for bamboo-based textiles (Kaur N., *et al.,* 2017).

Furthermore, the historical development of bamboo fiber has inspired ongoing research and innovation in the field of sustainable materials. Scientists and engineers continue to explore novel techniques for bamboo fiber extraction, processing, and application, to enhance the performance, versatility, and environmental sustainability of bamboo-based products.

The historical legacy of bamboo fiber stands as a testament to the resourcefulness, creativity, and resilience of human craftsmanship. From ancient civilizations to modern societies, bamboo fiber has persisted as a symbol of cultural heritage, technological advancement, and sustainable living, bridging the gap between the past and the present and inspiring future generations to embrace the potential of nature's abundance.

2.1.2 Geographical Distribution of Bamboo Fiber Production

The distribution of bamboo fiber production across different regions is closely tied to the worldwide demand for sustainable textiles and the deliberate cultivation of bamboo resources. Gaining an understanding of the major participants and production centres in the bamboo fiber industry provides valuable insights into the economic, environmental, and social factors that shape this sector.

Asia stands out as the primary focal point for bamboo fiber production, with China, India, and Vietnam taking the lead. China, especially, maintains a position of superiority as the biggest worldwide manufacturer of bamboo fiber. By utilizing its extensive bamboo resources, advanced manufacturing capabilities, and well-established supply chains, China has become a key player in meeting both domestic and international demands for bamboo-based textiles (Abbas, A. M., & Amanabo, U. H., 2017).

India, with its rich history of bamboo cultivation and craftsmanship, has also made significant progress in the bamboo fiber industry. The northeastern states of India, abundant in bamboo forests, serve as crucial production centres for extracting bamboo fiber and manufacturing textiles. Indian companies are increasingly investing in modernizing production processes, expanding market reach, and promoting sustainable practices to take advantage of the growing global demand for environmentally friendly textiles (Abbas, A. M., & Amanabo, U. H., 2017).

Vietnam has emerged as another significant contributor to the global bamboo fiber market, capitalizing on its favourable climate, abundant natural resources, and skilled workforce. Vietnamese companies are investing in research and development, technology transfer, and international collaborations to enhance the competitiveness of their bamboo fiber products and access new markets (Abbas, A. M., & Amanabo, U. H., 2017).

Beyond Asia, regions such as Africa, Latin America, and the Caribbean are also exploring the potential of bamboo fiber production to stimulate economic growth and promote environmental sustainability. For example, in Nigeria, where bamboo resources are plentiful, there is a growing recognition of the economic and environmental benefits of bamboo cultivation and processing (Abbas, A. M., & Amanabo, U. H., 2017).

The aforementioned source emphasizes the economic and environmental advantages of bamboo cultivation in Nigeria, highlighting its potential to drive rural development, create employment opportunities, and foster sustainable land management practices. By harnessing its abundant bamboo resources, Nigeria can diversify its economy, reduce reliance on traditional industries, and contribute to global conservation efforts (Abbas, A. M., & Amanabo, U. H., 2017).

In conclusion, the allocation of bamboo fiber creation across diverse locales mirrors the worldwide idea of the business and the fluctuated openings and difficulties confronted by bamboo-delivering nations. By leveraging their natural advantages, investing in technology and infrastructure, and fostering collaboration and innovation, these countries can unlock the full potential of the bamboo fiber to drive economic prosperity, environmental sustainability, and social inclusivity.

2.2. BAMBOO ANATOMY AND STRUCTURE: A COMPREHENSIVE OVERVIEW

Bamboo, a member of the Poaceae family, showcases a distinct anatomical and structural framework, which significantly attributes to its robustness, adaptability, and versatility. To fully grasp the inherent characteristics and potential applications of bamboo, it is imperative to gain a comprehensive understanding of its fundamental anatomical aspects. This segment aims to provide a comprehensive overview of bamboo anatomy, covering its composition, growth patterns, and structural attributes.

2.2.1 Composition of Bamboo

Bamboo primarily comprises cellulose, hemicellulose, and lignin, constituting the principal constituents of its cellular walls. This chemical composition is fiber, where 55% of the fiber is made of 34.5% cellulose, 2.5% hemicellulose, and 26% lignin, with the remaining portion consisting of volatile content, rendering it hydrophobic. In this composition, there is a bond between lignin and cellulose, known as lignocellulose, as well as the hemicellulose, and other extractive compounds, all of which contributes to the formation of a structural barrier that obstructs the bonding of cellulose polymer fibers to the matrix in the process of composite manufacturing (Martijanti et al., 2020).

Cellulose, an abundant polysaccharide within bamboo, imparts structural stability and rigidity to the plant. Conversely, hemicellulose acts as a binding agent, amalgamating cellulose fibers and contributing to the inherent flexibility and elasticity of bamboo. Furthermore, lignin, a complex phenolic polymer, enhances the overall rigidity and durability of bamboo, rendering it resistant to both mechanical stress and environmental factors (Liese, W., & Köhl, M., 2015).

To extract quality fiber form the bamboo culm without causing damage to the fiber, the lignin-cellulose (lignocellulose) and hemicellulose composition, as well as other extractive compounds need to be removed by the utilization of NaOH solution. This works by dissolving bamboo fiber in the solution through the steam explosion method, as well as kenaf fiber immersed in NaOH solution. The outcomes of the fiber extraction procedure exhibit a potential enhancement in adhesion, thereby reinforcing the bond between fibers and matrices (Martijanti et al., 2020).

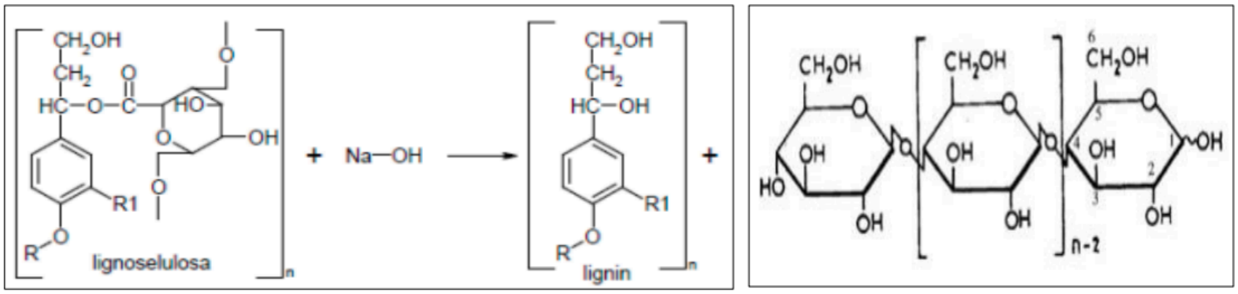

Fig. 2.1 Lignocellulose reaction in NaOH solution

Based on the data presented in figure 1, it is evident that lignin possesses a variety of functional groups including OH, C-O-C, C-C, C = aromatic, CH aliphatic, and CH2, whereas cellulose exhibits OH and C = O functionalities. The efficiency of the extraction of lignin from lignocellulose using a NaOH solution is impacted by factors such as the concentration of the

NaOH solution, pressure, extraction duration, and the diameter of the bamboo fiber. The influence of the NaOH extraction process can be analyzed through the use of FTIR spectroscopy.

2.2.1.1 Structure of Cellulose in Bamboo

Cellulose fibers within bamboo manifest in a hierarchical arrangement, encompassing microfibrils, fibrils, and macrofibrils. Microfibrils, the most minute cellulose units, possess diameters ranging from 2 to 4 nanometers. These microfibrils converge to form fibrils, which subsequently aggregate to construct macrofibrils. This hierarchical organization of cellulose fibers imparts bamboo with resilience, stiffness, and fortitude, enabling it to withstand various forms of mechanical strain, such as bending, compression, and tension (Mwaikambo, L. Y., & Ansell, M. P., 2002).

2.2.1.1.1 Determination of Cellulose in Bambusa Vulgaris

In Bambusa vulgaris specie, cellulose is a measure of the total carbohydrate content present in it. The quantification of cellulose was conducted following the ASTM designation D1104-50 (ASTM, 1978). The procedure involved saturating two grams of bamboo sawdust, free from extractives, and with a known moisture content, with cold distilled water, followed by the removal of excess moisture through suction. Subsequently, the sample underwent chlorination for a duration of five minutes, then was subjected to extraction using 50ml of 95% ethanol and a solution of hot ethanol-monoethanolamine. Upon completion of each extraction, the residue exhibited a white coloration. The rinsing process was reiterated until the residue displayed neutrality to litmus. The resulting residue was then dried in an oven until a constant weight was achieved. The percentage of cellulose, based on the moisture-free and extractive-free milled sample, was determined through the following calculation (John A., & Kamoru A.S., 2021).

$$\text{Cellulose (\%)} = \frac{W0}{W1} \times 100$$

Where: Wo = Weight of oven-dried cellulose residue

W1 = Weight of moisture-free and extractive-free milled sample

(Kappa Laboratories, 2018)

2.2.1.2 Distribution of Hemicellulose in Bamboo

Hemicellulose intricately permeates the bamboo cell walls, forming a matrix that firmly binds cellulose fibers together. Different from cellulose, which is made up of straight chains of glucose molecules, hemicellulose is composed of branched polysaccharide chains consisting of various sugar units. This branched structure significantly augments the overall flexibility and elasticity of bamboo, empowering it to endure external forces by bending and flexing without succumbing to breakage (Mohamad, S.S., *et al.,* 2016).

2.2.1.2.1 Determination of Hemicellulose in Bambusa Vulgaris

The determination of hemicellulose content was carried out as an experiment, following the Tentative Method for Preparation of Extractive-Free Wood (ASTM Designation: D 1105). A sample weighing accurately in a tarred alundum of fitted glass crucible consisted of approximately two grams of air-dry extractive-free wood with a known moisture content. The sample was then moistened with cold distilled water at 10°C, and any excess moisture was eliminated through suction. Employing moderate suction, the sample underwent chlorination by passing gas through a funnel placed upside down over the crucible, which was secured on a suction flask. Following three minutes of chlorination, the funnel was removed, the material stirred thoroughly, and re-chlorinated for an additional two minutes (Kappa Laboratories, 2018). Subsequently, alcohol was introduced to dissolve any surplus chlorine and the HCl produced during chlorination. After one minute, the suction ceased, the vacuum was released, and a sufficient quantity of hot alcohol-monoethanolamide solution was added to completely cover the dust, which was then stirred thoroughly. The solution was left to settle for two minutes before being suctioned out. This solvent treatment process was repeated. The cycle of chlorination and extraction was reiterated until the residue turned white post-chlorination and was no longer tinted upon the addition of the hot alcohol-monoethanolamine solution. The alcohol-monoethanolamine was eliminated by washing twice with alcohol, twice with cold water (10°C), and again with alcohol until the residue displayed neutrality to litmus. Finally, rinsing with ether was conducted to expedite the drying process. The hemicellulose was air-dried to eliminate any excess ether and subsequently dried to a consistent weight in an oven set at 105°C. The hemicellulose percentage was then computed based on the weight of moisture-free, extractive-free dust (Kappa Laboratories, 2018).

2.2.1.3 Content and Distribution of Lignin in Bamboo

Lignin, a complex phenolic polymer, serves as a cohesive agent within the bamboo cell walls, occupying the interstitial spaces between cellulose and hemicellulose fibers. By providing structural support and rigidity, lignin reinforces the cell walls of bamboo, rendering it impervious to compression and impact. The distribution of lignin across various bamboo species and culm sections varies, with higher concentrations typically found in the outer culm wall and lower concentrations within the inner culm tissues (Liese, W., & Köhl, M., 2015).

2.2.1.3.1 Determination of Lignin in Bambusa Vulgaris

Lignin constitutes a category of intricate organic polymers that serve as crucial structural components in the supportive tissues of vascular plants and certain types of algae (Martone *et al.*, 2009). The utilization of the Test Method for Acid-Insoluble Lignin in bamboo to ASTM Standard D 1106 – 96 (ASTM, 1996) facilitated this determination. Test specimens of bamboo samples, specifically three (3) grams each from the bottom, middle, and top segments were meticulously weighed in glass-stoppered weighing bottles that were tarred. Subsequently, the samples underwent a two-hour drying process at a temperature range of 100°C to 105°C in an oven, followed by cooling in desiccators. To equalize the pressure, the stopper was slightly loosened and then re-weighed. The drying and weighing cycle persisted for one-hour intervals until a consistent weight was achieved (Kappa Laboratories, 2018).

For lignin determination, two additional 10-gram test specimens were weighed in duplicate using extraction crucibles. The crucible containing the specimen was then positioned in a Soxhlet extraction apparatus for further processing. The extraction procedure involved the use of 95%

alcohol for four hours, followed by ethanol-toluene solution application as outlined in Test Method D 1107. Subsequent removal of the solvent was conducted through suction, with further washing using 50ml ethanol to eliminate any remaining toluene. Excess ethanol was subsequently eliminated, transferred to a beaker, and digested with 400 ml of hot water in a hot-water bath at around 100°C for 3 hours. Filtration of the solution took place, accompanied by two rounds of washing - first with 100ml of hot water and then with 50ml of ethanol to aid in the extraction of the test specimen from the crucible. Following these initial extractions, the specimens were left to air dry (Kappa Laboratories, 2018).

The process continued with the transfer of two grams of the air-dried test specimen into a small beaker, covered with glass, and combined with 15ml of cold H2SO4 (72%) poured slowly while stirring. The mixture was stirred continuously for at least one minute to ensure proper acid distribution. It was then left to settle for two hours, with regular stirring, at a maintained temperature of 18 to 20°C, achieved by utilizing a water bath. The material was subsequently transferred to a 1-litre beaker or Erlenmeyer flask, diluted with 560ml of distilled water to achieve a 3% H2SO4 concentration, and boiled for four hours, maintaining a nearly constant volume condition by occasionally adding hot water to the flask. After allowing the insoluble residue to settle, it was filtered into a dried filtering crucible, weighed in a glass-stopper weighing bottle, and rinsed free of acid with 500ml of hot water. The crucible and its contents were then dried for two hours at 100 to 105°C, cooled in desiccators, and the content of the crucible, designated as lignin, was precisely weighed.

2.2.1.4 Microstructure of Bamboo

At the microscopic level, bamboo unveils a sophisticated microstructure characterized by alternating layers of fibers and parenchyma cells. These fibers, constituting the predominant bulk within bamboo culms, confer mechanical strength and rigidity. Conversely, parenchyma cells play a vital role in nutrient storage, water transportation, and structural support. The arrangement of fibers and parenchyma cells exhibits diversity across distinct bamboo species and culm sections, thereby contributing to the distinctive properties and manifold applications of bamboo (Liese, W., & Köhl, M., 2015).

2.2.2 Fiber Distribution in Bamboo

The distribution of fibers within the bamboo plant's culm is vital for its mechanical strength and structural integrity. A comprehensive understanding of the spatial distribution, types, and characteristics of bamboo fibers is crucial in evaluating their mechanical properties and potential applications. This section presents a comprehensive overview of the distribution of fibers in bamboo, encompassing their concentration in different parts, various fiber types, as well as the characteristics of the xylem and phloem.

2.2.2.1 Concentration in Different Parts

The concentration of fibers in bamboo exhibits variations across different sections of the plant, with higher densities typically observed in the culm wall compared to the inner tissues. In mature bamboo culms, the outermost layers of the culm wall, known as the "epidermis" or "rind," contain the highest fiber concentration. These fibers, referred to as "primary fibers," are elongated, slender, and densely packed, thereby conferring structural support and mechanical strength upon the culm (Liese, W., & Köhl, M., 2015).

In contrast, the inner tissues of the bamboo culm, including the pith and vascular bundles, possess fewer fibers and primarily consist of parenchyma cells and vascular tissues. While these inner tissues contribute to nutrient transport and mechanical support, their fiber concentrations are comparatively lower than those of the culm wall (Liese, W., & Köhl, M., 2015).

2.2.2.2 Fiber Types and Classification

Bamboo fibers can be categorized into two principal types based on their anatomical origin and functional properties: "primary fibers" and "secondary fibers." Primary fibers, also known as "bast fibers," are derived from the vascular bundles in the culm wall and are responsible for providing tensile strength and flexibility to the bamboo culm. These fibers, characterized by their elongated, slender morphology and thick cell walls, are ideally suited for textile and composite applications (Alireza, J., *et al.,* 2019).

On the other hand, secondary fibers are sourced from the parenchyma cells and other non-vascular tissues in the inner regions of the bamboo culm. These fibers, also known as "parenchyma fibers" or "ground fibers," are shorter, finer, and less structurally significant compared to primary fibers. Although secondary fibers contribute to the overall mechanical properties of bamboo, they are often overshadowed in industrial applications, which prioritize primary fibers (Liese, W., & Köhl, M., 2015).

2.2.2.3 Xylem and Phloem Characteristics

The bamboo culm's xylem and phloem are two distinct vascular tissues responsible for the transport of water and nutrients. The pith, located towards the center of the culm, consists of parenchyma cells that store and transport nutrients within the plant. These xylem elements possess thick cell walls and lignified structures, offering mechanical support and rigidity to the culm (Liese, W., & Köhl, M., 2015).

On the contrary, the xylem, located towards the inner area of the culm, comprises of vessels, tracheids, and parenchyma cells that carry water and minerals from the roots to the other parts of the plant. Although the phloem fibers are less prominent when compared to their xylem counterparts, they contribute to the overall mechanical strength and flexibility of the culm, particularly in young and actively growing bamboo shoots (Liese, W., & Köhl, M., 2015).

2.3. METHODS OF EXTRACTION OF BAMBOO FIBERS

For centuries, indigenous communities have employed traditional techniques to extract bamboo fibers, showcasing their resourcefulness and ingenuity in harnessing the inherent properties of bamboo. These methods, deeply rooted in local craftsmanship and cultural customs, involve manual procedures and indigenous tools to convert bamboo culms into fibers suitable for various applications. This section offers an overview of the traditional approaches to extracting bamboo fibers, with a focus on manual extraction techniques and indigenous tools.

2.3.1 Manual Extraction Techniques

Manual extraction techniques entail the utilization of human labor and basic hand tools to remove, scrape, or extract fibers from bamboo culms. These approaches have been inherited through generations and remain foundational to the livelihoods and cultural practices of multiple rural communities.

2.3.1.1 Hand Scraping and Stripping

Hand scraping and stripping represent among the most ancient methods of extracting bamboo fibers, tracing their origins back to ancient civilizations. Skilled artisans employ sharp knives or blades to eliminate the outer layers of the bamboo culm, thereby uncovering the inner fibers. Subsequently, the culm is split or sliced into thin strips, which undergo further processing to extract individual fibers. Hand scraping and stripping necessitate precision and expertise to ensure consistent fiber quality and minimize wastage (Liese, W., & Köhl, M., 2015).

2.3.1.2 Retting Processes and Traditional Soaking

Retting processes encompass the immersion of bamboo culms in water or natural solutions to facilitate the separation of fibers from the surrounding tissues. Conventional retting techniques, such as water retting and microbial retting, rely on natural enzymes and microorganisms to break down the pectin and lignin bonds that bind the fibers together. The retted culms are subsequently beaten or washed to eliminate the softened tissues, leaving behind clean fibers that are ready for subsequent processing (Abbas, A. M., & Amanabo, U. H., 2019).

Retting methodologies and conventional immersion are fundamental processes in the extraction of bamboo fibers, entailing the submergence of bamboo culms in water or natural solutions to facilitate the separation of fibers from the encompassing tissues. These techniques have been employed for centuries and are integral to various traditional fiber extraction practices worldwide.

2.3.1.2.1 Water Retting.

Water retting is a prevalent technique for retting bamboo fibers, extensively employed in regions where bamboo cultivation is prominent. In this procedure, freshly harvested bamboo culms are immersed in water bodies such as ponds, rivers, or streams for a duration of several days to weeks. During this time, naturally occurring enzymes and microorganisms present in the water gradually disintegrate the pectin and lignin bonds that hold the fibers together (Liese, W., & Köhl, M., 2015).

The duration of retting varies depending on factors such as the species of bamboo, environmental conditions, and water temperature. In warmer climates, retting may transpire more expeditiously, whereas in cooler climates, it may take longer. Continuous monitoring is indispensable to ensure that the culms are not excessively retted, as this can weaken the fibers or induce decay (Abbas, A. M., & Amanabo, U. H., 2019).

Following the retting period, the softened bamboo culms are retrieved from the water and allowed to partially dry before undergoing further processing. The retted culms are subsequently subjected to beating or washing to eliminate the softened tissues, thereby exposing the pristine fibers underneath. Prudent handling is imperative during this stage to avert damage to the fibers and ensure consistent quality (Zakikhani, P., *et al.,* 2016)

2.3.1.2.2 Microbial Retting

Microbial retting constitutes an alternative retting technique that relies on specific strains of microorganisms to disintegrate the pectin and lignin in bamboo culms. This method is frequently employed in areas where water resources are scarce or where controlled microbial cultures are readily accessible.

In microbial retting, bamboo culms are stacked or piled in a controlled environment and inoculated with microbial cultures containing enzymes capable of breaking down plant cell walls. The microbial activity stimulates the enzymatic decomposition of the culm tissues, culminating in the separation of fibers from the surrounding matrix.

Microbial retting offers advantages such as expedited processing times and enhanced control over the retting process compared to water retting. Nevertheless, meticulous management of microbial cultures and environmental conditions is indispensable to ensure optimal retting outcomes (Liese, W., & Köhl, M., 2015).

2.3.1.2.3 Traditional Soaking:

In addition to retting processes, traditional soaking is a conventional technique employed to soften bamboo culms and facilitate fiber extraction. Unlike retting, which involves microbial or enzymatic degradation of the culm tissues, soaking relies on the physical properties of water to expand and loosen the fibers.

In traditional soaking, bamboo culms are immersed in water or natural solutions for a specific duration to soften the tissues and render them more flexible. This method is frequently utilized in conjunction with other fiber extraction techniques, such as hand scraping or stripping, to augment the efficiency of the process.

2.3.1.3 Indigenous Tools and Implements

Indigenous communities have developed a diverse array of tools and implements for the extraction of bamboo fibers, tailored to their specific cultural and environmental circumstances. These tools may include bamboo knives, machetes, scrapers, and beaters, crafted from locally available materials such as wood, stone, or bone. Each tool is purposefully designed to carry out specific tasks within the fiber extraction process, encompassing activities such as harvesting, stripping, retting, and beating [3].

2.3.2 Historical Practices

Gaining an understanding of the historical practices associated with the extraction of bamboo fibers offers valuable insights into the development of techniques, the challenges encountered, and the innovative solutions devised throughout time (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019; Zakikhani, P., 2016).

For thousands of years, ancient civilizations around the world have utilized bamboo for its fiber properties (Liese, W., & Köhl, M., 2015). In regions where bamboo thrives, such as Asia, Africa, and South America, indigenous communities recognized the strength, flexibility, and abundant nature of bamboo fibers, incorporating them into various aspects of their daily lives (Liese, W., & Köhl, M., 2015; Zakikhani, P., 2016).

In ancient China, bamboo fibers were skillfully woven into textiles for clothing, bedding, and household items (Liese, W., & Köhl, M., 2015). Similarly, in regions like Southeast Asia and South America, indigenous peoples employed bamboo fibers in the weaving of mats, baskets, and fishing nets (Zakikhani, P., 2016).

Over time, the techniques for extracting bamboo fibers have evolved in response to changing societal needs, technological advancements, and environmental considerations. Early methods relied on manual labor and basic hand tools, such as knives, scrapers, and beaters, to process bamboo culms into fibers (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019).

With the advent of industrialisation, mechanical processing methods, such as pulping and mechanical refining, were introduced to enhance efficiency and increase the scale of production ((Liese, W., & Köhl, M., 2015). Additionally, chemical processing techniques, including alkaline treatments, bleaching processes, and enzymatic treatments, were developed to improve fiber properties, eliminate impurities, and achieve desired characteristics (Liese, W., & Köhl, M., 2015; Zakikhani, P., 2016).

Throughout history, the extraction of bamboo fibers has faced various challenges, including labour-intensive processes, limited technological infrastructure, and environmental concerns (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019). Early methods heavily relied on manual labour, resulting in time-consuming and costly processes (Liese, W., & Köhl, M., 2015). Moreover, environmental degradation and deforestation pose threats to bamboo resources, thereby necessitating the implementation of sustainable harvesting and cultivation practices (Abbas, A. M., & Amanabo, U. H., 2019).

In reaction to these problems, advancements such as automated processing machinery, environment-friendly forestry practices, and sustainable processing technologies were created to improve effectiveness, decrease environmental impact, and guarantee the long-term stability of bamboo fiber extraction (Abbas, A. M., & Amanabo, U. H., 2019; Zakikhani, P., 2016). These solutions have played a pivotal role in advancing the bamboo industry and meeting the increasing demand for sustainable alternatives to traditional fibers (Abbas, A. M., & Amanabo, U. H., 2019).

2.3.2.1 Traditional Uses in Ancient Civilizations

Bamboo has been utilized for its fiber properties by ancient civilizations worldwide for thousands of years. In regions where bamboo thrives, such as Asia, parts of Africa, and South America, indigenous communities recognized the strength, flexibility, and abundance of bamboo fibers and incorporated them into various aspects of daily life (Liese, W., & Köhl, M., 2015; Zakikhani, P., 2016).

Bamboo fibers in ancient China were meticulously woven into textiles for clothing, bedding, and household items. The lightweight and breathable nature of bamboo fabrics made them particularly suitable for warm climates, while their durability ensured long-lasting practicality. Moreover, bamboo fibers were employed for cordage, basketry, and construction materials, highlighting the versatility and adaptability of this natural resource (Liese, W., & Köhl, M., 2015).

Similarly, in regions like Southeast Asia and South America, indigenous peoples utilized bamboo fibers for weaving mats, baskets, and fishing nets. The resilient and pliable nature of bamboo fibers made them highly suitable for crafting intricate designs and functional objects, thus showcasing the ingenuity and craftsmanship of ancient civilizations.

2.3.2.2 Evolution of Extraction Techniques

Over time, extraction techniques for bamboo fibers have undergone significant evolution in response to changing societal needs, technological advancements, and environmental considerations. Early extraction methods relied on manual labor and basic hand tools, such as knives, scrapers, and beaters, to process bamboo culms into fibers (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019).

With the rise of industrialization, mechanical processing methods, such as pulping and mechanical refining, were introduced to enhance efficiency and scale of production. These methods allowed for higher fiber yields, improved fiber quality, and reduced labor intensity, thus paving the way for mass production of bamboo fibers for commercial applications (Liese, W., & Köhl, M., 2015; Zakikhani, P., 2016).

Furthermore, various chemical processing techniques, such as alkaline treatments, bleaching processes, and enzymatic treatments, were developed to enhance the properties of the fibers, eliminate impurities, and achieve specific characteristics. These chemical processes brought about a revolution in bamboo fiber extraction by offering precise control over fiber quality, color, and functionality.

2.3.2.3 Historical Challenges and Solutions

Throughout history, bamboo fiber extraction has encountered various challenges, including labor-intensive processes, limited technological infrastructure, and environmental concerns. Early extraction methods heavily relied on manual labor, resulting in time-consuming and costly processes. Furthermore, environmental degradation and deforestation posed threats to bamboo resources, necessitating the adoption of sustainable harvesting and cultivation practices (Abbas, A. M., & Amanabo, U. H., 2019).

As a response to these challenges, advancements like automated processing equipment, sustainable forestry practices, and environmentally friendly processing technologies were created to improve efficiency, minimize environmental impact, and secure the long-term sustainability of bamboo fiber extraction (Abbas, A. M., & Amanabo, U. H., 2019; Zakikhani, P., 2016). These solutions have played a crucial role in advancing the bamboo industry and meeting the growing demand for sustainable fiber alternatives.

2.4. CHEMICAL PROCESSES INVOLVED IN FIBER EXTRACTION

Chemical processes play a significant role in the extraction of bamboo fibers, complementing traditional methods to enhance the quality of the fibers, eliminate impurities, and achieve desired properties. This section delves into the various chemical treatments utilized in the extraction of bamboo fibers, including alkaline treatments, bleaching processes, and the utilization of chemical preservatives.

2.4.1 Chemical Treatments

Chemical treatments are employed at different stages of the extraction process to modify the structure and properties of the fibers, rendering them suitable for specific applications. These treatments involve the utilization of diverse chemicals to dissolve lignin, hemicellulose, and other non-cellulosic components, thus facilitating the separation of the fibers from the bamboo culms.

2.4.1.1 Alkaline Treatments and Benefits

Alkaline treatments, such as alkali soaking and alkaline pulping, are commonly utilized in the extraction of bamboo fibers to eliminate lignin and hemicellulose from the culm tissues. In alkali soaking as described earlier in this text, bamboo culms are immersed in alkaline solutions, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), at elevated temperatures. The alkaline environment breaks down the bonds of lignin and hemicellulose, allowing for the easy separation of the fibers from the surrounding matrix.

The most basic chemical treatment method utilized for surface modification of natural fibers is alkali treatment, which is often preferred over artificial fibers.

Hydroxyl groups are present in natural fibers which aids their reactivity with NaOH. In this reaction, hemicellulose, wax, lignin, oils, and other impurities from the outer surface of the fiber are removed, causing a decrease in fiber diameter while increasing the aspect ratio and surface roughness, as illustrated in Equation (1) and Figure 2.2.

$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{fiber-O-Na} + + \text{H}_2\text{O}$ (1)

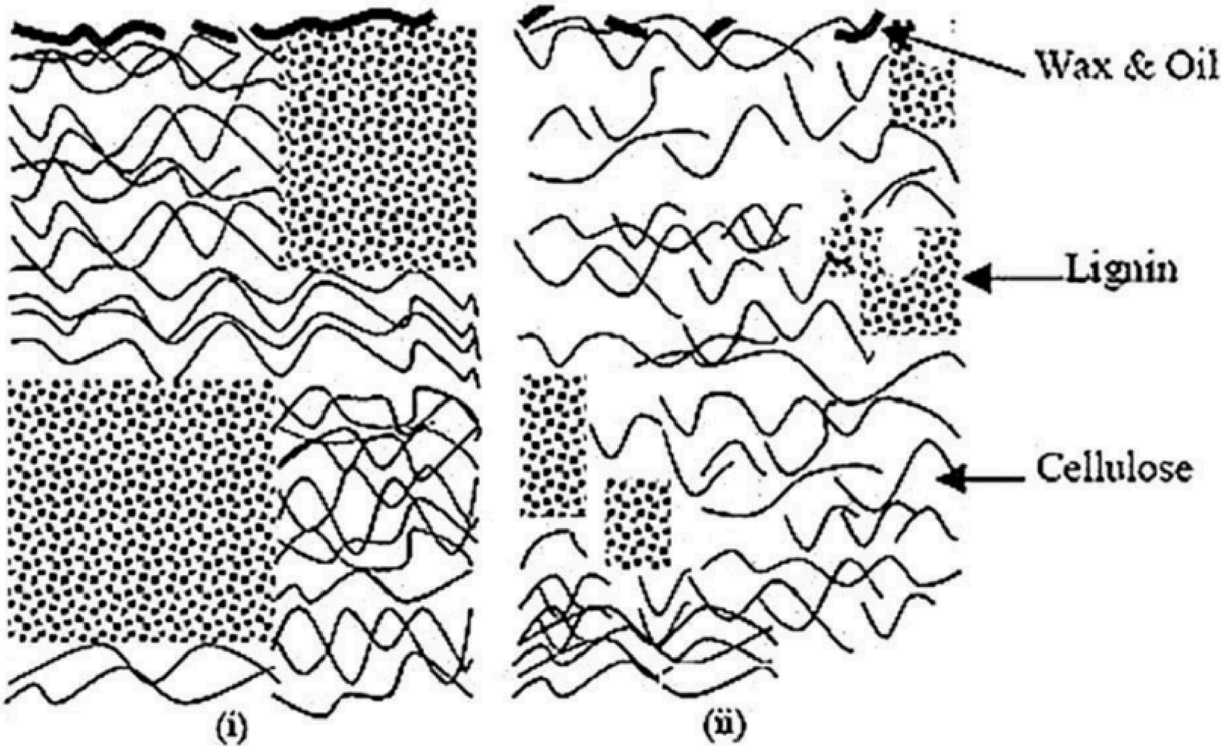

Fig. 2.2. Typical structure of (i) untreated and (ii) NaOH treated natural fiber

Alkaline pulping involves the cooking of bamboo chips or fibers in alkaline solutions under pressure, followed by mechanical refining to produce pulp. This process yields higher fiber quantities and improved pulp properties in comparison to conventional pulping methods. Alkaline treatments not only enhance the quality and purity of the fibers but also increase the fiber yield and reduce environmental impact by minimizing chemical usage and waste generation (Liese, W., & Köhl, M., 2015).

2.4.1.2 Bleaching Processes for Color Enhancement

Bleaching processes are implemented to eliminate natural pigments and impurities from bamboo fibers, resulting in brighter and whiter fibers suitable for textile and paper applications. Chlorine-based bleaching agents, such as chlorine dioxide (ClO2) and sodium hypochlorite (NaClO), are commonly employed to oxidize and decolorize the fibers.

Chlorine dioxide bleaching, in particular, is favored for its high efficiency and minimal environmental impact in comparison to traditional chlorine bleaching methods. It selectively targets lignin and chromophores within the bamboo fibers, preserving the integrity and strength of the cellulose. Alternative bleaching agents, such as hydrogen peroxide (H2O2) and oxygen (O2), are also utilized to achieve color enhancement without the detrimental effects of chlorine-based bleaches (Abbas, A. M., & Amanabo, U. H., 2019).

2.4.1.3 Chemical Preservatives in Fiber Extraction

Chemical preservatives are frequently applied during the extraction of bamboo fibers to prevent microbial decay and degradation of the fibers. These preservatives hinder the growth of fungi, bacteria, and insects, thereby prolonging the shelf life and durability of the fibers.

Commonly utilized chemical preservatives include borax (sodium borate), boric acid, and copper-based compounds, which exhibit effectiveness against a wide range of pests and microorganisms. These preservatives are applied to the bamboo culms via dipping, spraying, or impregnation methods prior to fiber extraction. Proper handling and application of chemical preservatives are imperative to ensure their efficacy and minimize environmental contamination (Zakikhani, P., *et al.,* 2016).

2.4.2 Impact on Fiber Quality

The quality of bamboo fibers is significantly influenced by the extraction process, which has an impact on their mechanical properties, chemical residues, and environmental consequences. This subsection delves into the effects of extraction techniques on fiber quality, including their influence on mechanical properties, concerns regarding chemical residues, and ongoing research on environmentally friendly chemical processes.

2.4.2.1 Effect on Mechanical Properties

The selection of an extraction method can have a substantial effect on the mechanical properties of bamboo fibers (Liese, W., & Köhl, M., 2015). Mechanical processing techniques, such as pulping and mechanical refining, may have the capability to modify the structure and morphology of the fibers, thereby potentially affecting properties such as tensile strength, modulus of elasticity, and flexibility (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019).

Moreover, chemical treatments, such as alkaline soaking or bleaching, can alter the chemical composition of the fibers, thus impacting their mechanical behavior. For instance, alkaline treatments have the potential to eliminate lignin and hemicellulose from the fiber matrix, thereby enhancing flexibility and reducing stiffness (Liese, W., & Köhl, M., 2015).

2.4.2.2 Chemical Residue Concerns

There are concerns regarding chemical residues resulting from extraction processes, specifically pertaining to fiber purity, environmental impact, and human health. Residual chemicals, including alkalis, bleaching agents, and preservatives, may persist on the fibers after processing, thus potentially causing contamination of downstream products and ecosystems (Liese, W., & Köhl, M., 2015; Zakikhani, P., *et al.,* 2016).

Furthermore, the exposure to chemical residues can pose health risks to workers involved in the extraction and processing of fibers. Proper handling, disposal, and treatment of chemical waste are crucial in order to minimize environmental contamination and ensure workplace safety Zakikhani, P., *et al.,* 2016).

2.4.2.3 Research on Environmentally Friendly Chemical Processes

Researchers are actively investigating environmentally friendly chemical processes for the extraction of bamboo fibers, with the aim of reducing chemical usage, minimizing environmental impact, and improving fiber quality (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019; Zakikhani, P., *et al.,* 2016). These processes may involve the utilization of alternative bleaching agents, such as hydrogen peroxide or oxygen, which offer safer and more sustainable alternatives to chlorine-based bleaches (Abbas, A. M., & Amanabo, U. H., 2019).

Furthermore, enzymatic treatments are being researched as a more environmentally conscious alternative to conventional chemical processes, leveraging natural enzymes to decompose lignin and hemicellulose without the requirement for harsh chemicals. Enzymatic treatments provide several advantages, including milder processing conditions, reduced energy consumption, and a lower environmental impact (Liese, W., & Köhl, M., 2015; Zakikhani, P., et al., 2016).

2.5. MECHANICAL TECHNIQUES FOR EXTRACTING BAMBOO FIBERS

Mechanical techniques play a significant role in the extraction of bamboo fibers, providing efficient and scalable solutions for converting bamboo culms into fibers. This section examines the machinery, equipment, and state-of-the-art innovations utilized in mechanical extraction methods.

2.5.1 Machines and Apparatus

The mechanical extraction of bamboo fibers relies on specialized machines and apparatus designed to process bamboo culms in an efficient and effective manner. These tools are essential for automating the fiber extraction process and increasing productivity.

2.5.1.1 Machines for Decorticating

Decorticating machines are commonly employed in the extraction of bamboo fibers to eliminate the outer layers of the culms and extract the fibers. These machines consist of rotating drums or rollers equipped with abrasive surfaces that strip off the bark and outer sheath of the culms, thereby exposing the inner fibers.

Decorticating machines come in various configurations, including drum decorticators, hammer mills, and abrasive disc machines, which are each optimized for specific bamboo species and processing requirements. These machines have the capacity to process large volumes of culms rapidly, making them well-suited for industrial-scale fiber production.

2.5.1.2 Equipment for Crushing and Combing

Crushing and combing equipment is utilized to further refine and separate the bamboo fibers after decortication. This equipment comprises rollers, brushes, and sieves arranged in sequential stages to crush, align, and purify the fibers.

In the crushing equipment, bamboo culms are fed through rollers or crushers to break them down into smaller fragments, thereby facilitating the separation of the fibers. Subsequently, the combing equipment aligns and separates the individual fibers, eliminating impurities and disparities in length to produce uniform bundles of fibers.

2.5.1.3 State-of-the-Art Mechanical Innovations

Advancements in mechanical engineering have led to the development of cutting-edge innovations in the extraction of bamboo fibers. These innovations leverage automation, robotics, and advanced materials to enhance processing efficiency, reduce labor costs, and improve fiber quality.

One example of cutting-edge innovation is the utilization of robotic systems equipped with artificial intelligence and computer vision algorithms to automate the fiber extraction processes. These robotic systems are capable of accurately identifying and manipulating bamboo culms, precisely controlling cutting, decorticating, and combing operations to optimize the yield and quality of the fibers.

A different advancement involves the creation of cutting-edge materials and coatings for processing equipment, including diamond-coated blades and ceramic rollers, that provide superior durability, wear resistance, and precision in cutting. These materials enable more efficient and reliable extraction of fibers, thereby minimizing downtime and maintenance expenses.

2.5.2 Efficiency and Output

Efficiency and output are of utmost importance in the extraction of bamboo fiber, exerting influence on production rates, resource utilization, and the overall effectiveness of the process. This subsection undertakes an examination of various factors, such as production rates and scalability, optimization of resource utilization, and the integration of technology to enhance efficiency.

2.5.2.1 Production Rates and Scalability

Production rates and scalability are pivotal elements in the extraction of bamboo fiber, as they determine the capacity and throughput of processing facilities (Liese, W., & Köhl, M., 2015). High production rates enable manufacturers to efficiently meet market demands, while scalability ensures the ability to adjust production levels according to fluctuating market conditions (Abbas, A. M., & Amanabo, U. H., 2019).

Modern processing technologies, including mechanized decorticating machines and automated combing equipment, offer significantly higher production rates in comparison to traditional manual methods. These technologies possess the capability to expedite the processing of large volumes of bamboo culms, thereby resulting in an overall increase in output and heightened profitability for manufacturers (Zakikhani, P., *et al.,* 2016).

2.5.2.2 Optimization of Resource Utilization

The optimization of resource utilization is an imperative aspect of sustainable bamboo fiber extraction, serving to minimize waste and maximize the value derived from raw materials (Liese, W., & Köhl, M., 2015). By implementing efficient processing techniques and adopting practices such as recycling or repurposing byproducts, manufacturers can reduce their environmental impact and enhance resource efficiency (Abbas, A. M., & Amanabo, U. H., 2019).

Techniques such as integrated biorefinery approaches enable manufacturers to extract multiple products from bamboo culms, encompassing fibers, cellulose, lignin, and biofuels [4]. Through the utilization of all components of the bamboo plant, these approaches maximize resource utilization and generate additional revenue streams, thereby contributing to the economic viability of bamboo fiber extraction (Popat, T.V., & Patil, A.Y., 2017).

2.5.2.3 Technological Integration for Enhanced Efficiency

Technological integration plays a pivotal role in elevating the efficiency of bamboo fiber extraction processes (Liese, W., & Köhl, M., 2015). By incorporating sensors, data analytics, and automation systems into processing equipment, manufacturers gain the ability to monitor and optimize process parameters in real-time, thereby enhancing yield, quality, and energy efficiency (Abbas, A. M., & Amanabo, U. H., 2019).

Advanced technologies, such as Internet of Things (IoT) devices and machine learning algorithms, facilitate predictive maintenance and proactive process optimization, leading to minimized downtime and maximized equipment uptime. Moreover, remote monitoring and control systems empower operators to manage processing facilities irrespective of their location, thereby increasing flexibility and responsiveness to dynamic production demands (Zakikhani, P., *et al.,* 2016).

2.6. PROPERTIES OF BAMBOO FIBER

Bamboo fiber manifests a diverse array of physical attributes that render it an exceedingly versatile material amenable to various applications. This segment delves into the distinctive properties of bamboo fiber, encompassing its variability in terms of length and diameter, as well as its density and porosity, along with the implications of color variation.

2.6.1 Physical Characteristics

Comprehending the physical characteristics of bamboo fiber is imperative for optimizing its utilization across diverse industries.

2.6.1.1 Length and Diameter Variability

Bamboo fibers exhibit substantial variations in length and diameter, influenced by factors such as bamboo species, age, and processing techniques (Liese, W., & Köhl, M., 2015; Kaur, N. *et al.*, 2017). Longer fibers typically contribute to heightened tensile strength and flexibility, rendering them desirable for applications necessitating durability and resilience, such as textiles and composites (Zakikhani, P., *et al.,* 2016). Conversely, shorter fibers may be more fitting for applications where bulkiness and absorbency are valued, such as in papermaking or insulation materials (Popat, T.V., & Patil, A.Y., 2017).

2.6.1.2 Density and Porosity

The density and porosity of bamboo fibers play pivotal roles in determining their mechanical properties and suitability for specific applications (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019). Fibers with higher density typically exhibit greater strength and stiffness, rendering them suitable for load-bearing applications, such as construction materials (Zakikhani, P., *et al.*, 2016). Conversely, fibers with higher porosity may offer enhanced moisture absorption and breathability, making them ideal for textiles and absorbent products (Popat, T.V., & Patil, A.Y., 2017).

2.6.1.3 Color Variation and Implications

Bamboo fibers inherently showcase a broad spectrum of colors, ranging from light beige to darker brown hues, influenced by factors such as bamboo species, growth conditions, and processing techniques (Liese, W., & Köhl, M., 2015; Abbas, A. M., & Amanabo, U. H., 2019). While certain applications may derive advantages from the aesthetic charm of natural bamboo colors, others may necessitate uniform coloration for consistency in end products (Zakikhani, P., et al., 2016).

Furthermore, the color of bamboo fibers can influence their resistance to fading and lightfastness when exposed to environmental factors such as UV radiation [9]. Manufacturers may employ bleaching or dyeing processes to attain the desired colour consistency and enhance the durability of bamboo fibre-based products (Liese, W., & Köhl, M., 2015).

2.6.2.1 Types of Bamboo Fibers Utilized

Bamboo fibres can be classified into natural and processed varieties, each exerting distinct influences on the mechanical behaviour of the composite.

2.6.2.1.1 Natural Bamboo Fibers

Natural bamboo fibres, obtained directly from bamboo stalks, possess inherent strength and stiffness. The hierarchical structure of these fibres plays a vital role in reinforcing composites, thus bolstering their effectiveness (Li *et al*., 2019).

2.6.2.1.2 Processed Bamboo Fibers

Processed bamboo fibers undergo treatments such as extraction, purification, and alignment processes, thereby enhancing their mechanical properties and ensuring improved compatibility with the matrix material (Zhang *et al*., 2020).

2.6.3 Mechanical Properties

The mechanical characteristics of bamboo fiber are crucial indicators of its performance and appropriateness for various applications. This subsection explores key mechanical properties, including tensile strength and elastic modulus, flexural properties, and compression strength analysis.

2.6.3.1 Tensile Strength and Elastic Modulus

Tensile strength and elastic modulus are fundamental mechanical attributes that depict the bamboo fiber's resistance to stretching and deformation under tension (Liese, W., & Köhl, M., 2015; Kaur, N. et al., 2017). Bamboo fibers typically demonstrate high tensile strength and elasticity modulus, rendering them suitable for load-bearing applications such as structural components and reinforcements (Zakikhani, P., *et al.*, 2016). The inherent potency and rigidity of bamboo fibers contribute to the endurance and longevity of products manufactured from bamboo composites (Abbas, A. M., & Amanabo, U. H., 2019).

2.6.3.2 Flexural Properties and Applications

Flexural properties, encompassing flexural strength and modulus, delineate the bamboo fiber's ability to endure bending and deformation under applied loads (Liese, W., & Köhl, M., 2015). Bamboo fibers exhibit exemplary flexural properties, enabling their utilization in applications necessitating bending resistance and structural stability, such as furniture, flooring, and construction materials (Popat, T.V., & Patil, A.Y., 2017). By capitalizing on the superior flexural properties of bamboo fiber, manufacturers can conceive innovative products that amalgamate aesthetic allure with structural integrity (Abbas, A. M., & Amanabo, U. H., 2019).

2.6.3.3 Compression Strength Analysis

evaluates the bamboo fibre's capability to withstand compressive forces without permanent deformation or failure (Liese, W., & Köhl, M., 2015). Bamboo fibers manifest notable compressive strength, making them appropriate for applications necessitating load-bearing capabilities, such as engineered structural components and support elements (Zakikhani, P., *et al.*, 2016). The elevated compression strength of bamboo fibre contributes to the stability and resilience of products subjected to compressive loads, assuring their long-term performance and reliability (Kaur, N. et al., 2017).

2.6.3.4 Testing Methods and Standards

Standardized testing methods, such as those established by ASTM and ISO, provide a consistent framework for evaluating the mechanical properties of bamboo composites.

2.6.3.4.1 ASTM Standards for Testing Bamboo Composites

ASTM standards, including D3039 for tensile testing and D790 for flexural testing, ensure a systematic approach to assessing the mechanical performance of bamboo composites (ASTM International, 2022).

2.6.3.4.2 ISO Testing Procedures

ISO testing procedures, exemplified by ISO 14125 for tensile testing, offer additional international benchmarks for evaluating the mechanical properties of bamboo composites (International Organization for Standardization, 2021).

2.6.4 Fiber Morphology

The comprehension of the morphology of bamboo fiber is of paramount importance for the clarification of its structure-property relationships and the optimization of its performance in various applications. This subsection delves into crucial aspects of fiber morphology, encompassing microstructure and ultrastructure, as well as surface morphology and fiber coatings.

2.6.4.1 Microstructure and Ultrastructure

The microstructure and ultrastructure of bamboo fibers offer insights into their composition, organization, and mechanical properties (Liese, W., & Köhl, M., 2015; Zakikhani, P., *et al.*, 2016). Bamboo fibers include cellulose microfibrils enclosed in a lignin-hemicellulose matrix, leading to a hierarchical structure distinguished by distinct fibrillar arrangements (Kaur, N. et al., 2017). By utilizing scanning electron microscopy (SEM) and transmission electron microscopy (TEM) techniques, it becomes possible to observe the internal structure of bamboo fibers at the micro- and nanoscale levels, thereby uncovering characteristics such as fiber diameter, wall thickness, and cellulose crystallinity (Abbas, A. M., & Amanabo, U. H., 2019).

The ultrastructure of bamboo fibers, which encompasses the configuration of cellulose fibrils and interfibrillar matrix components, exerts influence over their mechanical properties, moisture absorption behaviour, and processing characteristics. A comprehensive understanding of the intricate interplay between microstructural parameters is indispensable for the design of fiber-reinforced composites that possess tailored properties and enhanced performance (Popat, T.V., & Patil, A.Y., 2017).

2.6.4.2 Surface Morphology and Fiber Coatings

Surface morphology assumes a crucial role in the determination of interfacial adhesion, wetting behaviour, and compatibility of bamboo fibers with matrix materials in composite applications. The surface of bamboo fibers may exhibit features such as grooves, pores, and microcracks, which exert an impact on their surface energy and reactivity (Liese, W., & Köhl, M., 2015). Through surface treatments, such as chemical modification or plasma treatment, the surface chemistry and morphology of bamboo fibers can be modified, thereby augmenting adhesion and compatibility with polymer matrices (Zakikhani, P., *et al.*, 2016).

Fiber coatings, including sizing agents, coupling agents, and adhesion promoters, are frequently employed to enhance the compatibility of bamboo fibers with matrix materials and boost the mechanical properties of composites (Kaur, N. et al., 2017). These coatings generate a protective layer on the surface of the fiber, thus diminishing moisture absorption, boosting bonding strength, and lessening degradation at the fibre-matrix interface (Abbas, A. M., & Amanabo, U. H., 2019). By optimizing fiber coatings and surface treatments, manufacturers can customize the properties of bamboo fiber-reinforced composites to meet specific performance requirements and application demands (Popat, T.V., & Patil, A.Y., 2017).

CHAPTER THREE

3.0 MATERIALS AND METHODOLOGY

3.1 MATERIALS

3.1.1 RAW MATERIALS

Table 3.1: Details on the Materials Used.

S/N	MATERIALS	SOURCE	USE
1.	Bamboo Stem	The vicinity, University of Benin Ugbowo Campus, Benin City	For extraction of the bamboo fibre
2.	Sodium hydroxide	Shopping complex, University of Benin	As a solvent for extracting the essential fibre from bamboo stem
3.	Water	The vicinity, University of Benin	As a solvent for extracting the essential fibre from bamboo stem

3.1.2 EQUIPMENTS

Table 3.2: Details of Equipment Used for the Study.

S/N	MATERIALS	MAKE	USE
1.	Cutlass	Locally found	For harvesting and sorting the bamboo fibre.

2.	Containers	From a local market in Benin City, Edo State	To store the bamboo fibers when immersed in the solution.
3.	Weighing scale	The vicinity, University of Benin	For measuring the sample.
4.	FTIR Testing Machine	CERHI Laboratory, Energy Centre, University of Benin	To determine the content of lignin in the sample

3.2 METHOD

3.2.1 Sample Collection

The extraction of bamboo fibre from bamboo stem will be carried out at The Materials and Metallurgical Laboratory, University of Benin, Benin City, Nigeria using solvent extraction methods on a laboratory scale. The bamboo stem samples were harvested from the vicinity of the Ugbowo Campus of the institute.

3.2.2 Preparation of Bamboo Strips

3.2.2.1 Cutting and Sorting

The collected bamboo stems are then cut into customized-sized strips at the Production Engineering Laboratory, University of Benin to facilitate the extraction of fibres from the bamboo stems. A manual cutting method involving tools like a machete was used to segment the bamboo stems into sections of appropriate length (Liese *et al*, 2015).

In the preparation of the bamboo strip, unwanted parts of the bamboo stem such as branches, leaves, nodes and damaged sections are removed to improve the quality and purity of the extracted fiber, prevent contamination, and ensure the integrity of the final fiber products (Popat *et al,* 2021).

3.2.2.2 Measurement

The sorted bamboo strips are then measured before and after the soaking process to determine the amount of lignin content that was dissolved from the bamboo fibers.

3.2.3 Experimental Design

The extraction process was employed to optimise fibre extraction from the bamboo stems. This involves two extraction media: water and chemical extraction using sodium hydroxide NaOH. With a container of 1 litre (L), an accurate reading of the effect of sodium hydroxide used cannot be limited to just one concentration alone, hence, the concentration was treated with 5%, 10%, 15% and 20% concentration respectively and in varying volumes of water. The processes are further explained below.

3.2.3.1 Process of Extraction by Soaking in Water

The method of Jerachard K., *et al* (2023) was employed.

During the water process;

I. The bamboo strips for this are weighed (to help track the complete removal of lignin).
II. A container, without any additives, was filled with water and the bamboo strips were immersed in the water.
III. The submerged bamboo strips were then covered uninterrupted for some days.
IV. The fibre will become soft and ready for extraction.

3.2.3.2 Process of Extraction by Soaking in Sodium Hydroxide, NaOH

The method of Jerachard K., *et al* (2023) was employed.

During the sodium hydroxide process;

I. The bamboo strips for this are weighed (to help track the complete removal of lignin).

Fig. 3.1. Weighing scale

II. The samples were divided into four and put in 4 containers to measure the effect of sodium hydroxide at 5%, 10%, 15% and 20% concentration.
III. The containers, without any additives, were filled with a concentrated sodium hydroxide solution.
IV. The bamboo strips were then immersed in the concentrated solution of sodium hydroxide.

Fig. 3.2. Treatment process

V. The submerged bamboo strips were then covered uninterrupted for seven (7) days.
VI. The fibre will become soft and ready for extraction.

Mathematically;

An aqueous solution was assumed to weigh 1000g at 100%. To accommodate the different concentrations of NaOH the equation below was used:

The equation below was used:

0% NaOH = 1000g - (0% x 1000) = 1000g of water used.

5% NaOH = 1000g - (5% x 1000) = 950g of water used.

At 5% NaOH, the weight of NaOH used = 1000 - 950 = 50g of NaOH powder.

10% NaOH = 1000g - (10% x 1000) = 900

At 10% NaOH, the weight of NaOH used = 1000 - 900 = 100g of NaOH powder.

15% NaOH = 1000g - (15% x 1000) = 850

At 15% NaOH, the weight of NaOH used = 1000 - 850 = 150g of NaOH powder.

20% NaOH = 1000g - (20% x 1000) = 800

At 20% NaOH, the weight of NaOH used = 1000 - 800 = 200 g of NaOH powder.

3.2.4 Filtration and Separation Process

After being soaked in water and sodium hydroxide solution for the seven-day (7) period, the strips were then set to be removed. The products of the various concentrations and weights showed a bundle of fibers with a thread-like appearance as seen in the image below.

Fig. 3.3. A Sample of the Extracted Fiber Before Separation

The fibres were then drained of the solution in which they were immersed. As the solution was drained from the different varieties of fibre, the fibres were seen to possess different physical properties at that instant; the fibres had varying colours, with the sample immersed in the water revealing a light colour, to the sample immersed in 20% NaOH solution having a light colour. However, this colour change only lasted 10 days, after which they reverted to a normal colour.

This loosening of fibre and formation of single thread-like bundles happened as a result of the removal of the lignin, cellulose and hemicellulose contents in the fibre.

3.3 CHARACTERIZATION OF THE EXTRACTED FIBER

3.3.1 Determination of the Major Component

After the completion of the extraction process, the extracted fibre was tested to be sure a considerable amount of lignin had been extracted and to ensure the extracted fiber was of good quality. The Fourier Transform Infrared Spectroscopy (FTIR) Test is carried out on the extracted fibre to determine the effect of NaOH solution.

FTIR spectrometry is utilized for the characterization of organic compounds by analyzing their constituent functional groups, whereby each functional group within an organic molecule possesses distinct energy and rotation levels corresponding to wave numbers absorbed by the bonds of various functional groups. An infrared spectrum commonly obtained falls within the mid-infrared segment of the electromagnetic spectrum. This mid-infrared region typically ranges from 400 to 4000 cm-1 in terms of wave numbers, equivalent to a wavelength spanning from 2.5 to 25 microns. The relationship between peaks denoting specific wave numbers and the functional groups present in natural fibre compounds can be observed in a designated table as shown below (Martijanti M. *et al,* 2020).

TABLE 3.3

Band Assignment of Bamboo Powder as proposed by Cai, Q. (2018).

Wave Number (cm^-1)	**Assignment**
1735	C=O stretching band of hemicellulose
1604	Aromatic skeleton vibrations of lignin
1503	Aromatic skeleton vibrations of Lignin
1463	C=H deformations and aromatic ring vibrations of lignin

1426	HCH and OCH in-plane bending vibrations of lignin
1375	HCH deformation vibration of cellulose
1331	C=H bending of cellulose
1246	C=O stretching of hemicellulose and lignin
1163	C=O stretching of cellulose
1033	C=O stretching
896	C=O=C stretching at the b-(1 /4)-glycosidic linkage of cellulose
833	Benzene ring CeH bending of lignin

The effectiveness of the extraction process of lignin and hemicellulose from lignocellulose bamboo fibre polymer with NaOH solution can be measured by FTIR spectrometry where the functional groups are identified.

3.3.2 The FTIR Test

Fourier Transform Infrared Spectroscopy (FTIR) Test was quite a simple process. It is used to determine the presence and values of the major fiber components left in the fiber after the extraction process. The data obtained from the extracted fibre were analyzed statistically to fit the quadratic polynomial equation (model) generated by design expert 7.0.0 (Stat-ease, inc. Minneapolis, USA).

The values of the minuté amounts of fiber components left in the extracted fibre were according to experimental design which is now done with the FTIR. The experimental setup of the FTIR test is detailed below.

3.3.2.1 Sample Preparation

Samples at random measurements were taken from the main samples and were prepared first, after being crushed in the presence of potassium bromide, as shown in the image below.

Fig. 3.4. FTIR Sample Preparation

The crushed sample is then taken and put into the pelletizer. The pelletizer was used to form small ring-like samples that are suitable for Infrared readings.

3.3.2.2 Infrared Analysis

The pellet is then put in the machine, and left to read.

Fig. 3.5. FTIR Testing Machine

The readings from the FTIR spectroscopy test are displayed in the Results and Discussion section.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 FIBER EXTRACTION AND CHEMICAL COMPOSITION ANALYSIS

The process of fiber extraction entailed the treatment of bamboo culms with a solution of sodium hydroxide, followed by subsequent mechanical processing. The assessment of the extraction process's efficacy in the removal of lignin, cellulose, and hemicellulose components from the fibers was conducted using Fourier Transform Infrared (FTIR) spectroscopy.

The FTIR spectra of the extracted bamboo fibers, as depicted in readings of the undiluted sample, and NaOH at 5%, 10%, 15% and 20% concentrations below, reveal distinct peaks associated with various chemical components. Lignin peaks are notably present in the untreated fibers at wavenumbers approximately between 1600-1700 cm^-1, which notably diminish post-treatment with sodium hydroxide solution, indicating a partial removal of lignin. Similarly, peaks attributed to cellulose and hemicellulose components decrease in magnitude post-treatment, indicating a partial removal of these components as well (Faruk et al., 2012).

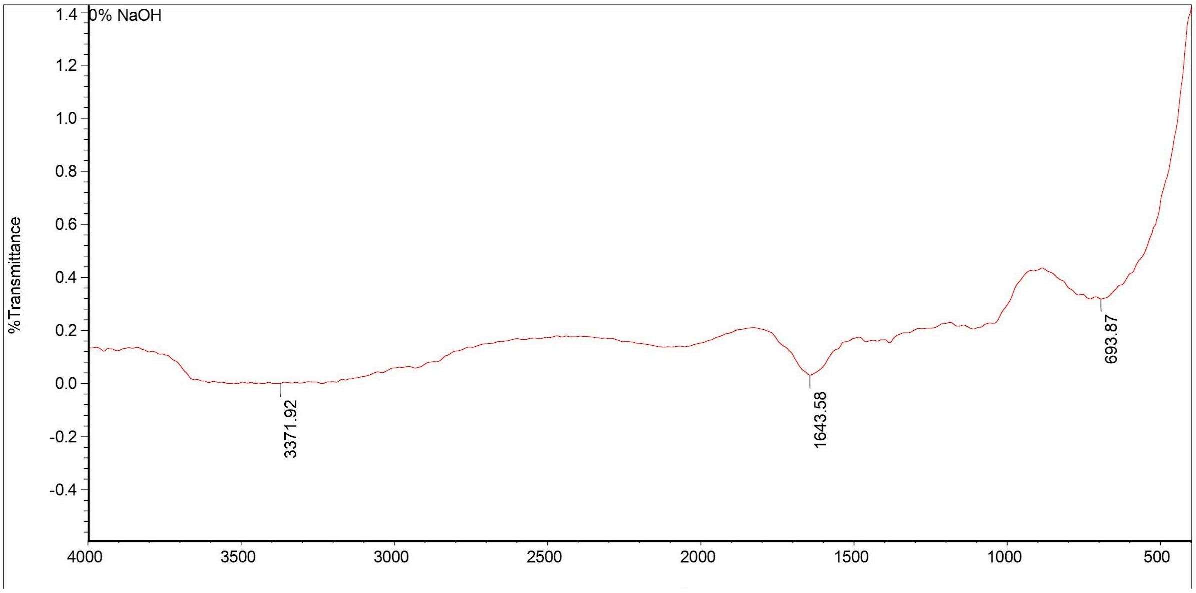

Fig. 4.1. 0% NaOH Peaks

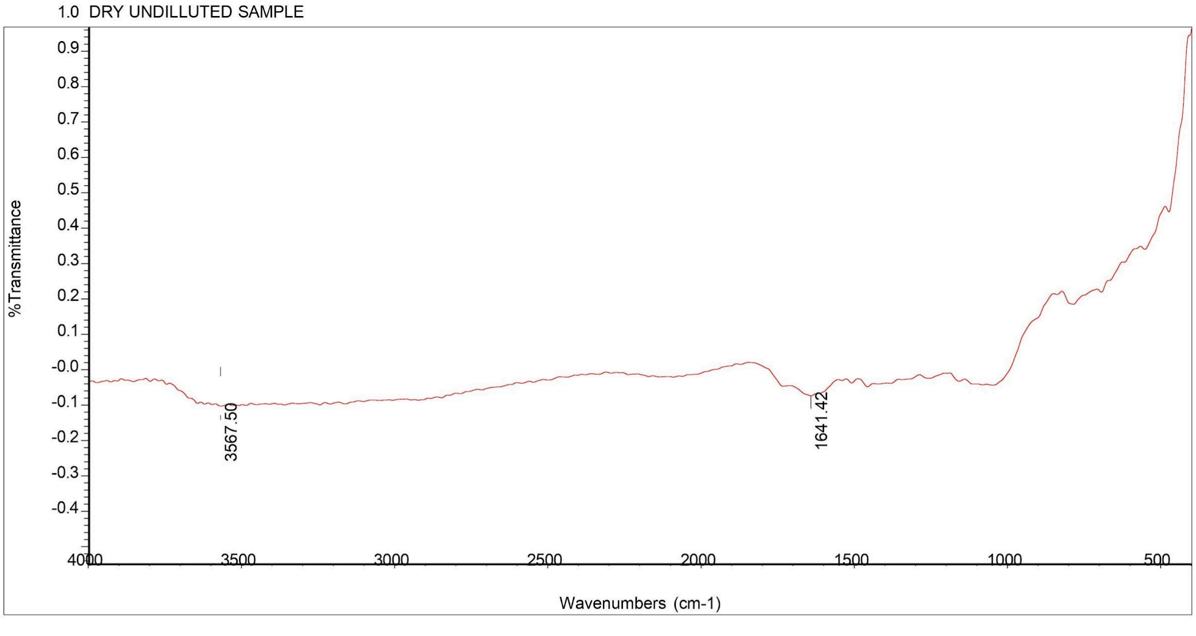

Fig. 4.2. Dry Undiluted Peaks

The analysis conducted using FTIR spectroscopy on the Dry Untreated Sample demonstrated the presence of two primary constituents: lignocellulose and the aromatic skeleton vibration of lignin. Identifying these components implies that the bamboo fibers are predominantly composed of lignocellulosic material, with lignin playing a significant role in maintaining the fibers' structural integrity.

Upon immersion of the bamboo strips in water, the bonds between lignin and cellulose start to deteriorate, resulting in the release of lignin. This alteration in the chemical composition was evident in the FTIR spectra, which exhibited the presence of lignin in conjunction with the lignocellulosic elements

This is because the lignin present in the bamboo fibre is in the form of lignocellulose as seen in the image below.

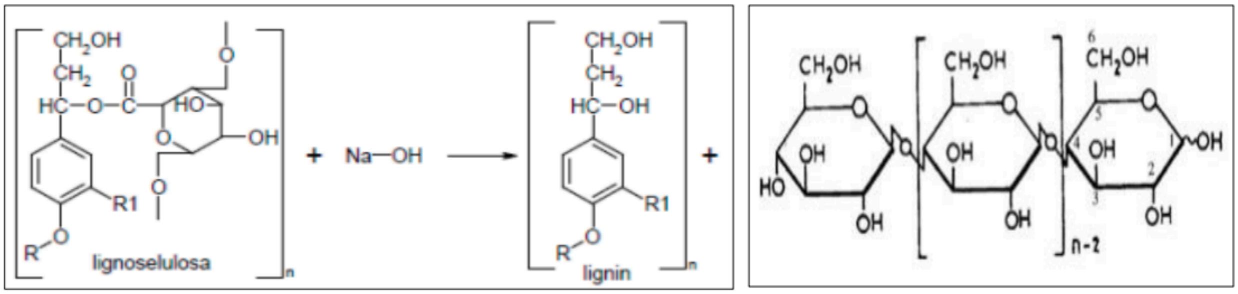

Fig. 4.3. Lignocellulose reaction in NaOH solution

4.2 EFFECTS OF SODIUM HYDROXIDE SOLUTION ON FIBER EXTRACTION

Sodium hydroxide (NaOH) solution plays a crucial role in the extraction process by facilitating the breakdown of lignin, cellulose, and hemicellulose bonds within the bamboo fibres. The alkaline nature of NaOH promotes hydrolysis and solubilization of lignin and hemicellulose, thereby loosening their association with cellulose and facilitating their removal (Oksman et al., 2016).

Furthermore, NaOH treatment leads to the swelling of cellulose fibres, which enhances accessibility to chemical reagents and promotes the diffusion of lignin and hemicellulose from the fiber matrix (Kaima et al., 2023). This swelling effect, coupled with the alkaline environment, results in efficient lignin and hemicellulose removal, leading to cleaner and purer bamboo fibers.

Optimizing the concentration and duration of NaOH treatment is crucial to balancing the removal of non-cellulosic components with the preservation of fiber integrity and mechanical properties. Higher concentrations and prolonged exposure to NaOH may lead to excessive degradation of cellulose and structural damage to the fibers (Martijanti et al., 2020). Therefore, careful control of process parameters is necessary to achieve the desired level of lignin and hemicellulose removal while maintaining fiber quality.

From observation, the subsequent treatment of bamboo strips with a sodium hydroxide (NaOH) solution induced further modifications in the chemical composition, as indicated by FTIR analysis. The application of NaOH facilitated the disruption of lignin-cellulose bonds, leading to the elimination of lignin and other substances from the fibers.

The resulting increase in the removal of components with the addition of NaOH concentrations signifies the increased effectiveness of NaOH in disintegrating lignin-cellulose complexes with increased concentration. Consequently, this process results in the separation of lignin from the cellulose framework, which resulted in the production of cleaner and more refined bamboo fibers.

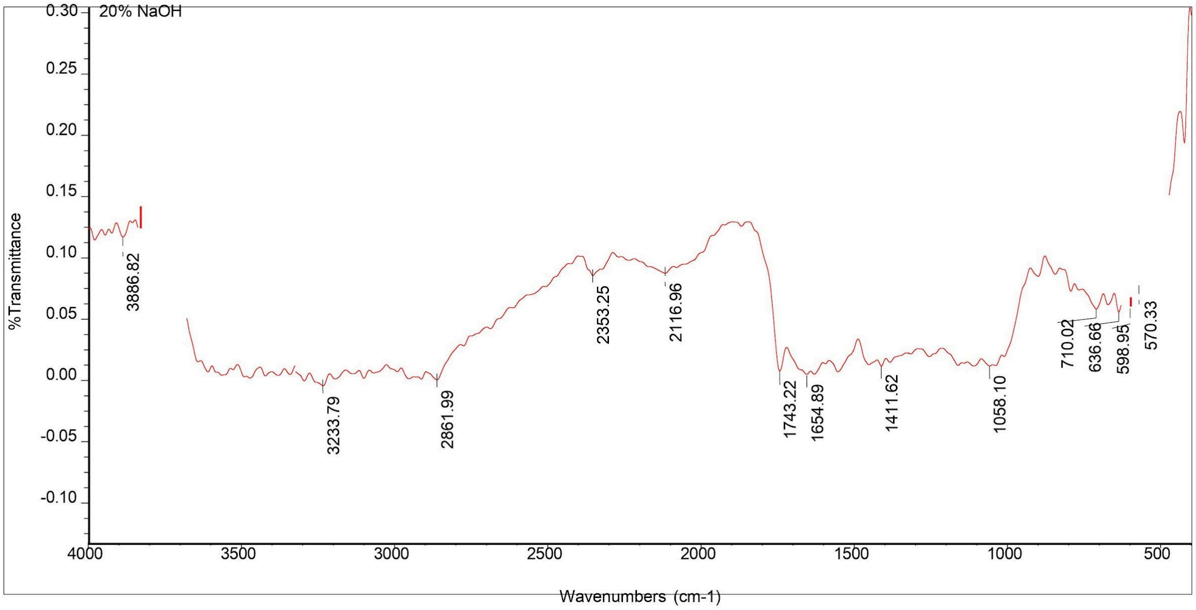

Fig. 4.4. 20% NaOH Peaks

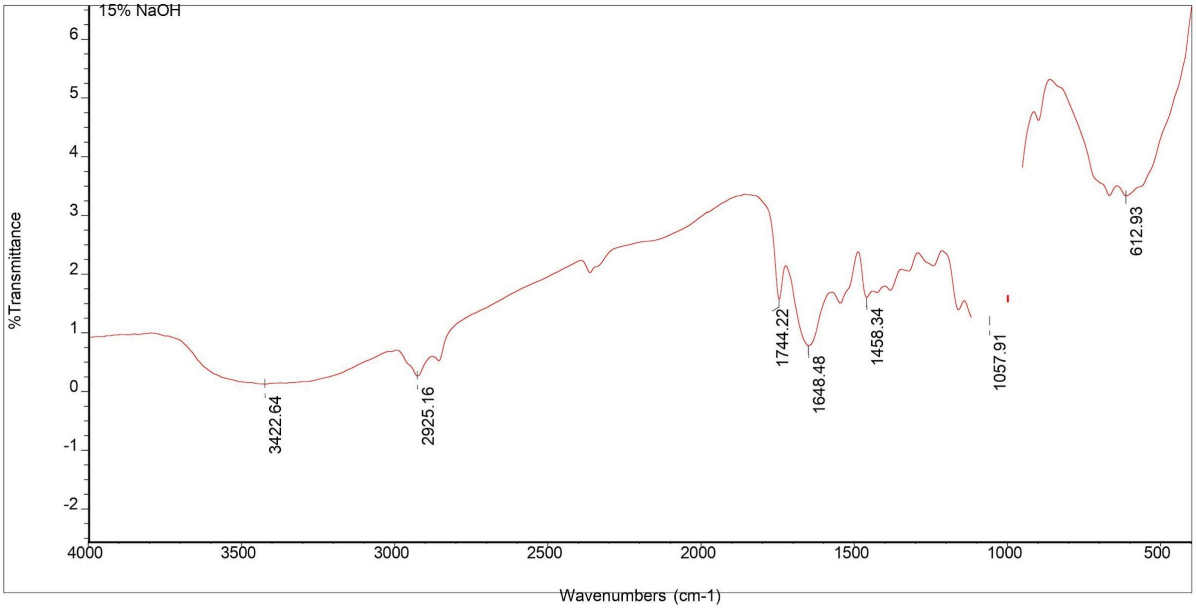

Fig. 4.5. 15% NaOH Peaks

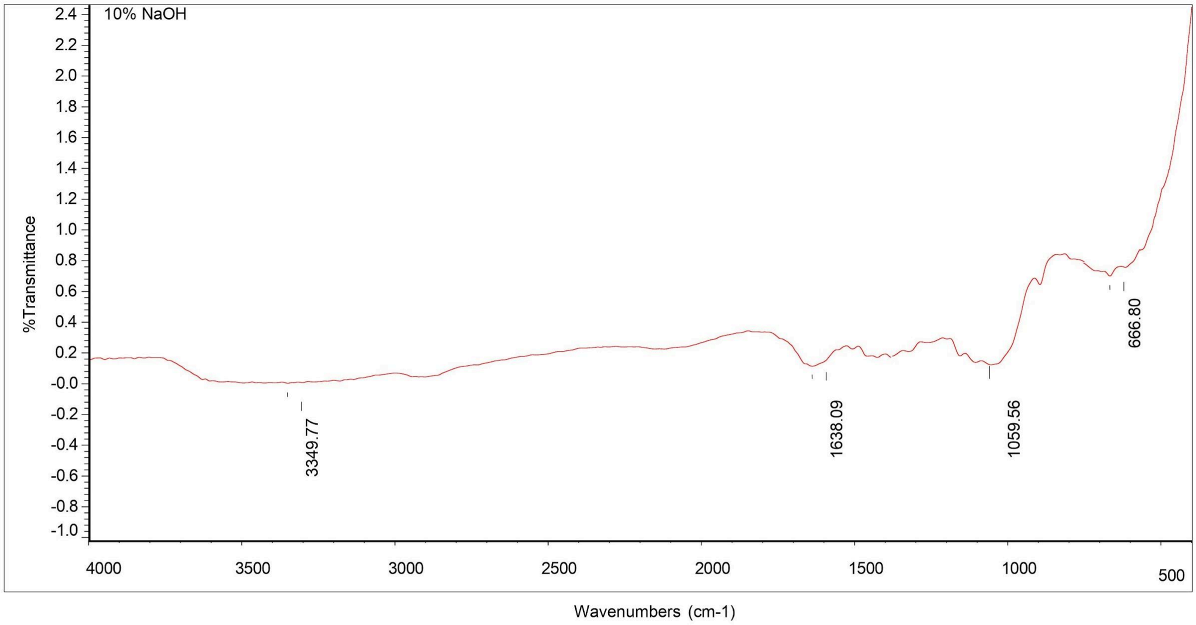

Fig. 4.6. 10% NaOH Peaks

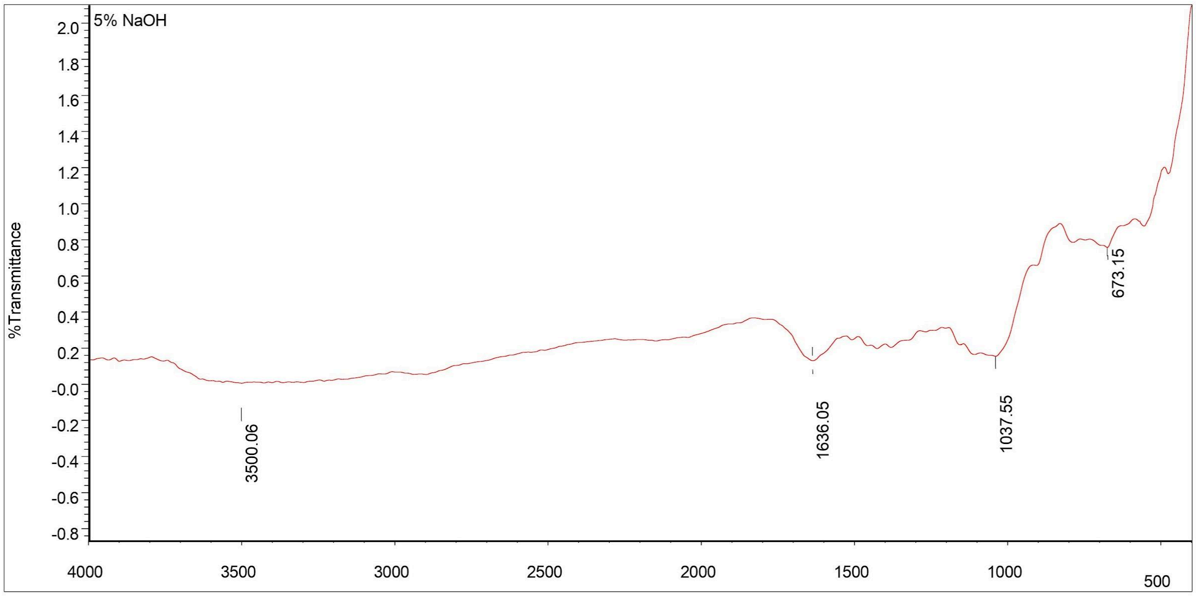

Fig. 4.7. 5% NaOH Peaks

Table 4.1 below presents an elaborate summary of peak assignments and alterations in peak intensities observed in the FTIR spectra, providing a quantitative understanding of the chemical makeup of the extracted bamboo fibers pre and post-treatment.

SAMPLE	LIGNOCELLULOSE	IN-BETWEEN	C=O STRETCHING BAND OF HEMICELLULOSE	AROMATIC SKELETON VIBRATION OF LIGNIN	HCH AND OCH IN-PLANE BANDING VIBRATION OF CELLULOSE	C-O STRETCHING	BENZENE RING C-H BENDING OF LIGNIN
UNDIL	3567.50			1641.4			

UTED				2			
0%NaOH	3371.92			1643.58			693.87
5%NaOH	3500.06			1636.05		1037.55	673.15
10%NaOH	3349.77			1638.09		1059.59	666.8
15%NaOH	3422.64	2925.16	1744.22	1648.48	1458.34	1057.91	612.93
20%NaOH	3886.82	3233.79-2116.69	1743.22	1654.89	1411.62	1058.10	710.02-570.33

Table 4.1 Tabulated Results of Chemical Components of Bamboo Fiber after Different Variations of NaOH Solution from FTIR Test

4.3 IMPLICATIONS FOR FIBER PROPERTIES AND APPLICATIONS

From past resources, the elimination of lignin, cellulose, and hemicellulose components through treatment with NaOH is thought to improve the purity and mechanical properties of bamboo fibers, making them more suitable for various industrial applications such as textiles, paper, and composites (Behera et al., 2018). These refined fibers demonstrate enhanced tensile strength, flexibility, and compatibility with matrix materials, thereby augmenting the effectiveness of composite structures (Martijanti et al., 2020; Behera et al., 2018)

Furthermore, the optimization of extraction parameters, encompassing NaOH concentration and treatment duration, permits the customization of fiber characteristics to fulfil specific application needs. Adjusting the extraction procedure aids in the manufacture of bamboo fibre products with enhanced functionality and performance characteristics, thereby expanding their possibilities in growing fields like healthcare and environmental cleanup (Behera et al., 2018).

4.4 COMPARISON WITH PREVIOUS STUDIES

The findings of this study concerning the effects of sodium hydroxide (NaOH) treatment on the extraction of bamboo fibers are in line with prior studies. Research by Behera et al. (2018) and Kaima et al. (2023) has also illustrated the effectiveness of NaOH treatment in eliminating lignin, cellulose, and hemicellulose constituents from bamboo fibers. The decrease in peak intensities in the FTIR spectra validates the successful elimination of these non-cellulosic components, resulting in improved fiber purity and mechanical characteristics.

Furthermore, the outcomes of this study are consistent with the findings from investigations on various natural fibers, like pineapple leaf fibers, documented by Srinag et al. (2023). Comparable patterns in the impacts of alkali treatment on fiber characteristics have been noted across diverse fiber sources, underscoring the broad relevance of NaOH treatment in fiber extraction procedures.

4.5 CONSIDERATION FOR FUTURE RESEARCH

While this study offers valuable insights into the effects of NaOH treatment on bamboo fiber extraction, there exist multiple avenues for future research exploration. One promising area is the optimization of extraction parameters, encompassing NaOH concentration, treatment duration, and temperature, to further enhance fiber properties while minimizing environmental ramifications.

Moreover, delving into the effects of post-treatment procedures, such as bleaching and drying, on fiber attributes could yield a more comprehensive insight into the extraction process. Assessing the feasibility of upscaling the extraction process to industrial levels and evaluating its economic feasibility are also crucial considerations for practical implementation.

Furthermore, examining the potential applications of extracted bamboo fibers in specific sectors like automotive, construction, and packaging could unveil novel opportunities for leveraging this sustainable and adaptable material. Evaluating the compatibility of bamboo fibers with diverse matrix materials and manufacturing techniques is imperative for optimizing composite performance and ensuring commercial success.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study compared the performance of fiber extraction using different concentrations of sodium hydroxide. The impact of all six (6) variables on the extracted fiber was examined, resulting in the following key findings:

1. Sodium hydroxide (NaOH) treatment proved to be highly effective in extracting bamboo fibers, as demonstrated by the experimental outcomes.

2. The extracted fiber became progressively thinner with increasing NaOH concentration across the various variables.

3. Analysis from the Fourier Transform Infrared (FTIR) spectroscopy confirmed the partial breakdown of lignin components in the bamboo fibers after NaOH treatment.

4. Alterations in chemical composition and peak intensities in the FTIR spectra indicated the efficient elimination of lignin and hemicellulose, resulting in cleaner and more refined fibers.

5. This research underscores the potential of bamboo fibers as eco-friendly substitutes in multiple sectors, such as pulp and paper, household materials, fiber-reinforced composites, and other promising applications.

5.2 RECOMMENDATIONS

Bamboo fiber is known to hold great potential for the creation of various items. The suggestions below are put forward for further exploration or future studies:

1. It is advisable, based on the findings, to refine the extraction process parameters, including NaOH concentration and treatment duration, in order to enhance the quality and performance of the fiber.

2. To shorten the treatment duration, subjecting the sample to a controlled temperature room is recommended.

3. Subsequent research should concentrate on examining the impact of post-treatment procedures, such as bleaching and drying, on fiber properties to boost the overall efficacy and sustainability of the extraction process.

4. Encouragement is given for collaboration with industry collaborators and stakeholders to support the expansion of the extraction process to a larger scale and evaluate its economic feasibility for mass production.

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