# PRODUCT DEVELOPMENT USING VEGETABLE FIBERS

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## ABSTRACT

This article is a comprehensive review on the mechanical and tribological behavior of four plant fibers (hemp, kenaf, coconut and broom) and the products design made based on these plant fibers. The treatments and the chemical and physical characteristics of these types of plant fibers are investigated to understand the applications in design field. The application of plant fibers are subject to many scientific and research projects, as well as many commercial projects. Data around these fibers are being collected and analyzed to arrange them and add new value for future applications. In most studies, natural fibers are used as replacement of traditional fibers in fiber-reinforced composites, or in automotive sector, geo textiles and other engineering fields. The research carried on is been organized so that mechanical and chemical–physical characteristics of these plant fibers can be used in conjunction with previous studies, to give a new scenario for design applications. In general, natural fibers have the advantages of biodegradability, low density, abundance and renewability, non-toxic nature, useful mechanical properties, and low cost. However, the main disadvantages of natural fibers are (i) the poor compatibility between fiber and matrix in composites and (ii) the relative high moisture sorption.

In addition, the project will improve opportunities for sustainable goods through the development of design, strategies of ecological sustainable products. Paper will outline a possible development of a product, which will be feasible gratefully to the direct application of the results and tests of the tools and methods made through out of the research.

*Keywords: mechanical and chemical properties, product design, sustainability, vegetable fibers.*

## 1 INTRODUCTION

The dependence of products based on petroleum fuels and the increase in environmental consciousness enabled studies of new sustainable materials to replace the existing ones. Environmental problems and regulations for cleaner processes have guided scientific researches towards eco-composite materials.

The most viable way is the use of vegetable fibers as reinforcement, e.g. the fibers that are mixed in a matrix that can be a polymer (epoxy, phenolic, polyester, polypropylene, and plastic), concrete, and other which are uniformly distributed and randomly oriented. This composite material containing fibrous material can increase its structural integrity. Furthermore, vegetable fibers have characteristics as renewable materials, biodegradable, and the high performance of composite materials, durability, low density, good mechanical properties, low cost and other, which depict environmental advantages followed with increased technical performances. For instance, the vegetable fibers in composite material are also used in the auto industry to create panels or pieces that need sound proofing or deadening.

Conversely, there are many different fibers that are produced and used, such as hemp, coir, kenaf, or spanish broom. Vegetable fibers are derived from sources as the stalks, leaves, seeds, and seed pods. In terms of other fibers, e.g. a coconut has been obtained from the outer husk of the fruit, and is used in vague variety of applications such as in doormats and the civil engineering, while reinforcing concrete applications or as seen in materials for roofing. Also, it is used in packaging industry and industrial designers are using it to make interior door panels, their ropes used in nautical as well as an acoustic absorber and sound barrier.


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## 2 VEGETABLE FIBERS

### 2.1 Spanish broom (*Spartium junceum L.*)

The success to obtain fibers from *Spartium junceum L.* has been known for many years, but the extraction process is low efficient. It limited applications on scaling the spanish broom fibers, despite the availability of the raw material and the high attractive characteristics of the fibers, such as biodegradability and mechanical strength [1].

The main problem in the extraction of cellulose fibers from spanish broom is the difficulty in removing the cortical cuticle, which causes a slow process, with limited applications in several fields [2].

Spanish broom fibers have advantages as abundance, biodegradable; they do not generate toxic gases and mainly produce materials by combination of plastic (fiber mixed in a matrix). These fibers still have tensile strength and flexibility.

Spanish broom fibers in composites provide specific improvements and have been used as reinforcement for polypropylene matrices [3]. However, spanish broom has disadvantages such as poor compatibility with a hydrophobic polymer matrix, high affinity towards water, as well as relatively poor thermal stability.

This way, there is a formation of weak interfaces that result in poor mechanical properties of the composites. These fibers need further treatments to improve fiber strength and fiber/matrix adhesion in fiber composites [4].

### 2.2 Hemp (*Cannabis sativa L.*)

Hemp can be cultivated in the climatic conditions experienced in temperate countries and hemp does not require any pesticide treatment while growing. However, hemp requires a license from the Home Office for its cultivation, which imposes disadvantages compared with other fiber as flax.

Hemp harvesting is annual. It is a fiber from bast, with stem diameter 4–20 mm and stem length 4.5–5 mm. It can be cultivated inclusive in the climate annual rainfall and high humidity. It is cultivated in countries such as Russia, Italy, China, Ex-Yugoslavia, Romania, Hungary, Poland, France, The Netherlands, UK, and Australia. Its practical applications are ropes, marine cordages, ships sails, and paper.

Fiber extraction is done through maceration (10–15 days), and the separation of the fibers is performed from the straw, which can be carried out mechanically [5].

### 2.3 Coir (*Coconut nucifera L.*)

The countries that cultivate coconut are Brazil, India, Indonesia, Sri Lanka, Thailand, Malaysia, Philippines, Mexico, Kenya, Tanzania, Asia, Africa, Latin America, and Pacific regions. Coconut plantations require temperatures between 20 and 32°C, as well as high humidity and plenty sunlight.

Coconut fiber is extracted from the outer husk of a coconut. There are two kinds of coconut fibers. Brown fiber is obtained from slightly ripened nuts and extracted from matured coconut; and white fibers are obtained from immature nuts (green coconuts). Brown coir fiber contains more lignin than other fibers cellulose, and this high lignin content makes it resistant to weathering, and resistant to abrasion, wet and dry conditions. Coconut fibers are available in the long fiber form, relatively short and mixed fibers. The leaves are used for roofs and mats, furniture, as husk for ropes, cordage and sail's clothes. These different types of fibers have different usage depending upon the application; for instance, brown fiber is mostly used in engineering [6].

Coconut fibers have advantages as being resistant to fungi and rot. They are also excellent insulators against temperature and sound, flame-retardant, durable, renewable, and other. However, coconut fibers can have variations in properties, which cast difficulty for their frequent usage as construction materials.

Fibers dimension vary according to individual cells and depends on the type of species, maturity of the plant, location and extraction processes. For example, the flexural and failure strength of the fiber are affected by the length to diameter ratio of the fiber. The hollow cavity helps as an acoustic and thermal insulator due to its presence and decreases the bulk density of the fiber [7].

The versatility and applications of coconut fibers in different fields are still being contested. But, it is concluded that these fibers have the potential to be used in composites and applied in different fields; for instance, in civil engineering (wall paneling system), coconut fibers have been used as reinforcement in composites for non-structural components. However, there is a need in further studies encompassing the behavior of coconut fiber reinforced concrete to use as columns of house construction as well as in other applications.

### 2.4 Kenaf (*Hibiscus cannabinus L.*)

Kenaf is a member of the Malvaceae family; it is indigenous to Africa, and probably native to southern Asia. The stem contains short and long fibers [8].

Kenaf is cultivated in India, United States of America, Indonesia, Bangladesh, Malaysia, South Africa, Thailand, parts of Africa, and small areas in the southeast Europe.

This plant grows 1.5–3.5 m tall, with leaves 10–15 cm long. The shape is variable. The fibers are in the bast (bark) and core (wood). The stem produces a coarser fiber (outer layer) and finer fiber in the core. The main uses of kenaf fiber are rope, paper, insulation, and vehicle applications such as material inside the door of cars.

Recently, the industry has increased a dependence on petroleum-based fuels and products. Upon this issue, there is a need to decrease the usage of these raw materials and to search for environmental-friendly products to replace the existing ones.

Vegetable fiber as kenaf is studied to use as no-woven mats in the automotive industries, textiles, and reinforcement of the composite. Some results of tests as elastic modulus were compared with other synthetic fiber as E-glass, and the results showed possibilities to replace some synthetic materials, already that these fibers have higher strength, lower cost and being more environmental friendly [9].

## 3 CHEMISTRY, STRUCTURE, AND MORPHOLOGY OF THE VEGETABLE FIBER

The main chemical constituent of plant cell is cellulose (see in Fig. 1), hemicelluloses, lignin, pectin, waxes, and other minors content. Cellulose is a polysaccharide polymer made up of glucose units, and it has the elements of an empirical formula $(C_6H_{10}O_5)n$. Its chains are parallel to form the bundles, denominated by microfibrils. Cellulose is the main chemical component of the primary plant cell wall, and it is organized in the form of microfibrils. Cellulose is a complex carbohydrate made up of several glucose molecules connected end to end. Hemicellulose is a short and branched heterogeneous group of polysaccharides. In addition, the cell wall contains the pectins and cross-linking glycans, which are groups of branched polysaccharides. Pectins and glycans are organized into a network with the cellulose, and the cross-linking glycans enhance the tensile strength of the cellulose, while the coextensive network of pectins supply the cell wall with the capability to resist the compression.

The secondary plant cell wall, which is deposited inside the primary cell wall, has a composition almost identical to the primary cell wall. However, there are other additional substances such as lignin. This component, lignin, is a group of polymers of aromatic alcohols that are hard and confer considerable strength to structure of the secondary wall. Lignin is common in the secondary walls of

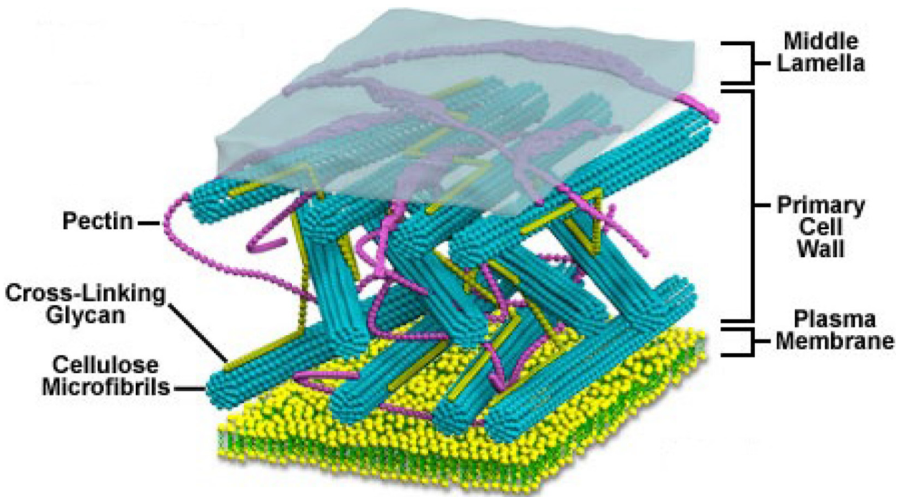


Figure 1: Plant cell wall structure [10].

Table 1: Chemical composition of the selected vegetable fibers.

| Fibers | Cellulose (%) | Hemicelluloses (%) | Lignin (%) |
|---|---|---|---|
| Hemp [11,12] | 70.2–74.4 | 17.9–22.4 | 3.7–5.7 |
| Kenaf [11,12] | 53–57 | 15–19 | 5.9–9.3 |
| Coir [13] | 68.9 | 16.8 | 32.1 |
| Spanish broom [2] | 44.5 | 70 | 18.5 |

xylem vessels, which are central in supplying structural support to plants. Another important characteristic is that lignin protects plant cell walls against attack by bacteria or fungi. Constituents such as cutin, suberin, and other waxy materials are found out in plant cell wall. The region denominated middle lamella is associated with the cell walls of plants. It is an area rich in pectins and shared by neighboring cells, which cements them firmly together.

These contents and the extraction processing methods conditions interfere in the physical and mechanical properties of plant fibers. The chemical composition of vegetable fibers studied is summarized in Table 1.

Table 1 shows high amount of cellulose in the cell wall of the plant fibers, which allows an increase in the strength of the fibers. Hemp fiber has high cellulose content and can be used in the development of products that require tensile strength. If there is a development in the product, there is a need for protection against attack by bacteria or fungi. For this, it is recommended to use the high lignin content as coconut fibers.

The structure of the cell wall, can be seen in Fig. 2, is organized by layers and the cell wall of the fiber is not a homogenous membrane. Cell fibers have a diameter of 10–25 μm, having four layers of microfibrils. It is constituted outer by a layer called primary, and internally have secondary layer, which is made up of three layers ($S_1$, $S_2$ and $S_3$). In the secondary layer $S_2$, the microfribrils are aligned according to an angle θ (the angle between the fiber axis and the microfibrils) with respect to the longitudinal axis of the cell [14].

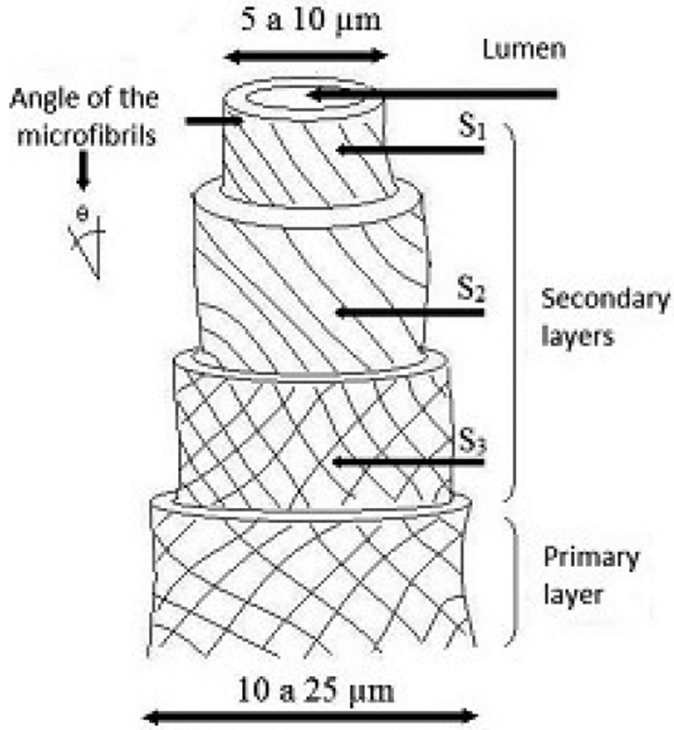


Figure 2: Structure constitution of cell wall of plant fiber [15].

There is the middle lamella (M) that determines the mechanical properties of the fiber. This layer M consists of a several 'wound cellular microfibrils' forming long chain cellulose molecules [16].

The outer secondary cell wall ($S_3$) has the thickness as the primary wall (P) and is composed of four to six lamellae spiral in opposite directions. The cell wall ($S_2$) consists in the main bulk and the microfibrils of this part have an angle of around 10–20°. The inner layer ($S_1$) is not well developed, and it has no significant technological importance. However, the $S_2$ layer has important mechanical properties such as its elasticity modulus [16].

Basic parameters such as cellulose content and the spiral angle characterize the mechanical behavior of plant fibers. The cellulose content increases, then the tensile strength of the fibers increase too. If the angle of helix axis of the fibers decreases, the tensile strength increases [17].

Vegetable fibers can be classified morphologically according to the part of the plant from which they are obtained [5]:

- Bast or phloem fibers (soft fibers): These fibers are enclosed in the inner bast tissue or bark of the stem of the dicotyledonous plants, and help to hold the plant erect. These fibers are free from the bast tissues with maceration process.
- Leaf fibers (hard fibers) are parts of the leaves' fibro vascular system. They are extracted by scraping the pulp from fibers with knife, manually or mechanically.
- Seed and fruit fibers are produced to protect the seed and the fruit. Extracting the fiber is when the fruit is husked and macerated.

Table 2: Properties of the selected vegetable fibers.

| Properties | E-glass | Hemp | Coir | Kenaf [9] | Spanish Broom |
|---|---|---|---|---|---|
| Density (g/cm$^3$) | 2.55 | 1.48 | 1.25 | 0.9 | 1.45 [19] |
| Tensile strength* (10E6 N/m$^2$) | 2400 | 550–900 | 220 | 340 | 700 [20] |
| E-modulus (GPa) | 73 | 70 | 6 | 1.4 | 20 [20] |
| Elongationat failure (%) | 3 | 1.6 | 15–25 | – | 2.7% [21] |

*Tensile strength strongly depends on the type of fiber, being a bundle or a single filament.

## 4 MECHANICAL PROPERTIES OF THE SELECTED VEGETABLE FIBERS

Vegetable fibers for technical applications require researches to better understand which parameters are the ones that influence and optimize the performance of the fibers. An important aspect relates to a mechanical property of the processes used to extract the fibers from plants, which have an effect on the mechanical performance of the fiber.

In latest years, vegetable fibers have gained interest in substituting glass fibers in composite components. Vegetable fibers like hemp, kenaf, coir are cheap and have better stiffness per unit weight. Structural applications and semi-finished materials manufactured with vegetable fibers have problems as low impact strength and poor moisture resistance. For this reason, the fibers need further pre-treatments to improve their usage in the matrixes [18]. The most important physical and mechanical properties are summarized in Table 2.

## 5 APPLICATIONS OF SELECTED VEGETABLE FIBERS

Considering the performances of composite materials in terms of maintenance, cost, durability, and the use of vegetable fibers reinforced composites in automotive field, construction material (wall paneling and roofs) ensures large potential and is fundamental for achieving sustainability. Currently, plant fiber composites are not much explored in applications in automotive sector, but in other fields the plant fibers are applicable as seen in the civil engineering, thermal insulation (roof insulation board) and acoustic (panels sound-absorbing).

Some mechanical properties of vegetable fibers prevent them from being used in high-performance applications; for instance, where carbon fiber is used as a reinforce composite. However, plant fibers can be used as replacements for glass fibers due to their properties such as stiffness, strength, lower weight, low cost, and easier recyclability [18].

Vegetable fiber can be used as the replacement to synthetic fibers reinforced composites. They can be molded into sheets, pallets, structural sections, boards and other shapes. Due to their adequate tensile strength and good specific modulus from the vegetable fibers, they leverage the right potential for usage in composites.

Although the tensile strength and Young's modulus of some plant fibers are lower than of glass fibers, the specific modulus from some plant fibers can be superior to that of glass. These characteristics together shows lower cost, renewable nature of plant fibers, and much lower energy requirement for the production of vegetable fibers. They also make them attractive as a reinforcing fiber in composites.

## 6 CONCLUSIONS

Mechanical properties from the vegetable fibers are attractive for composite industry. With advantages such are renewability, biodegradability, and low weight, the practical application of these plant fibers received increased attention from academy, industrial, civil engineering, automotive, packaging, and so on.

Assessing the importance of composites as an advanced performance material in various sectors such as automobiles, building and construction, marine, nautical, etc., the vegetable fibers have great possibilities of application and further studies to expand the usage of these in composites.

The role of natural fibers in composites demonstrate positive aspects as low abrasion, reduction in energy consumption, better vibration, dampening capabilities, better insulation and sound absorption properties, better degradation when time life is exhausted, reduction of the dependence on petroleum-based products, and other characteristics. However, some limitations must be overcome to explore the complete potential of vegetable fibers to expand the field of applicability of the fibers. The usage of vegetable fibers has given some marvelous products, and there is still a possibility of the invention of new products containing vegetable fibers with improved results.

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