GSC Advanced Engineering and Technology

Cross Ref DOI: 10.30574/gscaet

Journal homepage: https://gsconlinepress.com/journals/gscaet/

(Research Article)

# Physio-mechanical properties and applications of natural fiber reinforced bio-composites

Anindita Saha [1, 2], Kazi M Maraz [1] and Ruhul A Khan [1, *]

[1] *Polymer Composite Laboratory, Institute of Radiation and Polymer Technology, Atomic Energy Research Establishment, Savar, Dhaka-1349, Bangladesh*
[2] *Department of Chemistry, Jahangirnagar University, Savar, Dhaka, Bangladesh.*

GSC Advanced Engineering and Technology, 2022, 03(01), 001–010

Publication history: Received on 19 December 2021; revised on 29 January 2022; accepted on 30 January 2022

Article DOI: https://doi.org/10.30574/gscaet.2022.3.1.0021

## Abstract

At present, natural or lignocellulosic fiber-based bio composites are the talk of the town due to their low density, cost effective, eco-friendly, renewable properties. Bio fibers such as jute, kenaf, pineapple, sugarcane, flax, leaf, hemp, wool, silk etc obtained from plants or nature which can be utilized to obtain new high performance polymer composite materials. The physical and mechanical characteristics of these bio fibers (e.g., tensile properties, flexural stress-strain behaviour, fracture strength, impact strength) make them more sustainable and attractive than synthetic fibers with a remarkable biodegradable characteristic. The aim of this review is to give a thorough overview on natural fibers and natural fiber reinforced bio composite materials, their major physical and mechanical properties and potential applications.

**Keywords:** Bio fibers; Natural fiber reinforced biocomposites; Physical characteristics; Mechanical characteristics, Applications

## 1. Introduction

Nowadays, bio-composite materials are becoming more common as they are light weight, strong, cheap, biodegradable and sustainable. People start to depend on composite materials now more than ever and they use these materials in different aspects of their life. Recently, the whole world has been experienced with environmental concerns and issues such as sustainability and cost. As awareness of environmental issues spread, researchers and innovators are looking for a way to place more environment friendly materials such as biofiber on the market than conventional plastic [1]. Composites are formed when a material consisting of two or more individual constituents and the reinforcing constituent are embedded in a matrix [2]. Synthetic fibers of reinforcing agents like carbon, aramid, glass, nylon, as well as natural fibers such as jute, hemp, kenaf, sisal etc are being used in composite manufacturing [3,4]. Natural fiber has good properties compared to synthetic fiber [5]. For example, natural fibers used as an alternative reinforcement in polymer composites which has gained attention among many researchers and scientists due to their advantages over conventional synthetic materials [6]. These natural fibers include jute, hemp, sisal, kenaf, coir, banana, bamboo, sugarcane, flax, and many others [7] which provide good mechanical properties compared to man-made fibers and they are reasonable, recyclable and renewable, reduce energy consumption, less health risk and nonabrasive to the equipment, non-irritation to the skin [8]. It can be used as a reinforced material because of its thermoplastic and thermosetting behavior. Natural fiber is very cost-effective material that's why it is used in different sectors such as aerospace, packaging, automobile, building and construction sectors, railway coach interiors and storage device and also is used as a replacement of high-cost glass fiber [9-11]. Though natural fiber has several advantages (i.e., low

* Corresponding author: Ruhul A Khan
Polymer Composite Laboratory, Institute of Radiation and Polymer Technology, Atomic Energy Research Establishment, Savar, Dhaka-1349, Bangladesh.

density, low cost, biodegradability, etc.), it has some disadvantages as well such as high moisture absorption. Therefore, chemical treatments are necessary to control high moisture absorption. After chemical treatment, the mechanical properties of the natural fibers are greatly affected by many factors such as fiber length, fiber aspect ratio, fiber-matrix adhesion, etc. Bio composites are possible solutions when it comes to balancing costs and acquiring appropriate properties for various purposes and applications. Biocomposites are defined as a special class of composite materials obtained by blending natural fibers or bio fibers or lignocellulosic fibers with bio-based polymers. These materials represent an environmentally friendly and low-cost alternative to conventional petroleum-based materials [12]. For these reasons, the final use of these materials is gradually increasing. The increasing attraction and importance of the bio-composites increased the number of publications on that particular subject with a variety of different perspectives. These several articles present some of the reviews of different natural fiber reinforced biocomposites [13-17]. Biocomposites produced using the reinforcement of renewable resources and the reinforcement biopolymer matrix are now an extensive area of research and development due to the promising mechanical properties, recyclability after service, biocompatibility, and biodegradability of these materials. Various potential applications of such composites in various fields, such as automotive, packaging, and household goods. Natural fiber-reinforced biocomposites can be used as affordable materials with different structural properties at the same time [12,18-21].

This paper focuses on the review of natural fiber and natural fiber-based reinforced biocomposites. This study emphasizes on bio fibers, biocomposites, natural fiber-based reinforced biocomposites, physio-mechanical properties of fiber-reinforced biocomposites, globally current applications and also addresses future developments of natural fiber-reinforced biocomposites.

## 2. Fiber: natural fiber and synthetic fiber

Fibers are the reinforcing agents of the composite materials and main part of the composite system that carries structural loads. Fibers can be divided into two main categories: natural and synthetic. Synthetic fibers are generally petrochemical products. Natural fibers are obtained from plants or animals [6]. Plant based fibers are composed of cellulose and animal fibers includes proteins (hair, silk, wool, etc.). Plant fibers consist of leaf, seed, bast, fruit, wood, grass, and stalk etc [6-8]. Both natural and synthetic fibers offer strength and rigidity and serve as reinforcement in fiber-reinforced composite materials. Natural fibers like wood and some synthetic composites have been used by humans for thousands of years, but in recent times the major developments have occurred. Both vegetable fibers, whether of wood or non-wood origin, consist of three primary cell wall polymers: cellulose, lignin, and polysaccharides matrix (such as pectens and hemicelluloses) connected with cellulose and lignin in the cell wall. Several non-structural components, such as waxes, nitrogenous substances, and inorganic salts, are also present as extractives. In the structure of fibers, vegetable fibers are seen as miniature composites made up of millions of fibrous units known as microfibrils [21-26]. In this study, natural fiber sources were reviewed and the results were given in following sections.

## 3. Different types of natural fibers and their application

Natural fibers have been in existence since the beginning of the earth. In today's world, more and more consumers are realizing environmental benefits of using organic and natural fibers and so their demands have been increasing day by day. The most popular natural fibers are discussed below:

### 3.1. Jute

Among all the natural fibers, jute fibers are one of the most common, most useful, inexpensive and commercially available lignocellulose fibers. Jute fibers are one of the strongest natural fibers, fully bio-degradable and eco-friendly fibers [27]. Jute (*Corchorus capsularis/ Corchorus olitorius*) is bast fibers which is mainly grown for its fiber and also an important fiber after cotton fiber [28]. It mainly grows in India and Bangladesh. Corchorus capsularis type of jute is found in Indo-Burma including South China, and *Corchorus olitorius* is found in Africa [29]. Jute fiber has good insulation properties, high strength to weight ratio, high aspect ratio, good mechanical properties, and good thermal properties [30]. Jute fiber-based composite has been used for making a door, window, furniture, automotive, aircraft, water pipes, false roofing, floor tiles, etc [31]. Jute fiber is used as packaging material (bags), carpet backing, ropes, door, furniture, floor tiles, yarns, and also used for wall decoration [32].

### 3.2. Hemp

Hemp is another important crop used in fiber reinforcement and the history of hemp usage is very old. Hemp is an annual crop which has significant growth rate and suitable for temperature climates [7]. Hemp fibers always provide excellent mechanical strength and young's modulus. Hemp fiber is used in textile, paper, and rope and oil production

industries. It was first used in Asia. Currently, the European Union uses hemp fiber for nonfood agriculture. Hemp fiber is stronger, more absorbent, more resistant, high tensile strength, high luster, and durable than cotton fiber. Hemp fiber is used in rug and carpet manufacturing and also used for ship cordage as it is not rotted by water. Hemp fibers are used for interior design, apparel fabrics, also hemp fiber is used for blocking the sun's harmful ultraviolet rays. A recent report shows that one-third of the total production in China is based on hemp fiber [33,34].

### 3.3. Kenaf

Kenaf has a high potential to be the reinforcement material for bio-composite production due to its growth rate, and similar structure to jute and cotton which are the mostly used crop for fiber production [35]. Kenaf fiber (Hibiscus Cannabinus) is extracted from the bast (outer) and core (inner) fibers of the kenaf plant which shows similar characteristics like jute [29]. It has many advantages such as used for fabricating composites, produce twin, rope, sackcloth, paper production, animal foods, manufacture oil, medicine, food additive, and also used for industrial applications, platform for mushroom farming, environmental cleaning, absorbents, automotive industries and textiles, building materials, oil and chemical absorbents [31,36].

### 3.4. Bagasse

Bagasse also known as sugarcane bagasse is the waste (by-product) of sugar production. While paper is produced from bagasse in some Latin American countries, also bagasse can be used to produce animal feed, furfural, and bio degradable composite materials [37]. It is one of the most eco-friendly fibers which is used for a various application such as a biofuel in renewable power generation and also used to manufacture the composites materials [8, 38].

### 3.5. Bamboo

Bamboo fibers are cellulose fiber which is extracted from natural bamboo. Recently, bamboo fibers are getting more attention on the world market. Bamboo fiber is totally environment friendly fiber which has unique quality antibacterial property, moisture absorption, elasticity, UV resistant. It has wide application area such as food, paper, textile, furniture, construction, and in most of the woody goods. Bamboo fibers can provide fine mechanical strength, stiffness, low density and high modulus. It is used for manufacturing bathroom products, decorating items, hygiene products, etc. [39-41].

### 3.6. Coir

Coir is a by-product of different coconut products. Annually, over 50 billion coconuts are harvested and a very small amount of coconut husk is recycled (around 15%) [42]. Thus, coir husk fibers have a great potential for bio-composite reinforcement material production. Coir fiber reinforced composites manufactured for social, economic and industrial applications such as packaging material, helmets, rope, and finishing nets, brushes, mattresses, automotive interior, paneling and roofing as building materials, postboxes, mirror casing, storage tank, projector cover, voltage stabilizer cover [43,44].

### 3.7. Abaca

Abaca is one the of most important leaf fibers. Abaca is mostly cultivated in where its origin is Philippines. It is related with banana family [45]. It has many advantages such as low density, appropriate stiffness, and mechanical properties and high disposability and renewability, recyclable and biodegradable. It is one of the strongest cellulose fibers which is used for marine applications, resistant to saltwater, commonly used for fishing nets, used for meat casings and also abaca fiber is used in the production of the tea bags; also utilize as a raw material and that raw material is used in the processing of high-quality paper, machinery filters, hospital textiles, electric conductor, etc. [8,46].

### 3.8. Cotton

Cotton is one of the most important fibers that is used all over the world. It has variety of uses. But due to its relatively low mechanical properties, it is rarely used as reinforcement agent. It is generally used as secondary fiber in green hybrid-composites [47].

## 4. Bio-composites

The growing ecological and environmental consciousness has driven efforts for development of new innovative materials for various end-use applications. In this perspective, biocomposite materials from natural resources have gained considerable research interest in the recent years. In general, biocomposites are made up of biodegradable polymers (biopolymers) and bio-based reinforcing agents. Material is described as a biocomposite composed of two or more distinct components (one of which is naturally derived) that are combined to create a new material with improved

performance over individual constituent materials. The constituent materials are the matrix and the reinforcing component. The primary load bearing factor of the reinforcement portion, which may be in the form of fibers, particles, whiskers, and flakes. The matrix used to tie the reinforcement components together and provide mechanical support [20,48,49]. Production and application of biocomposites are remarkable achievements to replace conventional nonbiodegradable petroleum-based materials. The main and important benefit of these biocomposites is: it can be conveniently disposed of at the end of their life cycle without threatening the atmosphere that is not possible for conventional fiber-based polymer composites [17, 50,51].

### 4.1. Natural Fiber Reinforced Biocomposites

Biocomposites are natural fiber-reinforced biopolymers. Researchers have been developing these materials as an alternative to conventional materials that may be nonrenewable, recalcitrant, or manufactured by pollution emitting processes [52]. Lignocellulosic natural fibers are widely used among natural fibers as reinforcements for the production of biocomposites. Natural fibers such as jute, kenaf, hemp, oil palm, pineapple, flax, sugarcane, and leaf are inexpensive, environmentally sustainable, organic, partially and fully biodegradable, and can be used to produce modern high performance polymer materials. Natural fiber composite materials have significant characteristics that are ecofriendly, lightweight, strong, renewable, cheap, biodegradable, and sustainable. Compared to synthetic fiber it has relatively stronger properties. Recently, many researchers and scientists have used natural fibers as an alternative reinforcement in polymer composites because of their advantages over conventional synthetic materials [7, 53-55]. Natural fibers can be used as reinforced material in biocomposites as their thermoplastic and thermosetting properties are far better than synthetic fibers. Thermosetting resins such as epoxy, polyester, unsaturated polyester resin, polyurethane, and phenolic are widely used in the manufacture of composite material and offer a greater output in different applications. They have adequate mechanical properties and the price is fair for such products. Due to their good mechanical properties such as high strength, low density, and ecological advantages, academics, researchers, students, and also Research and Development (R&D) sectors of industries pay more attention to natural fiber-based composites than conventional synthetic fiber-based composites [56]. Efficient advantages of being biodegradable and made from renewable materials, natural fibers are often less abrasive to manufacturing equipment than synthetic fibers such as acrylic or ceramic fibers and conventional fillers such as mica and stone and have a lower density, which makes biocomposites lightweight, economical and environmentally safe [20,57].

## 5. Characterization of fiber reinforced bio-composites

The greatest challenge in working with natural fiber reinforced composites is their large variation in properties and characteristics. The properties of fiber reinforced biocomposites are influenced by a number of factors including the fiber type, environmental conditions (where the plant fibers are collected), processing methods, and any modification of the fiber [7]. Careful selection of the reinforcing fibers and matrix polymers is the first step to obtain a composite with the desired properties in light of the intended application. The performance of natural fiber reinforced biocomposites depends on several factors, including fibers chemical composition, cell dimensions, microfibrillar angle, defects, structure, physical properties, and mechanical properties, and also the interaction of a fiber with the polymer. To expand the use of natural fibers for composites and improved their performance, it is essential to know the fiber characteristics [58,59].

### 5.1. Physical Characterization

The advantage of natural fiber over synthetic fiber is increasing day by day because of its low cost, less weight, low manufacturing cost, abundance, renewable resources, relatively good physical and mechanical properties such as tensile strength, tensile modulus, bending strength and bio-degradable and environmentally friendly qualities. Natural fibers have been cultivated and used especially in rural developing countries for creating non-structural applications such as bag, broom, fishnet, and filters [29]. The fiber's dimensions, defects, strength, variability, crystallinity, and structure are very important variables in measuring their physical properties. Knowledge of fiber length and width is necessary to compare natural fibers of different types. Major structural differences such as density, thickness of the cell wall, length, and diameter result in differences in physical properties. Moreover, Interesting fact is that the morphology of fibers ground plant is very different from that of fibers water plant. The cellulose content and the angle of the spiral between the fiber qualities are different from fiber to fiber and also in a single fiber design. Natural fiber's crystallinity values vary across various parts of the plant. As the plant gets old, the crystallinity tends to decrease, but the difference between bast and core fibers is incompatible [12,59].

### 5.2. Mechanical Characterization

Tensile, flexural, and impact properties are the most widely studied mechanical properties of natural fiber-reinforced polymer composites. Impact strength in terms of mechanical performance is one of the undesirable weak points of such materials. In addition to these tensile, flexural and impact properties, the long-term performance (creep behavior), dynamic mechanical behavior, and compressive properties of natural fiber composites are also investigated [60-61]. Several factors i.e., the kind of natural fibers, surface chemistry between fiber, type of fibers, moisture content and form of fibers and other composition (e.g., epoxy resin) and the quality of the interface should be considered to achieve desired mechanical properties of the natural fiber reinforced based composites. These properties of the natural fibers depend on the types of natural fibers, their cultivation, growing period and extracting process, isolation and processing method [62-64]. Mechanical properties of the natural fibers especially flax, abaca, kenaf, ramie, hemp, jute, sisal, bamboo, and bagasse are very good and strength and modulus are higher than synthetic fiber [65]. Table-1 and Table 2 shows the type and mechanical properties of the common natural fibers and natural fiber-reinforced bio composites:

**Table 1** Mechanical properties of different kinds of natural fibers

| Fiber | Density (gm/cm$^{3)}$ | Tensile Strength (MPa) | Young's Modulus (GPa) | Elongation at break (%) |
|---|---|---|---|---|
| Jute | 1.3-1.46 | 393-800 | 10-30 | 1.5-10 |
| Hemp | 1.47-1.48 | 550-900 | 70 | 1.6-4 |
| Kenaf | 1.2-1.45 | 295-930 | 53 | 1.6-6.9 |
| Bagasse | 1.2-1.25 | 20-290 | 17-27.1 | 1.1 |
| Coir | 1.15-1.45 | 106-593 | 1.27-6 | 15-59.9 |
| Bamboo | 0.6-11 | 140-230 | 11-17 | - |
| Abaca | 1.5 | 400-980 | 3-12 | 3-10 |
| Cotton | 1.5-1.6 | 287-597 | 5.5-12.6 | 3.0-10.0 |

**Table 2** Variation of mechanical properties of natural fiber-reinforced bio composites [60-61, 66-67]

| Type of bio composite | Tensile Strength (MPa) | Young's Modulus (GPa) | Flexural Strength (MPa) | Flexural Modulus (GPa) | Impact Strength |
|---|---|---|---|---|---|
| Jute-pp | 23-29 | 1.6-2.4 | 45-54 | 1.7-2.8 | 30-51 J/m |
| Coir-pp | 25-28 | 1.7-2.7 | 47-49 | 1.6-2.8 | 41-54 J/m |
| Abaca-pp | 23-27 | 1.6-2.6 | 46-48 | 1.4-2.6 | 39-46 J/m |
| Bagasse-pp | 17-22 | 1.2-1.4 | 21-34 | 0.8-1.6 | 3.3–6.2 KJ/mm$^2$ |
| Hemp-pp | 27-29 | 1.6-1.8 | N.S. | N.S. | N.S. |
| Banana-pp | 36-41 | 0.82-0.98 | N.S. | N.S. | 10.2-12.8 KJ/mm$^2$ |
| Palm-pp | 21-30 | 1.1-1.6 | 44-55 | 1.6-2.6 | 39-53 J/m |

## 6. Current application of natural fiber composite materials

Natural fiber is a type of renewable sources and a new generation of reinforcements and supplements for polymer-based materials. The use of natural fibers within composite applications is being pursued extensively throughout the world. Consequently, natural fiber composite materials are being used for making components in the automotive sector. These materials are based largely on polypropylene or polyester matrices, incorporating fibers such as flax, hemp, and jute.

The applications of natural fibers are growing in many sectors such as automobiles, furniture, packing and construction. This is mainly due to their advantages compared to synthetic fibers, i.e., low cost, low weight, less damage to processing equipment, improved surface finish of molded parts composite, good relative mechanical properties, abundant and renewable resources [68]. Natural fibers are used in various applications such as building materials, particle boards, insulation boards, human food and animal feed, cosmetics, medicine and for other biopolymers and fine chemicals [69]. At present scenario, natural fiber reinforced based composite materials is used almost in every type of advanced engineering structures. This includes various components in aircraft, automobiles, helicopters, spacecraft, boats, ships, offshore platforms and also used in chemical processing equipment, sports goods, and civil infrastructure such as buildings and bridges [70]. Industrial uses of natural fibers increasingly gain attention from various manufacturing sectors. Moreover, several industries and factories are encouraged to use natural fibers as those products are more environment friendly and reduce their dependence on fossil fuels [71]. In particular, one data shows that the worldwide use of natural fiber composites has been grown to market around 11% from 2014 to 2019, and its extent $531.2 million in 2016, then market share of the natural fibers has been increased around 28% [72].

In the United States, composite building materials are being made from straw. Straw bales are being used in the construction of buildings. Many automotive components are already produced with natural composites, mainly based on polyester or Polypropylene and fibers like flax, hemp, or sisal. The adoption of natural fiber composites in this industry is led by motives of price, weight reduction, and marketing rather than technical demands [73]. In Germany, the major car manufactures such as Mercedes, Volkswagen, Audi and Ford use natural fiber composites for various interior and exterior applications. Mercedes-Benz used an epoxy matrix with the addition of jute in the door panels in its E-class vehicles back in 1996. Another paradigm of natural fiber composites' application appeared commercially in 2000, when Audi launched the A2 midrange car: the door trim panels were made of polyurethane reinforced with a mixed flax/sisal material. Toyota developed an eco-plastic made from sugar cane and will use it to line the interiors of the cars [74].

Coir fibers are used in the majorly in domestic sector for making a wide variety of floor-furnishing materials, for mattress/sofa bed and in gardening, while in the automotive sector it is used as a support for seats and seat cover. Biodegradable bark cloth reinforced green epoxy composites are developed with view of application to automotive instrument panels [72]. Another popular bio composite is jute fiber reinforced bio composite material. Jute-based green composites would be suitable for even primary structural applications, such as indoor elements in housing, temporary outdoor applications like low-cost housing for defense and rehabilitation and transportation [75]. Nowadays, mobile box is also made of white natural bagasse which improves the eco-friendly and biodegradable and also sustainable.

## 7. Future Development

The effort to develop biocomposite materials with improved performance for global applications is an ongoing process. Growing consumer demand and market activity for sustainable materials has led to the study and application of natural fibers in biocomposites. As natural fibers have some drawbacks regarding their performance, the behavior is changed when the polymer is added for manufacturing and processing new composite. The physical properties of the natural fiber are not consistent, their physical properties vary with harvesting season, harvesting reign. All these factors affect the properties of the natural fiber composites [76]. To overcome this drawbacks some modification of the natural fibers are needed such as treatment with alkali, saline, water repelling agents, to improve adhesion between matrix chemical coupling or compatibilising methods also used and many researchers have been already used plasma modification of natural fibers and these methods helps to reduce the water absorption of the natural fiber by removing hemicellulose and lignin or by imparting hydrophobicity and also help to improve the interface between natural fiber and polymeric matrix [77] . In a nutshell, it will be an effective way to develop the biocomposites which can be particularly used for daily needs of common people whether it is house hold furniture, house, fencing, decking, flooring, and light weight car components or sports equipments. Their low cost, easy availability and aesthetic designs will be the main driving force to transform the depended present to sustainable future.

## 8. Conclusion

In present scenario, eco-friendly biocomposites from plant-derived fibers are the blessing materials of this century. Most research works have been carried out to study the potential uses of natural fibers for various technical applications as they are sustainable, biodegradable, renewable raw material. Increasing concerns about natural resources and growing global environmental waste problems, researchers have recently focused their attention on biocomposites and developed the physio-mechanical properties of those materials for better performance. As a result, Petroleum-based materials are replacing day by day by the development of biocomposites and also an alternative solution of synthetic

fibers based plastic composite products and generating more economic opportunities for the civil engineering sector. This paper is a brief review study of the different kinds of bio fibers, physio-mechanical properties and applications of bio-fibers and bio-composites. The study showed that bio-composites are promising materials for the future applications in many industrial sectors especially in automotive sector which is the leading sector of the industrial and technological development. The remarkable advantages such as the renewability and sustainability and bio-degradable characteristics of bio-composite materials make bio-composites the "green materials". Above all, the increasing awareness of the people and the contribution of researchers and investigators will help the further development of biocomposite materials in near future.

## Compliance with ethical standards

### *Acknowledgments*

The research work was supported by the Ministry of Science and Technology, Government of the People's Republic of Bangladesh under the Special Allocation for Science and Technology Programme, Financial Year 2021-2022. The Project Title is: Fabrication of Jute Fiber Reinforced Polymer-Based Colored Composites for Interior Panel Applications: Effect of Gamma Radiation. GO No: 39.00.0000.009.14.019.21-745, Serial No. 465; Group Serial No. 465 EAS.

### *Disclosure of conflict of interest*

All authors state that there is no conflict of interest.

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