Natural fibers and their applications: A review

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Abstract : Natural fibers are playing a major role in so many applications such as biomedical applications, aerospace Industry, structural applications, and automotive. This review aims to provide an overview of technological process (chemical treatment), availability, and the most prominent applications of natural fibers that made them preferable to be employed in these applications.

Keywords: Applications, Chemical treatments, Eco-friendliness, Natural fibers.

الخلاصة: تلعب الالياف الطبيعية دورا رئيسيا في العديد من التطبيقات مثل التطبيقات الطبية وتطبيقات الفضاء والتطبيقات الهيكلية والسيارات. هذا البحث يهدف الى اعطاء صورة عامة عن تقنيات التصنيع (المعالجة الكيميائية)، الوفرة، وكذا أبرز التطبيقات الخاصة بالألياف الطبيعية التي جعلتها مفضلة في الاستخدام.

1. Introduction

In recent decades, there have been a consistent consumer's awareness towards new products made from renewable sources. Green marketing has new directives on recycling social impact and makes changes in cognitive values that led the consumer towards eco-friendly products.

In particular, composite materials are being developed with new styles targeting to improve, adapt, and introduce new products in a sustainable and responsible approach [1-2].

The improvement in environmental awareness and the willing to ensure sustainability of construction materials has encouraged many researchers to seek for some alternative fibers to strengthen those materials. In this respect, natural fibers show a considerable attention according to their reproducibility, low density, high specific strength, and cost effectiveness. Moreover, they do not pose any ecological problems in terms of closing important life cycles (especially CO_2). The replacement of the traditional synthetic fibers by their natural counterparts is preferred not only for the environment but also for economic reasons as the production of synthetic fibers is an energy-consuming process compared to the natural ones [3-4].

In addition, more merits can be obtained by natural fibers that include; but not limited to; low cost, low density, sustainable availability, and low abrasive wear of processing machinery [4].

Thus, polymer composites based on natural fibers as reinforcing agents have shown promising indications not only in mechanical performance, but also in physical and thermal properties compared to the neat polymers. Nevertheless, there are some limitations associated with using natural fibers in composites such as the absence of adequate adhesion between the fiber and the matrix, hydrophilic nature (moisture absorbing), and poor thermal stability [5].

Natural plant fibers possess a hydrophilic nature according to the presence of strong polarized hydroxyl groups in their structure. As a result, these fibers are innately incompatible with polymers matrices which have a hydrophobic nature. Furthermore, due to the presence of hydroxyl groups in natural fibers, moisture absorption is very high and this leads to poor interfacial bonding with the polymer matrices which consequently leads to de-bonding of fibers and makes voids in the final products. The interface between reinforcing fibers and the matrix plays a crucial role in the mechanical performance of the bio-composites. The overall characteristics of natural fibers based polymer composites are intimately associated with the nature of the natural fibers and their compatibility with polymer matrices [6-7].

A number of chemical treatments are available that can be utilized to enhance the compatibility between the fibers and matrices. Apart from the chemical treatments, there are many ways of physical treatments which are used to improve the interfacial bonding between natural fibers and the polymer matrices. The physical structure and surface properties of fibers can be altered by these treatments. Different types of chemicals are employed for the treatment of natural fiber.

The majority of the treatments used on natural fibers are alkali treatments. This kind of treatment removes the lignin, wax, and oil that are covering parts of natural fibers and increases the roughness of the fibers surfaces. This leads to a better interlocking with polymer matrices [7].

Surface modifications represented by chemical treatments offer an effective means to remove lignin from the natural fibers and hence enable better bonding in polymer composites [8].

The fibers from natural plants are utilized for commercial applications such as household applications, automotive industries, and so many others. The natural fiber-based composite's quality depends mainly on reinforcement properties and matrix attachment. The complete bio-based natural composites are made with a combination of natural fiber and natural-based resin.

This kind of composites is used in many applications such as industrial, construction, marine, electrical, household appliances, automotive, and sporting goods. In addition, these composites have high strength, high stiffness, light weight and high corrosion resistance [9- 11].

Although natural fibers contain commonly hemicellulose, cellulose, lignin, pectin, wax, and moisture, but the characteristics of those fibers completely depend on the growing environment of plant, type and maturity of the plant, fiber extraction method, and fiber extraction part of the tree [10].
The extraction of natural fibers is made from both resources, renewable and nonrenewable such as oil palm, sisal, flax, and jute in order to produce composite materials. The plants, which produce cellulose fibers can be classified into bast fibers (jute, flax, ramie, hemp, and kenaf), seed fibers (cotton, coir, and kapok), leaf fibers (sisal, pineapple, and abaca), grass and reed fibers (rice, corn, and wheat), and core fibers (hemp, kenaf, and jute) as well as all other kinds (wood and roots) [12].

2. Sources and Properties of Natural fibers
There are different types of plants-based natural fibers classified into two major categories, wood-based natural fibers, and non-wood-based natural fibers, as shown in Figure 1. The subcategories include bamboo, flax, wool, kenaf, jute, hemp, okra, sugarcane bagasse, hemp, banana leaf, pineapple, coconut shell, rice husk, wood or other fibrous materials. These fibers find a variety of applications in paper industry and polymer composites [13].

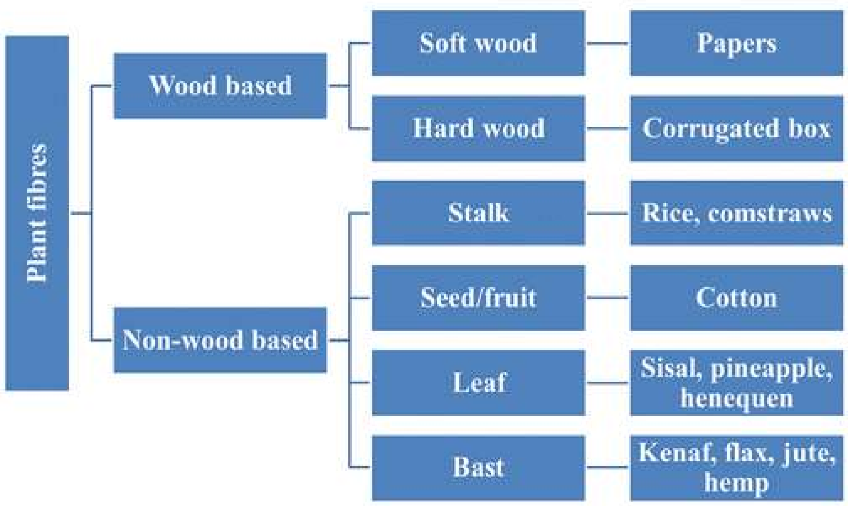

Fig. 1. Classification of plant fibers [13]

2.1 Kenaf (Hibiscus cannabinus)

The kenaf fibers are one of the most important fibers that belong to bast fibers and they are majorly used for producing papers and ropes [14]. Kenaf is a fibrous plant. These fibers have many unique features as they are tough, stiff, strong, and have high resistance to insecticides. These plants are cultivated 4,000 years ago in Africa, Asia, America, and some parts of Europe [15].

2.2 Hemp (Cannabis sativa)

The Hemp is a type of plants species grown particularly in Asia and Europe. It grows up to 1.2–4.5 m and 2.0 cm in diameter [16]. These fibers can be employed in ropes production, textiles, garden mulch, the assortment of building materials, and animal beddings. In recent developments, it is used to fabricate different kinds of composites [17].

2.3 Jute (Corchorus capsularis)

The jute is considered as an important natural fibre grown in specific parts of Asia including India, Bangladesh, China, and Myanmar [18-19]. The jute plant grows up to 15–20 cm within several months, and the fibers are extracted after harvesting which is performed about four months from cultivation. The retting process is done either chemically with the help of chemical agents such as ($N_2H_8C_2O_4$, Na_2SO_3, etc.) or biologically [20].

2.4 Flax (Linum usitatissimum)

The flax fibers are produced from the prehistoric period. These fibers are separated from the stems of the plant Linum usitatissimum that is mainly used to produce linen [21-22]. These are cellulosic plants but they are more in crystalline form. These fibers measure up to 90 cm length and diameter of 12–16 µm. Netherlands, Belgium, and France are the leading producers of these fibers. These fibers are e in furniture materials, textiles bed sheets, linen, and interior decoration accessories [23, 20].

2.5 Ramie (Boehmeria nivea)

Ramie is one of the herbaceous perennial plants cultivated extensively in regions native to China, Japan, and Malaysia where it has been used for over a century as one of the textile fabrics [24-25]. Ramie is a non-branching, fast-growing plant which grows up to 1–2 m height. The fibers extracted from the stem are the strongest and longest of the natural bast fibers. They are used to make sweaters in combination with cotton. Also they are used in upholstery, gas mantle, fishing nets, and marine packings [26]. In addition, attempts have been made for developing bio-based products related to Ramie by utilizing them in various applications of automotive, furniture, and construction. Ramie fibers are extensively used for the production of a wide range of textiles, pulps, papers, agrochemicals, and composites. The processing of ramie fibers is similar to linen from flax [27].

2.6 Nettle (Urtica dioica)

Nettle is commonly grown as a herbaceous plant that consists of 35–40 different species. It is generally grown in Europe, Asia, Northern Africa, and North America [28]. The plant usually grows up to 2.0 m in length, the leaves are soft and green which are 3.0–15 cm long. The leaves and stems are generally hairy and have stinging hairs on them [29]. The typical applications of nettle fibers are textile industry, bioenergy, and animal housing. Nowadays attempts are made to employ nettle fibers in different industrial scales [30].

2.7 Pineapple Leaf (Ananas comosus)

The pineapple plant is one of the abundantly cultivated plants. The pineapple leaf fibre is a crop waste after pineapple cultivation. It is a short tropical plant grows up to 1.0–2.0 m and the leaves are in cluster form consists of 20–30 leaves of about 6.0 cm width. Approximately, 90–100 tons of pineapple leaves are grown per hectare. Among the different natural fibers, pineapple leaf fibers show good mechanical properties. Pineapple leaf fibers are multicellular and lingo-cellulosic. The fibers are commonly extracted by bare hands using specific scrapers [31- 32].

2.8 Sisal (Agave sisalana)

The sisal is one of the most used natural fibers, and Brazil is one of the largest producers of this fibre. It is considered native to south Mexico that consists of the rosette of leaves grows up to 1.5–2.0 m tall [33-34]. The sisal produces about 200–250 commercially usable leaves in the life span of 6–7 years. The sisal fibers are possessing good range of mechanical properties and are used in the automotive industry and shipping industry.

2.9 Date Palm (Phoenix dactylifera)

The date palm is known as palm extensively grown for its fruit. The biodiversity of the date palm is all over the world comprising around 19 species with more than 5,000 cultivators all around the world; [36-37]. The date palm trees (Phoenix dactylifera L.) are the tallest among the Phoenix species and can grow up to 23 m height [38]. The date palm rachis and leaves are accumulated in large quantity after the harvesting of the date farm fruits every year in the farming lands of different countries. These fibers can be used as the potential cellulosic fibre sources. These fibers from leaves and rachis can be used as reinforcements for thermoplastic and thermosetting polymers. Some researchers have found ways to use the date palm fibers in the automotive application [39].

2.10 Cotton (Gossypium)

Cotton belongs to the subtribe Hibisceae and family of Malvaceae; is an important agricultural crop [40]. It is the commonly used natural fibre for the production of clothes. The cotton is grown in tropical and subtropical regions, and China is the largest producer of cotton followed by India and the United States [41]. The leaves of the cotton are removed, collected, and compressed into truckload-sized "modules." Later, the modules are transported to processing plant known as the cotton gin. The gin separates the seeds, sticks, and burrs from the cotton fibers. The cotton fibre is used extensively in textile industries. Recently, attempts have been made to develop the composites based on cotton fibres for improving some industrial applications [42].

2.11 Coconut Fibre (Cocos nucifera)

The coconut fiber is obtained from the husk of the coconut fruit. Among the different natural fibers, coconut fiber is the thickest. Coconut trees are mainly grown in tropical regions [43] Coir fibers (CFs) are versatile lignocellulosoic fibers and are comprehensively utilized in the scope of various industrial applications. Cocos nucifera or coir fibers can be obtained from the tissue surrounding the seed of coconut palm. They are composed of cellulosic fibers with hemicelluloses, pectin and lignin as a bonding material. Fibers used in this work (coir) have low cellulose and hemicelluloses; they are stiff and tough fibers due to high content of lignin [2].The major share of the commercially produced coconut fiber comes from India, Sri Lanka, Indonesia, Philippines, and Malaysia [44].

2.12 Kapok (Ceiba pentandra)

Kapok belongs to the Bombacaceae family. It grows in tropical regions [45]. Kapok fiber is a silk cotton and the colour of the fiber is yellowish or light brown. The fibers enclose the kapok seeds. Kapok fibers are cellulosic fibers, light-weight, and hydrophobic [46]. Conventionally, kapok fiber is used as buoyancy material, oil-absorbing material, reinforcement material, adsorption material, and can be employed as a biofuel [45].

2.13 Bamboo (Bambusoideae)

Bamboo fiber is also known as natural glass fiber due to the alignment of fibers in the longitudinal direction [47]. It is one of the extensively available trees in the dense forests especially in China, where about 40 families, and 400 species are found [48]. Bamboo fiber is used as a reinforcement agent in polymeric materials due to its light-weight, low cost, high strength, and stiffness. Bamboo has been traditionally used for making houses, bridges, and traditional boats. The fibers extracted from bamboo are used as reinforcements for making advanced composites in various industries [49].

2.14 Silk (Bombyx mori)

Silk fibers are extracted from silkworms for the clothing purpose since ancient times. Silk is produced largely in China, South Asia, and Europe [50]. Fibers are extracted from the Cocoons which are the larvae of the insects undergoing complete metamorphosis. Silk fibers possess good mechanical properties represented by high strength, extensibility, and compressibility [51]. Table 1 shows the natural fibers in the globe and their rates of production [52].

Table 1: Natural fibers in the globe and their world production [52].

Fiber	Source World production (10^3 ton)
Bamboo	30.000
Sugar can bagasse	75.000
Kenaf	2300
Flax	970
Grass	830
Sisal	700
Hemp	375
Coir	214
Ramie	100
Ramie	100
Abaca	70

3. Surface modifications as remedies

The above mentioned drawbacks of the natural fibres can be significantly overcome using different types of surface modifications. These methods may be either physical treatments (i.e. plasma, ultrasound, ultraviolet and so on) or chemical treatments (silane, alkali, acetylation, benzoylation, sodium chloride and so on). Stretching, calendaring, and thermo treatment are physical methods that do not vary the chemical composition of the fibres, but still modify the surface and structural properties of the fibres and thereby affect the mechanical bonding to polymers [53-54]. On the other hand, chemical modification of the fibres changes the surface properties and quantity of chemical compositions in order to enhance the wetting with polymer matrix.
Moreover, it eliminates the unwanted elements such as hemicelluloses, lignin, and pectin from the surface of the fibres which lead to enhance the adhesion with the matrix [55-56]. Compatibilisers are chemicals which decrease the surface energy of fibres to make them more non-polar and compatible with polymer matrices [57- 58]. Improvement in wettability and polymer reactivity can be done by matrix modifications which are generally done by adding coupling agents and Compatibilisers to the polymer matrix. Coupling agents are predominantly accountable for enhancing the adhesion between the matrix and fibres [59- 60].

4. Alkali treatment

Alkali treatment (mercerisation) is the extensively usage of chemical treatment in which the structure of fibre surface is modified by treatment of sodium hydroxide (NaOH) and potassium hydroxide (KOH). Moisture was absorbed by natural fibre in the amorphous region of cellulose, hemicellulose and lignin constituents, owing to the existence of hydroxyl groups. Alkali treatment includes the elimination of the hydroxyl group of fibre as it reacts with NaOH to produce water molecules (H–OH). Furthermore, Na-O combines with the cell wall of fibre to produce fibre cell- O-Na groups as given in equation (1) [61]

$\text{Fiber} - \text{cell} - OH + NaOH \rightarrow Fiber\ \text{cell} - O^{-}\text{-}Na^{+} + H_2O$-------(1)

Alkaline treatments of the natural fibres diminish the moisture related hydroxyl groups and thus weaken the hydrophilic nature of the fibres. This treatment also withdraws a small fraction of hemicellulose, lignin, pectin, wax, and oil coverings from the surface of fibre [56].

A common untreated natural fibre seems to be enclosed by cementing elements such as lignin, hemicellulose, and other impurities such as wax and oils, while the alkali treated natural fibres were found to be rough and clean owing to the partial exclusion of lignin, hemicellulose, and impurities (i.e. wax and oils). After alkali treatment, surfaces of the fibres become rougher which result in a decrease in diameter pointing to an increment in aspect ratio, thereby increasing interfacial bonding, and finally, improvement in the mechanical strength will take place [62]. Mechanical and thermal behaviours of the bio-composites are found to be enhanced extensively by this treatment. The concentration of NaOH, treatment times, and temperature employed during the treatment play a major role in attaining the optimal effectiveness of the fibre. However, a high alkali concentration may cause an excess elimination of covering materials from the cellulose surface and de-lignify the fibre extremely, which can negatively affect the strength of the fibre [63- 64].

5. Natural fibres Applications

Natural fibers reinforced composites are emerging very rapidly as potential substitutes to the metal or ceramic based materials in applications that also include automotive, aerospace, marine, sporting goods, and electronic industries [65]. Germany is a leader in the use of natural fiber composites. The German auto manufacturers, Mercedes, BMW, Audi, and Volkswagen have taken the initiative to introduce natural fiber composites for interior and exterior applications. The first commercial example is the inner door panel of the 1999 S-Class Mercedes- Benz, made in Germany, of 35% Baypreg F semi-rigid (PUR) elastomer from Bayer and 65% of a blend of flax, hemp and sisal. It should be emphasized that luxury automotive manufacturers are on board which could be seen as evidence that natural fiber composites are being used for environmental needs and not to lower costs [66]. 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 **[67].** Toyota used kenaf to strengthen a door trim [68]. The mechanical performance of bio-epoxy/flax composites along with the environmental benefits make

Them suitable for body chassis, crash elements

And body panels [1]. The applications are shown in Table 2 [69].

Natural fiber-reinforced composite materials are generally utilized in interior parts represented by door panels, dashboard parts, parcel shelves, seat cushions, backrests, and cable linings. Applications to exterior are limited due to the high demand of mechanical strength [70, 71- 72].

Table 2: Applications of bio-composite in industry [69].

Fiber	Applications
Hemp	Paper, textiles, furniture, bank notes, pipes, packaging
Oil Palm	Window, door frame, fencing, roof, panel
Wood	Deck, window, door, fencing
Flax	Tennis racket, bicycle frame, laptop case
Rice husk	Bricks, window frame, panels
Bagasse	Railing system, panel, deck, fencing
Sisal	Paper, pulp, panel, door, roof sheet, shutting plate
Stalk	Drains, pipelines, panel, furniture, bricks
Kenaf	Mobile case, packing, bag, insulation, clothing, animal bed, oil absorber
Cotton	Textile, yarn, goods, furniture, cordage
Coir	Flush door shutters, storage tank, helmet, projector cover, post box, seat filling material, broom, brush, yarn, rope, net, bag, mat, padding for mattresses, seat cushion
Ramie	Industrial sewing thread, fishing net, packing, filters, canvas, household furnishing upholstery, paper
Jute	Geotextiles, chip boards, packaging, door frame, door shutter, panel, roofing sheet

5.1 Other applications

Silk fiber applications

Silk which is a natural fiber and produced in more than 20 countries finds applications in various sectors. Silk proteins are used as special diet for cardiac and diabetic patients due to its low sugar content, easy digestibility, and low cholesterol [73-74]. The Japan Aerospace Exploration Agency (JAXA) has released a recipe as astronauts' food. Silk biopolymer is used in tissue regeneration for treating burn victims and as matrix for wound healing. Silk fibroin peptides are used in cosmetics due to their glossy, flexible, elastic powder coating, easy spreading, and good adhesion properties [75-76]. Silk is reported to be used to fight various health related diseases such as edema, cystitis, impotence, adenosine augmentation therapy, epididymitis, and cancer [77]. Due to the phenomenal mechanical properties of silk as a biopolymer, it is suitable for biomedical applications.

Building material applications

Various natural fibers have been exploited to be used as reinforcements for building/construction industry. Bamboo due to its lightweight and strength is a very popular construction material. Bamboo based materials have been developed to make eco-friendly roofing products. Other similar products such as bamboo mat board (BMB), bamboo mat veneer composites (BMVC), and bamboo mat corrugated sheets (BMCS) have been developed. Sisal fiber-based roofing sheets also have been under development as cost effective alternatives.

Rice husk and rice straw are nowadays used to manufacture medium density fibreboards, particle boards, straw bales, cement bonded boards, etc. Ground nutshell is used for manufacturing building panels, building blocks, chip boards, roofing sheets, and particle boards. Cotton stalk fiber is used for making panel, door shutters, roofing sheets, autoclaved cement composite, paper, and plastering of walls. Coir fiber is a highly durable fiber used in all types of matrices such as fly ash lime, polymers, bitumen, cement, mud, and gypsum. Jute coir composites are seen as cheap and economic alternatives to wood for construction industry. Jute coir boards are used for the production of boards which are more resistant than teakwood against rooting under wet and dry conditions with better tensile strength. Jute with rubber, wood, and coir are considered as good alternative to plywood [78].

6. Summary

Natural fibers and the products designed around these materials possess many distinctive advantages: cost-effectiveness, low coefficient of friction, easiness of availability, exhibition of good thermal and dimensional stability, environmental friendly, and so many other advantages. Because of these and many more reasons, the popularity of natural fibers is on increase, and a lot of scientific data and research is being done around the globe. However, for effective utilization of natural fibers in various potential applications, all the aspects associated with them should be studied and presented. Among these aspects: (a) Targeted applications, advantages and disadvantages of using natural fibers; (b) Product design, studies to be carried out on the development of prototype and other engineering software; (c) Preparation and fabrication technique, particular technique, or process to be identified which should reduce possibility of failure; (d) Commercial production, should be cost effective and eco-friendly; (e) Marketing and sales, product should be marketed to showcase its potential benefits toward society and environment with good after sale service.

Despite of current prevailing aforementioned issues, several commercial products have been launched by various manufacturers. Automotive industry is the most active sector that leading the development of natural fibers based products. Gradually, other sectors related to sports, furniture, and medical will be catching up.

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8. Conflict of Interest :

The authors would like to confirm that there is not any conflict of interest regarding this work. They also would like to confirm that they adopt a self-funding approach to fund their work.

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