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Recent Developments in Natural Fiber Composites: A Review

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Abstract: The present level of research activities in natural fiber reinforced composites is very promising and rewarding. The aim of this review of reviews is to identify from literature, the recent developments in natural fiber reinforced composites. The search was conducted on 7 databases with the final selection of 31 studies with a total of 3437 citations after full text review. In this review paper, published literatures within the last five years were revisited; various fibers, fiber treatments, fiber reinforced composites and their physicomechanical properties were identified. Developmental trends in the methods of fiber extraction, fiber treatment and characterization were reported. A comprehensive review of some natural fibers identified from recent literatures were given for comparative study. The research identifiedthat many workers prefer chemical modification (alkaline, silane, acetylation, benzoylation, acrylation and acrylonitrile grafting, maleated coupling, permanganate, peroxide, and isocyanate treatment) of the natural fibers than physical modifications/treatments. The maleated and silane treatments are increasingly applied in most chemical modifications as widely reported.
Keywords: Composites, Mechanical Properties,Natural Fiber,Reinforcements, Treatments,

1. Introduction

Natural fibers are used mostly as reinforcements in polymer matrix composites and this practice has been in use for ages. Natural fibers are biodegradable and environmentally friendly. Natural fibers can be classified into plant based and animal based fibers. Natural fiber composites are composites reinforced with natural fibers. They have excellent water resistance, lightweight, high strength, durability, fire retardant, electrical resistanceand chemical resistance. Their mechanical properties can be tailored to meet specific engineering requirements. Fiber composites can be applied in structural and infrastructural installations. They are widely used in ship building, marine installations, aerospace and automotive industries.

In fiber reinforced composites, the fiber adds strength and reinforcement in the composite while the resin acts as binders. The overall benefits of use of naturalfibers is to replace the costlier glass fibers to a cost effective and biodegradable fibers.

This work is aimed at reviewing recent review papers on natural fiber reinforced composites to identify the developments in natural fiber extraction, processing and modification. This work will update researchers working within the broad area of fiber reinforced composites on the recent advancements in this field.

2. Methods

2.1 Search Strategy

A thorough search was systematically conducted to identify reviews done on Natural fiber reinforced composites. This was made possible using the following online databases: SCOPUS, ProQuest (ABI/INFORM), Web of Science (Thomson Reuters), IEEE Explore, SAE International, COPAC, Crop Science Society of America (CSSA) Journals and EBSCO.

The screening was limited to review papers written in English Language and the search words include: "Natural Fibers", AND/OR "Fiber reinforced", AND/OR "Composites". A combination of words like "Natural Fiber Reinforced Composites" was also used. The search was limited to review papers published within the last five years (betweenthe years 2010-2015).

The review papers selected were found to have answered any/or all of the following questions:

- ❖ What type of Natural Fiber was used?
- ❖ What kind of fiber treatment was employed?
- ❖ What kind of characterizations were used?

2.2 Search Results

Similar and relatedreview papers were initially screened by their titles and abstracts. A total of 82 studies were initially selected for further examination and finally a total of 31 full text studies with 3437 citations were found to meet the criteria after removing repetitions as shown in the Paper Analysis of table 1.

Table 1. Paper Analysis

S/N	Authors and Country	Journal	Purpose of review	Number of papers reviewed	Publication dates of papers referenced in the journals reviewed
1.	Fiore et al. (2015) Italy	Composites Part B: Engineering	The aim of the review is to illustrate the results of research made on the development of sustainable composites reinforced with basalt fibers	145	1980-2014
2.	Ardanuy et al. (2015) Spain, Brazil	Construction and building materials	To review the development of commercially viable cellulosic fibers for cement-mortar composites	75	1983-2014
3.	Saba et al. (2015) Malaysia, Saudi Arabia	Construction and building materials	To explore the previous works done on the mechanical properties of kenaf fiber reinforced polymer composites	75	2001-2014
4.	Nirmal et al. (2015) Malaysia	Tribology International	To review the research progress made in the area of tribological performance of natural fiber polymeric composites	203	2000-2014
5.	Thakur et al. (2014a) USA, India	International Journal of Polymer analysis and characterization	To review the mechanical properties of fiber/polymer matrix composites	90	2005-2014
6.	Zini and Scandola (2011) Italy	Polymer Composites	To review the recent developments in the area of green composites which are the composites obtained on reinforcement of natural fibers on a bio-based polymer matrix	83	1988-2011
7.	Saba et al. (2014) Malaysia, Saudi Arabia	Polymers	To review current developments on the various classes of natural fibers, nanofillers, cellulosic fiber based composites, natural fiber/nano filler based hybrid composite with specific concern to their applications.	133	1986-2014
8.	Pandey et al. (2010) Korea, Canada	Macromolecular materials and engineering	To analyze the advancement in the application of cellulose based materials in different sectors with a discussion of fundamental research in these areas.	142	1976-2014
9.	Jancirani and Assarudeen (2015) India	Journal of Reinforced Plastics and Composites	To analyze the research conducted over a twenty-year period on selection of materials, fabrication processes, experimentations, CAD design and analysis of fiber reinforced composites.	27	1981-2014
10.	Sathishkumar et al. (2014) India	Journal of Reinforced Plastics and Composites	To review the mechanical, dynamic, tribological and water adsorption properties of natural fiber reinforced hybrid polymer composites and natural/synthetic fiber reinforced hybrid polymer composite	84	2002-2014
11.	Sathishkumar et al. (2013) India	Journal of Reinforced Plastics and Composites	To review reports on the extraction process of Natural fibers, characterization of natural fibers, and preparation of natural fiber-reinforced composites. The mechanical properties such as tensile, flexural, impact, and dynamic properties as well as thermal and machinability properties of the Composites with and without	115	1974-2013

			chemical treatments of the fibers were reported. The water absorption capability of the composites and its effect on mechanical properties were also reviewed.		
12.	Kumar and Sekaran (2014) India	Journal of Reinforced Plastics and Composites	To review and discuss the natural fibers like banana, aloe vera, kenaf, and sisal fibers and their extraction processes.	77	1995-2014
13.	Nunna et al. (2012) India	Journal of Reinforced Plastics and Composites	To study the mechanical behavior of natural fiber hybrid composites with consideration on the variations in fiber volume/weight fraction, variations in fiber layer stacking sequence, fiber treatments and environmental conditions.	70	1983-2012
14.	Faruk et al. (2014) Germany, Poland, Canada	Macromolecular and Materials Engineering	To critically have an overview of the research progress and essential findings in natural fiber reinforced composites with emphasis on natural fiber types and sources, processing methods, modification of fibers, matrices (petrochemical and renewable), and their mechanical performance within the period 2000 to 2013.It also addresses future research, recent developments and applications.	75	2000-2013
15.	Liu et al (2012) China, Canada	Cellulose	To review the various mechanical, chemical, and biological approaches for preparation and separation of macro-, micro-, and nano-sized fibers from raw bamboo.	104	1971-2012
16.	Fuqua et al. (2012) USA	Polymer Reviews	To gain insights on the use of bio-based fibers as composite reinforcements	307	1984-2012
17	Thiruchibatrambalam et al. (2010) India	Journal of Natural Fibers	To undertake an in-depth review on the roselle fiber composites and to understand the effect of alkali treatment and moisture absorption on the mechanical properties of the composites.	80	1978-2008
18	Lee et al. (2014) Malaysia	Advances in Materials Science and Engineering	To review the factors affecting flammability in kenaf and other related fibre composites	58	1970-2013
19.	Verma et al. (2012) India	Journal of Materials and Environmental Sciences	To review recent developments and research works on Baggase fibers	43	1965-2012
20.	Verma et al. (2013) India	Journal of Materials and Environmental Sciences	To review recent developments and research works on Coir fibers	47	1976-2012
21.	Sahari and Sapuan (2011) Malaysia	Review of Advances in Material Sciences	To review the application of some natural fibers as reinforcements in biodegradable polymer composites	44	1995-2011
22.	Thiruchitrambalam et al. (2012) India	Review of Advances in Material Sciences	To study the various studies conducted on kenaf fiber reinforced composites.	43	1999-2011
23.	Ku et al. (2011) Australia	Composites: Part B	To review tensile properties of natural fiber reinforced composite and chemical treatments of some fibers.	27	1999-2009
24.	Thakur et al. (2014b) USA, India	Carbohydrate Polymers	To ascertain the research done in the area ofnatural cellulose fibers/polymer composites	126	1971-2013
25.	Abdul Khalil et al. (2012) Malaysia, Indonesia	Materials and Design	To critically examine the developments in Bamboo fibre reinforced composites	121	1976-2012
26.	Akil et al. (2011) Malaysia	Materials and Design	To review the achievements made in the area of kenaf fiber reinforced	79	1995-2010

			composites with respect to their market, manufacturing methods, and properties.		
27.	Dhand et al. (2015) Korea, USA	Composites: Part B	To review basalt fibers as a reinforcement fiber for composites	178	1967-2014
28.	Mukherjee and Kao (2011) Australia	Journal of Polymers and the Environment	To investigate the effects of processing methods, fibre length, fibre orientation, fibre-volume fraction, and fibre surface treatment on the fibre/matrix adhesion and Mechanical properties of natural-fibre-reinforced PLA composites.	73	1964-2010
29.	Ticoalu et al. (2010) Australia	Southern Region Engineering Conference 11-12 November 2010, Toowoomba, Australia	To review the current development in natural fiber composites for structural and infrastructure applications	40	1986-2009
30.	Faruk et al. (2012) Germany, Poland, Canada	Progress in Polymer Science	To review some works done on natural fibers from 2000-2010.	525	2000-2010
31.	Xie et al. (2010) Germany, United Kingdom	Composites: Part A	To review the progress made in fiber treatments using silane coupling agents	148	1963-2009

3. Recent Studies On Natural Fiber Reinforcements

Basalt fibers have found applications in aerospace, automobiles, building construction and the military. They areenvironmentally friendly, non-toxic and non-hazardous. They can be used as reinforcements in thermoplastics, biodegradable polymers, hybrid composites, metallic matrices and concrete matrices.(Dhand et al., 2015;Fiore et al., 2015).They have superior mechanical properties than the synthetic fibers on treatment with silane and are more desirable than carbon fiber due to their excellent qualities of being eco-friendly, non-toxic and green (Dhand et al., 2015).

Saba et al. (2015) explored the various research works on the mechanical properties of kenaf fiber reinforced polymer composites to develop a literature base for further studies as it relates to construction and building materials. It was observed that the composites reinforced with kenaf possesses excellent tensile and flexural strength asreported from the mechanical tests carried out in the various research works reviewed. This qualifies the fiber to be used in automobile, packaging, construction and in other products like fabrics, ropes and yarns.

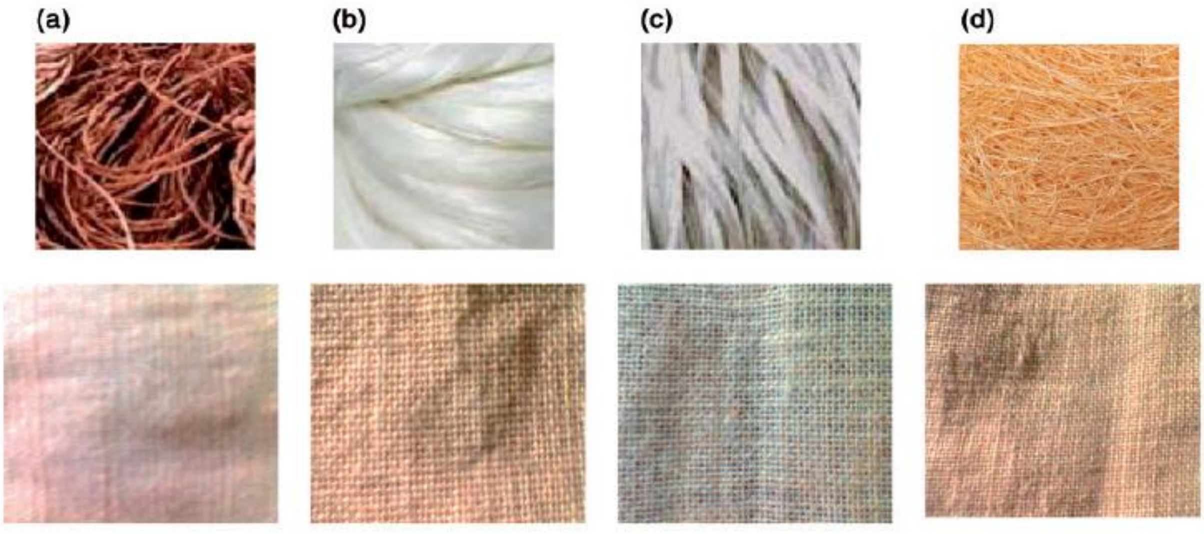

Figure 1. Fibers and woven fabrics of different Natural fibers. (a) Banana, (b) Aloe Vera, (c) Kenaf, (d) Sisal (Source: Kumar and Sekaran (2014)).

Cellulosic fibers have been reviewed by many researchers and different methods of processing, various classification of natural fibers, nanofillers, cellulosic fiber based composites, nanocomposites and natural fiber/nano-filler based hybrid composite with specific concern to their applications, fiber treatments (surface treatments or hornifications) with silanes and pozzolanic additions. Emerging new aspects of nanotechnology for development of hybrid composites for sustainable and greener environments were reported (Ardanuy et al., 2015;Saba et al., 2014; Thakur et al., 2014b; Pandey et al., 2010).The authors submitted that the barrier properties of degradable polymers can be improved through the introduction of nano-reinforcements and that surface modification of cellulose whiskers enhances the compatibility with synthetic polymers. Amongst the fillers reviewed were cotton, hemp, kenaf, flax, coir, ramie (yarn), sugar beat pulp, bamboo and wood fiber.

Faruk et al (2014) in their review gave an insight on the recent developments and applications in the area of natural fiber reinforced composites with respect to the status of research, structure, performance, surface treatment and application. They opined that nanocrystalline cellulose has found applications in composites specified for structural applications due to their processing techniques and fiber modifications which enhanced the matrix-fiber adhesion.Fuqua et al (2012) in their review provided information on the use of bio-based fibers for composite reinforcements. The importance of fiber type, length, architecture, and surface characteristics as they pertain specifically to natural fibers as reinforcements in a variety of plastics were reviewed in this article. They further discussed the varieties of natural fibers, the importance of fiber type, fiber length, surface characteristics and the resultant properties from their constituents and hierarchal structures. The methods used to enhance the interface of these fibers with a variety of polymer matrices were also reviewed. Their review concluded that spiral angle of the cellulose structures in the primary and secondary walls vary from one plant species to the next and they move elastically during deformation within the fiber structure and this influences the performance of the composites.

In their study, Zini and Scandola (2011) reviewed the development of green composites obtained from reinforcing natural fibers on the matrices of thermoplastic and thermosetting bio-based polymers. For the bio-composites obtained using thermoplastic resins, the following reinforcing natural fibers were used: flax, wood flour, pineapple leaf, wood, straw, wheat straw, soy stalk, wool, hemp and for thermosetting resins the following fibers were used: chicken feather, hemp, flax, jute, wheat straw, coir, sisal, kenaf and *Luffa cylindrical*. Their study concluded that green composites have great tendencies in the area of lightweight sustainable composites if natural fiber wastes are utilized.

Jancirani and Assarudeen (2015)examined various researches conducted over twenty years on fiber reinforced composite leaf spring. Their studies were limited to natural fibers used in structural and automotive applications such as Jute, coir, sisal, banana, flax etc. Thevarious techniques employed in composite formulation and production such as material selection, fabrication processes, experimentation, CAD design and Finite Element Analysis were reported. It was found that natural fiber based hybrid composites performed better over synthetic fiber based mono- composites in terms of weight reduction, costs, availability and recyclability.

Sathishkumar et al. (2014)reviewed the mechanical properties (tensile, flexural and impact), dynamic, tribological and water absorption properties of natural fiber reinforced hybrid polymer composites and natural/synthetic fiber reinforced hybrid polymer composites. The following natural and synthetic fibers used in hybrid composites were studied: Bamboo, cordenka, coir, *roystonearegia*, hemp, cellulose, jute, banana, palmyra, snake grass, oil palm fruit bunch, flax, sisal, kenaf, basalt, yarns, pineapple leaf, glass fiber, carbon, Silicon Carbide and boron fibers. Thereview concluded that natural fibers used in hybrid composites have improved mechanical, water absorption, dynamic and tribological and properties over the synthetics.

Nunna et al. (2012) highlighted the factors affecting the mechanical behavior of natural fiber based hybrid composites such as variations in fiber volume/weight fraction, variation in fiber layer staking sequence, fiber treatments and environmental conditions. They observed that the mechanical properties of the hybrid composites were found to be improved proportionally with the volume fraction of high strength fibers up to a value beyond which agglomeration sets in. The behavior of the hybrid composite was mainly influenced by the properties of the fiber layers at the extremes with optimum mechanical properties obtained by placing high strength fibers as the skin layers. Alkali treatments of the fibers with NaOH was found to improve interfacial adhesion between the fibers and matrix thereby enhancing their mechanical properties. Finally, the degradation of the mechanical properties is dependent on the temperature and time of exposure related to various environmental condition.Thiruchibatrambalam et al. (2010)gave insights on Roselle fiber as reinforcements for polymer composites and the effect of alkali treatment and moisture absorption on the mechanical properties of the composites. Their study further revealed that roselle fibers are not popular as reinforcement fillers for composites. The authors opined that because of the low cost, global availability, high specific strength, and reduced equipment abrasion of the fibers, composites reinforced with roselle fibers looks promising for future structural applications.Thiruchibatrambalam et al. (2012) in a later review on Kenaf fibers, discussed the physical structure and properties of the fiber, influence of chemical treatment of the fiber on the mechanical properties of the composites and its potential of replacing glass fibers in structural composite application. Ku et al. (2011) conducted a review on the tensile properties of natural fiber reinforced polymer composites. Their study covered both plant and animal based natural fibres. Some of the fibres studied are silkworm, silk, chicken feather and spider silk. It was noted that mathematical models were employed to predict tensile strengths of the composites. The authors observed the limitations faced with reinforcements of natural fibers with plastics due to incompatibility.

The morphology and properties of different natural fiber/polymer matrices and polymer composites were reviewed by Thakur et al. (2014a). The study concluded that natural fibers offers a wide range of advantage over synthetic fibers.

Vermaet al. (2012) in their review on bagasse fibers indicated that the source of bagasse fiber has an influence on the mechanical properties of the composites. In another similar study, Verma et al. (2013) reviewed the recent progress and findings in the use of coir fibers as it relates to its applications as a reinforcement filler and their surface modifications.

Lee et al. (2014) reviewed the issue of fire flammability for safety purposes in some natural fiber reinforced polymer composites including kenaf fibers. The following factors relating to flammability were considered in their review: nature of matrices, fiber content, fiber treatments, pH conditions, and fire-retardant filler’s type. Their study established that ignition time, propagation rate, and fire behavior are the most important factors for fire flammability while thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) are the most favourable methods for investigating the fire flammability of composites.

Liu et al. (2012) gave a summary on the preparation and separation of macro-, micro- and nano-sized fibers from raw bamboo using mechanical, chemical and biological methods. The differences in the mechanical, thermal, and other properties of fibers from different materials were studied and found to be related to their size, aspect ratio, surface charge and groups, and their function in nature. Their study concluded that Bamboo fibers have a relatively high strength, narrow micro-fibril angle, and low cost, and can be utilized as reinforcements in polymer matrix composites and this serves as a replacement for synthetic fibers. The treatment methods employed for Bamboo fiber composites improved their mechanical properties due to the enhanced fiber matrix adhesion after treatment. Abdul Khalil (2012) in a similar study on Bamboo fibres, reviewed published literatures with special interests on the methods of processing, and properties of the bamboo fibers-polymeric matrices.

The application of natural fibers to biodegradable polymers and their characterization where reviewed by Sahari and Sapuan (2011). Their study gave insights into publish literatures on cellulose-natural fiber composites, polylactic acid (PLA)-natural fiber composite, thermoplastic starch (TPS)-natural fiber composite. The following agro-fibers were mentioned in their review: ramie, kenaf, cotton, sisal and bamboo. The authors recommended that further research work be explored in the area of reinforcement of natural fibers on biodegradable polymers.

Akil et al. (2011) presented an overview of the future prospects in the kenaf fibres with respect to its marketability and manufacturing methods. Their study identified that kenaf fibers can adapt to other processing methods uncommon to other natural fibers like pultrusion and filament winding.

Table 2 Fiber sources and description

S/No	Name of fibers	Sources	Description	Papers reviewed
1	Bastfibers (such as Jute, Flax, Ramie (yarn), Kenaf, Bamboo, Roselle)	Vegetable source	They are the soft, woody fibers obtained from stems of dicotyledonous plants (flowering plants with net-veined leaves) and used for textiles and cordage.	• Saba et al.(2015) • Ardanuy et al.(2015) • Nirmalet al. (2015) • Jancirani and Assarudeen (2015) • Sathiskumar et al. (2014) • Lee et al. (2014)

				• Kumar and Sekaran (2014) • Thakur et al. (2014) • Sathiskumar et al. (2013) • Liu et al. (2012) • Verma et al. (2012) • Zini and Scandola (2011) • Saba et al. (2014) • Faruk et al.(2014) • Nunnaet al. (2012) • Fuqua et al. (2012) • Thiruchibatrambalam et al. (2012) • Abdul Khalil et al. (2012) • Sahari and Sapuan (2011) • Ku et al. (2011) • Akil et al. (2011) • Mukherjee and Kao (2011) • Pandey et al. (2010) • Thiruchibatrambalam et al (2010)
2.	Leaf fibers (sisal, pineapple, palm, banana, henequen, abaca)	Vegetable source	They are the hard, coarse fibers obtained from monocotyledonous leaves of plants (flowering plants that usually have parallel-veined leaves, such as grasses, lilies, orchids, and palms), used mainly for cordage.	• Nirmal et al.(2015) • Jancirani and Assarudeen (2015) • Ardanuy et al.(2015) • Kumar and Sekaran (2014) • Thakur et al. (2014) • Saba et al. (2014) • Saba et al. (2015) • Kumar and Sekaran (2014) • Sathiskumar et al. (2014) • Sathiskumar et al. (2013) • Faruk et al. (2014) • Nunnaet al. (2012) • Fuqua et al. (2012) • Zini and Scandola (2011) • Ku et al. (2011) • Mukherjee and Kao (2011) • Sahari and Sapuan (2011) • Pandey et al. (2010)

3.	Seed (e.g. Cotton and kapok)and fruit fibers (e.g. coir)	Vegetable source	They are the fibers obtained from seed cases or seeds and also from some fruits.	• Nirmal et al.(2015) • Jancirani and Assarudeen (2015) • Sathiskumar et al. (2014) • Lee et al. (2014) • Thakur et al. (2014) • Faruk et al. (2014) • Sathiskumar et al. (2013) • Nunna et. al.(2012) • Verma et al (2013) • Saba et al. (2014) • Zini and Scandola (2011) • Sahari and Sapuan (2011) • Ku et al. (2011) • Pandey et al. (2010)
4.	Wool and hair fibers (They include cashmere from goats, mohair from goats, qiviut from muskoxen, angora from rabbits, and other types of wool from camelids).	Animal sources	They are the textile fibers obtained from sheep and other animals.	• Saba et al. (2014) • Zini and Scandola (2011) • Ku et al (2011)
5.	Silk and related filaments	Animal sources	They are fibers and filaments that comes in continuous to near continuous lengths and are derived from the cocoon of a silkworm.	• Saba et al. (2014) • Zini and Scandola (2011) • Ku et al (2011)
6.	Basalt, Asbestos(including the chrysotile of the serpentine class; amphibole classes like amosite, crocidolite, tremolite,anthophyllite and actinolite), wollastonite and palygorskite	Mineral sources	Mineral fibers are the types of fiber obtained from geological processes which include the basalt group which are derived from volcanic rocks and asbestos group which are the naturally occurring long mineral fibers.	• Fiore et al., 2015 • Dhand et al., 2015

3.2 Natural Fiber extraction processes

There are lots of studies available on the extraction processes of natural fibers. Several authors have reviewed extraction processes of the following fibers: Banana/Plantain, Aloe vera, coir, sisal, kenaf, bamboo,baggase, roselle etc.(Kumar andSekaran, 2014;Lee et al., 2014;Sathiskumar et al., 2013; Verma et al., 2013; Thiruchitrambalam et al., 2012;Fuqua et al., 2012;Abdul Khalil et al., 2012; Liu et al., 2012;Verma et al., 2012; Akil et al., 2011;Thiruchitrambalam et al., 2010).

Banana and Plantain Fibers

The Banana and Plantain fibers (Musa Spp) are lignocellulosic fibers which are obtained as bast fibers from the pseudo stems of Banana and Plantain. The fiber volume fraction, aspect ratio and orientation were identified by Kumar and Sekaran (2014) as the key factors affecting the mechanical properties of the Banana fibers with the fiber orientation as the least significant when evaluating the hardness strength of the fiber using these key factors. The silane and alkali treatment on the Plantain empty fruit bunch (EFP) were found to improve the tensile strength than the untreated Plantain EFB.Banana Fibers can be extracted using the chemical, mechanical and biological processes. The chemical process will eventually cause environmental pollution in the long run, the mechanical process may not effectively remove the lignin from the fiber while the biological process will not cause any harm to the environment and will subsequently yield more fibers. Kumar and Sekaran (2014) identified two mechanical methods for banana fiber extraction as: (a) Bacnis method and (b) Loenit method. In the Bacnis method which is very popular in the Philippines, the fiber is extracted from the waste pseudo stem of the banana plant. The outer sheath of the pseudo stem is covered by layers of fibers and are gradually removed in ribbon-like strips of about 5-8cm width and thickness of 2-4mm from the total length of the sheath. The act of removing the layers in the Bacnis method is known as tuxying the strips or tuxies. The sheaths are separated according to their positions in the stalk and flattened with the fibers removed from the pseudo stem by cutting the pulps and pulling away the tuxy. The Loenit method involves pulling the tuxies out of the stalk gradually from one sheath at a time using a stripping knife to scrape out the plant tissues between the fibers. The stripped fibers are dried in air and made in bundles for grading as bails. The stripping of fibers can be achieved manually by hand or by the use of a machine called Raspador. In the Raspador machine, the pseudo stem sections are crushed between the rolls and the pulps are scrapped off about half the length by two revolving large drums with rims fitted with scrapping blades which scrapes the sheath. The extracted banana fibers are oven dried and the fibers obtained are about 10 times greater in yield than those obtained mechanically but the fiber quality is inferior as compared to the mechanically extracted fibers.

Kenaf fibers

The Kenaf fiber (*Hibiscus cannabinus L*) is aherbaceousseasonalbast fiber similar to Jute and Cotton which is cultivated mainly for its fiber which is used in making sackcloth, twine and ropes (Lee et al., 2014; Kumar and Sekaran, 2014;Thiruchitrambalam et al., 2012;Akil et al., 2011). The fibers are found in the bark and core of the plant in the ratio of 40:60.Kumar andSekaran (2014) opined that the process employed for extraction of kenaf fibers depends on their method of harvesting. The mechanical extraction and water retting were identified as methods of extractionfor the kenaf fiber. In the mechanical extraction, a special kenaf fiber extraction machine is designed and used in the extraction process while the water retting method is a wet process involving the submerging of fibers in water over a period of time to enable the separation of fibers from the lignins, pectin, hemicellulose and other gummy materials present in the fibers.

Figure 1 Kenaf fiber and its processing. (a) Kenaf water retting process, (b) kenaf stem showing fibers, (c) kenaf fiber (source: Kumar and Sekaran (2014))

Sisal fibers

Sisal fiber (*Agave sisalana*) is a hard fiber obtained from the leaves of the sisal plant. The plant can be found in tropical countries. The fiber is very popular and is easily cultivated. A sisal leaf contains about 1000-1200 fiber bundles which is made up of 4% fiber, 0.75% cuticle, 8% dry matter, and 87.25% water.

Figure 2 Sisal fiber extraction. (a) Sisal plantation, (b) sisal fiber extraction, and (c) sisal fiber(source: Kumar andSekaran (2014))

Kumar and Sekaran (2014) identified that the sisal leaf contains three types of fibers: (1) mechanical fiber- extracted from the periphery of the leaf, (2) ribbon fiber- which are the longest fibers located along the median line of the sisal leaf, and (3) xylem fibers- which are obtained in the opposite direction of the ribbon fibers and are composed of the thin walled cells.

The extraction methods reported for Sisal fibers are the retting method and mechanical decortication using a decorticator (Kumar and Sekaran, 2014; Sathishkumar et al, 2013). The authors also identified the following retting methods: water retting, dew retting, stagnant water retting and tank water retting. The extracted fibers are dried in sunlight to remove moisture.

Aloe vera fiber

The Aloe vera plant (*Aloe barbadensis miller*) is a popular medicinal plant. The name is derived from the Arabic word "Alloeh" meaning "shining bitter substance". The leaf is comprised of three layers: (a) An inner clear gel with 99% water and varying amounts of aminoacids, lipids, sterols, glucomannans and vitamins (b) A middle latex layer containing anthraquinones and glycosides (c) An outer rind containing thick layers of cell which acts as a protective layer and for carbohydrates and protein synthesis.The Aloe vera fiber is extracted using a special extractor designed for this purpose.

Coconut (coir) fiber

The coconut tree (*Cocos nucifera*) belongs to the palm family (Arecaceae). The fiber obtained from the husk is called coir fiber. The extraction of the coir fiber is achieved by water retting of the harvested coconut husks for about five months (Sathiskumar et al., 2013; Fuqua et al., 2012;Verma et al., 2013).

Bamboo Fiber

The Bamboo belongs to the grass family Poaceae subfamily Bambusoideae, tribe Bambuseae. Fig 3 shows the morphology and composition of the Bamboo fiber cell wall. The Bamboo is a perennial plant and is evergreen (Liu et al., 2012; Abdul Khalil et al., 2012). The Bamboo fiber is extracted from the pulp of bamboo plants (Fuqua et al., 2102).

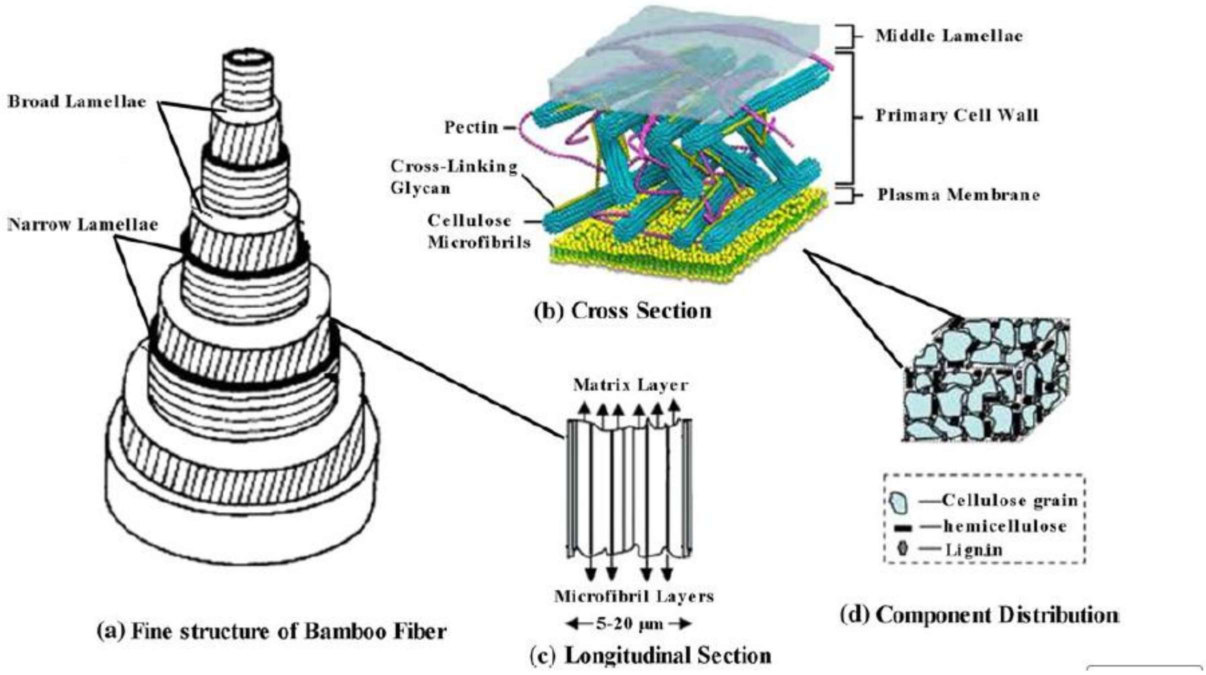

Figure 3 (a) Model of the polylamellate wall structure of a bamboo fiber. The fiber cell wall exhibits a polylamellate structure with alternating broad and narrow lamellae. The narrow layers consist of unidirectional microfibril layers, alternatively in transverse and longitudinal lamellae, with orientation 2–20°/ 85–90°; the broad layers are the matrix. (b) The middle lamella is the outer-most layer, followed by the primary wall. (c) The spindle-like short tiny fibers, tapered at both ends, are intercalated longitudinally each other along the culm. (d) Nanoscale cellulose grains with orientation and other distributed components (Source: Liu et al. (2012).

A variety of chemical and mechanical methods are employed for Bamboo fiber extraction as reported (Liu et al., 2012; Abdul Khalil et al., 2012). In the chemical method, an alkali or acid hydrolysis is used to delignify the cellulose fiber. The alkali solution removes the cellulose, hemicellulose, lignin and pectin from the Bamboo. Sodium chlorite is used where necessary to bleach the fiber to a whitish colour. The mechanical method for bamboo fiber extraction involves treatment using a high-pressure refiner, a super grinder, a microfluidizer and/or a high pressure homogenizer. The mechanical methods used for the fiber extraction from swollen bamboo stems include crushing, heat steaming and shearing. In the pulp and paper industries, a combination of chemical and mechanical processes is used. The two common mechanical methods used are the compression molding technique (CMT) and roller mill technique (RMT).

Roselle Fiber

The Roselle fiber is obtained from the plant, Roselle (*Hibiscus sabdariffa*) (*Pulichaikearai*) which belongs to the family *Malvaceae*. The chemical composition of the fiber is as follows: (cellulose = 60%, hemi-cellulose = 15%, lignin = 10%). The fiber is popularly known with different names in some countries like Java jute in India, Thai jute, Pusa hemp, Tengrapat, Lalambadi, Chukair, Yerragogu, Palechi, and Pundibeeja (Thiruchibatrambalam et al., 2010). The fibers are obtained by water retting for a period of 3-4 days and the fibers are washed, cleaned and dried in sunlight.

Figure 4 Roselle Fiber Extraction (Source: Thiruchibatrambalamet al.(2010))

Bagasse Fiber

Bagasse is obtained from sugar cane as a fibrous residue and consists of 48.7% fibers, 2.3% soluble solids and 49% water (Verma et al., 2012a).

Figure 5 Bagasse Fiber(Source: Verma et al. (2013))

3.3 Natural Fiber treatments and modifications

Various fiber chemical treatments and surface modifications such as alkaline (or mercerization),silane, acetylation, isocyanate and permanganate treatments were identified from literature.Physical fiber treatments such as fiber stretching, solvent extraction, electric discharge, laser, thermo-treatment, calendaring and rolling or swaging were also reported (Fuqua et al., 2012).Some identified fiber modification/treatments are detailed in table3 below. Alkaline treatment (or mercerization) involves the modification of fibers using a NaOH solution.The fibers are soaked in a NaOH solution over a period of time and this process removes the unwanted hemicelluloses, lignin, wax and oils found on the fiber cell walls. Alkaline treatment were reported to cause the fibers to fibrillate (Akil et al., 2011). Silane treatment involves the use of a chemical compound containing silane (SiH_4)as a coupling agent to reduce the cellulose hydroxyl groups found in the fiber-matrix interface. Modification of fibers using silane coupling agents enhances wettability of the fibers. Acetylation is a form of esterification process which makes the cellulosic fibers to plasticize. It is widely applied to wood cellulose to improve dimensional stability of the cell walls.

Table 3 Treatment and modification schemes for some natural fibers

S/No.	Fiber type	Treatments/ Methods Used	References
1.	Kenaf	Silane coupling agent Isocyanate; acetylation;alkaline (mercerization);acetylation, NaOH, sodium lauryl sulphate	• Sathishkumar et al. (2014) • Saba et al. (2015)

2.	Abaca	Silane coupling agent; Maleic Anhydride Poly propylene copolymer (MAPP); Maleic Anhydride grafted styrene/ethylene-butylene/styrene triblock polymers (SEBS-g-MA); Maleic Anhydride grafted poly ethylene (PE-g-MA);Silane A174 (γ −methacryl oxypropyl trimethoxy-silane); Silane A151 (vinyl triethoxysilane); NaOH	• Faruk et al.(2012)
	Flax	Vinyl trimethoxy silane (VTMO); Maleic Anhydride (MA);MAPP; Acetylation;	• Faruk et al.(2012) • Xie et al. (2010)
3.	Hemp	MAPP	• Faruk et al.(2012)
4.	Sisal	MAPP, Hornification, Silane Alkaline, H_2SO_4, conjoint $H_2SO_4$and alkaline, Benzol/alcohol dewax, Acetylation, thermal, alkali–thermal and thermal–alkali	• Faruk et al.(2012) • Ardanuy et al. (2015) • Thiruchitrambalam et al. (2010) • Nunna et al. (2012) • Kumar and Sekaran (2014) • Sathishkumar et al. (2014) • Xie et al. (2010)
5.	Jute	Alkaline, Acetylation, NaOH;MAPP	• Faruk et al.(2012) • Xie et al (2010)
6.	Bamboo	Alkaline, Acetylation, NaOHMAPP; MA, Acid hydrolysis,HNO_3–$KClO_3$	• Abdul Khalil et al. (2012) • Liu et al (2012)
7.	Coir	Alkaline	• Sathishkumar et al. (2014)
8.	Oil Palm	Alkaline	• Sathishkumar et al. (2014)
9.	Pine apple leaf	Silane	• Xie et al (2010)

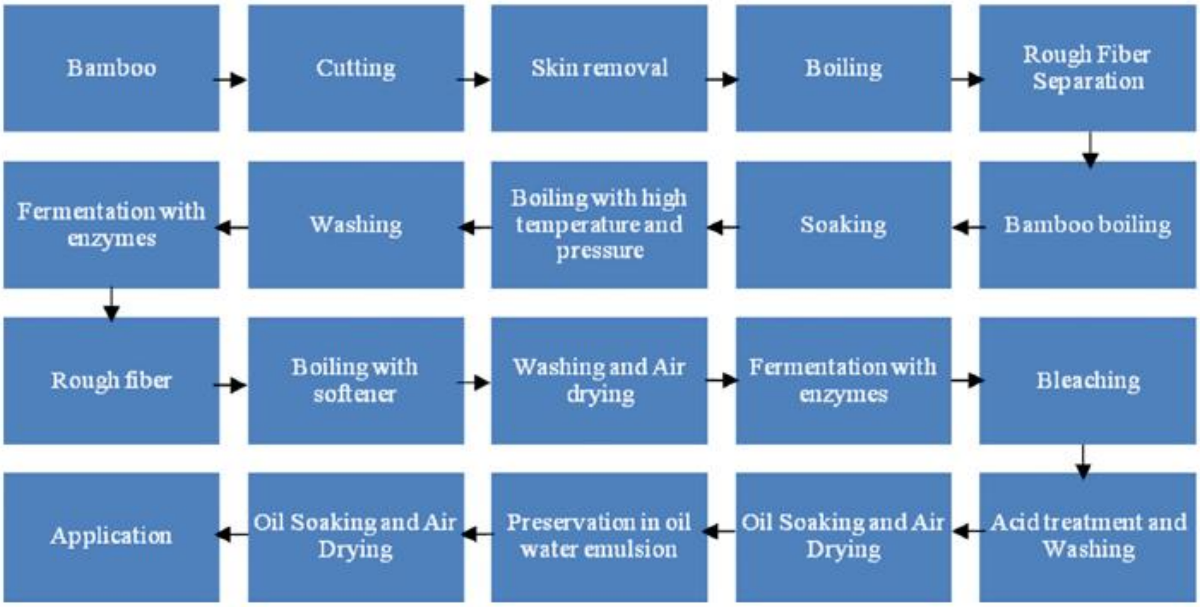

Figure 6 Extraction and treatment of rough and fine bamboo fibers (Source: Abdul Khalil(2012))

4. Conclusions

The study concludes that natural fibers are low cost, ecofriendly, recyclable, low dense and possesses good tensile mechanical properties which favourably surpasses in most cases those of synthetic fibers and are highly recommended as fillers for most polymer matrices. Many researchers reported that silane coupling treatments and maleated anhydride coupling treatments are the most recently explored chemical treatments for natural fiber modification.This review therefore provides a valuable insight for researchers currently working on the area of natural fiber reinforced polymer composites on the latest advancements in the area of fiber extraction, processing techniques and modifications.

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