Natural Fibers as Viable Sources for the Development of Structural, Semi-Structural, and Technological Materials – A Review

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Abstract

A systematic and critical review on the potentials and viability of naturally occurring fibers as suitable reinforcements for the development of composite systems for structural, semi-structural and technological materials is presented in this article. Globally, the movement towards greater protection of the environment and the use of cost-saving technologies has led to a surge in the consideration of natural (biodegradable) products for the development of technological materials. In this regard, natural fibers have been proven to be good substitutes to synthetic fibers for the development of composites - because they possess similar mechanical and physical characteristics, to the synthetic fibers. In addition, natural fibers are lighter non-toxic and biodegradable. It is on this premise that several studies on their use in a number of applications where composites are desirable have been reported. Therefore, this article discusses various types of natural fibers, their properties, and their applications in different technological domains. The documentation of this review is thought-provoking and provides challenges and future prospects in the development and application of natural fibers and their composites. Copyright © VBRI Press.

Keywords: Natural fibers, composites, biodegradability, reinforcements, technological applications.

Introduction

Natural fibers are nature-derived materials that have been utilized for several applications for ages. For centuries, the applications have extended widely, and of significance is its application in the improvement of reinforcements for composites. Naturally-occurring fibers have several benefits which have spurred interest in their utilization as replacement for synthetic fibers, which have been in use for so long in industry [**1**]. As recorded and documented, **Fig. 1** and **Fig. 2** depict the trend in the development of natural fibers and synthetic fibers from 1950 to 2018 [**2**]. The figures indicate that natural fibers/synthetic fibers have been employed as replacements/reinforcements in composites since 1950. Some of the properties of interest possessed by natural fibers are: low density, non-abrasiveness, cost effectiveness, renewability, and good mechanical properties when compared to synthetic fibers. They are also non-carcinogenic, exhibit CO_2 neutrality, and are biodegradable in nature [**3**, **4**]. These excellent properties have paved the way for the application of natural fibers in technological and industrial sectors such as the automobile, aerospace, building and construction, biomedical [**5**, **6**]. The vast areas of use, seem to agree with the projection made in 2016 that the market for natural fiber based composites will grow to US$ 5.83 billion by 2019, with a 12.3% Compound Annual Growth Rate (CAGR) [**7**]. Currently, there are several commercially processed automotive components and parts that are made from natural fiber reinforced composites, composed of natural fibers like jute, coir, flax, sisal, hemp or kenaf [**8, 9**]. These composites as reported by Leveque [**10**] are principally utilized as structural or engineered parts of automobiles. Most of the leading automobile manufacturers use composites reinforced with natural fibers in making products like seat backs, door panels, noise insulation panels, spare-tyre linings [**11**]. It has been acknowledged that a very good way of increasing fuel efficiency without compromising safety is to make use of natural fiber reinforced composites in the body of cars in order to achieve weight reduction [**12**]. Also, the use of materials developed among natural fibers has been reported to record a significant reduction in the final cost of production [**13**].

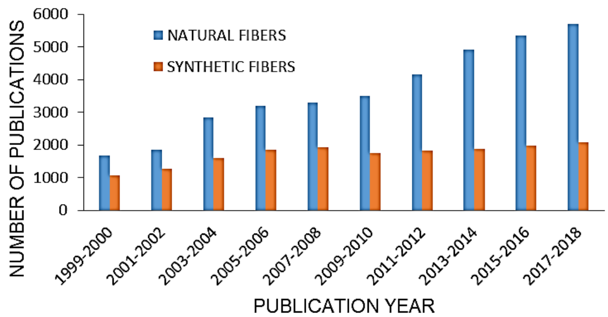

Fig. 1. Number of Publications on Natural fibers compared to Synthetic fibers (obtained from [**2**]).

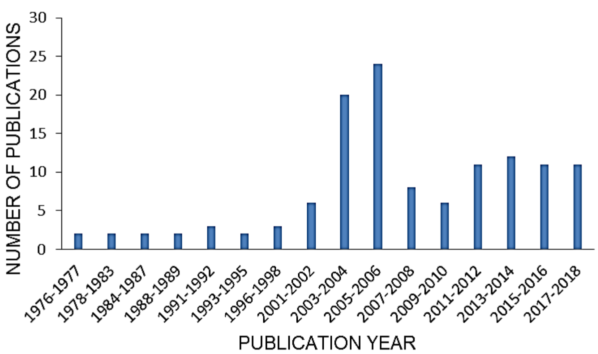

Fig. 2. Number of Patents on Natural fibers (obtained from [**2**]).

Previous applications of natural fiber composites have been limited to non-structural parts, but recent development and research on fibers have led to increased applications in semi-structural and structural parts. The use of flax/poly(lactic-acid) in medical environment [**14**]; sheep's wool reinforced composite cement for production of mortar [**15**]; banana fiber/eco-polyester and banana fiber/epoxy composites in automotive and transportation applications, have been reported. Automobile interior headliner and package tray modules developed from kenaf-fiber reinforced composites [**16**], flax/polypropylene in vehicle panels [**17**] and broom-fiber reinforced composite for acoustic application [**18**], have been reported.

A few recent reviews on natural fiber reinforced composites have been documented. Mohammed *et al.,* [**1**] carried out a review on natural (plant) fiber-reinforced composites and their technological applications in automotive industry, buildings and constructions. In the same vein, Westman *et al.,* [**19**] reviewed on the possible replacement of glass with kenaf in fiber reinforced composites. Dixit *et al.,* [**20**] reviewed documented articles on plant fiber reinforced composites and their applications in automobile, construction and household applications. Rohit and Dixit [**21**] provided a review on natural-fiber reinforced composites for applications in automobiles. Norhidaya *et al.,* [**10**] documented a review of plant fiber reinforced composites for automotive applications. A review from Chauhan and Chauhan [**22**] concentrated on natural fiber reinforced composites and their application in house construction materials, furniture and automotive parts. Review of Darshan *et al.,* [**23**], showcased the use of waste silk fiber reinforced polymer matrix composite in structural applications (building and construction industry-panels, door and window panels, false ceilings, partition boards), storage devices, packing, automobile and railway coach interiors. However, most of these review articles concentrated primarily on the assessment of composites reinforced with plant fibers. As far as could be ascertained there is limited information, in form of a review article on the use of natural fibers based on animal and mineral composites in open literature. Therefore, this review aims to illuminate knowledge on the applicability and the need for more research on the development of natural (plant, animal and mineral) fiber reinforced composites for structural and semi-structural applications.

Natural fibers

Naturally occurring fibers from natural resources, that are not man-made, are known as natural fibers. They are obtained from plants, animals and minerals. **Fig. 3** provides a schematic illustration of different types of natural fibers.

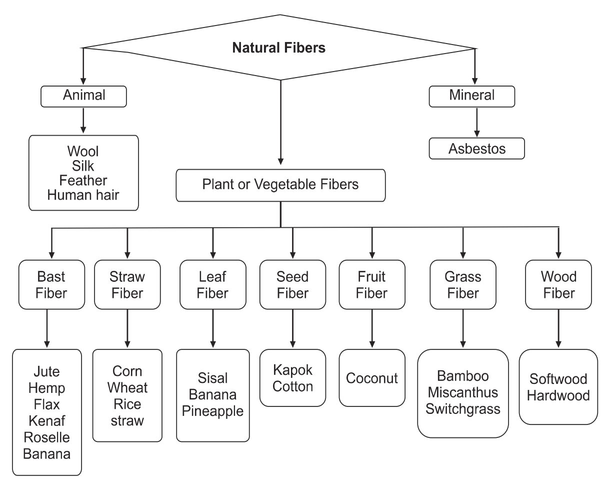

Fig. 3. Natural Fibers and their groups (Adapted from Alavudeen *et al.,* [**24**]).

Animal fibers

After plant fibers, animal originated fibers are the next in their usage for composite reinforcements. Generally, the animal fibers are made up of protein. Examples include; wool, human hair, feathers and silk. Animal fibers are more expensive than plant fibers because they are not as readily available as plant fibers, which consequently limit their utilization in many applications. However, they have an edge over the plant fibers because they are not seasonal as the latter. Composites reinforced with animal fibers have found wide applications in biomedical procedures such as; implants, bone grafting, sutures, medical devices [**25, 26**]. Wool or hair fibers obtained from mammals or animals include; camel hair, goat hair (cashmere and mohair), sheep wool, angora rabbit hair, alpaca hair (related to camel), and yak hair [**27**].The hair fibers are named according to their origin, and their properties differ. A fairly-fine soft fiber is obtained from alpaca while a highly prized fine short hair is obtained from cashmere. The undercoat of the camel gives a strong soft fiber, but the outer coat produces a strong coarse fiber. A long lustrous, springy fiber is got from the angora goat (mohair); fine, short, and long spiky hairs from angora rabbit; and soft fine hair from yak [**27**]. Wool from sheep is extensively used industrially because it is more available and relatively inexpensive. Unprocessed wool contains other constituents apart from the fiber which are: wool grease, water-soluble material obtained from perspiration, and contaminants such as vegetable matter and dirt which can be washed out [**15**]. The main constituent of wool after it has been thoroughly washed and cleaned is keratin protein, which is made up of amino-acids building blocks, and cysteine [**28**]. The keratin has a high concentration of sulphur (about 3%), which determines the strength of the fiber [**15**]. Wool fiber has low tenacity due to its excellent elongation and elastic recovery, but it is sensitive to some alkalis but fairly resistant to bacteria, and also a poor conductor of heat [**29**]. Cotton and silk are less coarse than wool, and the coarseness of the fiber affects its length [**30**].

Another animal fiber that has not received much attention is the human hair. The human hair is a proteineous fiber that develops from follicles below the skin. Apart from the skin, the human body is coated with follicles that give rise to strong and fine vellus hair .Interestingly, lots of attentions have been given to how the hair grows, hair varieties, and ways of taking care of the hair, although the human hair contains about 95% keratin [**31**, **32**, **33**]. Keratins are long chains of amino acids linked together by peptide bonds. The elements that are found in the human hair are shown in **Fig. 5**. The amino acid contained in the hair is made up of glycine, threonine, leucine, valine, cytosine, glutamine, arginine and serine [**34**].

Apart from the two types of animal fibers (wool and human hair) already discussed, fibers from feathers are also used as composite reinforcements. The constituents that make up the feather are shown in **Fig. 5**. Feathers belong to the group of complex keratin structures found in vertebrates. They are mainly composed of glycine, proline, cysteine, serine, little or no histidine, methionine, or lysine [**35**, **36**]. A feather consists of four main components; quill or rachis, barbs, barbules, and hooklets [**37**]. Quill is the central shaft that is attached to the body of the bird, while the barbs branch out from the quill. Barbules further separate from barbs, and hooklets separate from barbules, (**see Fig. 5**) [**38**, **39**]. Although the four parts are different, they all contain keratin. The quill part of the feather is not suitable for use as fiber because it is brittle and sheet-like, but the other parts can be used for they are soft and fibrous [**37**, **39**]. Feather fibers can be used as reinforcements in both hydrophilic and hydrophobic resins. This is because about 40% of the 95 amino acids in keratin are hydrophilic and the remaining 60% are hydrophobic [**40**].

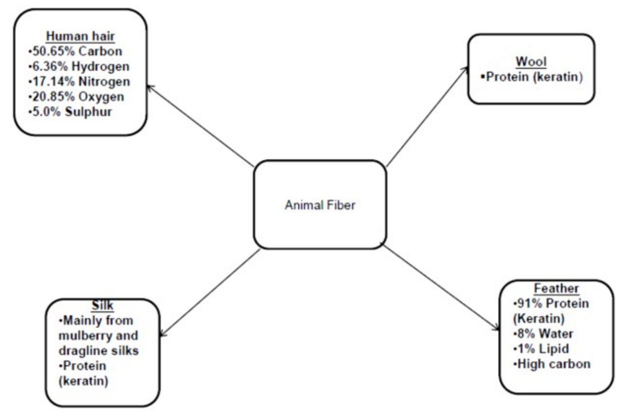

Fig. 4. Types of animal fibers and their corresponding constituents [**15**, **33**, **34**].

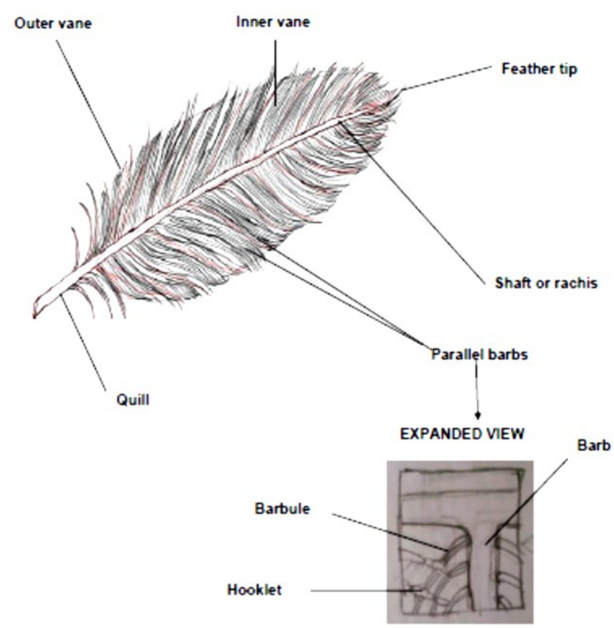

Fig. 5. Parts of a chicken feather [**39**].

Silk fiber is another type of animal fiber, usually produced by silkworms, spiders, scorpions, flies and mites. The structure, composition and material properties differ largely and which are dependent on the specific source and the unmanageable spooling conditions of the insects [**23**]. The most widely discussed and used silk fibers are mulberry silk (*Bombyxmori)* and dragline silk (*Nephila*) from silkworm and spider respectively [**25**]. Most often, the raw silk used is being produced by silkworm. The mulberry silk is mainly composed of sericin (gum) and fibroin (fiber). Several processes are involved in the extraction of silk fiber from mulberry silk [**41**]. The female moth lays hundreds of about 355-405 eggs, the egg transforms to larva, caterpillar and then to cocoon.

The cocoon can then be gently boiled with gentle soap solution which helps in dissolving the gum and thus, loosening the silk fibers. The fibers are later washed to get rid of the sericin and other impurities remaining. However, a lot of time and much labour are required to extract silk fiber from spider. When the temperature is cool, the spider is sedated, kept upside down, and with a small brush the production of the fiber is initiated; thereafter, the fibers are separated under a microscope [**25**, **32**, **42**]. Although silk fibers are not readily available as compared to fibers from plants, they are more advantageous than plant fibers for they possess the following properties; continuous fiber type, uniform fiber properties, high toughness, high tensile strength, good insulation properties and high crystallinity [**23**].

Mineral fibers

Mineral fibers mainly occur as natural fibers but can also be slightly processed from minerals. Asbestos is the only class of minerals that naturally occur as bundles of fibers in the environment. It belongs to a group of crystalline and relatively insoluble silicates of chain or ribbon structure, basically containing a silicon atom and four hydrogen atoms [**43**]. Asbestos minerals are made up of six minerals and are classified into two major groups. The first group is the serpentine having a layered-structure of curly fibers, and the other group is the amphiboles with a chain-like structure [**44**]. The representative of serpentine group is chrysotile, while the amphiboles are represented by amosite, antophyllite, crocidolite, actinolite and tremolite. The natural weathering of rocks and mining practices release asbestos to the environment. Asbestos fibers can be carried by wind to the environment or released through erosion. In the processing of asbestos from ores, mining is the first step, followed by wet or dry milling, depending on the part of the stockpile from which the ore was mined [**45**]. As a result of the durability, thermal and oil resistance, asbestosis usually added into materials for friction (e.g. brake linings). However, asbestosis highly carcinogenic and the inhalation of free asbestos fibers can cause a lot of lung diseases (Gopal *et al.,* [**46**]), thus limiting its continued usage in the development of building and general engineering materials.

Plant fibers

The natural fibers of plant origin have been the most used because of their natural abundance in the environment. Plants produce the most interesting groups of fibers used for composite reinforcement, especially in polymer matrices [**47**]. From the environmental point of view, plant fibers are biodegradable, recyclable, and absorb more carbon dioxide than they release to the atmosphere [**48**]. The plant fibers are grouped according to the part of the plant that produced the fibers (**Fig. 3**). The morphology, constituents and properties of plant fibers depend on the type of plant, the crop, the age of the plant, where extraction was carried out, chosen part of the plant and condition of the soil where they are grown [**49**, **50**, **51**]. The most studied plant fibers include: flax, jute, hemp, sisal, ramie, abaca, banana, bagasse, coir, pineapple leaf, rice husk and oil palm [**51**]. Whereas fibers obtained from the stems (bast fibers), such as hemp, ramie, sisal and jute are mostly used because of their excellent mechanical properties [**52**]. The primary components of these plant fibers are cellulose, lignin, hemicellulose and waxes. The quantities of these constituents in a fiber depend on the age of the plant, source of the fiber and the conditions employed in the extraction of the fibers [**53-55**]. These plant fibers are thus known as lignocellulosic or cellulosic fibers. When the lignocellulosic materials are used, reused and recycled, environmental problems are minimized, thereby improving the health conditions of persons and making the environment more habitable.

The properties of natural fibers are highly different. The large difference in their properties depends on some factors, which include the following; fiber type, amount of moisture contained, and structure of the fiber (twine, felt, chopped, woven, yarn, etc.) [**5**]. The types and properties of some naturally occurring fibers are shown in **Table 1**, with emphasis on properties which

Table 1. Some plant fibers and their properties.

Type of fiber	Density [g/cm^3]	Tensile Strength [MPa]	Young's Modulus [GPa]	Specific Strength	Specific Modulus	Elongation at break [%]	Moisture Content [%]	Ref.
Sisal	1.3-1.5	350-700	9-38	341-423	5-6	2-7	10-11	[**49**, **56**, **57**, **58**]
Kenaf	1.2-1.6	240-930	14-53	226-600	25-34	1.6	-	[**56**, **59**]
Hemp	1.47	368-800	17-70	374-612	48	1.6	8	[**59**, **49**, **56**]
Coir	1.15-1.25	131-220	4-6	146	3-5	15-40	10	[**49**, **56**, **57**]
Jute	1.3-1.46	400-800	10-30	302-595	7-21	1.5-1.8	12	[**56**, **49**, **57**, **58**]
Abaca	0.8-1.5	418-980	12-14	545	15.6	-	-	[**58**, **60**]
Flax	1.4-1.5	345-1500	27-80	230-1000	18-46	1.2-1.8	7	[**49**, **59**, **58**]
Bamboo	0.6-1.1	140-503	11-36	383-553	22-40	-	-	[**56**, **61**]
Banana	1.35	54-914	7.7-32	392-677	20-24	1.3-5	60	[**61**, **62**, **63**, **64**]
Pineapple	0.8-1.6	413-1627	34.5-82.5	-	-	1.6-14.5	11.8	[**63**, **65**]
Urenalobata	1.22-1.41	160-418	17.4-57	78868	-	2-5.2	2-6	[**66**, **67**, **68**]
Bagasse	0.55-1.25	20-290	2.7-17	-	-	0.9	-	[**63**, **65**]

are essential requirements in the development of lightweight structures for structural and semi-structural applications.

Table 2 presents comparison between natural and synthetic fibers (Faruk *et al.,* [**51**]). It is observed that natural fibers perform better than synthetic fibers in materials selection criteria, namely: price, weight, energy consumption, and recyclability except for strength.

Table 2. Comparison of natural fibers and synthetic fibers (Adapted from Faruk *et al.,* [**51**]).

Areas Considered	Natural Fiber	Synthetic Fiber
Price	Low	High
Weight	Low	High
Energy Consumption	Low	High
Tensile strength	Low	High
Recyclability	Yes	No

The density of E-glass fibers is more than that of natural fibers [**68**], whilst the specific modulus and specific strength of natural fibers are comparable to those of E-glass fibers, being the least expensive of all reinforcing glass fibers used in composite reinforcements [**69**]. Factually, there are several natural occurring fibers which possess more specific modulus than those of E-glass (Pickering *et al.,* [**71**]), thus there is a good opportunity in the use of natural fibers to replace E-glass fibers.

Natural Fiber-Reinforced Composites (NFRC)

Composites have been confirmed to be high performance and weight-saving materials suitable for several applications; however, the current demand lies in making them cost effective and eco-friendly for component design as structural and semi-structural applications. Synthetic fibers, such as; glass, carbon and aramid fibers have long been utilized as reinforcements for composite manufacture in applications ranging from transportation to building [**4**]. But they present a problem to the environment, as they are only restricted to last disposal by burning in thermo-electric plants. Moreover, synthetic fibers are hazardous to health, from the period of the processing of the composite to the latter end-of-life degradation [**72**].

Although synthetic fiber reinforced composites have high mechanical strengths, their inherent limitations (which include; high density, high cost, etc.) have led to extensive research in natural fiber composites, as their substitutes in automotive and other engineering applications [**73**]. The most important market requirements of natural fiber reinforced composites consist of high impact strength, flexural properties, dimensional stability, elongation, acoustic absorption, ultimate breaking force, processing suitability, temperature and dwell time, low flammability, odour, fogging characteristics and crash behaviour [**50**].

Some studies have been carried out on the use of these natural fibers as suitable reinforcements for composite production. Kim *et al.,* [**74**] produced polypropylene/wool composite sheets by continuous extrusion. The authors reported increased tensile modulus and strength, and improved fire retardancy as the wool fibers were added with maleic-anhydride grafted polypropylene (MAPP) compatibilizer. Conzatti *et al.,* [**75**] studied themorphological, thermal, mechanical and dynamic-mechanical properties of polyester-based biocomposites containing up to 40 wt% of as-received or pre-treated wool fibers, and melt blending was used to achieve the uniform distribution of the wool fibers. The author reported an increment in Young's modulus up to 500% from poly(vinyl alcohol) (PVA) treated wool fibers as compared to the neat polyester matrix, and attributed this to high degree of fiber/matrix adhesion.

In most parts of the world, the human hair has been regarded as waste, but several research works have been done to harness the excellent properties in this natural fiber. The viability of the human hair as a potential fiber was supported by the findings of Hernandez *et al.,* [**76**] in their study on the mechanical and chemical analysis of human hair fiber reinforced polymer composites. Polypropylene matrix reinforced with 3-5wt% human fibers displayed higher izod impact strength, flexural strength, flexural modulus, than those of 10-15wt%, and of the non-reinforced matrix [**77**]. The inclusion of human hair to a mixture of asphalt cement significantly improved its ability to carry additional loads applied to it [**78**]. The structure and mechanical properties of fibers from alpha-keratin which include; human hair, furs of mammals, and wool, together with their nails, horns, claws and quills were studied by Feughelman [**79**], and it was concluded that the human hair has the highest tensile strength amongst the fibers compared.

The mechanical properties of 0-3wt% chicken feather fibers reinforced polyester composites were studied by [**37**]. The part of the chicken feather used to reinforce the polyester matrix to produce the composite was the barb, using hand lay-up process. The results showed that enhanced mechanical properties were obtained for up to 2wt% of the feather fibers. Zhan and Wool [**80**] carried out statistical investigations of the mechanical properties of fibers from chicken feathers. They found out that the strain at break had a Gaussian (normal) distribution with mean value of 6.93%, tensile modulus of 3.59±1.09 GPa and average tensile strength of 203±74 MPa, proving that the chicken feather fibers can be very attractive for composite applications. The thermal expansivity of chicken feather fiber reinforced epoxy composites was studied by Zhan and Wool [**81**] using compression molding method. The results showed that chicken feather fibers can be used to control the overall coefficient of thermal expansion of the composites. Cheng *et al.,* [**82**] produced green composites from chicken feather fiber and poly(lactic acid) (PLA), and the results showed that the addition of chicken feather fibers enhanced the thermal stability of the composites as compared to pure PLA. Performance evaluation of Emu feather fiber reinforced polymer composites were carried out by Reddy *et al.,* [**83**]. The results from the study showed that emu feather fiber reinforced epoxy composites had better mechanical properties than emu feather fiber reinforced polyester composites for all the fiber loadings investigated.

Shah and colleagues [**84**] explained that silk fiber reinforcements are far more compressible than typical plant fiber reinforcements, more compactable than even glass fibers, and also offer a unique opportunity in the production of high fiber volume fraction natural fiber composites. The mechanical properties of compression moulded silk fiber reinforced polypropylene composites were compared with those of jute fiber reinforced polypropylene composites by Shubhra *et al.,* [**85**]. The results showed that the mechanical properties of silk-based composites had greater values than those of jute-based composites, and, the silk-based composites were less degradable than jute fiber reinforced composites. A comparative study was carried out on the preparation and characterization of natural silk fiber-reinforced polypropylene and synthetic E-glass fiber-reinforced polypropylene composites by Alam *et al.,* [**86**]. From the findings, the values obtained for the tensile, bending and impact strengths of E-glass/PP composites were higher than those of silk/PP. Moreover, the environmental and soil degradation, and thermal aging of silk/PP composites were faster than those of E-glass/PP composites.

Sumaila and Ibhadode [**67**] studied the technical properties of some plant fibers found in Northern Nigeria to ascertain their suitability in the replacement of glass fiber in the plastic industry. The results showed that three of the plant fibers (kenaf, sisal and *urenalobata*) are possible replacements for the classic glass fiber. Also, with improved mechanical properties (high specific tensile strength, durability and high toughness values), the fibers possess very essential properties for applications in automotive and aerospace industries. Margem *et al.,* [**87**] studied the flexural performance of *urenalobata* fiber reinforced epoxy composite. The results obtained showed that the flexural properties of the composites improved significantly as the amount of reinforced u*renalobata* fibers increased. The unique potential of *urenalobata* composites for engineering applications was revealed from the results. De Oliveira and Marques [**88**] carried out a study in which u*renalobata* fibers were subjected to alkali treatments with NaOH aqueous solutions at different concentrations, times and temperatures. The results showed that the crystallinity index and thermal resistance significantly increased when the alkaline treatment was conducted with 7 % NaOH solution. Also, the mechanical properties and thermal degradation resistance improved for the composites produced from treated fiber and poly (3-hydroxybutyrate) matrix.

The effect of the processes of compounding (mixer-compression, mixer-injection molding, and direct compression molding process) on the mechanical properties of polypropylene-based composites reinforced with abaca fibers were studied by Bledzki *et al.,* [**89**]. It was observed that the method of molding by mixer-injection showed better mechanical performance than the other molding methods, and that compression molding process brought about reduced odour concentration which favours its application in the automobile sector.

Zampaloni and his co-workers [**90**] studied the production of kenaf fiber reinforced polypropylene sheets that could as well be thermoformed for several applications. The composites produced by compression molding of kenaf fibers and PP matrix had higher flexural and tensile strength as compared to other natural fiber composites produced by compression molding, which includes isal, kenaf, and coir reinforced thermoplastics. The results from the study showed that the kenaf-maleated polypropylene composites produced, had higher modulus/cost and higher specific modulus than sisal, coir, and even E-glass. Pan*et al.,* [**91**] used the method of melt-mixing in the fabrication of a bio-based polymer composite based on kenaf fiber and poly(L-lactide) (PLLA). The consequence of the weight percent of kenaf fiber on crystallization performance, morphology of the composite, dynamic mechanical properties, and mechanical properties of PLLA/kenaf fiber composites were studied. The observation was that the inclusion of kenaf fibers appreciably improved the rate of crystallization, storage modulus and tensile. Also, by the addition of 30 wt% kenaf fiber, the tensile strength of the composite increased by 30%, and the storage modulus by 28%. The effect of sisal fiber length reinforcement on epoxy and polyester matrices were investigated by Saxena *et al.,* [**45**]. From the results, increasing the fiber length increased the flexural strength of the sisal-reinforced epoxy composite, but did not show any changes for the polyester composite.

Hashemi *et al.,* [**92**] carried out a study on bagasse fiber reinforced polypropylene. The fiber surfaces were treated by using silane coupling agents (vinyltrimethoxysilane and y-Glycidoxypropyltrimetho-xysilane). Through microstructural examination, it was observed that there was improvement in the fiber-matrix adhesion and dispersion. The melt viscosity reduced when fibers treated or modified with silane coupling agents were added but increased for the fibers not modified, and also the viscosity reduced at increased loading as compared to those not modified. The tensile modulus and tensile strength of the fibers that were modified increased more than those of the unmodified but the elongation at break of the unmodified was greater.

The physical, mechanical and morphological behaviour of bundle fibers of some plants which include; coconut, pineapple, abaca, sanseviena, ramie sisal and kenaf fiber, were studied by Munawar *et al.,* [**61**]. The results showed that the tensile strength, Young's modulus and density reduced as the fiber bundle diameters enlarge. Almeida *et al.,* (2008) [**93**] studied the mechanical properties and structural features of polyester-based coir fiber composites. Two moulding pressures were applied, and coir fibers amounting up to 80 wt% were involved in the composite production. The results showed that up to 50 wt% of fiber gave rigid composites, while fiber proportion higher than 50 wt% brought about flexible composites. Liu *et al.,* [**94**] reported that compression moulded kenaf fiber reinforced soy-based bioplastic composites have more impact strength than those that were injection moulded. The impact strength of composite reinforced with different fiber lengths and contents were investigated. The results showed that the strength of the composite increased with increase in fiber length and content.

The treatment of jute fibers with silane brought about improvements in the tensile, flexural strength and stiffness of jute-epoxy composites [**95**]. Yan *et al.,* [**96**] reported in the study of polypropylene-based Noil hemp fiber composite that modification of resin with MAPP and fiber modification with hydrophobically modified hydroxylethyl cellulose (HMHEC) improved the interfacial bonding. This resulted in the improvement of tensile, flexural and impact strength. The results showed that after the resin modification and fiber treatment, fracture mechanism changed from fiber pullout to fiber breakage.

The global need to make composites less expensive and environmentally friendly, can be met using natural fiber reinforced composites; the fibers ranging from wool, human hair, chicken feather and silk fibers to several plant fibers. Although, animal and mineral fibers are not readily available as plant fibers, they possess comparable properties to E-glass fibers than plant fibers [**79**, **85**, **81**, **23**].

NFRC as structural and semi-structural materials

The two most important driving factors in the development of natural fiber reinforced composites are reduction in: (a) the environmental pollution encountered in the discarding of available polymer composites, and (b)overdependence on the petroleum-based materials in the production of polymers and composites [**57**]. Monk [**97**] reported that in Germany, natural fiber reinforced polymer composites are not included in the quota for thermal recycling, and can be burnt to regain energy with no charges; for natural fiber reinforced composites can be disposed by burning to a low ash residue at the end of the service life. The research carried out by Mwaikambo [**98**] indicated that the reinforcement of composites with natural fibers significantly speeds up the process of biodegradation. When the fibers are used as reinforcements, the effective surface area of the natural fiber composite will be increased; this will create more paths for moisture absorption into the bulk of the material, and thus quickens the biodegradation of the composite.

Semi-structural applications can be defined as those that the part can at least carry its own weight and are able to bear light external loads [**57**]. Structural applications are those that mainly support the structure of the final designed part. Currently, natural fiber composites are not only used in structural and semi-structural applications for the automotive industry, but also in other areas such as sporting, aerospace, building and construction, medical, electrical and electronics [**51**].

Applications in building and construction activities

Majid [**99**] reported that the use of natural fibers as reinforcement of composites (such as cement paste, mortar and/or concrete) is a cost-effective basis of increasing the shear strength, toughness, and tensile strength of these ceramic based materials. There is a reasonable opportunity to easily introduce natural fiber composites in applications such as the roofing sector, corrosion resistance pipes and tanks (industrial infrastructure), where high strength is necessary but not critical for the service applications [**5**].

Some research works have been carried out with animal and asbestos fibers for applications in building and construction. Wool fiber reinforced composite for construction [**28**]. Sheep wool has been used in civil engineering works for both acoustic and thermal insulation applications [**15**]. The main advantage of using wool fibers in building material production than polypropylene is their reduced cost, reduced environmental impact, improved thermal behaviour and reduced density [**100**]. Stirmer *et al.,* [**15**] developed mortars with sheep wool fibers which can be used to repair historical buildings. From the results, mortars with 5% sheep wool fibers showed better workability and better mechanical properties (flexural strength, compressive strength, and Young's modulus) than mortars with 9% fibers. They concluded that the introduction of sheep wool fibers reduced the density of the mortars and generally improved the thermal insulation properties.

Nila *et al.,* [**101**] studied human hair fiber reinforced concrete for application in civil constructions. The hair fibers were washed with acetone, dried and sorted, before they were added to concrete specimens that were used to produce concrete cubes for testing. The results showed increased compressive, crushing and flexural strengths for 1.5-2 wt% human hair, which makes the reinforced concrete suitable for applications in crack resistant and seismic resistant structures, road, pavement and water proof constructions. Manaf *et al.,* [**102**] reported that the addition of human hair fibers to concrete improved the mechanical properties of the concrete, reduced crack formation and also prolonged the life span of the structures. Yang *et al.,* [**103**] prepared epoxy-based silk fabric composites using simple hot press and treatment by vacuum, to ensure the highest reinforcement fraction of 70 vol. % silk. The silk fabric significantly increased the mechanical behaviour of the resulting composite, especially the impact strength which shows the potentiality of silk as reinforcements in impact-resistant composites.

Several researchers have reported on the use of plant fibers for application in building and construction. Dweib *et al.,* [**104**] developed all-natural composite for use as structural panels and unit beams with soybean oil-based resin and natural fibers (flax, cellulose, pulp, and recycled paper, chicken feathers) using vacuum assisted resin transfer molding technology. The flexural modulus increased from 2-6 GPa when natural fiber reinforcements of 20-55 wt% were used. It was reported that the use of this kind of natural fiber reinforced composite in building construction brings about high specific strength and stiffness, desired ductility, design flexibility, resistance to harsh weather conditions and fatigue resistance.

Ochi *et al.,* [**105**] worked on reinforcements of starch thermoplastics with continuous fiber arrangements of bamboo and hemp. It was observed that tensile strengths of about 188 MPa were obtained using compression moulding, which gave an indication that materials with these strengths have great prospective for structural applications. Four different types of wood fibers were used to reinforce polypropylene matrix by Bledzki and Faruk [**106**]. The wood fibers used were soft wood fiber, wood chips, long wood fiber and hard wood fiber; and maleic-anhydride grafted-polypropylene (MAH-PP) was used as a coupling agent to increase adhesion of the fibers to the addition of 5% MAH-PP brought about increased tensile and flexural properties as compared to other wood fiber-PP composites. They also reported that with the addition of 5% MAH-PP, hard wood fiber depicted more improved impact characteristic values as compared to other wood fiber-PP composites. According to the authors, the wood fibers would be suitable for use as building and automotive materials. Ramakrishna and Sundararajan [**107**] developed composite cement-sand mortar (1:3) slabs using natural fiber (coir, sisal, jute and *H. canabinus*), and experiments were carried out to measure their resistance to impact loading. The impact resistance increased by 3 to 18 times for tested fiber reinforced mortar slab, and also among the fibers tested, coir fibers were the only ones that showed fiber pull out at ultimate failure.

Kalyankar and Uddin [**108**] carried out a research on the development and structural feasibility of natural fiber-reinforced polymeric structural insulated panels for panelized construction. The focus of the study was on the manufacturing possibility and structural categorization of natural fiber reinforced structural insulated panels with jute fiber-reinforced polypropylene laminates for skin material. From the results, there was a significant increase in the mechanical properties of natural fiber reinforced structural insulated panels, for there was a 53% increase in load-carrying capacity compared to oriented strand board structural insulated panels. Also, the bending modulus of the natural fiber reinforced structural insulated panels was 190% higher, and there was a 70% weight reduction of the jute fiber-based panels as compared to oriented strand board structural insulated panels. Dweib *et al.,* [**109**] successfully developed roof structures from cellulose fiber reinforced soy oil composites, having the form of paper sheets made from recycled cardboard boxes. When the recycled paper was tested in structural unit beams and composite sheets, it depicted the desired strength and stiffness required for the construction of roofs. Agopyan *et al.,* [68] carried a study of coir, sisal and pulp from eucalyptus, for the development of roofing tiles in place of asbestos. The results showed that coir fibers were more suitable among the three fibers studied. According to Pai and Jagtap [**63**], golden cane reinforced unsaturated polyester composites can find applications as building/construction materials because of their excellent mechanical properties, good impact strength and flexural modulus. It was also reported that due to the lightness in weight, better mechanical and insulating properties of Typhaaugustifolia reinforced unsaturated polyester composites; they will be suitable for applications such as insulation boards, building constructions, automobile parts and electronic packages.

Applications in automobile and aerospace

Several plant fibers have found wide applications as automobile and aerospace materials. Oladele and Adewuyi [**110**] in the study of the development of automobile gaskets reported that the combination of bamboo, coconut husk, sponges and wood gave the best hardness suitable for automobile gaskets in fuel pump carburetors and in engine oil pump seals. Chandramohan and Bharanichander [**111**] developed automobile accessories which include; rear view mirror, visor in two-wheeler, billion seat cover, indication cover and cover L-side from a hybrid of sisal and roselle fibers and epoxy matrix. This was intended as replacement tothe costly and non-biodegradable plastic fibers. Also, Norhidayah *et al.,* [**12**] reported that various car parts such as dash board, car roof, door handle and car door panels can be developed using the hybrid reinforced composite because of the observed excellent properties. It was reported that automobile industries make use of kenaf, hemp, flax, sisal and jute mixed with polypropylene or polyester in the development of automotive seat backs, headliners, door panels and pillars.

Margem *et al.,* [**112**] carried out a comparative analysis of charpy impact energy in polyester composites reinforced with *urenalobata* (malva), ramie and curaua fibers, in the development of impact panels in the automotive industry. Ramie fibers generated better reinforcement to polyester composites when compared to curaua and *urenalobata* (malva) fibers, and had the highest impact energy of 1005.1±78.6J for fiber percentage of 30%. According to Akil *et al.,* [**113**], kenaf has high aspect ratio and reduced energy absorption during production as compared to other fibers (including glass). These excellent properties have led to the increased use of kenaf-based composites in automobile parts. Jamrichova and Akova [**114**] studied the mechanical behaviour of corn fiber/polyester and hop fiber/polyester composites fabricated by the method of hand lay-up. The composites produced have adequate properties for use as door storage or other less stressed parts of the car interior. According to Staiger and Tucker [**58**], Techni-Lin (France), a supplier to automotive industry recently supplied interior door panels produced by compression moulding to Citroen and Opel at the rate of 2000 vehicles/day. These door panels are mostly compositing of flax fibers and polypropylene matrices. Also, Rieter Automotive System (Switzerland) partnering with Manila Cordage Co. (Philipines) and Daimler Chrysler AG (Germany) manufactured abaca leaf fiber reinforcement in polypropylene matrix for application in under floor components [**115**, **116**]. Principally the automobile parts such as dashboards, seatbacks, package trays, and seatback linings are made by natural fibers which include; kenaf, jute, sisal banana, and flax [**117**].

A potential application of flax fibers as a better substitute to glass fibers is in the parts used in aircraft cabins [**118**]. A study was carried out by Researchers at German Aerospace Center on the life cycle assessment of flax fibers to quantify the environmental impacts as against glass fibers in a phenol resin prepreg cabin panel. The results showed that flax is more advantageous as it consumes less energy through-out its life cycle, and its energy-recovery ability through incineration at the stage of it being disposed [**59**]. According to Marsh [**119**], the foremost reported aircraft natural fiber reinforced composite, British Super marine Spitfire, was made from flax linen roving/urea formaldehyde resin.

Plant fibers especially those of the bast group have been widely used and reported as suitable composite reinforcements for use in automobile and aerospace applications.

Applications in sports and medicine

Some naturally occurring fibers have been utilized as materials for sporting and medical applications. There are recent reports that flax fibers are being considered as viable sources for application in sporting equipment, which include the reinforcement material for racing boats, tennis rackets, snowboards and bicycle frames [**120**]. Gebai *et al.,* [**121**] reported that bamboo fibers are mostly used in the production of sporting goods, which includes; skateboards, snowboards and bicycles. Popzyk *et al.,* [**122**] reported that the high mechanical properties and high damping capacity of flax fibers; make them suitable for sports equipment such as hockey sticks and alpine skis.

Moothoo*et al.,* [**14**] studied the mechanical properties of flax reinforced polylactic acid (flax/PLA) and flax reinforced polypropylene biocomposites (natural fiber composites) made bare to a medical environment (cleaning and disinfectant treatments) to be used as a semi-structural component. Both natural fiber reinforced composites were put into varying cleaning products to take the measurement of the absorption kinetic, and also observe how the mechanical properties will evolve in conditions that are severe. The report showed that the gain in weight of the natural fiber reinforced composite was very low, and also that there was a recovery of the first weight before each cleaning cycle. The composites did not reach the saturated state in service condition, and also the tensile modulus and strength reduced a little. This implied that the composites subjected to cycles of cleaning and disinfectant
will be able to be used in a medical environment. Chandramohan and Marimuthu [**52**] carried out a research on the use of sisal, banana and roselle fiber reinforced epoxy matrix composites for internal and external fixation on human body for fractured bone. The stress values obtained from the natural fibers were lower than those of titanium, meaning that when the natural fibers are used for bone fixation, the human body experiences less stress than when titanium is used. The development of this type of biocomposite/natural fiber composite promotes an increase in bone density because of high resistance to corrosion of the natural fibers. Also, there is increase in fracture healing with natural fiber reinforced polymer composite bone plates.

Ho *et al.,* [**123**] discovered that using of silk fiber as reinforcement can improve the modulus of poly(lactic-acid) and also vary the rate of its biodegradability, which are the main factors in the design of implants for bone fixation. According to Rogers [**124**], spider silks are super-strong, light, tough, flexible, biodegradable and biocompatible; making them appropriate for applications in medicine, such as artificial skin, muscle grafts, medical implants, and bone regeneration. They are also suitable for sutures [**39**]. Reddy [**125**] in his report, said that the tenacity and gum-like attributes of sericin found in silk fiber makes it a good candidate for biomedical joining and sealing applications. Cheung *et al.,* [**39**] reported that when chicken feather fibers are used as reinforcements in the biopolymer, PLA (poly(lactic-acid), the composite formed can be used for medical implant applications.

Applications in electrical and electronic devices

There are evidences to show that natural fibers are used as reinforcements for composites in electrical and electronic devices. According to Gorobinskay *et al.,* [**126**], continuous mineral fibers can serve as composite reinforcements in the production of printed circuit boards for they provide special stability of the dielectric parameters to fiber laminates. Zhan *et al.,* [**127**] studied the electrical behaviour of epoxy-based chicken feather fiber composites. The study revealed that the composite can be used in the development of printed circuit boards which electrically connect and mechanically support electronic components by the use of pads, conductive tracks and other features. A novel low dielectric constant material that can replace dielectrics found in circuit boards and microchips was developed by Hong and Wool [**128**] with the use of hollow keratin fibers and chemically modified soybean oil. The reduced coefficient of thermal expansion of the composite was suitable for electronic applications and has resemblance to the value of polyimide or silicon materials used in printed circuit boards. Jayamani *et al.,* [**129**] studied the dielectric behaviours polypropylene and unsaturated polyester based jute/bamboo fibers hybrid composites to be used as dielectric substances in circuit boards, connectors, microchips, and transformer parts. The results showed that jute/bamboo fiber reinforced unsaturated polyester showed improved dielectric properties than jute/bamboo reinforced polypropylene.

Foley [**130**] developed a mobile phone casing made up of about 90% kenaf fiber reinforcements in polylactic acid (PLA) matrix. It was reported that the high fiber content reduced the amount of PLA used, increased the impact resistance of the casing and also improved heat deflection when compared with non-reinforced PLA casing. A research report by Technavio said that kenaf and flax can be used to make low-cost mobile phone cases and laptop cases respectively in the electronic industry [**131**]. Charn and Mamun [**132**] in their research on the characterization of textile-insulated capacitive biosensors; recommended cotton amongst the studied textile materials (linen, rayon, nylon, cotton, polyester and PVC-textile), as the most suitable textile insulator used for capacitive biosensor, in sensing systems to be worn, and also individual healthcare gadgets Nayak *et al.,* [**133**] reported that natural fiber reinforced composites are fit for electrical and electronic purposes because of their high dielectric strength and arc resistance properties.

Table 3 shows some applications of natural fiber reinforced composites (NFRC) in different market segments, and the accompanying fibers and the manufacturing processes employed.

Challenges and outlook

Undeniably, natural occurring fibers have attracted lots of interest as replacements of synthetic fibers for use as structural and semi-structural materials; there is however some challenges associated with their usage. The major drawbacks of natural fibers used for composite reinforcements are their low wet-ability, high moisture content, heterogeneity, and reduced resistance to environmental degradation and sensitivity to elevated temperatures [**144**]. The fibers are mainly hydrophilic in nature and thus cannot be easily wetted when placed in the matrix (especially when hydrophobic polymer matrix is used). The high moisture content can lead to low tensile strength, poor dimensional stability and process-ability [**145**, **146**]. The use of appropriate chemical or physical treatment methods on these fibers can reduce their hydrophilic nature and enhance fiber/matrix adhesion.

There have been concerns on the ethical, safe and eco-friendly collection, treatment, usage, and disposal of animal/human-sourced fibers for structural applications. These have led to the introduction of accreditation schemes [**147**], policy guidelines and government interventions [**148**] to ensure that the practices/processes are carried out under conditions that

Table 3. Natural fiber reinforced composite (NFRC) applications in various market segments.

Application Sector	Area of application of NFRC	Fibers used	Manufacturing Processes	Ref.
Automotive/ Aerospace	Door panels, Headliners Seatbacks, Dash boards Trunk liners Gaskets, aircraft wings	Hemp, flax, kenaf, coir, abaca, wood fiber, sisal, roselle, banana, jute.	Compression moulding Injection moulding, Resin transfer moulding, sheet moulding compound, hand layup, thermoforming	[**10**, **111**, **134**,**135**, **136**]
Building/ Construction	Decking, Bridge, Pillars, Elevator ropes, Door panels Window frames, storage tanks, Railing, dams Roof structures and paneling Fencing	Wood, flax, rice husk, coir, bagasse stalk, sisal, bamboo, Silk	Compression moulding, Extrusion Vacuum assisted resin transfer moulding, Injection moulding	[**1**, **137**, **104**, **138**, **139**]
Electrical and Electronics	Mobile cases, Laptop cases, Fiber optic probes, printed circuit boards	Kenaf, flax, silk, jute, bamboo	Injection moulding Cold press	[**140**, **129**]
Sporting/Recreational goods	Bicycle frames Snowboards, Tennis rackets, Fork seat post Surf and stand-up paddle boards, violin strings, helmets, Yacht desk hatch	Flax, hemp, Silk	Oven cure Hand layup Vacuum bagging Vacuum infusion	[**141**, **142**]
Medicine	Implants, Bone grafting Sutures, Medical devices	Flax, silk,	Extrusion Injection moulding	[**143**, **137**]

are ethically and environmentally acceptable. In the case of natural mineral fibers, several legislations have been passed to limit the use of asbestos, being the only naturally-occurring mineral fiber. Amongst these legislations include: Toxic Substances Control Act (TSCA), Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), Safe Drinking Water Act (SDWA), Asbestos Information Act (AIA), Federal Hazardous Substances Act (FHSA), Clean Air Act [**149, 150**].

The heterogeneity in natural fiber properties is due to several factors, which include geographical location of the plant, size, maturity, chemical composition, part of the plant from where the fibers are collected. Equally, several phases such as growing, reaping, fiber removal method contribute to the heterogeneity of the natural fiber [**25**]. Apart from the variability due to the complex nature of the fibers, the observed variability can be from the measurement and testing of parameters [**151**]. It is essential to understand the nurture and growth, of natural fibers and how to extract them for composite manufacture. Using suitable coupling agents and compatibilizers can bridge the gap between the inherent variableness of the fibers and the matrices [**152**]. Also, standard techniques and appropriate equipment should be used for measurements.

At temperatures above 200 ºC, natural fibers may thermally degrade thus leading to reduction in the mechanical behaviour [**17**]. The thermal degradation of natural fibers can reduce the mechanical properties (bending strength and toughness), lead to poor organoleptic properties (colour and odour), and possibly produce volatiles. When the resulting composites are exposed to sunlight, it may lead to biodegradation by ultraviolet light [**17**]. Utilizing appropriate chemical or physical treatments on the natural fibers, compatibilizers and also use of proper additives to the matrices can make them compete with and even supersede the synthetic fibers; thus, overcoming the inherent challenges.

Designing parts with natural fiber reinforced composites poses a challenge because of lack of design and data handbooks, due to lack of database. As more researches are being carried out on natural fiber reinforced composites, good database should be developed for use in the design of relevant technological components and parts.

Conclusion

A review on the property and application of natural fibers as reinforcement in the development of composite systems for structural, semi-structural and technological materials is hereby presented. Types of natural fibers and their inherent properties and some composite systems where natural fibers have been used as reinforcements and in other areas of applications have been adequately discussed as well. Information in this piece highlights great potential of natural fibers in reinforcements particularly for polymer matrix composites which can compete favourably with synthetic fiber-reinforced composites in a good number of structural and technological applications. Furthermore, the bast plant fibers have been shown to be the most utilized natural fibers for structural and semi-structural applications due to their excellent mechanical properties. However, it should be noted that the natural fibers also have limitations specifically linked with fiber-matrix interface bonding due to a few factors which have been highlighted in this review. Nonetheless, the identified drawback could be eliminated /reduced with the use of chemical treatment and other articulated processing modifications. In conclusion, the need for a dependable scientific database for natural fiber database usable for technological design of components and parts has been emphasized in this review. In addition, future direction for research and development in natural fiber reinforced composites that could pave the way for pervasive and sustainable use of natural fiber reinforced composites is highlighted in this review. Therefore, information documented in this review could be thought-provoking to material scientists/engineers and other stakeholders in sectors where composites are employed towards developing sustainable means to sustainably and adequately utilize natural fibres in the development of composite materials.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

1. Mohammed, L.; Ansari M. N. M.; Pua, G.; Jawaid, M.; Islam, S. M.; *Int. J. Polym. Sci.*, **2015**, *2015*, 15.
2. https://www.scopus.com/natural fibers. **2018**. Accessed on 10 October 2018
3. Bongarde, U. S. and Shinde, V. D.; *Int. J. Eng. Sci. Technol.*, **2014**, *3*, 431.
4. Begum, K., Islam, M. A.; *Res. J. Eng. Sci.*,**2013**, *2,* 46.
5. Ticoalu, A.; Aravinthan, T. and Cardona, F.; A review of current development in natural fiber composites for structural and infrastructure applications. Proc. South. Reg. Eng. Conference (SREC), Toowoomba, Australia, **2010.**
6. Sudell, B. C. and Evans, W. J.; Int. Conf. Wood-Fiber-Plastic Composite (ICWFPC) (Forest Products Society, Madison, WI). **2013**.
7. Ali, A.; Shaker, K.; Nawab, Y.; Baheti, V.; Hussain, M.; Militky, T.; Vijay.; *J. Ind. Text.*, **2016**.
8. Malkapuram, R.; Kumar, V. & Negi, Y.; *J. Reinf. Plast. Compo.,* **2009**, *28,* 1169.
9. Bavan, D. and Kumar, G.; *J. Reinf. Compo.,* **2010**, *29,* 3600.
10. Leveque, J.: The challenge of natural fibers in composite reinforcement. JEC Magazine, *25,* **2006**. Accessed on 13 August 2011.
11. Sudell, B.: Industrial fibres: recent and current developments. Nat. Fib. Symp. Proc, 71, **2009**.
12. Norhidayah, M. H.; Hambali, A.; MohdYahazri, Y.; Zolkarnain, M.; Taufik and Saifuddin, H. Y.; *Appl. Mech. Mater.*, **2014**, *564*, 3.
13. Araujo, J. R.; Mano, B.; Teixeira, G. M.; Spinace, M. A. S. and De Paoli, M. A.; *Compo. Sci. Technol.*, **2010**, *70,* 1637.
14. Moothoo, J.; Ouagne, P.; Allaoni, S. and Soulat, D.; *J. Reinf. Plast. Compo.*, **2014**, *33,*1823.
15. Stirmer, N.; Milovanovic, B.; Sokol, J. M.; Cement composites reinforced with sheep's wool. https://www.bib.irb.hr>datoteka, **2014**. Accessed 07August 2017.

16. Kim, H., Lee, B., Choi, S.: Sustainable bio-composites for automotive interior parts. 18th ICCM. South Korea, **2011**.
17. Zhu, J.; Zhu, H.; Njuguna, J.; Abhyankar, H.; *Mater.*, **2013**, *6*, 5171.
18. Berardi, U.; Lannaceb, G.; Gabrielec, M.; *J. Nat. Fibers*, **2017**, 1.
19. Westman, M. P.; Laddha, S. G.; Fifield, L. S.; Kafentzis, T. A.; Simmons, K. L.; Natural fiber composites: A review. National Technical Information Service, U. S. Department of Service, Springfield, **2010**.
20. Dixit, S.; Goel, R.; Dubey, A.; Shivhare, P. R., and Bhalavi, T.; *Polym. Renew. Resour.,* **2017**, *8,*71.
21. Rohit, K and Dixit, S.; *Polym. Renew. Resour.,* **2016**, *7,* 43.
22. Chauhan, A. and Chauhan, P.; *J. Chem. Eng Proc. Techno.*, **2013**, *6,* 1.
23. Darshan, S. M.; Suresha, B. and Divya, G.S.;*Indian J. Adv. Chem. Sci.*, **2016**, *1*, 183.
24. Alavudeen, A.; Rajini, N.; Karthikevan, S.; Thiruchitrambalam, M.; Venkateshwaren, N.; *Mater. Des.: Elsevier;* **2015**, *66(A),* 246.
25. Ramamoorthy, S. K.; Skrifvars, M.; Persson, A.; *Polym. Rev.*, **2015**, *55,* 107.
26. Sanjay, M. R.; Arpitha, G.R.; Naik, L.L.; Gopalakrishna, K. and Yogesha, B.; *Nat. Resour.,* **2016**, *7*, 108.
27. Ryder, M. L.; *Anthropozoologica*, **1992**, *16*, 131.
26. Loana, B. I.; Sustainable Alternatives for Wool Valorization. Annals of the University of Oradea https//:www.textile.webhost.uoradea.ro>Annals. **2017**. Accessed: 7 April 2017
29. Harris, M.; *J. Res. Nat. Bur. Stand.*, **1935**, *15*, 1.
30. Wool, Encyclopedia Britannica; The editors of Encyclopedia Britannica, **2014**.
31. Robbins, C.; Chemical and Physical Behaviour of Human Hair (3rd Edn.), Springer, New York, **1994**.
32. Saxena, M.; Pappu, A.; Haque, R. and Sharma, A.; Sisal fiber based polymer composites and their application; Kalia, S., Kaith, B. S., Kaur, I. (Eds.), Springer-Verlag, Berlin, **2011.a**, pp.589-660
33. Verma, A.; Singh, V.K.; Verma, S.K.; Sharma, A.; *Int. J. Waste Resour.*, **2016**, *6,* 1.
34. Popescu C.; Hocker H.; *Chem. Soc. Rev.*, **2007**, *37*, 1282.
35. Fraser, R. D.B.; Parry, D. A. D.; *Int. J. Biol. Macromol.*, **1996**, *19,* 207.
36. Shalwan, A.; Yousif, B. F.; *Mater. Des.*, **2013**, *48*, 14.
37. Choudary, R. B.; Prasad, A. S.; Bhargava, N.R.M.R.; *Mater. Sci. Res. India*, **2007**, *4,* 487.
38. Kock, J.W.; Thesis presented to the Academic Faculty, Georgia Institute of Technology, **2006**
39. Cheung, H. Y.; Ho, M. P. H.; Lau, K. T.; Cardona, F.; Hui, D.; *Composites Part B*, **2009**, *40,* 655.
40. Barone, J. R.; Schmidt, W.F.; *Compo. Sci. Technol.*, **2005**, *65,* 173.
41. Banale, A. K.; *J. Mater.*, **2017**, 1.
42. Mussig, J. (Ed.); Industrial Applications of Natural Fibers: Structure, Properties and Technical Applications. Wiley: N.J, **2010.**
43. Wachowski, L.; Domski, L.; *Polish J. Environ. Stud.*, **2000**, *9,* 443.
44. Libby, M. T.; Types of Asbestos. http://www.asbestos.com>Asbestos Exposure>Asbestos **2016**. Accessed on 28/07/2016
45. Saxena, M.; Pappu, A.; Sharma, A.; Haque, R.; Wankhede, S.;Composite Materials from Natural Resources: Recent Trends and Future Potentials, Dr. Tesinova, P. (Ed.), ISBN: 978-953-307-449-8, **2011.b**, pp.121-162.
46. Gopal, P.; Dharani, L. R.; Blum, F. D.; Tribological study of non-asbestos fiber reinforced phenolic composites for braking applications. Ame. Soc. Compo., Ninth International Conference Proceedings, pp.106-109, **1994**
47. Weager, B.; Biocomposites: Technology Overview. A major revision of best practice Guide. Natural Fiber Composite. NetComposites, commissioned by Materials KTN, pp.1-69, **2014**.
48. Joshi, S. V.; Drzal, L. T.; Mohanty, A. K.; Arora, S.; *Composites Part A*, **2004**, *35*, 371.
49. Mohanty, A. K.; Misra, M.; Drzal, L. T.; Natural fibers, biopolymers and biocomposites, Boca Raton: CRC Press, **2005**.
50. Wallenberger, F. T.; Weston, N.; Natural fibers, plastics and composites, Boston: Kluwer Academic Publishers, **2004**.
51. Faruk, O.; Bledzki, A. K.; Fink, H.; Sain, M.; *Macromol. Mater. Eng*. **2014**, *299,* 9.
52. Chandramohan, D.; Marimuthu, K.;*Int. J. Adv. Med. Sci.*
Carvalho, L.; *Revista Brasileira de Engenharia Agricola e. Ambiental*, **1999**, *3,* 367.
54. Rowell, M. R.; Han, J. S; Rowell, J. S.; *Nat. Polym. Agrofibers Based Compo.*, **2000**, 115.
55. Pereira, P. H. F.; Rosa, M. F.; Cioffi, M. O. H.; Benini, K. C. C. C.; Milanese, A. C.; Voorwald, H. J. C.; Mulinari, D. R.; *Polimeros*, **2015**, *25,* 9.
56. Celino, A.; Freour S.; Jacquemin, F.; Casari, P.; *Front Chem;* **2013**, *1*, 43.
57. Staiger, M. P.; Tucker, N.; Natural fiber composites in structural applications, In Properties and Performance of Natural-Fiber Composites, Elsevier Inc., **2008**, pp.269-300.
58. Brouwer, W.: Natural fiber composites in structural components: Alternative applications for sisal? Common fund for commodities-alternative applications for sisal and henequen, Technical paper No.14, Sem. Proc. FAO and CFC, **2000**.
59. Silva J, M.; Sabatini R.; Gardi A.; Opportunities offered by naturally occurring materials in light-weight aerostructures design, PRCC Conference. Melbourne, Australia, **2014**.
60. Munawar, S.S.; Umemura K.; Kawai S.; *J. wood Science*, **2007**, *53,* 108.
61. Rao K. M. M.; Rao, K. M.; *Compos. Structure*, **2007**, *77,* 288.
62. Satyanarayana, K. G.; Sukumaran K.; Mukherjee P. S.; Pavithran C.; Pillai S. G. K.; *Cem. Concr. Compos*, **1990**, *12,* 117.
63. Pai, A. R.; Jagtap R. N.; *J. Mater. Environ. Scie*, **2015**, *6,* 902.
64. Pujari, S.; Ramakrishna, A.; Kumar, S. M.; *Int. J. Curr. Eng. Technol.,* **2014**, *2,* 121.
65. John M. J.; Anandjiwala R. D.; Wiley InterScience (www.interscience.wiley.com), *Polym. Compo.*, **2008**, 188.
66. Agu, C. V.; Njoku, O. U.; Chilaka, F. C.; Agbiogwu, D.; Iloabuchi, K. V.; Ukazu, B.; *African J. Biotechnol.,* **2014**, *13,* 2050.
67. Sumaila, A.; Ibhadode, A. O. A.; *Int. J. Eng. Res. Africa*, **2013**, *11*, 11.
68. Agopyan, V.; Savastanojr H.; John V.; Cincotto M.; *Cem. Concr. Compo.*, **2005**, *25,* 527.
69. Drzal, I.; Mohanty, D.;Burgueno, R.; Misra, M.; Biobased structural composite materials for housing and infrastructure applications opportunities and challenges, NSF Housing Research Agenda Workshop, Proc 2, 129-140, **2004**.
70. Arpitha, G. R.; Sanjay, M. R.; Yogesha, B.; *Adv. Eng. Appl. Sci.,* **2014**, *4,* 44.
71. Pickering, K. (Ed.); Natural fiber composites in structural applications, **2008**.
72. Monteiro, S.; Calado, V.; Rodriguez, R.; Margem, F.; *J. Mater. Res. Technol.*, **2012**, *1,* 117.
73. Bettini, S. H. P.; Uliana, A. T;Holzschuh, D. J.; *J. Appl. Polym. Sci.*, **2008**, *108*, 2233.
74. Kim, N. K.; Lin, R. J. T.; Bhattacharyya, D.; *Composites Part B*, **2014**, *67*, 472.
75. Conzatti, L.; Glunco, F.; Stagnaro, P.; Patrucco, A.; Marano, C.; Rink, M.; Marsano, E.; *Composites Part A,* **2012**, *43,* 1113.
76. Hernandez, A.L.; Velasco-Santos, C.; de-Iaza, M.; Victorm, C.; *J. Compo. Sci.*, **2007**, *38*, 405.
77. Choudhry S.; Pandey, B.; *Int. J. Mech. Ind. Eng.*, **2012**, *2*, 118.
78. Ganiron, T.U.; *Int. J. Adv. Sci. Technol.*, **2013**, *55*, 53.
79. Feughelman, M.; Mechanical Properties and Structure of Alpha-Keratin Fibers: Wool, Human Hair and Related Fibers. University of New South Wales Press, Sydney, **1997**.
80. Zhan, M.; Wool, R. P.; *Polym. Compo.*, **2011**, *32,* 937.
81. Zhan, M.; Wool, R. P.; *J. Appl. Polym. Sci.*, **2013**, *128,* 997.
82. Cheng, S.; Lau, K.; Liu, T.; Zhao, Y.; Lam, P. Yin, Y.; *Composites Part B*, **2009**, *40,* 650.

83. Reddy, N. K.; Chanrasekar, V.; Reddy, K. T.; Hussain, S. A.; *Int. J. Mech. Robotics Res.,* **2014**, *3,* 272.
84. Shah, D. U.; Porter, D.; Vollrath, F.; *Composites Part A*, **2014**, *62*, 1.
85. Shubhra, Q, T. H.; Alam, A. K. M. M.; Gafur, M. A.; Shamsuddin, S. M.; Khan, M, A., M.; Dipti S.; Quaiyyum, M. A.; Khan, J. A.; Ashaduzzaman, Md.; *Fibers Polym.*, **2010**, *11*, 725.
86. Alam, A.K.M.M.; Shubhra, Q. T. H.; Al-Imran, G.; Barai, S.; Islam, M. R.; Rahman, M.; *J. Compo. Mater.,* **2011**, *45.*
87. Margem, J. I.; Gomes, V. A.; Margem, F. M.; Ribeiro, C. G.; Braga, F. O.; Monteiro, S. N.; *Mater. Res.,* **2015**, *10*, 1590.
88. de Oliveira, P.; Marques, M.; *Chem. Technol.*, **2015**, *9,* 211.
89. Bledzki, A. K..; Mamun, A. A.; Faruk, O.; *J. Primery*, **2008**, *2,* 35.
90. Zampaloni, M.; Pourboghrat F.; Yankovich, S. A.; Rodgers B. N.; Moore J.; Drzal L. T.; Mohanty A. K.; Misra, M.; *Composites Part A*, **2007**, *38,* 1569.
91. Pan, P.; Zhu, B.; Kai, W.; Serizawa, S.; Iji, M.; Inoue, Y.; *J. Appl. Polym. Sci.*, **2007**, *105*, 1511.
92. Hashemi, S. A.; Arabi, H.; Mirzaeyan, N.; *Polym. Compo.*, **2007**, *28,* 713.
93. Almeida, J. R. M. D.; Monterio, S. N.; Terrones, L. A. H.; *Elsevier Polym. Test.,* **2008**, *27,* 591.
94. Liu, W.; Drzal, L. T.; Mohanty, A. M.; Misran, M.; *J. Compo. Eng. Part B*, **2007**, *38*, 352.
95. Bledzki, A.K.; Gassan, J.; *Prog. Polym. Sci.*, **1999**, *24*, 221.
96. Yan, Z.; Zhang, J.; Zhang, H.; Wang, H.; *Adv. Mater. Sci. Eng.*, **2013**, *2013*, 1.
97. Monk, J.; Recycling and End of Life Vehicle Issues, Knibb Gormezona and Partners, Faraday Advance, **2003**.
98. Mwaikambo, L. Y.; Tucker N.; Clarck, A. J.; *Macromol. Mater. Eng.*, **2007**, *292,* 993.
99. Majid, A.; *J. Civil Eng. Construct. Technol.*, **2012**, *3,* 80.
100. Rivera-Gomez, C.; Galan-Marin, C.; Bradley, F.; *Polym.*, **2014**, *6*, 977.
101. Nila, V. M.; Raijan, K.J.; Susmitha, A.; Riya, B. M.; Neena, R. D.; *Int. J. Curr. Res.*, **2015**, *7*, 21205.
102. Manaf, A.; Adarsh, M. V.; Jomichan, A.; Varghase, G. M.; *Int. J. Eng. Res. Technol.,***2017**, *6,* 460.
103. Yang, K.; Ritchie, R. O.; Gu, Y.; Wu, S. J.; Guan, J.;. *Mater. Des.*, **2016**, *108*, 470.
104. Dweib, M. A.; Hu, B.; O'Donnell, A.; Shenton, H. W.; Wool, R. P.; *Compo. Struct.*, **2004**, *63,* 147.
105. Ochi, S.; Takagi, H.;Tanaka;*Zairyo/J. Soc. Mater. Sci., Japan*, **2003**, *52,* 916.
106. Ochi, S.; Takagi, H.; Tanaka; *Zairyo/J. Soc. Mater. Sci., Japan,* **2003**, *52,*857.
107. Ramakrishna, G.; Sundararajan, T.; *Cem. Conc. Compo.,* **2005**, *27,* 547.
108. Kalyankar, R. R.; Uddin N.; *Int. J. Polym. Sci.*, **2011**, 1.
109. Dweib, M. A.; Hu, B.; Shenton, H. W.; Wool R. P.; *Compo. Struct.*, **2006**, *74*, 379.
110. Oladele, I. O.; and Adewuyi, B. O.: *J. Sci. Technol.*, **2008**, *28,* 569.
111. Chandramohan D.; Bharanichandar J.; *Ame. J. Environ. Sci.*, **2013**, *1,* 494.
112. Margen, F. M.; Gomes, A. R.; Borges, X. G.; Monteiro, S. N.;A comparative analysis for charpy impact energy in polyester composites reinforced with malva, ramie and curaua fibers, John Wiley & Sons, New Jersey, **2015**, pp.127-130.
113. Akil, H. M.; Onar, M. F.; Mazuki, A. A. M.; Safie, S.; Ishak, Z.A. M.; Bakar, A.; *Mater. Des.*, **2011**, *32*, 4107.
114. Jamrichova, Z.; Akova, E.; University Review, **2013**, *7,* 20.
115. Brosius, D.: Natural fiber composites slowly take root. Composites World. http://www.composites.world.com/articles. **2006**. Accessed 29 March 2015.
116. FAO, Food and Agriculture Organization of the United Nations. Future fibers. http://www.fao.org/economic. **2015**. Accessed 30 March 2015
117. Ramli, N.; Mazlani, N.; Ando, Y.; Leman, Z.;Abdan, K., Aziz, A. A.; Sairy, N. A.; Natural fiber for green technology in automotive industry: A brief review. WOBIC 2017, Materials Science and Engineering, 368, **2018.**
118. Wiedermann, M.; Sinapius, M.; Melcher, J.; Innovation Report 2012: Institute of Composite Structures and Adaptive Systems, DLR, Germany, **2012**.
119. Marsh, G.; *Reinf. Plast.*, **1996**, *40,* 44.
120. Dicker, M. P. M.; Duckworth, P. F.; Baker, A. B.; Francois, G.; Hazzard, M. K.; Weaver, P. M.; *Composites Part A*, **2014**, *56*, 280.
121. Gebai, S.; Hallai, A. M.; Hammoud, M. S.; Mechanical properties of natural fiber reinforced polymers: Emerging research and opportunities, IGI Global, USA, 19, **2018**.
122. Popzyk, M.; Reimer, V.; Gries, T.; Hockey stick made using natural fibers.https://www.textileworld.com. **2017**. Accessed on 13 June 2017
123. Ho, M-p.; Lau, K-t.; Wang, H.; Bhattacharyya, D.;*Composites Part B*, **2010**, 1-24 (Accepted Manuscript).
124. Rogers, K.; The amazing spider silk: the natural fiber that can help regenerate bones, https://motherboard.vice.com/en_us/article/wnjknm**2015**. Accessed 12 march 2015.
125. Reddy, M. R.; *Acad. J. Entomol.* **2009**, *2,* 71.
126. Gorobinskay, V.; Kravtchenko, I.; Zabava, L.; Continuous mineral fiber-a reinforcing element for composites. https://www.iccm-central.org>papers>pap1163 1999.
127. Zhan, M.; Wool, R. P.; Xiao, J. Q.; *Composites Part A*, **2011**, *42,* 229.
128. Hong, C. K.; Wool, R. P.; *J. Nat. Fibers*, **2004**, *2*, 83.
129. Jayamania, E.; Hamdanb, S.; Rahmanb, R.; Bakri, K.; Comparative study of dielectric properties of hybrid natural fiber composites. Procedia Eng., 12th, GCMM **2014**, *97*, 536.
130. Foley D.; NEC & UNITIKA realize bioplastic reinforced with kenaf fiber for mobile phone use. NEC Press. http://www.nec.co.jp/eco/en/annual 2006/02/2-1.html. **2007**. Accessed on 16 June 2007
131. Jesse M.; Natural Fiber Composites Market - Segmentation Analysis and Forecast by Technavio. Business Wire. http://www.businesswire.com/news/home/20171108006483. **2017**. Accessed 08 November 2017
132. Charn L. N.; Mamun B. I. R.; *Sensors*, **2017**, *17,* 574.
133. Nayak, N.; Reddappa, H. N.; Kalagi, G.; Bhat, V.; *Int. J. Eng. Res. Technol.*, **2017**, *6,* 165.
134. Gibson, R. F.; *Compo. Struct.*, **2010**, *92,* 2793.
135. Ebisike, K.; AttahDaniel, B. E.; Babatope, B.; Olusunle, S. O.O.; *Int. J. Eng. Sci.,* **2013**, *2,* 95.
136. Khondker, O. A.; Ishaku, U. S.;Nakai, A.; Hamada, H.; *J. Polym Environ.*, **2005**, *13,* 151.
137. Saravanan, D.; *J. Text. Apparel, Technol. Manage.,* **2006**, *5,* 1.
138. Yousif, B. F.; Ku, H.; *Mater. Des.*, **2012**, *36*, 847.
139. Nadir, A.; Songklod, J.; Vallayuth, F.; Piyawade, B.; Robert, W. H.; *Fibers Polym.*, **2011**, *12*, 919.
140. Penman, D.; Spider silk delivers finest optical fibers. *Daily News,* 19th March, **2003**.
141. Osaki, S.; *Phys. Rev. Lett.*, **2012**, *108,* 154301.
142. Palmer, J.; Spider silk spun into violin strings. *Sci. Technol. Reporter*, BBC News. 7th March, **2012**.
143. Cheung, H.; Lau, K.; Study on silkworm silk fiber/ biodegradable polymer biocomposite. 16th ICCM, Kyota, Japan, 1-9, **2007**.
144. Muller, M.; Valasek, P.; Ruggiero, A.; *Bioresource,* **2017**, *12,* 255.
145. Alkabir, M. F. M.; Sapuan, S. M.; Nuraini, A. A.; Ishak, M. R.; *Compo. Struct.*, **2016**, *148*, 59.
146. Mizera, C.; Hrabe, P.; Muller, M.; Herak, D.; *Manuf. Technol.*, **2016**, *16,* 188.
147. Hassan, M. M. and Shao, J. Z.; *Key Eng. Mater.*, **2016**, *671*, 32.
148. Gupta, A. *J. Waste Manage.,* **2014**, *2014*, 1.
149. Nelson T.; Asbestos Legislation. https://www.maacenter.org/asbestos/legislation, **2018**. Accessed on 24 October 2018.
150. LaDou, J., Castleman, B., Watterson, A. *Environ. Health Perspec.*, **2010**, *118,* 897.
151. Everitt, N. M.; Aboulkhair, N. T.; Clifford, M. J.; *Conf. Papers Mater. Sci.*, **2013**, *2013*, 1.
152. Prasad, N.; Agarwal, V. K.; Sinha, S.; *Iranian Polym. J.,* **2016**, *25,* 229.