Chapter

Improving the Mechanical Properties of Natural Fiber Composites for Structural and Biomedical Applications

Owonubi J. Shesan, Agwuncha C. Stephen, Anusionwu G. Chioma, Revaprasadu Neerish and Sadiku E. Rotimi

Abstract

Natural fiber composites are designed for different purposes including structural and non-structural ones. These natural fiber composites vary greatly in their properties including mechanical properties. Mechanical properties which include the tensile and flexural properties are highly dependent on factors such as matrix type, filler type, processing, post processing treatment and many more, factors which are quite application specific. However, many research works develop their natural fiber composite before considering the possible applications. This chapter intends to X-ray the factors that affect the mechanical properties as it relates to structural and biomedical applications and suggest ways of improving the mechanical properties.

Keywords: natural composites, mechanical properties, structural applications, property improvement

1. Introduction

In recent times, the application of natural fiber polymer composites (NFPCs) for structural purposes has increased [1–7]. In the past, carbon fibers and basalt fibers reinforced polymer composites were commonly used due to their high performance to cost and high strength to weight ratios [8–15]. However, due to fundamental concerns, such as high cost of materials, durability, bonding integrity and gap in the development of standards for practice of abrasing or wearing of machines among others, their uses have been limited [16–19]. More importantly is the environmental concerns, which has strengthened the call for complete replacement of all synthetic fibers. Hence, the increase in research output for possible replacement of synthetic fibers with natural fibers in polymer composites [20–22].

Structural materials required for structural applications encompass materials that are primarily for the purpose of stress transmission or support. Structural materials may be in transportation (aircraft and automobiles), construction (building and roads), or in components used for the purpose of protecting the body (helmets and body armor), energy production (turbine blades), etc. [23–25]. Also, those used in microelectronics, are designed to meet specific performance requirements. Structural requirements may vary based on end use; hence the requirement for a material to be used for vehicle part may differ widely from what is required for manufacturing casing for electronic equipment. Generally, of more interest are the following properties: mechanical, thermal, electrical conductivity, dimension stability, water absorbability, etc. [26–31]. This work intends to critically review the mechanical requirements and suggest ways of improving the mentioned properties for structural and biomedical applications.

2. Mechanical properties of NFPCs

NFPCs are different depending on the type of polymers or fibers employed, the processing condition and the characteristic properties developed after processing [32, 33]. The use of these NFPCs for structural applications depends more on the mechanical properties. There are different mechanical evaluations carried out on a material and some are very specific to individual application. However, the general focus of most researchers is on a few tests including tensile test, flexural test, impact test, compression test and hardness. These few tests can describe the mechanical behavior of any material to a large extent and also gives an insight to other possible areas of applications.

2.1 Tensile properties

Tensile test is one of the fundamental and common types of mechanical test widely used for testing polymeric materials. It is also known as tension testing; it is used to determine the stress-strain behavior under tension [32]. In tensile testing, tensile force (pulling force) is applied to a material and the specimens' response to that applied force (stress) is measured. Under this test condition, samples are subjected to controlled tension until failure occurs. Tensile test determines how strong a material is and how long it can be stretched. Important information that can be obtained from tensile test includes; Young's modulus, yield strength, percentage elongation and ultimate tensile strength (UTS).

2.2 Flexural properties

Flexural test is used to determine the capability of a material to resist bending forces applied perpendicularly to its longitudinal axis and often called the transverse beam test. Flexural test properties are among the major parameters used in assessing the suitability of composite materials for structural applications. Parameters such as flexural load, flexural Young's modulus, flexural strength and deflection at break are measured and used to interpret the mechanical behavior under flexural stress.

2.3 Impact properties

Impact test is employed in assessing the impact strength, toughness and notch sensitivity of structural materials. In summary it is the capability of the material in question to withstand high rate loading. Toughness is the total of energy absorbed per unit volume of material before rupturing. The toughness is a measure of balance between strength and ductility of the material. Impact test is very critical for most polymer materials because it relates to the product performance and service life. It also influences other properties related to product safety and liability.

2.4 Compressive properties

Compressive tests evaluate the materials behavior when subjected to uniaxial compression load at a relatively low and uniform loading rate. These tests are very important for product design analysis, especially materials for building purposes. Compressive strength and compressive Young's modulus are the two major properties that are used; however, there are also compressive strain, deformation beyond yield point, and compressive yield stress.

2.5 Hardness properties

Hardness is that property of an engineering material which enables it to resist scratching, indentation, penetration and plastic deformation. It is a very significant property for any structural material from the engineering point of view, because hardness generally leads to increase in wear resistance by either erosion by water, oil and steam or friction.

2.6 Crashworthiness

This is the degree to which a vehicle or aircraft will protect its occupant from the effect of an accident [34]. It is the most important concept in vehicle defect cases. That is, the ability to prevent injuries to the occupant in the event of collision. Therefore, crashworthiness focuses on occupant protection to reduce fatality in the case of an accident. Different criteria can be used to determine crashworthiness depending on the nature of the impact and vehicle involved [35].

In general for composites, these properties depend on other factors such as fiber length, fiber weight percentage content and the extent of polymer/fiber interactions as will be discussed later.

3. Natural fiber polymer composites in structural purposes

Natural fiber reinforced polymer composites are attracting widespread interest for purposes which are sensitive to the materials weight, because their strength and stiffness combine well with their low density, however, their toughness is a major concern [36]. NFPCs are prepared using plant fiber as fillers, which are hydrophilic in nature and do not interact well with hydrophobic polymer matrix [37–39]. NFPCs are a set of important materials developed for numerous areas application; medical, pharmaceutical, food packaging, electronics, aerospace, automobile, construction, building, transport and many more [40–43]. This is because of the many unique qualities these materials possess or can be designed to possess. Qualities which include, but are not limited to; light weight, resistant to chemical attraction, resistant to corrosion, ability to be molded to any shape, can be processed using existing technology, environmental friendliness and sustainability. That is why the interest in these materials has grown tremendously in the last two decades [36, 44–46].

Dweib et al. fabricated bio-based composites for roof structures in the form of paper sheets, entirely from cellulose fibers and soy oil-based resins [47]. These developed sheets were tested for structural unit beams and were established to have given the necessary strength and stiffness for consideration in roof construction. Also Bektas et al. manufactured panels with a density of 0.7 g/cm^3 with a sunflower stalks percentage of 25, 50 and 75% fiber contents [48]. From the results of the mechanical tests, the panels were observed to have the required properties as required for general purpose-use particle board by normal standards.

Wood fibers/plastic composites have been used in large quantities for applications in window and door frames, decks, docks and molded panel components [49–51]. Natural fiber composites have been used to replace asbestos in the building industry, because of their health related issues [52]. The European Union policy tagged "end of life vehicle (ELV)" regulations, promulgated in 2003 and amended in 2005 and 2010, projected reduction of the final waste to be disposed at the end of life of vehicles to 5% by the year 2015. In the stated regulations, 85% of material used in manufacture of the vehicle must be recoverable through reuse or through recycling mechanically [49, 53]. This has generally increased interest and widespread use of NFPCs worldwide. It is noteworthy that this policy was promoted basically because of environmental and social concerns and not necessarily because of economic or technological reasons.

NFPCs durability and the availability of technology has allowed for large and complex shaped manufacturing of NFPCs, making them appealing in the automobile industries [54–56]. In Brazil, automobile industries consume, on average, 10–12.7 kg of natural fiber reinforcement per vehicle. These are circulated through the vehicle, such as rear door liners, front doors, boot liners, parcel shelves, sun roof interior shields and headrests [54]. Although NFPCs have gained tremendous interest in the industries, their applications are not unconnected to their environmental sustainability, low cost and renewability [57–60]. According to a review by Kiruthika [61], the challenge of replacing synthetic fibers completely in widespread applications is far from being overcome, with the improvement to the mechanical properties of composites being the major challenge.

4. Factors influencing the mechanical properties of NFPCs

NFPCs are prepared by compounding polymer matrix (either pristine or blend) with natural plant fibers. The fibers can be single or hybrid, microcellulose or nanocellulose. The natural fibers are made up of different chemical constituents and are exposed to different physical and chemical treatments, therefore, the properties of the resulting composites varied widely. Factors influencing their eventual composite(s) include the following:

4.1 Fiber type

Plant fibers are categorized based on the parts of the plant they are extracted from. Fibers can be extracted from the seeds, leaves or bast of the plants. Bast fiber is collected from the "inner bark" or the surrounding of the stem of certain dicotyledonous plants [61], like banana, flax, hemp, jute kenaf and ramie. These fibers have higher tensile strength and are mostly used in the packaging and paper industries [62, 63]. Sisal, pineapple and many others are extracted from the plant leaves while coir, cotton and abaca are examples of fibers extracted from plant seed. Generally, plant fibers give higher strength and stiffness; however their properties depend mainly on their structure and chemical composition. These invariably relate to the source of fibers, method of extraction, maturity, growing conditions, harvesting period, degree of retting and modification [64–67].

4.2 Fiber length, orientation and weight percentage loading

NFPCs properties are affected by the length of the fibers used, their distribution, the percentage of the fiber volume or volume fraction and their orientation within the matrix. For polymer composites, stress is transferred by the matrix through the fibers both at the interface along the fiber length and at the ends of the fibers by shear [68, 69]. Hence, the degree of load conveyed from the matrix to the fibers is a function of: (i) fiber length, which is referred to as critical fiber length or aspect ratio, (ii) orientation of the fibers and their direction relative to each other. If the fiber orientation and direction is not in the line of the applied stress, failure is bound to occur easily. Unidirectional fiber composites tend to transmit external stress better, that is why hand laid fiber composites performs better mechanically [70, 71].

Depending on the fibers in the matrix's orientation and direction, we can obtain three different types of reinforcement which include (i) longitudinally aligned fiber-filled composites, (ii) transversely aligned fiber-filled composites and (iii) randomly oriented short fiber composites [68, 72, 73]. While the longitudinally filled composites have low compression strength due to buckling of fibers and high tensile strength, the transversely filled composites on the other hand have low tensile strength. However, in the randomly oriented composites, it is far more difficult to predict the mechanical properties, due to the complexities of the distribution of load along the interface of the fiber and the matrix. Hence, considerable control over such elements as orientation dispersion and aspect ratio of the fibers, considerable improvement in the mechanical properties of the composites can be attained.

In general, high performance NFPCs can be obtained mainly by using materials with high fiber content, hence the effect of fiber loading on the properties of the NFPCs is of great significance. Also it is noteworthy to mention that additional fiber content of the composites invariably causes to increased tensile properties [74, 75].

4.3 Fiber-matrix adhesion

The effect of fiber-matrix adhesion cannot be over emphasized. A good number of researchers have reported their experimental results on the effect or importance of a good and strong fiber-matrix adhesion in the fabrication of composites with good mechanical properties [76, 77]. The type of bonds existing at the fiber-matrix interface greatly influences the mechanical properties of any fabricated composites. For a good transmission of stress from the matrix to the fiber to occur, the bond existing among the two components must be strong [64]. Due to the hydrophilic nature of the natural fibers, the interaction between the fibers and the hydrophobic polymer matrix is very weak [4, 78, 79]. Hence, the need to modify the fibers and introduce organic moiety that makes them more hydrophobic is necessary.

Fiber-matrix interface has been described as the reaction zone which plays a significant role in characterizing the composites mechanical properties [80]. A poor interaction between the two surfaces leads to poor transmission of load and therefore poor mechanical performance [81–83]. In addition, plant fibers need chemical modification for the distention or enlargement of the crystalline region, removal of surface impurities and elimination of hydrophilic hydroxyl groups for improvement to some of its relative properties [68].

4.4 Choice of polymer matrix

Polymer matrix could be either a thermoset or a thermoplastic, with varying preparation procedures and conditions, the performances of polymer matrix are affected quite differently. Thermoset are made in such a way that they develop good bonding with the fibers, especially during curing stage. However, the processes involved are time and energy consuming. Although in the case of tensile loading of the composites, the significance of matrix is evident, some researchers have reported good improvement with the same fiber when the matrices are changed. However, for compressive, in-plane shear and inter-laminar strength, they are highly influenced by the type of matrix used [84].

4.5 Processing conditions

The properties of NFPCS have been shown to vary from one processing technique to another [85–89]. Common techniques for the preparation of NFPCs include injection, extrusion, compression and resin transfer molding. These techniques use different processing conditions or parameters even when the materials being processed are the same. Changes in factors such as mixing speed, pressure and temperature can change the properties of the final product with any slight change [90]. For example, the preparation of sisal fiber polyester composites by employing both the compression molding and resin transfer molding technique (RTM) gave products with varying mechanical properties. The products of the RTM gave a composite with higher Young's modulus, tensile strength and flexural strength than the product of the compression molding [90]. Vacuum molding technique is one the simplest manufacturing methods for plastic materials [91]. It is suitably adapted for molding a required shape from a plastic sheet material. In this molding technique, a plastic sheet is heated up to its molding temperature using electric heat; it is then transferred to a molded shape. To obtain the shape, a vacuum is created between the mold and the sheet. Vacuum molding is an inexpensive method when compared to other molding methods. It has numerous application including, aircraft, skin tight packing, disposable tray and caps. It is a low cost methods already being employed in many areas of endeavors as mentioned. A lot of research work is being carried out on how to improve the vacuum forming method, for instance, vacuum-assisted resin transfer (VARI), also known as vacuum infusion process (VIP) which was reported by [92] to be considered as an attractive method for the production of NFPCs low cost and good performance. It uses low-cost one-sided tooling and injects low-viscosity resin into dry fiber that was performed under low pressure. The method was found to be economically suitable for the manufacturing of large composite structures, such as boat hull, wind turbine blade and aircraft structures with low or high volumes of production.

However for vacuum forming method the cycle time of production is still much affect by the cool rate and time, amount of pressure applied and the fiber content [93]. These factors can greatly affect the mechanical properties the final product.

4.6 Presence of void

The introduction of fibers into the matrix during processing is accompanied with the introduction of air and other volatile substances. These substances which are mostly trapped in the fibers may form voids in the composites after processing and curing along the individual fibers. This can negatively affect the composites mechanical properties. In addition, the rate of cooling during processing can also result to the formation of voids [73]. When the void content is too high, it leads to greater affinity for water diffusion, lowering fatigue resistances and increased disparity in mechanical properties [94].

4.7 Thermal stability

The importance of the stability in the preparation of the composites cannot be over emphasized as it affects the mechanical properties considerably. The different components of plant fibers are sensitive to different range of temperatures, i.e., hemicellulose, cellulose, pectin [95, 96]. Most fibers start degrading thermally at 220°C, thereby limiting the composites thermally [68]. In recent reports, the thermal stability of these fibers were greatly improved by removing maximally the lignin, hemicellulose and other alkaline soluble substances in the fiber through physical, chemical or biological means [97].

In general, the above mentioned factors do not influence the mechanical properties of NFPCs individually or in isolation. Rather, in the fabrication of a composite, the cumulative effect of two or more of these factors may be responsible for the composites mechanical failures. Jain et al. evaluated the effect of inter-fiber interactions of different class of reinforced polymer composites on the mechanical properties and the relation to stress field [98]. The research findings highlighted the important role of microstructural arrangement in the determination of the final response of the composites. They reportedly concluded that the local fiber matrix arrangement and their neighborhood density are highly influenced and sensitive to the stress and overall strain energy.

5. Methods for improving mechanical properties of NFPCs

There are different methods which can be employed for mechanical properties improvement of NFPCs. These methods are not rigid formulas that once applied will result in massive enhancements, rather improving mechanical properties of NFPCs is an active area which is ongoing. Mechanical improvement in one area of application may not necessarily yield the same result in another area of application. For example, improving stiffness of a material might be good for the construction and building industries but may not be required or worthwhile for biomedical applications, as it might prefer improvement in flexibility and toughness. Therefore all possible options will be provided; it is left for the researchers to select as appropriate. Furthermore, these methods can be combined to produce synergistic effect.

5.1 Surface modification

There are many literatures and reviews on the benefits of surface modification of natural fibers to the enhancement of fibers mechanical properties and by extension, the composites [99–101]. The mechanical properties of plant fibers depend greatly on the chemical structure, chemical composition and the structural arrangement of cellular fibrils [101]. Other factors such as climatic conditions, age, extraction procedures, growth condition and time of harvest also influence the mechanical properties of natural fibers. All these affect the percentage composition of cellulose in the fibers. Furthermore, the hemicelluloses and lignin are less thermally stable compared to cellulose, modification is one way of reducing the percentage content of hemicelluloses and lignin or even eliminating them completely.

Graphical sample of cellulose structure which consists of amorphous (untreated) and crystalline (treated) regions is shown in **Figure 1** [69]. There exist strong intra-molecular hydrogen bonds with large molecules in the crystalline regions of the cellulose ensuring the crystalline region is very compact and this makes it difficult for chemical penetration. On the other hand, the amorphous region is loose and allows penetration for possible modification.

Surface modification of plant fibers involves the treatment given to the plant fibers in order to increase its cellulose content, improve its interaction with the polymer matrix and also improve their mechanical, thermal and dimensional stability properties. Surface modification can be physical, chemical or biological [11, 21, 79, 102, 103].

Chemical modification involves chemical reaction with the fiber components, thereby making them soluble so that they can be removed by repeated washing. Alkali treatment also known as mercerization involve the use of alkali solution to dissolve all soluble contents of the fibers including wax, oil, pectin, lignin and some part of hemicelluloses [11, 104–107]. Alkali treatment makes the fibers surface rougher and reduce the fibers to fibrils [108, 109]. It improves the aspect ratio and

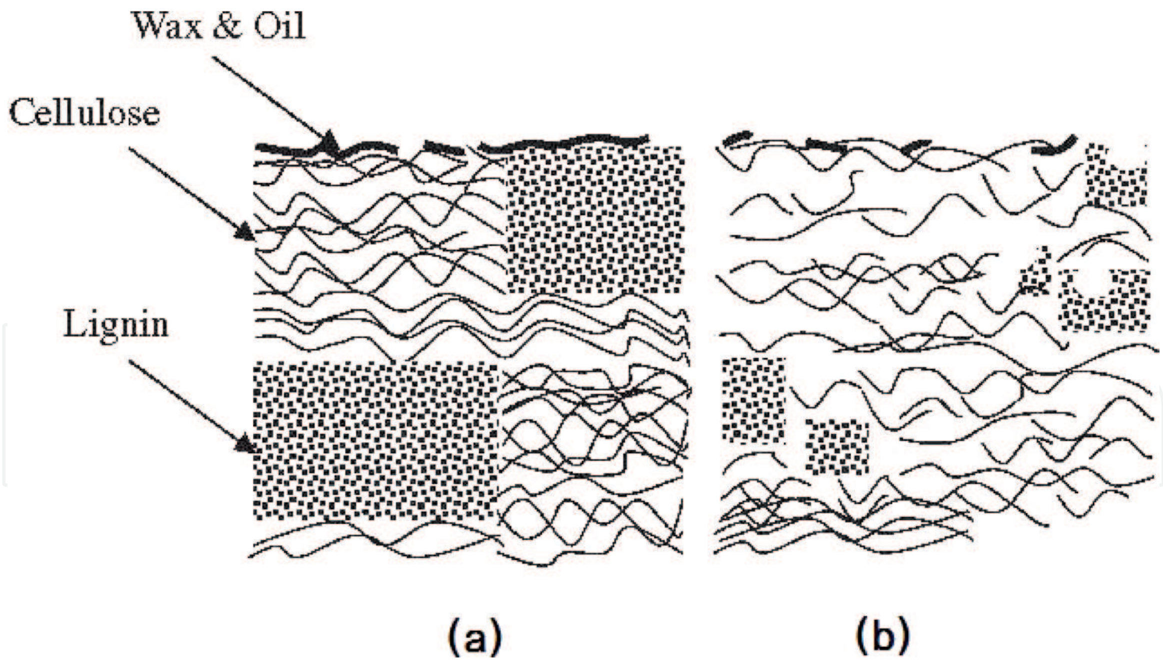

Figure 1.
Schematic diagram showing the crystalline (a)/amorphous (b) regions in a fiber material [69].

creates room for mechanical interlocking in composites [23, 110–112]. To improve chemical interactions in NFPCs which may lead to improved mechanical properties, more chemical treatments are required other than alkali treatment. Another advantage of alkali treatment is that it exposes the OH group on the cellulose chains which can again be utilized for further chemical modification in some cases and in others it can allow for chemical treatment to introduce functional groups onto the surfaces of the fibers. These functional groups can then be used for chemical interaction during the preparation of the composites [27, 113, 114]. Such chemical treatments include silane, sodium silicate, oxidization treatments with DCP, or $KMnO_4$ treatments.

Biological methods involve the degradation by biological organism of all other components of the fiber except the cellulose. This is because the cellulose is highly crystalline and so cannot be easily degraded. Biological treatments are more environmentally friendly, produces more crystalline cellulose with better mechanical and thermal properties and it is cost effective. However, it is laborious and time consuming [115–121].

Physical methods of surface modification involve the use of plasma and corona treatment to change the fiber surface physically. This helps to create rough surfaces that are beneficial for mechanical interlocking [122–124]. However, plasma treatment can be used to introduce chemical functionality onto the fibers so that they can undergo chemical reaction with the polymer matrix [122–124]. Surface treatment introduces rigidity and stiffness to the fibers and by extension, the composites will be suitable for possible structural applications in industries such as building, aerospace marine, packaging, automobile, etc.

Liu et al. [125] reported the improved mechanical characteristics, resulting from alkali treatment on Indian grass fiber used as reinforcement. The tensile Young's modulus of grass fiber reinforced composites treated with 30 wt% alkali improved by 60%, while their impact and flexural strengths improved by 30 and 40% respectively when compared to the 30 wt% raw fiber refeinforced composites. The structural and morphological changes of alkali modified kenaf fibers modified using: 3, 6 and 9% NaOH solutions were reported by Edeerozey et al. [126]. From their SEM results, it was found that 6% and 9% NaOH treatment gave better results. However, the 9% NaOH treatment was considered to be too strong for the fibers, as it led to low tensile properties.

5.2 Blending

Polymer blends have been defined as the combination of two or more polymers, prepared to enhance the properties of the products as well as to lessen the cost. Blends of polymer can simply be viewed as a polymer alloy. Therefore, blending is the mixing of two or more distinct polymers, in a way that gives a new material which has properties that are slightly different from the singular polymers involved. Polymer blending is a versatile procedure to obtain new polymer materials with characteristics far better than the individual polymers [127, 128]. It is a well-recognized option to solving emerging problem related to application requirements.

The ability to combine existing polymers into new one with superior qualities that are commercially acceptable makes blending a better option [129]. There are large numbers of polymer blends reported in literature by researchers in academics and industry [130–132]. Polymer blending can give rise to miscible or phase separated blends. For miscible blends, mixing approaches a molecular dimensional scale and the properties of the new polymer blend are more like those of a single polymer. While phase separated blends still exhibit the different properties of the polymers involved [133–136]. Although, miscibility is extremely rare in blends, the advantage of miscible blends over phase separated blends is in the property profile, especially mechanical properties. Most phase separated blends exhibit inconsistency in their mechanical properties due to the poor adhesion at the interface of the blend phases. However, researchers have developed specific methods by which these phase separation problems can be alleviated [129]. Hence, polymer matrix can be designed to suit the required properties expected of the composites. Blending also helps to modify the matrix with specific chemical functionality that could be added deliberately to enable good interaction between the fibers and the blended matrix. Many researchers have shown that the performance properties of blends can be heightened significantly by reinforcing them with either synthetic or natural fibers [137–141]. However, bio-fiber reinforcements have gained ground in recent time because of their numerous advantages over glass and carbon fibers [142].

According to Linares et al. [143], polymer blends have a recognized potential to produce high performance materials, however the polymer combination must be carefully selected. Müller-Buschbaum et al. [144] showed that blend composition has great influence on surface topography which is just one of the many factors that may affect the properties of the blend. Therefore, in the preparation of any blend, the selection of complementary polymers that will give the right kind of material hybrid with the required properties is the most important step. For a biodegradable polymer that will be green in all its ramifications, a blend of biopolymer material with a biodegradable counterpart is highly desirable. Among these, are: polycaprolactone, polybutylene succinate, etc. The use of blend started some decades ago [145], however, in the present day, the understanding of miscibility has undergone several changes [146]. The broad range of application of polymer materials requires varying properties according to the specific application area. With homopolymers, the range usually calls for special surface treatment or in some cases new polymer synthesis for each and every application. However, an economical alternative could be the preparing blends from specifically designated homopolymers [144].

5.3 Compatibilization

Compatibilization is described as the addition of a chemical substance to an immiscible or phase separated blend that help increase their stability. Compatibilizers are also referred to as coupling agents. They react at the interface of the blend to stabilize the phases. That is, they help to improve the compatibility between the two phases and increase miscibility [146]. The high interfacial tension caused by coalescence phase separated blends can be reduced by the compatibilizers, allowing a continuous flow of externally applied stress from the matrix to the fibers [130]. Compatibilization can be done by (i) introduction of specific interacting groups, (ii) in-situ polymerization grafting, (iii) addition of a ternary polymeric component, (iv) addition of block co-polymers of the blend polymers, (v) interpenetrating networks of crosslinked system and (vi) using reactive compatibilization methods [147–150]. For instance, polyhydoxyether of bisphenol A (Phenoxy: PHE) a non-reactive compatibilizer has been noted in some reports to have provided improved interfacial adhesion between immiscible and marginally compatible polymer blends [129]. Specifically, the addition of PHE to some polymers blends led to the blends yielding improved dispersion of the polymers within the blend, gave uniform injection molded surfaces and considerably increased the notched impact strength of the blends (polysulfone (PDF)/ABS; PSF/PA, PMMA/PA6 and PHE/PBT) [129, 151, 152]. Also reactive compatibilizers can be design to react with the fiber when introduced during processing. This method will involve modifying the fiber surfaces prior to the composite preparation. If successful, this method has the capability to improve interfacial interaction and subsequently improve mechanical properties.

5.4 Addition of nanoparticles

The use of nanoparticles to enhance the properties of NFPCs have been widely reported [99, 153, 154]. Nanoparticles are inorganic materials which possess a very high surface to volume ratio in which one or its entire dimension is less than 100 nm [155]. The addition of these nanoparticles influences the crystallization process during the solidification of the polymer composites leading to improved mechanical and thermal properties. These particles can be modified to selectively interact with a particular phase of the composites in a controlled manner [23, 156–158]. They can also be modified to act as a compatibilizer and react with both the matrix and the fibers to bring about good interaction and a better composite with stress transfer behavior.

Vargas et al. [159] reported the influence of nanofilters on some properties of polypropylene including mechanical properties. Their findings revealed that the nanofilters, in the presence of PP grafted MA, improved the tensile strength and Young's modulus properties which are indicative of the synergistic effect between the nanoparticles and compatibilizers. According to Lee and Youn [160], the addition of layered silicates worsened tensile properties of PP nanocomposites prepared by them. Similar investigation was presented by Rault et al. revealing that the addition of a maximum 1 wt% led to improvement in tensile properties but above the maximum, the silicate nanoparticle caused difficulties for processing the composites due to the formation of aggregates [161]. However, Joshi et al. [162] has reported improvement in tensile properties of PP/nanoclay composites. Therefore, we can conclude with certainty that there are other factors interfering in the positive influence expected from the addition of nanoparticle such as clay. According the Vargas et al. [159], fibers geometry plays a vital role in determining the composites eventual properties. Nanoparticles of different shapes and sizes were used to prepare polyamide 6 (PA6) composites in some research work conducted by Vlasveld et al. [163]. Their findings revealed that the rheological properties of the composites samples were highly dependent on the aspect ratio of the nanoparticle used. Therefore utmost care must be taken when the option of nanoparticles are being considered. Other nanoparticles have been used and their influence on the mechanical properties have been positive and very encouraging [164, 165].

5.5 Hybridization

Hybrid composites involve the combination of two or more different types, shapes or sizes of reinforcement in one composite material [166]. The hybrid composite properties have been reported to depend on many factors such as; fibers individual property, fiber-matrix compatibility, roughness of fiber surfaces, orientation of fibers and the extent of their intermingling [167]. Recently, investigations on the hybrid composites properties were based on the natural/synthetic fibers, natural/natural fiber and natural/synthetic/additive modified reinforced polymer composites. The popularity of these types of composites are increasing rapidly owning to their capability to provide freedom to tailor the composites and realizing properties that cannot be obtained in fabricated composites containing singular type reinforcement [21, 79].

Fiber-based hybrid composites have been reported to have improved properties compared with the unhybridized composites having single reinforcement [168–170]. Many research reports have shown that the addition of synthetic fibers at various amount to form hybrid fibers have composites of better-quality, especially in respect to their mechanical properties [171–179]. According to Ashik and Sharma [180], in one of their reviews, they listed some factors that may impact the mechanical properties of natural fiber hybrid polymeric composites, with the processing parameters featuring as one of the factors. Also, Nunna et al. [181] listed fiber content, fiber treatment, and the environmental conditions as some of the conditions that affect the properties of hybrid composites. For hybrid natural/synthetic fibers, it has been reported that as wt% of the synthetic fiber rises, the mechanical properties also rises. However, at a certain wt% of the synthetic fiber content added, the properties of the composites mechanical properties starts dropping and this may be ascribed to poor interfacial adhesion, high fiber-to-fiber contact, and poor wettability.

Mishra et al. [182] prepared hybrid glass fiber (GF) and pineapple leaf fiber (PLF) polyester composite with a total fiber content of 25 wt%. The tensile strength was observed to have increased as the GF was increased from 0 to 7.5 wt% to approximately 70 MPa, after which the strength started dropping. The flexural strength kept increasing as glass content increased from 4.3 to 12.9 wt%, in the hybrid biocomposite. The authors also prepared a similar hybrid biocomposite, but this time with 30 wt% total fibers (sisal and glass fibers). They reportedly observed a major improvement in tensile strength as the GF content was increased to 5.7 wt%. After this, the tensile strength was almost static even as the GF content was increased above this value. A similar trend was observed for the flexural strength. However, comparing the hybrid biocomposites with the biocomposites containing only pineapple or sisal fibers, the hybrid showed better improvement. Nevertheless, more evidence is available to show that the overall properties of hybrid composites depend greatly on (i) the percentage elongation at break and (ii) Young's modulus of the reinforcing fibers present.

Shahzad [183] presented the impact and fatigue properties of hybrid biocomposites of hemp and chopped strand mat glass fibers using unsaturated polyester resin as the matrix. Two different variations of hybrids composites were prepared. The first denoted with "A" containing 35.8 wt% hemp fiber and 11.1 wt% GF, while the second denoted with "B" had 36.6 wt% and 11.3 wt% hemp and glass fibers respectively. From the results, "A" had 70.1 ± 10.2 MPa, 8.3 ± 0.4 GPa and 1.31 ± 0.25% for tensile strength, Young's modulus and strain to failure respectively, while "B" showed 81.6 ± 3.7 MPa, 7.7 ± 0.3 GPa and 1.73 ± 0.08% for tensile strength, Young's modulus and strain to failure improvement respectively when compared with biocomposites reinforced only with hemp fibers, having

46.4 ± 4.6 MPa, 7.2 ± 0.9 and 1.03% respectively. The increase in the percentage of GF led to the observed increase in tensile strength and better strain to failure in "B" as compare to "A." The hemp fiber is a low strain to failure fiber while the glass fiber is a high strain to failure fiber. Their combination, leads to enhance strain to failure composites. This is referred to as "hybrid effect" and it has being well observed in hybrid composites. Therefore the increase in strain to failure of the hemp-glass fiber composites can be attributed to the hybrid effect. Also, there was an observed improvement in the fatigue strength of hybrid biocomposites while the fatigue sensitivity showed no improvements when compared to hemp only fiber composites.

Hybrid of glass/natural fibers have been reported to have improved impact, tensile and flexural strength [182]. Furthermore, Velmurugan and Manikandan [184] reported that good strength, especially mechanical strength is achieved when the synthetic fiber is placed at the ends of the composite for laminated composites.

In another research work, Ahmed and Vijayarangan [185] prepared composites with jute only and jute/glass fibers hybrid reinforced polyester composites, keeping the total weight fraction of fibers constant at 42 wt%. From their results, the composites consisting of 40:60 ratio of jute:glass fibers, the reinforced hybrid laminate gave an increase in the tensile strength, Young's modulus, flexural strength and flexural Young's modulus of 53, 30, 31 and 62% respectively over those of the jute only fiber composites. They further indicated that in the event properties, environmental impact and costs were to be considered, composites with 60:40 fiber fraction of jute:glass fibers ratio gave optimum material combination. This clearly highlights that the type of matrix and/or fiber, method of preparation, fiber content and fiber modification have a huge impact on the mechanical properties of hybrid biocomposites.

5.6 Other factors

In the preparation of NFPCs, there are many other additives or processes that can also influence the final properties of the composites but are seldom considered, for example impurities in the polymer matrix are introduced via fibers addition. These elements can influence the process of crystallization, just like the nanoparticles, although, this depends greatly on their chemical nature. Also it is worthy to mention that the annealing of the composites allows the crystals to grow to their maximum size. Thus, the temperature at which the materials are annealed is also very influential to the final properties of the composite obtained. Therefore from the selection of materials to the final product, care must be taken to achieve the properties desired.

Liu et al. [186] assessed the influence of processing method on the physical properties, especially mechanical properties, of kenaf fiber reinforced biocomposites prepared using soy fiber. The compression molded specimens were observed to have similar Young's modulus to those from injection molding at room temperature. However, at elevated temperature, the heat deflection temperature (HDT) and notched Izod impact strength were higher compared to those obtained from injection molded specimen. The improvements observed with the compression molded samples were attributed to a surge in Young's modulus at high temperature and fiber bridging effects.

Generally, biomedical applications desire for fabrication of grafts which are biocompatible and enable cell differentiation and expression with apt mechanical properties, but the ability to achieve such mechanical capacity has been a challenge for decades. As over the years, the focus and efforts have been geared towards biocompatibility and not necessarily mechanical prowess. But the formation of stresses occurring in implant locations due to mechanically inept implant materials have

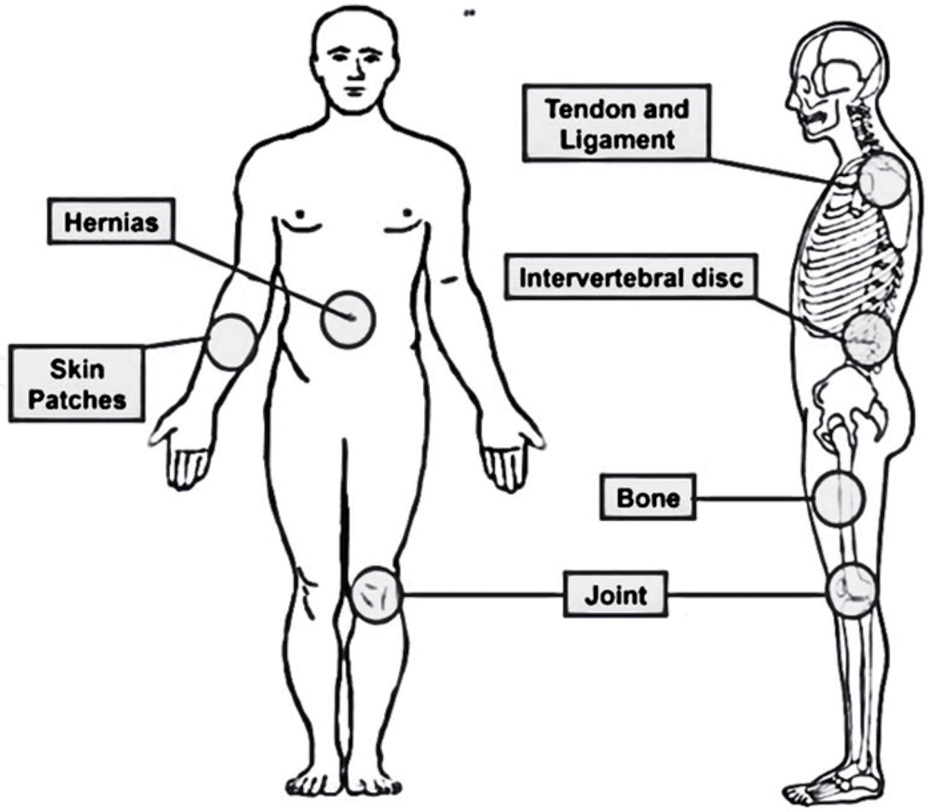

Figure 2.
Illustration of potential application of collagen fibers embedded in a hydrogel bio-composite for medical applications with adjusted mechanical properties that provide support and allow motion and flexibility of the tissue under repair [187].

No.	Patent title	Patent no.	Year
1.	Medical balloon with incorporated fibers	W0/2013/148399	2013
2.	Polyester cool-fiber antibacterial pillow	CN102715804	2012
3.	Medical natural porous fiber filler and vacuum sealing drainage device thereof	CN102715983	2012
4.	Manufacturing process of antibacterial bamboo pulp used for high-wet-modulus fiber	CN102677504	2012
5.	Flushable moist wipe or hygiene tissue	CN102665510-	2012
6.	Far-infrared fiber fabric functional bellyband by utilizing nano-selenium, germanium and zinc elements traditional Chinese medicine	CN101703317	2010
7.	Medical device for insertion into a joint	US20090234459	2008
8.	Medical device for insertion into a joint	EU1896088	2008
9.	Antiviral fiber and producing method and use thereof	CN1609336	2006
10.	Manufacturing of nano-fibers, from natural fibers, agro based fibers and root fibers	CA2437616	2005
11.	Natural antibacterial material and its use	CN461827	2003
12.	Absorbable protective coatings for wound with the use of sponge and process for producing the same	W0/20021054998	2006
13.	Medical prosthesis, especially for aneurysms, with a connection between its liner and its structure	EPOB18184	1998

Table 1.
Summary of some patents published employing nature fibers for biomedical applications (adapted from Namvar et al. [188]).

led to numerous implant failures and lead to investigations to improve mechanical properties of biomedical devices for diverse applications (**Figure 2**).

There have been quite a number of patents registered over the years of researchers employing natural fiber for biomedical applications and **Table 1** presents a summary of some of these patents.

6. Conclusion

The natural fiber polymer composites have gained a lot of ground in terms of acceptance and applications. For these interests to increase continuously, the materials must be designed to meet certain requirements for their specific applicability. For structural applications, the most important property that is of concern is the mechanical properties as they help to predict the behavior of the materials under stress. As discussed in this chapter, NFPCs are being applied in the building and construction works, automobiles, aerospace, packaging, electronics and biomedical devices. The mechanical strength and toughness require by these various industries are quite different and can vary widely from one application to another. Even though the mechanical requirement varies, the factors that determine the mechanical properties are the same. These factors include type of fibers used, source of the fibers, surface treatment and modification carried out on the fibers, type of polymer matrix used (pristine and blended), type of fiber-matrix bond formed, and the internal arrangement which depends on the type of curing treatment after processing or annealing. In addition to this list are the fiber length, fiber orientation and distribution, fiber loading or volume faction, the type of functionality present and the extent of modification. All these factors can be manipulated to give a combination of the right measure of mechanical strength and stiffness or toughness required for the application it is being designed for. The use of compatibilizers and nanoparticles to modify the composites for specific purpose has been widely reported to improve the mechanical properties as well, but proper integrations must be considered. Furthermore, the use of hybrid fibers has also gained wide acceptance because of the improved stiffness and strength owing to the synergy observed in such fiber combination. The possibilities of NFPCs can be best imagined with the right improvement in their mechanical properties and this chapter has highlighted some of these benefits as presented by numerous research investigations across diverse fields.

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Author details

Owonubi J. Shesan[1*†], Agwuncha C. Stephen[2†], Anusionwu G. Chioma[3], Revaprasadu Neerish[1] and Sadiku E. Rotimi[4,5]

1 Department of Chemistry, University of Zululand, Kwadlangezwa, KwaZulu-Natal, South Africa

2 Department of Chemistry, Ibrahim Badamasi Babangida University, Lapai, Nigeria

3 Department of Applied Chemistry, University of Johannesburg, Johannesburg, South Africa

4 Department of Chemical, Metallurgical and Material Engineering, Tshwane University of Technology, Pretoria, South Africa

5 Institute of Nano Engineering Research (INER), Tshwane University of Technology, Pretoria, South Africa

*Address all correspondence to: oshesan@gmail.com

† These authors contributed equally.

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